

The background of the entire image consists of a dark, abstract geometric pattern of facets and shadows, resembling a stylized architectural or crystal structure.

The Virtual and the Physical

Between the representation of space and the making of space

A. Benjamin Spaeth
Wassim Jabi

eCAADe RIS 2017

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A. Benjamin Spaeth, Wassim Jabi

Welsh School of Architecture, Cardiff University, Wales, United Kingdom

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The Virtual and the Physical

Between the representation of space and the making of space

The realm of computation in architecture extends from the virtual representation of space through to its physical making. Beyond the visualisation of space we are concerned with the different models of space to explore and uncover its relevant properties. At the symposium we explored the dimensions of space beyond its physical existence and tried to understand the implications of computation in architecture on social, political and environmental discourse.

At the other end of the spectrum computation in architecture seeks to optimise, automate and integrate effective methods and concepts into architectural production. Through biomimicry/biophilia and material computation, we explore alternative approaches to spatial construction. We are interested in the gravitational field between the aforementioned extreme ends of computation in architecture. At the symposium we intend to uncover how computation in design and fabrication influences our understanding of space and, reciprocally, how the computational representation of space impacts the production of architecture. We aim to reach to the extremes of the spectrum of architectural space to critically speculate about its creation in theory and practice.

We called for academic papers, practical work or design propositions that engage with the transition from the virtual to the physical, or vice versa and that explore the realm between the representation of space and the making of space. We are interested in how we represent architectural space and its manifold diversity of social interactions, economic determination, environmental impacts, functional requirements and spatial quality to make it available and impactful on computational design processes.

Some questions include: How does architectural space manifest itself in built shape and solid form? How do we represent non-geometrical parameters to find their role in the design process? How do we account for spatial quality to be sustained during computational design procedures? Where do we integrate potential social interaction and functional interconnection in the various design systems? What are the driving forces of architectural design computing?

Apparently these questions exist in academia but they are increasingly infiltrating architectural practice. The question of what and how and who is influencing and controlling the design process is increasingly pressurising the practicing architect. Is the academic promise of computationally-driven design really viable in practice? Is robotic fabrication an alternative way for mass customising building elements in a cost-effective way? How is virtual reality supportive in the daily design routine of architectural practices? What are some of the viable procedures to transform the virtual representation of space into the physical space of a building? What material properties impact the fabrication process and become manifest in the design system?

Evidently the advances in integrating computation into architectural design and production has a vast influence on how we educate future architects at our universities. We are interested in how education has changed. We want to discuss how methods of learning and teaching have changed, what content has been added to curricula and what impact this might have had – and will have - on the understanding of pedagogy, architecture and computation.

A. Benjamin Spaeth
Wassim Jabi

Acknowledgments

We, the organisers of the 5th eCAADe Regional International Symposium (RIS2017), are grateful to the many helping hands who made it possible for us to bring people from different parts of the world together at the Welsh School of Architecture (WSA) in Cardiff to share and discuss their latest research in computational architecture and design.

We want to thank Joachim Kieferle, President of the eCAADe, for trusting the organisation of the RIS2017 to us at the WSA. The intellectual and practical support by Jose Manuel Pinto Duarte, Bob Martens, Henri Achten and Nele de Meyere was greatly appreciated.

We are extremely grateful for the outstanding web-based services provided by Martin Winchester, Gabriel Wurzer and Wolfgang E. Lorenz in handling the paper submission, including their peer-review and editing the proceedings.

At the Welsh School of Architecture we received generous support from Chris Tweed, Head of School, whose trust in our acquisition and running of this symposium at Cardiff has, we hope, been borne out in its success.

Among the many people at WSA who supported the RIS2017, we want to mention Alicia Nahmad Vazquez for her indefatigable engagement: initialising, organising and coordinating the "Frictional Assemblies" workshop.

Last but not least we want to thank the eCAADe for providing basic funding for the symposium. Without the financial support this symposium would not have been possible.

Organising committee

A. Benjamin Spaeth, Chair

Wassim Jabi, Chair

Janice Joyce, Web Design, Graphic Design

Alexander Opoku, Graphic Design

Kate Nash, Facilities Management

Annie Golledge, Facilities and Financial Management

Samantha Johnson, Finances

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Alicia Nahmad Vazquez, Workshops Organisation

Wassim Jabi, Robotic Lab Supervision

Dan Tilbury, Wood Working Workshop

Nikolina Georgieva, Registration Management

Scientific Committee

The eleven papers presented in this volume have gone through a double blind review by a scientific review committee consisting of distinguished academics in the field of computation in architecture as well as practitioners who apply computational methods in their architectural work.

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Elif, Erdine, Architectural Association (AA) School of Architecture, United Kingdom

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Uwe, Woessner, HLRS, University of Stuttgart, Germany

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Henri, Achten, Czech Technical University in Prague, Faculty of Architecture, Czech Republic

Wolfgang, Lorenz, Vienna University of Technology, Austria

Wolfgang, Dokonal, TU Graz, Austria

Keynotes

Urs Hirschberg

Urs Hirschberg is Professor for the Representation of Architecture and New Media at Graz University of Technology, Austria and Head of the Architecture Faculty's Institute of Architecture and Media (IAM). Having served as Dean of his Faculty for nine years, in 2013 he was appointed Director of the TU Graz Field of Expertise "Sustainable Systems", one of the University's five interdepartmental research fields.

Born and raised in Switzerland he holds an Architecture Diploma and a Doctorate from ETH Zurich. Before joining TU Graz he served as Research Assistant and Lecturer at the Chair of Architecture and CAAD at ETH Zurich and then as Assistant Professor of Design Computing at the Harvard Graduate School of Design. His research interest is Augmented Architecture: to explore the ways in which the use of new media can enhance architectural design and production and augment our built environment. Digital fabrication in research as well as in studio teaching has been a primary focus of IAM. Hirschberg is a founding editor of GAM, the Graz Architecture Magazine. A former president of the European Association of Architectural Education he is a founding member of the European Architectural Research Network ARENA and a Technology Editor at AJAR, the Arena Journal of Architectural Research.

Robert Aish

The influence of representations, operations and interaction on design

Robert Aish is Visiting Professor of Design Computation at the Bartlett School of Architecture, University College London.

Over the last four decades, Robert Aish has played a pivotal role in the development of new computational technologies in architecture. As Director of Software Development at Autodesk, he led the recent development of the 'DesignScript', a special end-user programming language for architectural computation. At Bentley Systems he led the development of 'GenerativeComponents', which was used in the design of the Velodrome at the 2012 Olympics. He is cofounder of the SmartGeometry group, and through his

teaching and publications, he has helped to create a vital bridge between architectural research, education and practice. Robert Aish studied Industrial Design at the Royal College of Art and has a Ph.D. in Human Computer Interaction from the University of Essex.

Michael Weinstock

The City and the Future – Dreams, Speculations and Projections.

Michael Weinstock studied Architecture at the Architectural Association 1983-1989 and has taught at the AA School of Architecture since 1989 in a range of positions from workshop tutor through to Academic Head. Whilst his principal research and teaching has been conducted at the Architectural Association, he has published and lectured widely, and taught seminar courses, studios and workshops on Emergence, Evolutionary Computation, Design through Production and other associated topics at many other schools of Architecture, in Europe including Delft, Rome, Barcelona, Vienna and in Stuttgart; and in the US at Yale, Berkeley and Rice.

His research interests extend from his published research into the dynamics, forms and energy transactions of natural systems, and the abstraction and systematisation of knowledge of biological morphogenesis and evolution to contribute to innovative computational processes of architectural design and materialisation. His current work is focused is on developing new paradigms for sentient cities in extreme climates and ecological contexts.

Workshops

Frictional Assemblies

This workshop extends ongoing design research in the area of compressive structures and digital form-finding methods by exploring how frictional forces between components contribute to static equilibrium. Design attention will be focused on the interface between discrete elements calling into question issues of component geometry and surface quality which will be investigated through robotic fabrication methods. The workshop will examine

the use of cork as a potentially productive material within the context of compression structures. Its high durability and friction combined with its low density will enable careful articulation/calibration of component-component interfaces with respect to varying physical demands within the proposed structure. This investigation will be formatted as a collaborative design-build exercise culminating in the production of a sizeable prototype. In addition, participants will explore the design space of compression structures using provided methods and tools while speculating on alternate materialisations/tectonic strategies.

Instructors:

Vishu Bhooshan

Vishu Bhooshan currently works as a senior designer at Zaha Hadid Architects as part of the Computation and Design (ZH CODE) group at London.

He completed his bachelor degree from Pune, India (2010) and completed his Master's degree at the Architectural Association, Design Research Lab (2013). He previously worked as an architect in India at B.S Bhooshan & Associates, Mysore & Mindspace Architects, Bangalore.

His research focuses on topology optimisation, development of tools using statistical learning methods to predict structural and material optimization results in the early design pipeline and development of computational design tools using the current 3D printing fabrication methodology as a constraint. He has taught and presented/published work at various workshops, professional conferences and symposiums including ACADIA, simAUD, AAG, AAVS Global Summit and at various institutes in India including Anthropology Institute of India Mysore, College of Engineering Trivandrum.

David Reeves

David Reeves is a designer, programmer, and researcher currently working at Zaha Hadid Architects as a member of the Computation and Design (ZH CODE) team. His research focuses on the application of numerical methods within architectural design modelling. Specifically, he is interested in how such methods can facilitate the exploration of novel

solution spaces by augmenting the designer's ability to negotiate large sets of highly coupled design criteria.

David currently teaches within the Design Research Lab (DRL) at the Architectural Association. Previously, he has taught and presented work at various institutions including The Bartlett, CITA, Aarhus School of Architecture, Yale University, and University of Toronto. His work has also been published and presented at a number of conferences and events such as Acadia, SimAud, IASS, and Smart Geometry.

BIM + VR: Real-time Visualization and Interaction

In this workshop, we will explore how BIM models can be visualized in an interactive VR environment. The participants will get a hands on course on how to prepare 3D models for interactive presentations directly through Revit or by using 3DStudio MAX. Beyond the visualization, we will look more specifically at which interactivities are needed in Virtual Environments and how they can be prepared in the basic model.

In the workshop, a temporary powerwall will be installed to experience the projects directly in 1:1 scale. Participants will learn of some of the benefits of using powerwall stereo projection compared to other VR devices, such as head-mounted displays (Oculus Rift, Gear VR and others).

The course is focused on practitioners - from architecture offices as well as construction companies – who can explore their current projects, but will also be of use to students and tutors by enabling them to visualize their studio projects and gain experience or improve their skills in Virtual Reality and the BIM – VR link.

The VR software used in the workshop is COVISE/OpenCOVER, which is available as opensource.

Instructors:**Joachim Kieferle**

Since 2002 Joachim Kieferle is Professor for Computer Aided Design and Digital Fabrication at the RheinMain University of Applied Science in Wiesbaden Germany.

Uwe Woessner

Since 2004, Uwe Woessner has headed the visualization department at HLRS. He received his PhD in Mechanical Engineering from the University of Stuttgart in 2009. Since 1996 he has been working in the Collaborative Research Centre “Rapid Prototyping” established at the University of Stuttgart in the field of VR-based virtual and augmented prototyping. His current research interests include collaborative virtual environments for scientific visualization, Augmented Reality, 3D user interfaces and interaction techniques for computational steering. He is on the committee of several VR and 3D User Interface-related conferences, such as IEEE VR, IEEE Vis, EuroVR, and GI VRAR.

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Spatial Representation

Graphical Representation of Sonic Urban Morphologies

Simulation Interface for the Design Process

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Although the interdisciplinary field of Soundscape was originally intended as a paradigm-shift for urban design, the process of designing the aural spatial signature of urban open spaces has not yet been made readily accessible to the designer in modes that align with architectural design procedures. This paper is part of an on-going investigation (Barakat, 2012; 2015; 2016a; 2016b) with the primary objective of developing a computational tool that generates qualitative aural spatial patterns and predicts the perceived aural spaces within an urban environment. The ultimate goals are to provide a spatial designer with 1) good estimated predictions of the patterns generated by the design, and 2) feedback for possible spatial alterations. To that end, this paper discusses the graphical representations of the mapping tool that are mediated by standard architectural processes and visual representation standards. These methods aim to show the spatial formation of the separate acoustic spaces that are centred on possible foreground signals, occurring within urban spaces.

Keywords: *Urban Design, Soundscape, Simulation, Architectural Visualisation , Computation Design*

INTRODUCTION

Every urban space has a unique aural signature and is part of a hierarchical meta-system of acoustic spaces. The aural signature is a result of the distribution of sonic events within a space that create an aggregate of acoustic spaces at different scales, ultimately creating a sound environment. Evidence suggests that fidelity of aural stimuli is a significant parameter in creating an accurate spatial mental map of the surrounding environment. The field that is concerned with the acoustic qualities of urban spaces is the interdisciplinary field of *Soundscape*. Soundscape, as a

field and a term, was originally defined as a relationship between the human ear, sonic environment and society, and was intended to be an integral part of urban design. The concept is based on physical parameters as well as on the perceptual and cognitive restrictions.

Spatial designers lack adequate design concepts, metrics and tools to integrate acoustic sensory aspects into the design process of urban spaces. Practicing architects have not developed a basic intuition of how sound behaves in a space, and they rely on acoustic specialists when considering sound in the

design. Architectural training does not incorporate an understanding of the fundamentals sound phenomenon and cannot predict these aspects during the preliminary design process. Among these lacking concepts is the fundamental properties determining the behaviour of sound in space, and the measurable auditory response phenomena.

A number of commercial packages and sound distribution models are available for acoustic engineers. While highly quantitative, the available acoustic platforms are highly technical and the associated interfaces are designed for sound specialists. At the scope of soundscape that integrates multiple specialties, there is an issue of inconsistency. Kornfeld et al. state that there is a "*shortage of appropriate tools supporting an interdisciplinary discourse about the sonic environment*" (2011, p. 29). Multiple domains develop individual means of urban sound description that have created different visual "languages." Kornfeld et al. further point out that the various approaches are "[incompatible] means that, when it comes to an exchange of perspectives, interdisciplinary discourse is difficult...[However], appropriate tools for supporting this activity do not exist" (2011, p. 14). Architects and urban designers use plans, sections and CAD models to coordinate with different consultants, and the client, but there are no available platforms for integrating soundscape design without entirely referring to a sound specialist.

The majority of the models simulating urban sound propagation consider the acoustic index of Sound Pressure Level (SPL) distribution in the field. This concern is of significance because it disregards the frequency dependent indices that are critical when considering more than one source. Indeed, in his recommendations, Kang indicates that some of the "*challenges in the simulation of urban sound propagation [is] consider[ing] more sound sources. Much work has been done for traffic sources, but very limited work has been done for other sources, especially positive sources [and] more calculation indices are needed, in addition to simple SPL*" (2011, p. 2364).

This paper discusses the in graphical interface

aspect of an on-going investigation (Barakat, 2012; 2015; 2016a; 2016b) that has a primary objective of developing a computational simulation tool for urban design that generates qualitative aural spatial patterns and predicts the perceived aural spaces within an urban environment. The investigation is founded on establishing a relationship between aural architecture theories and the urban spatial experience and design. It also explores the merging of spatial and acoustical computational approaches, through integrating the physical/mathematical representation of sound to the mapping of the spatial envelopes and phenomena of human aural responses. The aim is the development and calibration of a computational design and decision-aiding tool that can predict qualitative patterns of aural spatial perception, and translate them into spatial attributes within a modelled urban space. The fields of computation simulation, soundscape, and psychoacoustics inform the structure of the tool development.

The tool produces spatial patterns as representations of the distribution of sound energy of predicted acoustic spaces and the intermediary domains between them. The tool structure is built as a JAVA-Based program. The system is designed as a Multi-Agent Based (MAB) deterministic system. The ultimate goal of the aural mapping tool is to provide a spatial designer (architect, urban or event designer) with 1) good estimated predictions of the patterns generated by the design, and 2) feedback for possible spatial alterations.

To that end, this paper discusses the graphical representations of the mapping tool that are mediated by standard architectural processes and visual representation standards. The discussion presents the assimilated nomenclatures, corresponding definitions considered within this scope that is informed by the interdisciplinary psychoacoustic, soundscape research, and architectural practice. The use of the tool is explained in the form of schematic illustrations. The explanation also includes how the user, i.e., architect, urban and/or event designer, can operate this tool, and what decision-making aspects to

expect.

ASSIMILATED SEMANTICS

As a relatively new domain, the soundscape terminology has yet to be conclusively defined, necessitating explicitly stating which terms pertain to this research and the associated definitions. The spatial terms are assimilated from soundscape literature (Truax 1999), including soundscape ecology (Farina 2014) and aural architecture (Blesser and Salter 2007). Given the spatial character of this research and the need for quantifiable spatial factors, this study is aligned with the definition provided by Genuit and Fiebig (2006). They define soundscapes as domains that “consist of a number of spatially distributed sound sources, which give the soundscapes their distinctive features” (2006, p. 953).

Genuit and Fiebig’s (2006) definition allows this research to map the aural spatial patterns at a microscale urban space. The focus is on the foreground signals that are immediately located on site. Signals that are beyond the perimeter of the considered urban space are reduced to background signals with a particular sound level.

The terms *receiver* and *sensor* refer to a human listening/perceiving the sonic environment. The mapping tool designates agent systems to simulate human response, namely the *Sensor Agent*. The considered foreground signals are denoted as *sonic events*, *sound sources*, and *signals*. These terms refer to the events emitting a signal that are located within the urban space. The simulation engine reduces the events (or objects) to point sources, namely *Sonic Event Agents*. If the distance between a receiver and a sonic event allows the listener to detect and distinguish the signal, then an *auditory channel* forms. The level of information determines the strength of that channel. A receiver can be connected to multiple channels. An auditory channel can be disconnected for various reasons, including an increase in distance, other competing channels, the presence of a stronger channel connection, and the diversion of the listener’s attention (1999). The simulation engine

is only concerned with the strongest receiver-signal auditory channel.

Truax (1999) presented the term acoustic space. Blesser and Salter (2007) adapted the idiom for aural architecture as an acoustic arena. A similar concept is known in the field of soundscape ecology, known as a patch (Farina 2014). These three terms refer to the area of space where a sonic event can be cognitively de-coded, and it is centred on that event. An acoustic arena is delineated by the human response to frequency dependent parameters, including the auditory threshold, and attention and spectral masking. In the presence of multiple adjacent sonic events, a number of auditory channels are connected to the receiver, and the associated acoustic arenas ‘overlap.’ In that intersecting domain two conditions may occur: 1) the strongest auditory channel severs the other weaker connections, or 2) all connections are of equal strength negating each other. In the former case, the receiver is considered in the arena associated with the strongest auditory channel and the emitting signal is considered dominant. In the latter case, the receiver is not connected to an auditory channel. The receiver may be counted in the edge domain. Edge is a term assimilated from the patch-edge epistemological concept (Farina 2014).

As an extension of Genuit and Fiebig’s (2006) definition of soundscape, *soundscape patterns* may be regarded as the spatial morphologies mediated by the acoustic arenas (or patches) centred on the spatially distributed sonic events, and the edges forming between them. Since the event spatial distribution distinguishes the features of the soundscape, each soundscape would have a characteristic morphological pattern.

GRAPHICAL REPRESENTATIONS ELEMENTS

The aural mapping tool uses architectural visual symbology to represent the resulting sonic morphology. Line-weight, hue, alpha, saturation, and ‘red-lining’ are used as analogies for absorption coefficient, spectrum, energy levels, boundaries, and decision-

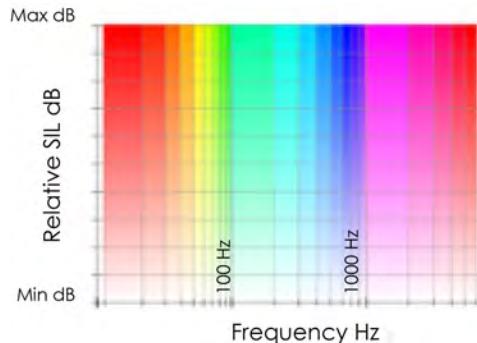
making feedback, respectively. These methods aim to show the spatial formation of the separate acoustic spaces that are centred on possible foreground signals, occurring within urban spaces.

Frequency Spectrum | Hue & Energy Level | Alpha channel

"Frequency of a sound is the number of complete vibrations (cycles) occurring per unit time (seconds)." [Measuring unit: Hertz (Hz)] (Cavanaugh and Wilkes 1999, p. 321)

Frequency is one of the wave based properties that distinguish every signal (Turner and Pretlove 1991). Hearing adults can detect sounds between 20 and 16,000 Hz. Hearing sensitivity is frequency dependent. The human response to frequency is evident in multiple psychoacoustic phenomena, such as loudness and masking, that defines the audible threshold of the associated frequencies (Vorländer 2008). Two signals sharing the same SPL but have different frequencies will not have equal perceived loudness (Kuttruff 2007).

The proposed graphics use hue and alpha values to represent frequency and detected energy contribution, respectively. The colour key in Figure 1 shows the audible frequency range (20 Hz - 16 kHz) mapped logarithmically along the hue spectrum. The first red (hue= 0°) and the second (hue = 360°) represent 20 Hz and 16 kHz, respectively. Any parameter related to a signal is assigned a colour corresponding to that frequency.



"The unit Decibel (dB), which is one-tenth of a Bel, is a logarithmic (to base 10) unit used to measure a ratio that may be represented by power, sound pressure, voltage, or intensity." (Farina 2014, p. 229)

The human internal ear system perceives acoustic attributes similar to dB logarithmic scale. Therefore, dB is a measuring unit relative to the human perception of sound energy (Farina 2014). Although human physiology is sensitive to small changes in pressure, a linear change in intensity is undetectable (Cavanaugh 1999). For example, a difference in SPL of 1 dB is barely detectable in a controlled laboratory environment. Only with a shift of 3 dB, can a person perceive a difference in level.

"Sound pressure level (SPL, Lp) is a logarithmic measure of the effective sound pressure of a sound relative to a reference value ($2 \times 10^{-5} \text{ N/m}^2$)." [Measuring unit: decibel] (Farina 2014, p. 227)

The minimum value of SPL on the decibel scale, 0 dB, is set as a reference pressure level Pref value of 2×10^{-5} Pa. This reference pressure level corresponds to the threshold of hearing for a typical healthy young person (Cavanaugh 1999). The decibel scale translates indices to manageable units that are related to human perception. This is beneficial for manual calculations. In computation, it seems more manageable to remain within the linear scales and maintain the input and output interface as converted dB values. Accordingly, the tool computes the energy on a linear scale and uses the decibel scale in the user interface, including the graphical representation of the

Figure 1
A hue and alpha mapping key of frequency and energy contribution, respectively. The key is generated by an auxiliary JAVA code using the same colour code methods embedded in the system.

Figure 3
Wall line weight representation according to the absorption coefficient.

detected relative energy distribution.

Detected relative energies are mapped to the alpha channel. An entirely opaque colour that is usually adjacent to a sonic event represents the maximum relative energy contribution. The transparency is an indication of a decrease in energy distribution within the patch domain. Fully transparent (or white) regions represent the edge condition, where the energy values may be below the auditory threshold and ambient levels. The edge condition may represent a case where two energy levels are detected at the same magnitude, or the difference between contributions is less than 10% of the highest contribution.

It is worth noting here that the absence of colour does not mean the absence of sound. It is an indication of absent auditory channels due to conflicting foreground signals. An edge condition may also occur if the value of energy contribution is lower than the energy of the background signals or the audible threshold. Figure 2 is a schematic diagram that shows the attenuation of the relative energy contribution and the maximum distance of energy detection. The outermost contour is considered the sphere of influence of the sonic event agent, which is similar to the MAB concept of an acoustic arena.

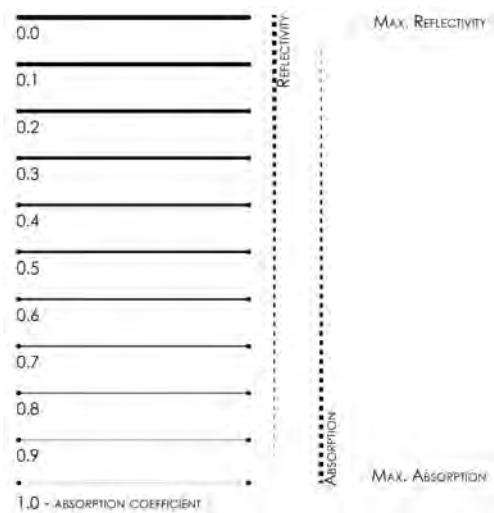
Absorption Coefficient | Line-weight

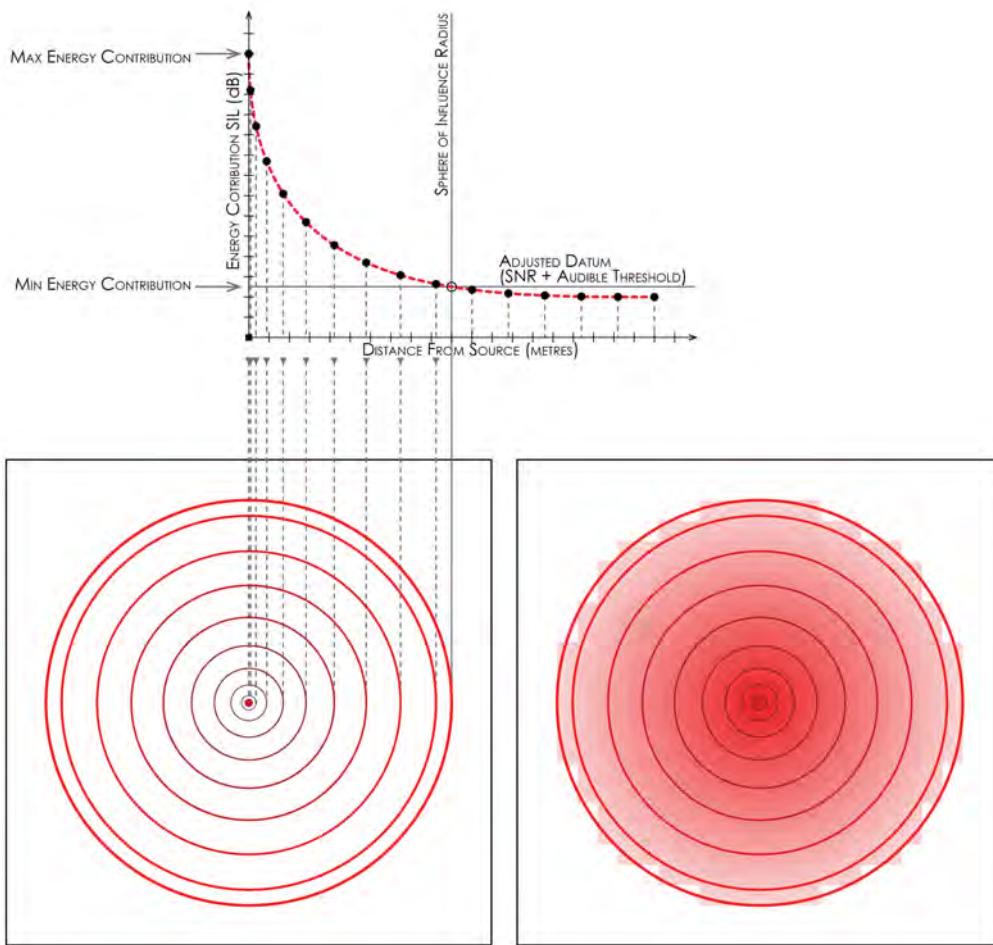
Soundwave reflection occurs when an acoustic wave impinges on a boundary between the air and another medium. When a wave falls on a boundary, the energy is partially reflected, partially absorbed and partially transmitted. In the case of a perfectly reflective wall, all sound energy is reflected with no depreciation, whereas a perfectly absorptive surface reflects no energy. Perfect reflective and absorptive surfaces do not exist in reality (Kuttruff 2007).

"Absorption coefficient α is the ratio of sound-absorbing effectiveness (at a specific frequency) of a unit area (m^2) of acoustical absorbent to a unit area (m^2) of a perfectly absorptive material, usually expressed as a decimal value between 1.0 (perfect absorption) and 0 (perfect reflection)." [A non-dimensional a ratio] (Cavanaugh and Wilkes 1999, p. 324)

The absorption coefficient is one of the principles governing the behaviour of a sound wave at the surface of a wall. It is a fraction of the incident energy not reflected from or transmitted through the surface (Kuttruff, 2007). Sound reflection, transmission, and absorption are frequency dependent (Kang 2007). In practice, material manufacturers produce absorption specifications manuals for their products in the form of a table of coefficients corresponding to each frequency band (Cavanaugh 1999).

Among the graphics that are designed to integrate standard architectural language is line-weight. The aural mapping system accepts an architectural model as an input, and the walls are inserted with the values of the absorption coefficients corresponding to each frequency band. The simulation environment is set up to show black walls against a white background. In architecture, the visual opacity of a wall is represented as line weights. This simulation engine uses the same concept to translate the reflectivity of the wall ($1 - \alpha$); i.e., the higher the absorption coefficient (low reflectivity) the thinner the line representing the wall, as schematically shown in Figure 3.





Different line weights are also used to represent the acoustic space contour levels but in reverse. The thickest line represents the outermost contour that signifies the lowest detected contribution. Figure 2 shows that the exterior contour indicates the ‘wall surface’ of that acoustic patch; the figurative ‘wall’ is the patch boundary.

'Red-lining' | Feedback

The concept of ‘redlining’ is a customary procedure in architectural practices, where an architect indicates revisions with a red pen. This simple function is designed to perform a similar indication. Although the designer would find the graphical representation of the energy distribution informative, it can be argued

Figure 2
Schematic Diagram
of the
representation of
the relative energy
contribution. (Top)
A Schematic graph
of energy
attenuation
according to the
inverse square law.
The adjusted datum
mediates the
maximum and
minimum
contribution. The
minimum
contribution
delineates the
sphere of influence.
(Bottom Left)
Contours generated
representing
attenuation of
detected energy
(Bottom Right).
Contours
superimposed on
energy detection
represented using
the alpha channel
(red gradient)
and the lack of energy
detection (white).
The sphere of
influence is the
outermost contour.

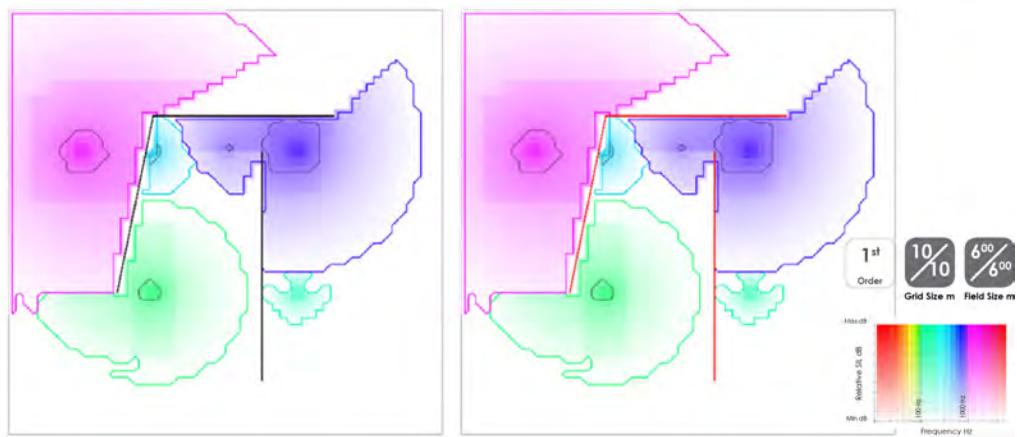
that only the outermost contour is of significance. *This isoline determines the area and configuration of the patches and the edges between the considered domains, which is the primary goal of this design tool.* In addition, the redline mode simulates energy distribution adjusted according to the A-weighting networks that mimics the frequency human response and does not follow the inverse square profile. The weighting significantly changes the contributions detected by the sensors, and the isolines graphically overwhelm the field.

To that end, the principle isoline that is considered in this mode is the outermost isoline. The area of that domain is measured and compared to the initially designed program area designated for each sonic event. If there is a discrepancy (i.e., the arena area is larger than the program area), the colour of the walls affecting the patch configuration 'red line' (or flag) possible walls to be altered, prompting the designer to revise the configuration of the location, materiality, and orientation, as shown in Figure 4 [Right].

ARCHITECTURAL DESIGN APPLICATION

Public squares are good examples of special use projects. A client (usually governmental entities or private developers) may approach a designer soliciting recommendations on adding events, providing

Figure 4
Calibration test run output patterns for a simulation that consider A-Weighted sonic events in normal (left), and redline (right) mode.



entertainment and services for the community, or reviving the economy of a certain district. These types of projects are normally complex, and multiple parameters are simultaneously considered to find optimum solutions. For example, designing the outside space considers the occupants of the enveloping buildings, who have a direct connection with the square and are the first to benefit from (or disturbed by) the interventions.

Large projects require a collaborative team of landscape and urban designers, planners, architects and event designers. Different specialists are consulted and incorporated into the team at later stages of the project depending on the budget and the type of client. Unless a large multidisciplinary firm is commissioned to conduct the project, the team is usually lead by one of the spatial design specialists. This person handles communications with the client and coordinations between specialists to meet that client's goals.

Figure 5 is a square scheme selected for a series of vignettes that assume the spatial designer is conducting a preliminary design within a small firm before potentially taking on the project and assembling a team of experts. The scale of the project dictates the amount of time the designer is allowed before the client selects a different office that is usu-

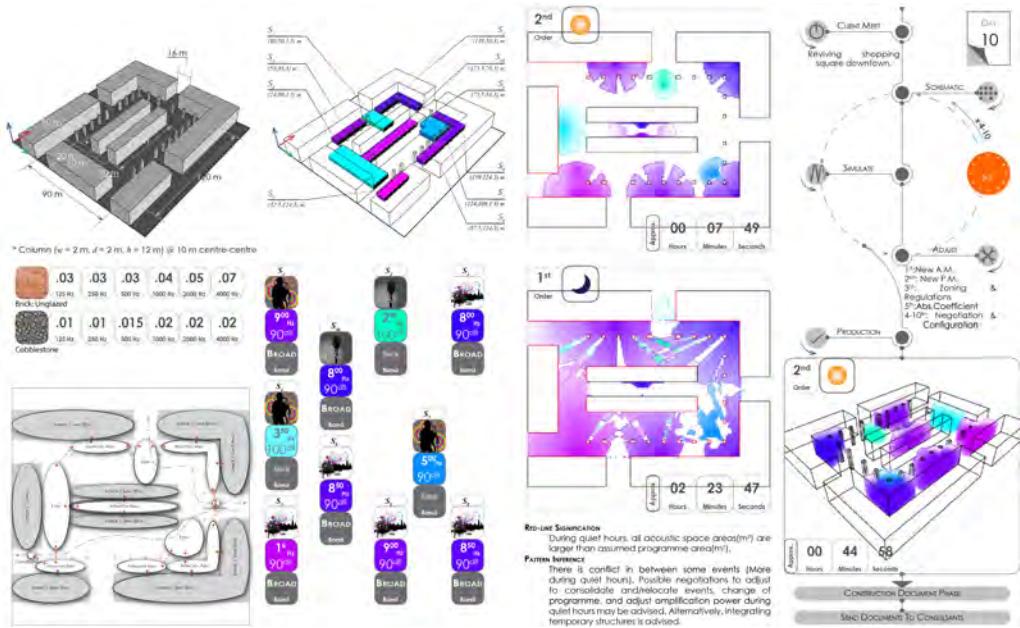


Figure 5
Schematic of a square morphological configuration and materiality and bubble diagrams and spatial and signal distribution (left). Patterns generated at 2nd reflection order for daytimes when ambient levels are high, and 1st reflection order for quiet hours when ambient levels are low, both run in redline mode. And, a schematic timeline for the possible design process cycle (right).

ally between 2-3 business weeks. As a general practice, most projects undergo the same process that is independent of scale. The materials and geometry are selected, the site is investigated, and the relation between the programmatic spaces is analysed. Schematic drawings and CAD models are then generated, analysed and adjusted to find an optimum design that satisfies requirements such as the client's needs and possible neighbouring conflicts. The lead designer generates the final scheme as a set of graphical documents that the client can understand. The process usually takes a relatively large portion of the limited timeframe.

Focusing on the use of this tool and on how it can be used for quick qualitative mapping during an assumed design phase the schemes is set up with: 1) spatial morphology (geometry and materiality); 2) site properties; 3) the programmatic use determined by the client; and 4) the associated occupancy classification.

These four design aspects are progressively translated into a CAD file accompanied by metadata of the spatial configuration and possible sonic event distribution, which are input as a comma-separated values (CSV) file. The parameters include the footprint of the buildings and the 3D location of each sonic event, along with the estimated mean frequency and maximum relative energy levels. The site parameters include the estimated ambience level and absorption coefficients of the façades and ground that are obtained from general tables or the manufacturer. In the context of setting up the parameters of the pattern simulation tool, the designer may select particular areas (e.g. attraction area and entertainment events) as foreground signals and reduce other events (e.g. vehicular traffic) to the ambient levels. The patterning tool is then executed in 'redlining' mode so that the output simulations flag façades that the designer may want to consider adjusting.

The tool has the capability of creating patterns on multiple planes simultaneously. One patterning-plane is sufficient for quick qualitative results. This would minimise computation time and allow for multiple design iterations. The designers may interpret these patterns by two methods: 1) checking which façades are flagged, or 2) visually deducing possible information. The designer may consider adjusting the design based on one or both of these methods.

The tool aims to help the design process in multiple ways. Attraction areas similar to those employed in the square configurations (see Figure 5) are examples of reviving a commercial square, where negotiation and cooperation are key when maximising profit is the main consideration. The patterns simulated for quiet hours show multiple interferences and large edge domains. These areas may be interpreted as zones where none of the contributing sonic events can be singularly de-coded. The designer may consider consolidating sonic events by coordinating with shop owners and temporary event performers.

CONCLUSION

Architects' training enables them to consider intuitively most of the projects aspects, e.g. structural or thermal comfort, and provide consultants workable models that do not require drastic changes to the client agreed aesthetics and configuration, or other incorporated systems. This training does not include aspects pertaining to the phenomena of sound. By providing the designer a computational environment that provides qualitative aural patterns, the designer can consider sound in urban spaces, the process can be shortened and the budget can be adequately appropriated.

The tool is intended to be used as a decision-aiding programme that can predict qualitative patterns of aural spatial perception, and translate them into spatial attributes within a modelled urban space. The tool is tailored for spatial design processes, architectural drawings mediate the inputs and outputs, and the graphical information provides patterns that can be de-coded by an architect. The output is in

the form of geometrical spatial maps of the distribution of detected sound energy and isolines delineating the predicted patches of acoustic spaces, and the edges between them. The decision-making function compares the intended architectural programme area to the delineated spaces and flags possible changes prompting the designer to adjust the design (material and geometry) during the preliminary phase. This contributes to a significant reduction in the expenses associated with redesigning in a later phase or, worst case scenario, retrofitting after the project is completed.

This paper discusses the graphical interface of the tool. The results are spatial maps that have graphics that follow architectural practices, namely line weights, hue values, alpha channels, isolines and redlining that represent reflectivity, frequency, energy attenuation, acoustic spaces peripheries, and design amendments, respectively. The visual association of these acoustic parameters allows the results to be an integral part of the design process. The overall research adopts a number of semantics that describes soundscape in spatial metrics and links the perceptual parameters of context and meaning to the architectural programme. Although there are accounts of considering SPL distribution in simulating sound in an urban space, the selection of acoustic and psychoacoustic frequency dependent indices allows this research to simulate multiple sound sources simultaneously.

Of course, there is room for development. Potentially, the redlining package prepares the tool to be developed as a generative decision-making tool. The tool has the capability to generate 3D representations of enveloping acoustic arenas. For complex configurations, the number of hours required to compute multiple horizontal planes simultaneously, may not be feasible for the schematic phase. If required the algorithm that maps in two-dimensional planes can be adjusted for 3D simulation at low computation cost.

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FEEL YOUR DESIGN

exploring the sensorial experience of Architectural space through immersive architecture models

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This paper describes an experiment entitled Experiment 2- ``Feel your Design'', which belongs to a group of experiments undertaken in the context of a PhD in architecture. The goal of the experiment described in this paper was to evaluate the emotional reaction of a viewer to changes in the sensory perception when being stimulated by viewing, listening and smelling immersive architectural models. The Experiment was taken as part of a workshop with students of architecture. The workshop incorporated concepts of ``Sensory Design'' and ``Emotional Design''. The task assigned to the students proposed that immersive, atmospheric models were built according to a specific narrative and included specific scents and sounds which were supposed to re-enforce such a narrative or induce a certain mood. The results of the Experiment were evaluated through the use of a ``Presence Questionnaire'' and a ``SAM chart''. The Experiment had the participation of 7 students who produced one model each and served in the Experiment as subjects. Experiment 2 took place on the last day of the ``Feel your Design'' workshop. The host institution was Fachbereich Architektur, Digitale Werkzeuge, TU Kaiserslautern. The experiment had the technical support of the Deutsches Forschungszentrum für Künstliche Intelligenz GmbH (DFKI).

Keywords: *Architecture, Immersion, Emotion Measurement, Sensory Design*

INTRODUCTION

This paper describes an experiment which was taken as part of the research work developed for a PhD thesis dedicated to the topic of the relationship between body and architecture (Ferreira, 2016). Four experiments were done in the context of the aforementioned PhD research. The goal of the experiment described in this paper, called Experiment 2 - "Feel your Design", was to evaluate the emotional reaction of a viewer to changes in the sensory perception when being stimulated by viewing, listening and smelling immersive architectural models. This experiment took place on the last day of a student workshop. The workshop functioned as an elective course for students of architecture and dealt with the physical construction of immersive architectural models and the evaluation of subjects' response to the atmosphere's created by the models. The name of the workshop comes from the assumption that an architectural space can be designed as an experience if the architect takes in consideration sensory aspects such as haptics, sound, and scent in addition to vision (Damásio, 1999). The idea was inspired by Pallasmaa's (2005) work and his proposal that architects should use an embodied, sensorial approach to design as a way of stimulating the body, as a holistic sensory system which is not exclusively dependent on vision, but also on other senses. The workshop also incorporated concepts of "Sensory Design" and "Emotional Design" (Norman, 2004). The task assigned to the students proposed that immersive, atmospheric models were built according to a specific narrative and included specific scents and sounds which were supposed to re-enforce such a narrative or promote a certain mood. The Experiment had the participation of 7 students who produced one model each and served in the Experiment as subjects. Experiment 2 took place on the last day of the "Feel your Design" workshop. The host institution was Fachbereich Architektur, Digitale Werkzeuge, TU Kaiserslautern. The experiment had the technical support of the DFKI.

DESCRIPTION

Each participant was given a cube measuring 50 x 50 x 50 cm and was requested to choose a room type which could be any kind of interior space such as an attic, a bedroom, a working room, a library, a museum, or a hospital room. The students were asked to choose a narrative that described a mood that was to be explored through the model and design an immersive experience through the combined design of an interior space, the choice of a scent which accentuated the narrative ("scentscape"), and a specifically created sound-loop which re-enforced the desired atmosphere (soundscape). The scale of the interior spaces was left for each student to choose according to her/his idea for the model, as well as the location and dimension of the peeping holes which were meant to condition the viewer's gaze.



Figure 1
Immersive models
with peep-in holes

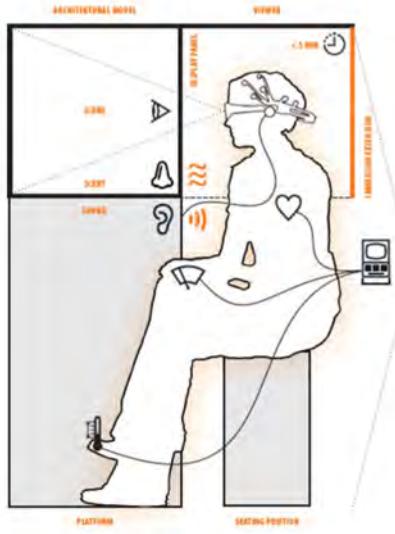
The setup of the Experiment consisted of Architectural models placed at seating level, installed with peep-holes (Fig.1), scent- and soundscape in the interior of a box with the same dimensions as an old phone booth (Fig.2), with a bench for the viewer to sit and look at the models and a black fabric curtain to keep the booth in the dark. The tools used for the experiment were one laptop with plugged headphones which was set at a table next to the booth where the models were installed. While inside the booth, the viewer was asked to sit on the bench and take a look into the peeping hole of the model, while listening to the soundscape through the headphones connected to the laptop outside of the booth (Fig.3). Students were advised to install, if possible, small vents inside

Figure 2
Setup with focus on
model location

the models so that the viewers could feel the chosen "scentscape" more intensely. The students had to define the possible views into the model space on the display side of the cube, to create a soundscape as a loop in mp3-format, and to complete the experience by adding a specific scent to the model. The selected title had to describe the desired mood for the architectural space and provide the viewer with the key to the understanding of the narrative. The goal of the exercise was to explore through these immersive models the multi-sensory experience of architectural space (Pallasmaa, 2011) and evaluate viewer's emotional reactions (Damásio, 1999) to the narrative experienced inside the booth through the analysis of data collected and processed with emotion measurement methodology. To support the design process during the workshop, students were introduced to artwork on the topics related with the task such as cinema, model making, art installations, as well as basic notions of architectural archetypes and Plutchik's (1962) vocabulary of basic emotions. Students were also introduced to the concepts of emotion measurement (Bradley et al., 1994; Kim et al. 2015), immersion, presence (Witmer et al., 1998), sensory design and emotional design (Norman, 2004). Students were encouraged to use CAD/CAM technologies to aid in the process of manufacturing the models. The results of the Experiment were evaluated through the use of a "Presence Questionnaire" (Witmer et al., 1998) and a "SAM chart" (Bradley et al., 1994). Recall that the main goal of this experiment was to qualify users' response to immersive architecture models, by analysing sensory data, having in mind that our main hypothesis was:

H1 - a user's emotional response as "compelled or not compelled", "positive or negative", "aroused or not aroused" and "dominant or dominated" to an immersive architecture model can be evaluated through objective measurements of emotion using a Presence Questionnaire (PQ) and a SAM chart.





Two secondary hypotheses were then formulated:

H2 - architecture is an immersive experience which can be consciously composed by the architect; the techniques of "emotional design" and "sensory design" are an effective strategy to compose specific experiences of architectural spaces and develop the sensorial awareness of students and designers;

H3 - the feeling of presence and emotional activation can be induced through the experience of analogical models, in this case, immersive architectural models;

To verify these hypotheses, the experiment was developed considering four stages:

1. Identify the design characteristics that are more suitable to induce certain sensations in the user, such as "positive, aroused, dominant, compelled", "negative, not aroused, dominated, not compelled", "joy, sadness, anger, boredom, ecstasy";
2. Design an immersive model so that those

characteristics are the most important aspects of the design;

3. Perform experiments with users interacting with these architectural models and assess their emotional experience through the use of a PQ and a SAM chart;
4. Process and analyse the sensory data collected to understand if significant differences can be found in the classification and differentiation between a "compelling-positive" experience and a "not compelling-negative" one.

RESULTS

Experiment 2 - "Feel your Design" evaluated the emotional experience of architectural models by analysing changes in the sensorial perception of the viewer, while looking at the model, listening to specifically created sounds (soundscape) and inhaling specifically chosen scents ("scentscape"). The results of this experiment were the answers to the Presence Questionnaire and the SAM chart, where recall of experience and believability of simulation were systematised. Such data describes the subject's physiological response and emotional activation, thereby enabling one to evaluate the model's ability to alter the subject's emotional state. The data is organized according to Presence Questionnaire's "Factors" and "Subscales", as defined by Witmer and Singer, as well as SAM's parameters of Valence, Activation and Control. The final values considered in the analysis of the PQ results were obtained by averaging the ratings assigned by the subjects to each of the questions, according to Witmer and Singer's (1995) 1-9 point scale. The analysis of the data collected through the SAM chart also followed the same principle, as the three parameters of "valence", "activation" and "control" were rated by the subjects using also a 1-9 point scale. After making these calculations, we obtained values that qualify the subject's individual experience of the "Feel your Design" models regarding the parameters of "presence", "emotional response", "valence", "activation", and "control". From the data collected, we can also qualify the experience of the

Figure 3
Diagram of "Feel your Design" experimental setup

group of subjects as a whole, by averaging the results for the same parameters.

level of "arousal";

Figure 5
Interior of model
"Surfstation"

DISCUSSION AND CONCLUSIONS

Experiment 2 - "Feel your Design" evaluated the emotional experience of architectural models by analysing changes in the sensorial perception of the viewer, while looking at the model, listening to specifically created sounds (soundscape) and inhaling specifically chosen scents ("scentscape"). The experimental results support the main research hypothesis H1 - a user's emotional response as "compelled or not compelled", "positive or negative", "aroused or not aroused" and "dominant or dominated" to an immersive architecture model can be evaluated through objective measurements of emotion using Presence Questionnaire and SAM charts. The results collected through these means show that:

Figure 4
Interior of model
"Psycho"



Figure 6
Interior of model
"Spiegel"



- for the immersive model "Spiegel" (Fig. 6), the majority of subjects experienced high levels of "Presence" and "pleasure" and a low level of "arousal";

- for the immersive model "Psycho" (Fig.4), the majority of subjects experienced a high level of "Presence", "Arousal" and "pleasure";
- for the immersive model "Turm", the majority of subjects experienced a high level of "Presence", "Arousal" and "pleasure";
- for the immersive model "Surfstation" (Fig.5) , the majority of subjects experienced high levels of "Presence" and "pleasure" and a low





- for the immersive model "Blumenpassage" (Fig. 7), the majority of subjects experienced high levels of "Presence" and "pleasure" and a low level of "arousal".

All subjects felt they were able to control their emotional response to the scenes in the models and also described them as a positive experience. Most subjects described the scenes as "not very dominating", although the scenes "Turm" and "Surfstation" were described as "dominating". Interestingly enough, these experiments explored opposite atmospheres, anxiety in the case of "Turm" and relaxation in the case of "Surfstation". All subjects reported to have felt compelled by all the scenes in the experiment, with the scenes "Psycho", "Turm" and "Spiegel" being rated in average as "very stimulating" and the remaining

two "Surfstation" and "Blumenpassage" as "stimulating". The scenes in the models were unanimously rated by the subjects as "convincing", "engaging" and "consistent" with real life experiences in terms of the sensual information. Most subjects reported to have been visually involved by all the scenes, as well as by the corresponding "scentscapes", soundscapes and, surprisingly, by the haptic aspects as well, since the latter was not directly explored in this experiment, but the former three were. This suggests that the models induced a very high level of immersion. All scenes were rated by the subjects as able to trigger the imagination of real actions and the majority of subjects reported to have had their attention dedicated to the scene. This permits us to conclude that Hypothesis H2 is verified - architecture is an immersive experience which can be intentionally composed by the architect and the simulation techniques of "emotional design" and "sensory design" are an effective strategy to compose specific experiences of architectural spaces and develop the sensorial awareness of students/designers. The majority of subjects reported that they were able to survey inside the models, were not distracted by the quality of their execution and could move inside the booth and manipulate the interface objects without being distracted by them. Subjects also adjusted quickly to the experiment, could concentrate well on the scene and the majority rated it as a good learning experience. Still, except for the case of the scene "Psycho", which the final average score shows that the subjects lost track of time, this did not happen in the remaining scenes. This suggests that the experience of the model "Psycho" was the most immersive. Finally, it can be concluded that the illusion of presence and arousal situations can be intentionally induced through immersive architectural models, although further research is necessary to understand which specific design elements are responsible for this. Therefore, Hypothesis H3, which suggests that the feeling of "presence" and emotional activation of the body of a user can be intentionally induced through the experience of immersive architectural models, also is confirmed.

Figure 7
Interior of model
"Blumenpassage"

Experimental results of this experiment show that PQ and SAM are effective in identifying arousal responses related to “positive” or “negative” emotions, from the neutral condition, when users experience immersive architectural models. On-going research in the fields of IT, psychology and marketing uses an established range of values that also were user used as reference in this experiment. The use of electroencephalogram (EEG) and biometric markers is an additional, interesting method to be used in future experiments to observe how the emotions of a user are triggered while experiencing immersive architectural models. Such technology was unavailable for this experiment, but it was used in other experiments in the context of the aforementioned PhD research (Ferreira, 2016). The experiment described in this paper will be repeated and eye-tracking sensing technology will be incorporated to the experimental setup. We believe this method might be useful to detect which points are of most and least interest for the viewer of a scene and give a more comprehensive analysis of the subjective experience of looking at an architecture scene.

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Open Virtual Reality

A new open sourced communication medium in Architecture

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This study lends itself to recent advances in open source virtual reality technology and its application within the field of architecture. The research focuses on open sourcing and the relatively inexpensive hardware solutions readily available, such as Google Cardboard. The outline proposal architectural detail level is relative to the project and architectural practice, but ideally, it is assumed that an initial proposal presented to the client is based on a considerable amount of work and detail expressed in the form of plans, sections, elevations and various internal and external visualisations where materiality is considered using simple textures and understandable queues to make the material choice clear in order to draw out as much feedback as possible from the client. The paper addresses the problem of information loss when trying to communicate an architectural design proposal following traditional methods such as information on printed paper; also it compares the subjects impression of static and interactive three-dimensional panoramic spheres viewed through the pairing of a phone and a cardboard headset. The two representations use the same three-dimensional model of the project. The study experiment with open virtual reality (OVR) show great potential for seeing more information that clarifies common problems in visual graphic communication.

Keywords: *Virtual reality, Open source, Head mounted display, Perception, Google cardboard , Immersion*

RATIONAL

With recent breakthroughs in technology, Virtual Reality (VR) equipment and interfaces have become affordable at a consumer level while also being increasingly easy to use and operate. This emerging technology started with a solid background within the entertainment industry. However, its applications within architecture cannot be overlooked and it is only re-

cently that the technology has reached a level where it become appropriate for efficient use, especially when cheap open source hardware alternatives such as Google Cardboard [2] are making their way on the market. There is a general consensus that information is often lost when a client is being presented with an architectural proposal. Without much architectural knowledge, he can misinterpret the architect's

intention. Two dimensional drawings like plans or visual perspectives can be limited in their expression. Ultimately, a client may not fully understand an architectural proposal and might come up with radical changes further down the design process, not because of the inconsistency of the presented proposals, but rather by his own limited spatial perception. This can ultimately lead to financial loss on both parties. A virtual immersion in the critical phases of design such as an outline proposal could help reduce the loss of architectural information, thus creating a bridge between the client's understanding and the architect's vision. This could lead alleviate the design process where the architect is not required to invest extra effort into project specification. Virtual reality can become a valuable medium from which both the architect and the client can benefit.

Theoretical Basis

In terms of definition, virtual reality had a rough start. Alternative dimensions have been pondered for centuries. An idea came to realisation in the 1950s when a handful of people imagined the scenario of watching a screen that never ceases to broadcast. It is said that concept goes even back as the 1860 when artists created a series of three-dimensional panoramic murals. The 80's and 90's revitalised the ideals of a virtual reality universe. It was in this period that the personal computer became a mass consumer product and that virtual reality believers were impatient to experience it. However, limitations shadowed the enthusiasm to experience a realistic digital environments. The vision was still outmatched by the means. Later on, in the 1990's, the technology's hype faded, making way for other interesting emergent technologies. Recently, that interest started focusing on virtual reality , yet again when Palmer Luckey developed a crude headset which was later named as the Occulus Rift, which was launched in March 2013 [1]. However, the virtual reality was still hindered by limited graphical representation, but the experience was starting to become believable.

External representations

The use of external representations (sketch, drawing, model, etc) combines internal, intellectual actions with external actions and their external result (physical) (Salman 2011). It is claimed that designers produce various types of external representation (virtual/physical) to overcome problem-solving and information uncertainty (Christensen 2005; van der Lugt 2000). As such, at a certain point in time, each type produced (within the design process) has a different degree of information uncertainty, in that it represent a certain level of specification of the problem under consideration. Stacy and Eckert (2003) emphasised "the importance of combining sketches, words, gesture to disambiguate each other". Externalisation is thought of as an indication of the designers' level of information uncertainty (Christensen 2005). According to Christensen (2005), different levels of information uncertainty could be assigned to different externalisation-types.

Graphic representation continuity

In order to represent, visualise and communicate three dimensional information, one must have a firm grip on principles of graphic language. The elements that make up the language are driven by rules which influence information about the three-dimensional form. They are hard to convey using words, pictures or diagrams. Thus, an issue of continuity arises between three dimensional representation using two dimensional methods (Gill 2004). Current methods do not exemplify the relation among observer, object and representation, while computer visualisation does not fully display characteristics of the computer/virtual environment. An idea is initially developed by an architect on paper or on a computer. Afterwards, it is externalised and communicated through drawings, sketches, models or visualisations. Such two-dimensional representations belong to a specific language which conveys information about a three-dimensional object in space. A designer's success depends in his ability to efficiently communicate and idea. Perspectives and isometric projections

illustrate a relationship between: the observer, an object, the picture plane, and projection lines. In turn, they are affected by the distance between object or projected plane and the observer and element angles. Therefore, design needs communication tools that focus on continuity within representational methods. Recently developed high end computer graphics could be used to illustrate these relationships through immersive environments where a user's perception is assisted in creating his own understanding and conclusions and being able to identify inconsistent information. The application of virtual reality in this case may influence a user's capability to develop his mental ability towards three dimensional forms and to relate the traditional two dimensional representational methods to his mental projection. This expected availability makes it interesting to explore the potentials of (re)using VR in architectural education as well as for professionals communicating architectural designs to customers or community." (Kreutzberg 2014).

Research Aim

This study aims to answer the following question: How efficient is open sourced virtual reality in helping the client understand an architectural outline proposal compared to two dimensional representational methods? from the perspective of final year Master of Architecture student, this question led to setting the following two main objectives:

- To identify whether open sourcing virtual (VR) reality as technology simplifies the generation and setup of VR scenes and experiments for improved visualisation
- To see how efficient open source virtual reality is in communicating architectural design , does it improve client's spatial perception of a project?

OPEN SOURCED VIRTUAL REALITY

The wait for the consumer version of the Oculus Rift spurred a need to create alternatives using DIY meth-

ods and open sourcing. Such initiatives are enthused by both creative communities, as well as big companies, such as Google . At Google I/O conference [3], Google announced project Cardboard, a cheap virtual reality headset kit that costs approximately \$20 from various providers or if built independently. It was developed as a side project by Google employees as part of a program called "20% project". In principle, it is a smartphone mount, only made out of cardboard and comes in various sizes according to smartphone size. Additional components beside the pair of 40mm biconvex lenses that make up the headset are: a NFC magnet tag used for virtual navigation input, a hook and loop fastener and a head strap. The virtual reality experience is provided by a side by side projection capable smartphone. Each image corresponds to one eye and are separated visually. The result between the juxtaposition of the side by side images create one three-dimensional projection. Google's design is made by the openly provided schematics, components and instructions for assembly. There are no official manufacturers for the headset and the open sourced hardware is only one aspect to project Cardboard. Developers of software for virtual reality applications are provided with a standard development kit from Google's website. That means that users are not only provided with cheap hardware alternatives for head mounted displays, but also the tools to create virtual reality experiences. This open source alternative has proven that virtual reality solutions and experiences can be cost effective, provided a user owns an increasingly indispensable tool such as a smartphone.

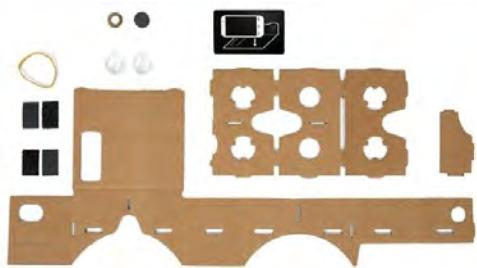


Figure 1
Google Standard development kit



EXPERIMENT DESIGN

In order to quantify the differences in perception when a client might be subjected to a traditional representational method (in this case, printed material) and then a virtual reality presentation of the same project, this paper will analyse an experiment conducted specifically for this purpose. The initial proposal mentioned an experiment which will try to obtain data from the perceptual difference between two dimensional representation and virtual three dimensional representation, made possible also by open sourced virtual reality. Therefore, the experiment aims to prove that virtual reality can be an efficient and reliable communication medium between a client and an architect in the initial phases of architectural design.

The experiment was conducted in two successive stages of data collection. The first stage was completed using 2D visualisation of the project scheme. This was pinned as A0 printed posters (two posters), participants then were asked to study and understand them, then answering the assigned questions.

The second stage was conducted using VR

scenes of the same project scheme. On average, the virtual tour lasted for approximately eight minutes per student. Then, the students had to complete a second and final questionnaire with similar questions relating to their new understanding of the project..

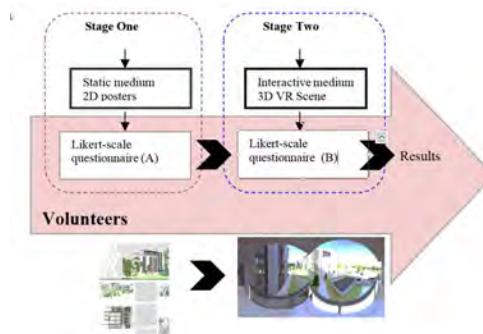


Figure 2
Open source
alternative to head
mounted displays

Figure 3
Experiment design
and methods

One questionnaire was designed to be used for the two successive stages, each addressing the used representational methods and its effect on understanding. Therefore, one rating system was used, consistency in the likert scale (rating) and number of questions was important to provide data that is comparable to show any differences in subjects response (if any). The experiment sample consisted of volunteers of stage 1 architecture (first year's architecture students). The choice was meant to simulate a real life scenario where a client does not possess greatly developed three dimensional vision. On average, the virtual tour lasted for approximately eight minutes per student. The questions focused on initial impressions, the level of architectural detail, the space between the two buildings, heights, interior space, balcony sizes and the overall quality of the project.

Figure 4
Post impression
questionnaire A

Questionnaire A

Questionnaire (A) represents part 1 of the experiment. Here, you will rate your impression of the two posters and clarity of information within each on a scale of 1-10. 1 is Not Clear and 10 is Very Clear. Please circle the number (using the scale below) for each of the following questions that best describes your level of understanding.

Q1 How complete is your initial impression of the project?
 1 2 3 4 5 6 7 8 9 10

Q2 How satisfied are you with the level of architectural detail the posters offer?
 1 2 3 4 5 6 7 8 9 10

Q3 How would you rate the exterior space between the buildings, in terms of size?
 1 2 3 4 5 6 7 8 9 10

Q4 How clear are the posters trying to convey the height of the buildings?
 1 2 3 4 5 6 7 8 9 10

Q5 How would you rate the amount of space in the apartments (A) facing North?
 1 2 3 4 5 6 7 8 9 10

Q6 How would you rate the amount of space in the apartments (B) facing West?
 1 2 3 4 5 6 7 8 9 10

Q7 How would you rate the amount of space in the apartments (C) facing South-East?
 1 2 3 4 5 6 7 8 9 10

Q8 How would you rate the amount of space in the top-most floor (D) (penthouse)?
 1 2 3 4 5 6 7 8 9 10

Q9 How strong is your impression on the overall size and scale of interior spaces?
 1 2 3 4 5 6 7 8 9 10

Q10 How well do the posters communicate the overall size of balconies?
 1 2 3 4 5 6 7 8 9 10

Q11 How strong is your grip on the size of penthouse balconies?
 1 2 3 4 5 6 7 8 9 10

Q12 How strong is your impression on what the balcony views might be?
 1 2 3 4 5 6 7 8 9 10

Q13 How good are the posters in trying to communicate the overall size of the project?
 1 2 3 4 5 6 7 8 9 10

Many thanks for your participation.

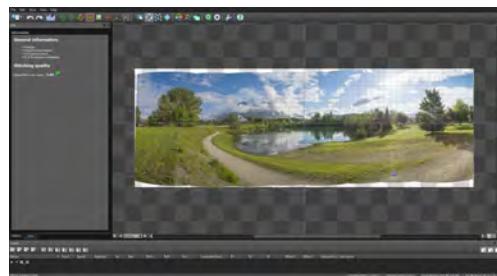
Figure 5
Program used-Auto
Pano Giga.

Technical requirements

There were a number of requirements that needed to be met in order for the experiment to be carried out. In order to define the two dimensional representational medium or the traditional way in which architects present their projects to their clients, a set of two A0 posters had to be printed out. They contained a multi-story residential outline proposal level project of modern Scandinavian style with an appropriate level of detail. The other representational method was the virtual reality presentation with the help of an open sourced head mounted display, or Cardboard, the open sourced project created by Google. The headset was supplemented with high resolution display smartphone, the Nexus 5 by LG (researcher's private smart phone). While the head mounted display was the tool, the presentation itself had to be created. The virtual presentation consisted of several spherical panoramas rendered inside the three dimensional project model. It represents a 360 degree sphere shaped image where the observer is placed at its center, able to look around just like in real life at the surrounding environment. Then, the observer is able to fully observe the environment from a static vantage point (view point) at

the sphere's core, similar to Google's Street View.

After acquiring the Cardboard Headset and using the in-built 360 degree spherical panorama viewer, it was clear that custom panoramas would have to be adapted in order to be viewed with the device. These custom panoramas would not make use of the regular camera software capabilities of an Android phone. Therefore, they would have to be imported and made in a way as to mimic the regular spherical panoramas which are the result of a process of photo stitching and editing being done automatically by the camera software after taking a photo sphere picture.



The panoramas were created using a real time rendering engine plugin called LumenRT(TM) from a three-dimensional model made in SketchUp(TM). The real time rendering engine enables the user to walk inside an enhanced version of the model where quality lighting, shadows and environments are added, similar to a game engine. In order to create the spherical image, screenshots covering a full spherical field of view had to be taken manually and then stitched together with the help of stitching software such as AutoPano Giga(TM). Vray(TM) enables the automatic creation and rendering of such panoramas, without the need for manual stitching. However, the rendering quality using Vray was unsatisfactory for the given scenario. Thus, the panoramas used a real time rendering engine such as LumenRT(TM) for a better control over the results. The panoramas required post-processing in Adobe Photoshop (TM) to clear out any stitching errors. Once completed, additional parameters were added to the images using the Google Maps Street View Tool in

order to give spatial coordinates along three dimensional axes for correct panorama viewing inside a gyroscopic sensor enabled smartphone. Here the image was split into two small screens for each eye. The virtual environment or the person's view responded in relation to the movements of the user's head.



Results

A group of 10 (stage one students) students volunteered to test out the two representations by first analysing the architectural posters pinned up on two review boards. They would have to imagine themselves as clients trying to fully understand the project in terms of size and scale. The average time it took a student to analyse the two posters lasted for approximately five minutes. After this, they had to assess the limits of two dimensional representations and reflect on the quality of architectural information by completing the first set of questionnaires (A). This first set would focus on the project's exterior space, interiors and balconies. The subject would have to rate the clarity of information they' have perceived on a scale of 1 to 10 within the previously mentioned aspects. Once they completed the questionnaire, they had to look into the same project using open source virtual reality headset. Here, they had to place the head mounted display over their heads and go through nine spherical panoramas which consisted of different exterior, interior or balcony vantage points within the same project. After this, they had to assess the limits of VR representations and reflect on the quality

of architectural information by completing the second set of questionnaires (B).

In order to compare each participant's responses, a graph for the Likert scale data for questionnaire A and B was produced using Excel, each graph represents the individual differences with regard to clarity of information (figure 7-11), when the two representations were used . Then a graph with average values of each question was produced for all participants which compare the average score for all subjects (10), figure 12.

Looking at the graphs individually, one can notice that there are many differences that a simple summary would not be appropriate since it would mask these individual differences. However, some consistent results are also apparent, the graphs (figure 7-11) show the difference between the initial impression and the virtual reality impression for each participant.

In general participants scored clarity of information and understanding higher in VR from 2D posters. But there are some lower scores in VR when it compare to 2D posters. For example, participant 1 felt that the overall quality of interior space (Q9) was lower by 1 point after experiencing it in virtual reality. participant 2 also felt that the quality of space in the apartment facing West (Q6) was lower after seeing the second representation. Participants 5 and 10 felt that the quality of exterior space between buildings (Q3) was lower by 1 point after experiencing the virtual reality presentation. Participant 5 also had a lower score for the balcony views (Q12) -(by 2 points). Participant 6 scored a general decrease of 1 point for all interior spaces (Q5-9). Participant 8 seemed to have rated the quality of architectural detail (Q2) lower by one point after experiencing space in virtual reality. Participant 10 felt that the quality of space inside the penthouse (Q8) was lower by 1 point after experiencing it virtually.

In general the average graph shows that all participants have rated VR impression higher than two dimensional posters. A detailed description is followed: with regard to project completeness (Q1),

Figure 6
Example of the panoramas were created using a real time rendering engine plugin called LumenRT(TM)

Figure 7
Students 1 and 2
results

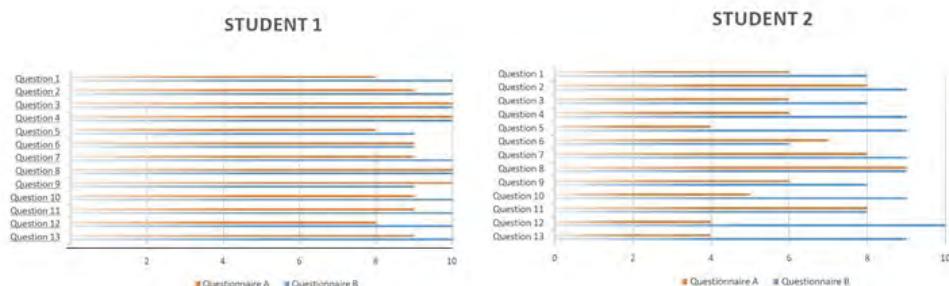


Figure 8
Students 3 and 4
results

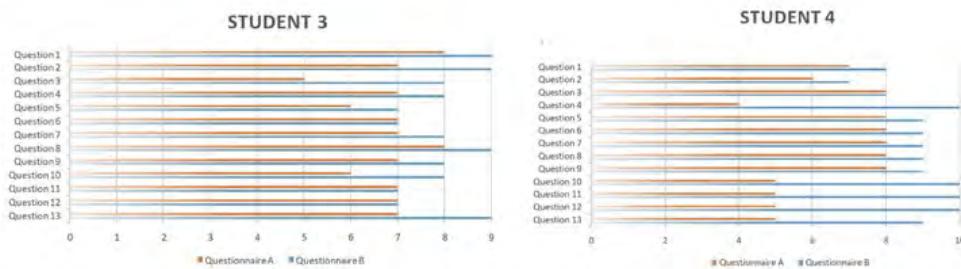
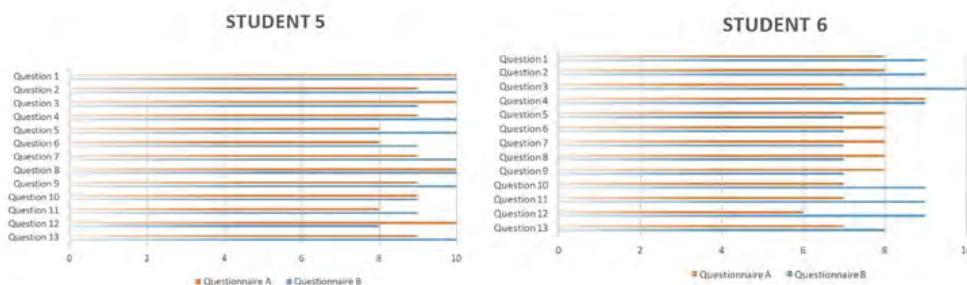


Figure 9
Students 5 and 6
results



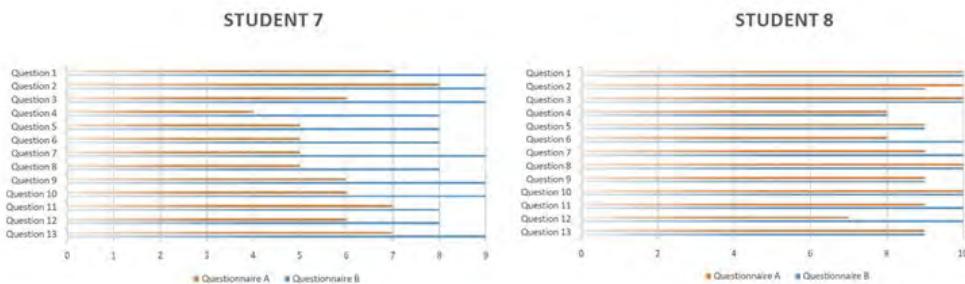


Figure 10
Students 7 and 8
results

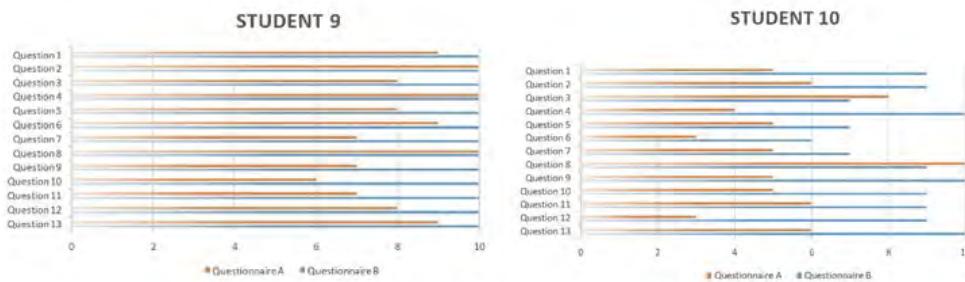
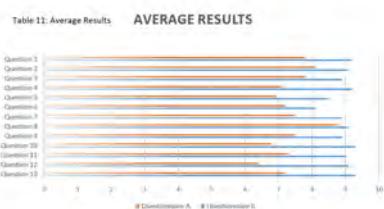


Figure 11
Students 9 and 10
results

participants' average score for VR was higher by 1.4 points. Also, the level of architectural detail (Q2) seen in VR was higher with an average of 1 point. The average values for the exterior space between the buildings (Q3) are also higher with an average of 1.1 points. However, a significant average value difference is scored with the building heights (Q4) at a 2.1 points average. With regard to rating space qualities within the three apartments (Q5-8), participants rated the amount of space in apartment facing north (Q5) in VR at an average point of 1.6. A smaller rating of 0.9 point average increase is recorded for the apartments facing West (Q6). For the apartments facing South East (Q7), the students rated their understanding of it at an average of 1.4 point increase. The smallest difference recorded for an interior space refers to the penthouse (Q8) with a 0.3 point average. The overall difference in size of interior spaces (Q9) understanding is rated at an averages 1.5 points increase. Another significant difference is notices with communicate the overall size of balconies (Q10), a difference value of 2.5 points average is recorded. Also, rating their understanding of the size of penthouse balconies (Q11) recorded a difference of 1.7 point average, while the biggest recorded difference is at 2.7 points average on balcony views (Q12). The overall perceptual difference in project size (Q13) is significant and stands at an average of 2.1 average points. These are total averages of participants.

Figure 12
Average score for all participants.



To summarise, the most notable perceptual differences can be notices in understanding the following two aspects of a project; (balcony) sizes and views,

then, building heights. Also, the overall project size has a significant difference in perception and was just as important. Interior spaces were also better understood and measured a significant increase in understanding. From the students who rated the quality of spaces interior spaces were the most frequent ones which came up. However, The representations used in the experiments where useful and valid for communication. Participants have rated their understanding of both representations differently, higher rates were given to VR, these responses have demonstrated that student (client) understanding and learning about architectural projects can be enhanced to an extent. Moreover, using new representation technology was welcomed by participating students as better tool for them to understand the different aspects of the project.

OUTCOME AND RECOMMENDATIONS

Open source virtual reality proved especially valuable in conveying interior space, whether the user thought it was larger or smaller. The difference in perception was most obvious in this area and helped pinpoint where people struggle most in identifying space: interiors. The data shows improvement across all aspects from the traditional two dimensional representational method and average values, with the occasional negative result, which might be caused by each individual's unique perceptual and cognitive abilities. The students seemed to get a better grasp on the design intent, proving that their understanding and judgement is not only improved, but better equipped in expressing disagreement at such an early stage within the design process . As such, this empowers the architect by reducing misinterpretation of information between the two parties and by better bridging his intention to that of the client's perception. Accessible VR technology has come a long way since its inception. Today, architects can make use of cheap open source hardware such as Google Cardboard [2] to efficiently and better express space. While the means have become affordable, it is still up to the architect to create the spaces

for virtual representations. A good virtual representation is dependent on detail and the architect's three dimensional modelling capability. Virtual reality representations act as an extension to the existing skills needed for good visualisation.

Virtual reality representations are another way to present and to efficiently communicating design. Quality high resolution panoramas will involve more effort and it is up to the architect on how much control they want to have within the process of creating such representations. As mentioned, lower fidelity breaks immersion and representations can suffer. The clearer the information, the better the understanding. A manual process of stitching rendered images to form the sphere panoramas is recommended, as it gives more control over the process. One of the students made a remark that the virtual representations would be better if the user would be able to walk inside the model in real time. However, open sourced hardware making use of smartphones as displays do not possess the processing power yet to create real time immersion. The Oculus Rift, HTC Vive and Sony Morpheus are more suited for this kind of immersion, however, they are not open sourced. Real time virtual reality will become one of the main ways in which architects present their projects until a better alternative will replace it. However, there are many factors which be responsible for a slow adoption. High fidelity real time representations require great amount of graphical processing power and appropriate hardware is still expensive. The price cannot be justified and traditional representational methods can relatively express most building modelling information at a fraction of the cost. However, adoption of the technology pays back in the long term when money is saved by reduced design iteration. Emergent technologies are usually met with scepticism, especially in the conservative architectural profession.

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Computational Thinking

Qualitative Representation and Spatial Reasoning in a Rule-Based Computational Design Model

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Integrating social and cultural constraints in computational models remains a challenge due to the difficulties in representing them algorithmically. This research aims to find a mechanism for combining shape grammars and space syntax methods for exploring spatial-formal features that affect the social life in residential buildings. 'Spatial reasoning' as a method for understanding the social logic of spaces and the residents' behavior, integrated with 'discursive grammar' as a method for describing formal and topological relationships, are adopted. Several computational tools are used for analysing qualitative aspects, such as privacy, social interaction, and accessibility. An automated model of spatial/syntactical analysis, embedded in Rhino/Grasshopper, offers an alternative method for extracting topological relations and syntactic calculations. Using this tool, designers can add new aspects to the justified graph of Hiller and Hanson, as a representation to formal and social realities, such as orientation and geometric configuration. Results of analysis are transformed into codes, parameters, and descriptions, to be used for designing future developments, inspiring from local traditions. The target is to generate different alternatives for socially sustainable, and 'contemporary vernacular' buildings, which respect the context, and the needs of users.

Keywords: *Spatial Reasoning, Syntactic Analysis, Discursive Grammars, Computational Models, Social Sustainability, Visibility Graph Analysis*

INTRODUCTION

Computation is about manipulating ideas and solving problems in a clearly defined steps that are routinely made by computer (Terzidis 2006). This approach involves in the thinking process of the architectural design and could be used in different phases: analysis, animation, simulation, and form generation. Currently, the main focus of computational models

is primarily limited to formal and environmental requirements. Yet, qualitative factors, such as social and cultural constraints, are also important as they lead the building to be in harmony with its context and the needs of its users. Integrating these criteria in the computational process remains a challenge due to the difficulty of algorithmic representation (Yüksel 2014).

This research aims to address such social and spatial issues in the design of vertical residential developments. One approach is to draw inspiration from local traditions for generating a 'contemporary vernacular' building. The Middle East and North Africa (MENA) region is selected for the implementation of the model, as most of the current projects ignore the specifics of the place and the society (Wood 2013). In contrast, the vernacular model of houses shows that these precedents are good examples of socially cohesive and healthy environments (Al-Masri 2010).

'Spatial reasoning' as a method for understanding the social logic of spaces, combined with 'discursive grammar' as a method for describing formal and topological relationships, are adopted. Different computational tools are used for analysing such qualities. These software include Syntax2D for specifying spatial elements that affect the visual privacy; AGraph for carrying out syntactic calculations; and DepthmapX for understanding the behaviour of people in relation to the spatial configuration of the built environment. Finally, a combined model of spatial/syntactical analysis, embedded in Rhino/Grasshopper, is presented.

SPATIAL REASONING AND 'DESIGN SPACE EXPLORATION'

Jerome Bruner, in his studies about the psychology of knowing, defined 'reasoning' as 'going beyond the information given' (Bruner 1973). In the field of architecture, spatial reasoning is a logical process of analysis that enables designers' understanding of the layout complexity, and the exploration of features that have social or experiential significance (Abshirini and Koch 2013). For instance, tracing the visual fields from a certain location in a building allows a clear evaluation of spatial elements that affect the privacy of occupants. Different methods, such as space syntax and shape grammars, could be used for carrying out reasoning analyses to derive social and spatial parameters that affect the design of the built environment.

Space syntax: a topological analysis approach

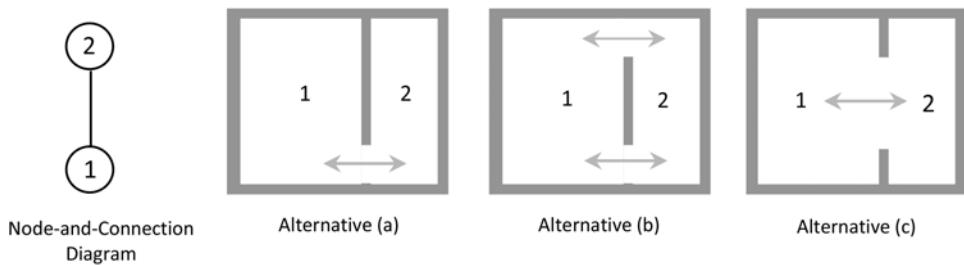
Space syntax theory, developed by Hillier and Hanson in 1984, explores social relations implicit in the architectural setting. Based on their book 'The Social Logic of Space', this process requires understanding physical topologies between design elements, taking into account all other spaces in the system (Hanson 1998). These relations are represented visually, through 'justified node-and-connection' graphs, to show the hierarchy of the overall layout. However, these diagrams does not generate descriptions for the formal reality of the design (Osman and Suliman 1994). For instance, spaces could be connected in different alternatives, and have the same justified graph (see Figure 1). Furthermore, functions located on different levels/floors need to be identified from other nodes in the system. The next section suggests how these limitations are addressed.

Hillier and Hanson (1987) also suggested that spatial relationships can be described mathematically. For example, they proposed different measurements, such as connectivity, integration, and control values, to quantify syntactical analyses. Results extracted from these tests are useful for interpreting the overall configuration and the social life in the building (e.g. high integration values indicate that spaces are busy, more accessible, and less private). In contrast, low values can mean that these functions are more segregated and more controlled in movement. However, studies focusing on how such an approach might be used for generating or inspiring new designs remain limited (Lee et al. 2013).

Shape grammars: a formal geometric analysis and generative approach

Shape grammars, developed by George Stiny and James Gips in 1970s, is a formal system that works with geometries rather than symbolic computations (Stiny and Mitchell 1978). It allows designers describing and analysing existing forms, and then generating new alternatives based on the original style. The roots of this approach builds on the work of Christo-

Figure 1
A node-and-connection diagram that is applicable for three alternatives of spatial relations (Adapted by authors, after (Osman and Suliman 1994))



pher Alexander, 'A Pattern Language', in 1977. A 'pattern', which could vary in its scale from a city to a building or a detail, addresses a problem and then recognises solutions and design practices that are balanced within the defined context, in an attempt to reconstruct the knowledge about what makes architecture beautiful (Alexander 1977).

The framework for developing a shape grammar could be outlined in four stages. (1) defining vocabularies (basic shapes); (2) determining spatial relationships; (3) formulating rules to be applied on forms; and (4) combining/articulating shapes through applying rules recursively to define a language of design or to generate new solutions (Eilouti and Al-Jokhadar 2007). After reviewing several cases that use this method for generating new spatial configurations, four types of rules could be applied: (1) additive rules, where geometries are added around the initial shape, such as the grammar of Queen Anne house (Flemming 1987); (2) subdivision rules, which divide the original shape into new zones with new proportions, such as the grammar of Malagueña house (Duarte 2005); (3) rules that are based on a grid, which start with defining dimensions and proportions for the grid, and then applying transformations, such as Palladian grammar (Stiny and Mitchell 1978); and finally (4) transformational rules, which combine additional and subdivision rules for creating openings, terraces, and roofs (Verkerk 2014).

However, shape grammars do not clarify social, cultural, and environmental dimensions of designs, as they deal only with geometric properties (Co-

Iakoglu 2000). Moreover, some design possibilities have no architectural meaning or are irrelevant to the local context (Eilouti and Al-Jokhadar 2007).

Discursive grammars

To control the process of form generation and the production of unique solutions, George Stiny (1980) introduced labels, such as letters; symbols; or points, associated with shapes. Furthermore, specified equations, constraints and transformations, such as translation; rotation; reflection; or scale, could be applied to increase the number of solutions and the flexibility in design.

Another method for controlling the process is to add descriptions or textual information to the definition of rules. Rudi Stouffs (2015) defined three schemes for these descriptions. The first type is 'reflections', which reveals spatial vocabularies that form the design. The second category is 'expressions' that describe some properties of the design, such as volume, cost or manufacturing plan. The final scheme is 'design briefs', which define conditional specifications, or functional zones and their adjacency relations. The following example shows descriptions that are associated with spatial rules for generating part of a courtyard house (see Figure 2).

DEVELOPING A SYNTACTIC-DISCURSIVE MODEL FOR ENCODING SOCIAL AND SPATIAL QUALITIES OF DESIGNS

This research aims to build on the benefits of shape grammar and space syntax methods for exploring

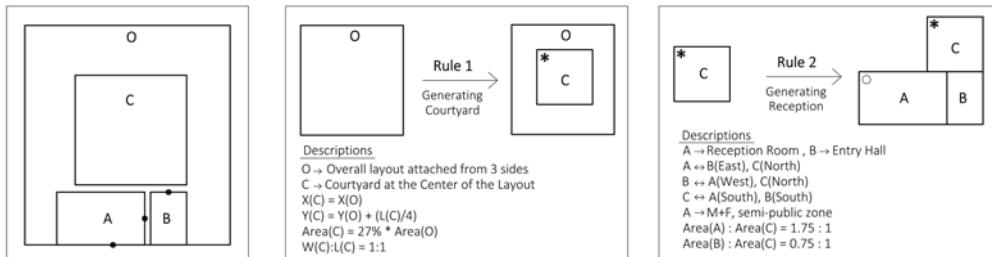


Figure 2
 Part of a discursive grammar that generates the semi-public zone in a courtyard house (Authors)

spatial-formal features that affect the social life of occupants. Moreover, it tries to find solutions for the different limitations faced by these tools, through developing a syntactic-discursive model that encodes spatial constructs.

Based on a literature review of social sustainability in residential buildings (Modi 2014; Oldfield 2012), the authors identifies 13 indicators that need to be addressed in the design process. These indicators include: Population density and crowding; hierarchy of spaces; amount of living spaces that affect social interaction; human comfort; accessibility; visual privacy; acoustical privacy; olfactory privacy; spirituality; security and safety; viewing the exterior; availability of services; and hygiene.

To measure the current needs of residents and capture such qualities, we conducted a phenomenological study in the Summer of 2016, through distributing a questionnaire to 211 families from 17 countries within the study area. Furthermore, we implemented a formal-geometric study for extracting typologies of historical precedents through examining 48 traditional town houses and neighbourhoods distributed on MENA region. We then used three computational tools for carrying out these typological and syntactic analyses:

- *AGraph*: an open-access software, developed by Bendik Manum, Espen Rusten, and Paul Benze, in 2005, at the Oslo School of Architecture and Design. This 'node-and-connection model' produces syntactic calculations, and

two types of justified graphs: depth of spaces from the root space; and integration of functions (Manum et al. 2005) (see Figure 3).

- *Syntax2D*: an open-source software developed in 2007 at the University of Michigan to execute isovist analysis. It addresses the visual fields of a person at one location of the environment, and along a movement path (Wineerman et al. 2007) (see Figure 4).
- *DepthmapX*: a 'Visibility Graph Analysis (VGA)' tool developed firstly in 2000 by Alasdair Turner at the Space Syntax Laboratory, The Bartlett, University College London (UCL), and then by Tasos Varoudis (2011-2015). VGA is based on the reflection of light to understand the spatial configuration of the environment. VGA includes five types of tests: (a) connectivity analysis; which creates visibility connections between all spaces; (b) visual integration, which specifies the degree of privilege of one point over its immediate neighbours; (c) through-vision analysis, which looks at how visual fields varies within an environment; (d) depth analysis, which shows changes of direction that would take to get from the selected location to any other locations; and (e) agent analysis, which indicates patterns of movement, and the frequent use of spaces released from one point (Turner 2001) (see Figure 5).

The developed model of analysis adds new aspects to the justified graph of Hiller and Hanson, as

Figure 3
A justified graph showing the integration value for each space, produced by AGraph software (Authors)

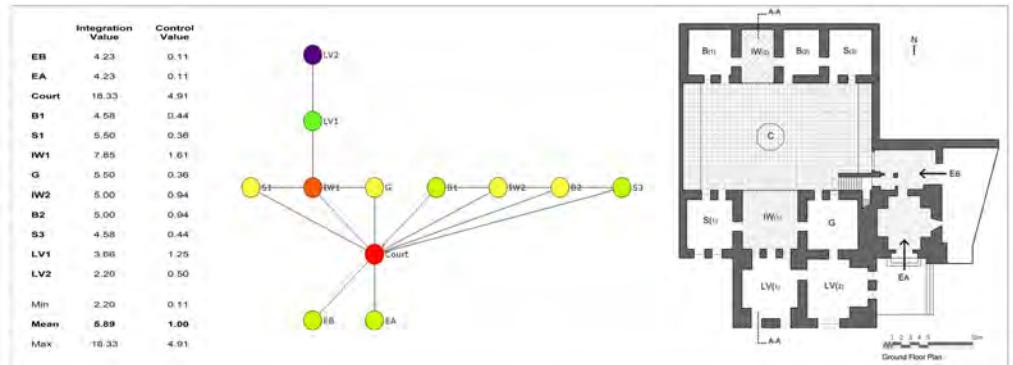
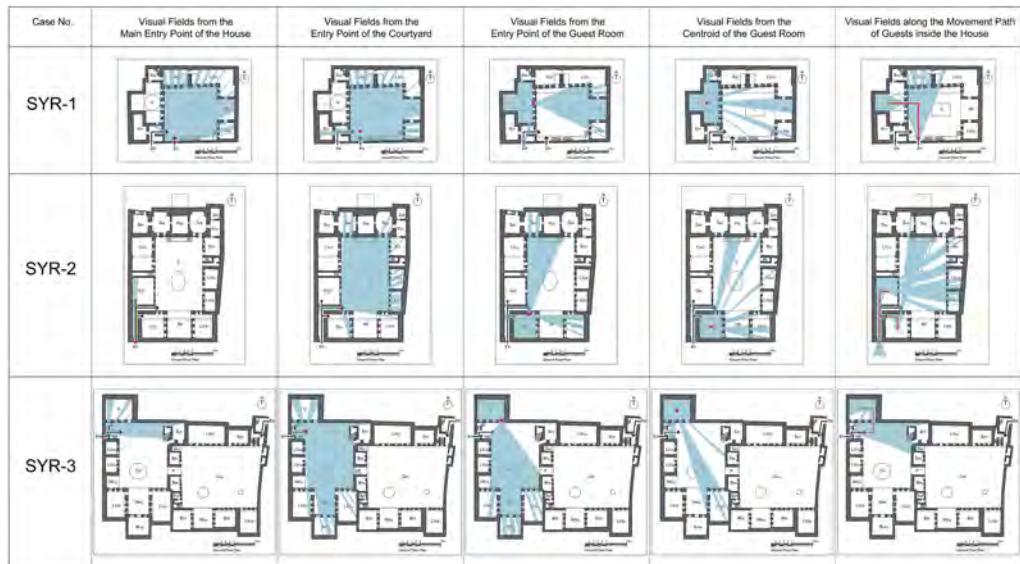
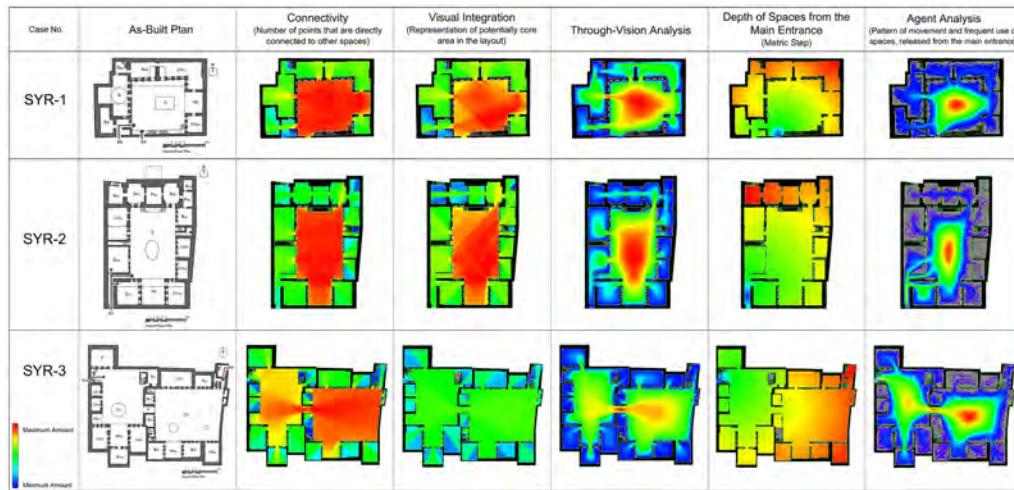


Figure 4
Samples of Isovist analysis for three traditional courtyard houses located in Syria, produced by Syntax2D software (Authors)





a representation to formal and social realities. These issues are (see Figure 6):

1. Patterns of movement, and distances between the centre of the courtyard and the centre of each space, to analyse accessibility and security inside houses.
2. The actual geometry of each space rather than symbolic nodes. Shapes are arranged to show:
 - Hierarchy of spaces (public, semi-public, semi-private, private, and intimate);
 - Orientation (West, East, North, South, North-East, North-West, South-East, and South-West);
 - Type of enclosure (covered, open, semi-open);
 - Shared surfaces between adjacent spaces; and
 - Entry point(s) between spaces.

Moreover, the spatial analysis includes geometric proportions for each space; percentage of space area from the overall area of the house; area of the space in relation to the area of the courtyard; and the dominant users for each space (male, female, or both).

A COMPUTATIONAL TOOLKIT FOR PERFORMING SYNTACTIC-FORMAL ANALYSIS USING GRASSHOPPER

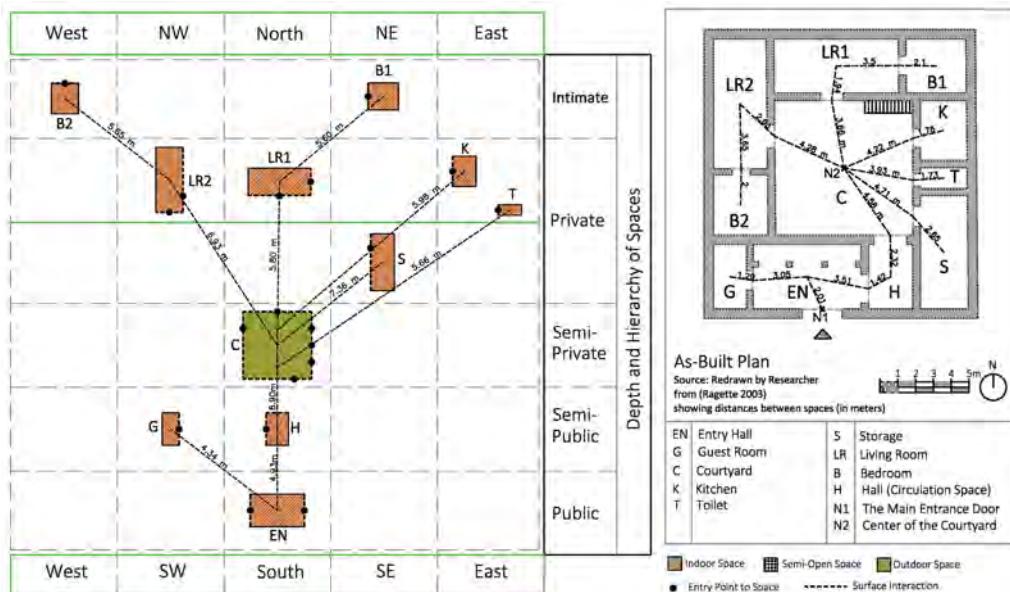
The above mentioned method requires from designers an extra effort to calculate spatial qualities, such as areas and proportions of spaces. Moreover, the use of *AGraph* software for extracting syntactic values requires drawing the 'node-and-connection' justified graph manually. Thus, errors could easily occur during this process. Therefore, it is useful to develop an automated computational tool for analysing floor plans in a short time of execution, and with a high degree of accuracy that does not require the user to possess an advanced level of knowledge in syntactic analysis.

For this research, Grasshopper, a plugin for Rhinoceros, is used for carrying out the needed analysis. Grasshopper is a visual scripting tool that helps the design to process (Fathi et al. 2016). It allows input data to be passed from one component to another via connecting wires. Several plugins could be downloaded for executing different utilities without leaving the tool itself. The following section illustrates a detailed workflow of the automated model.

Figure 5
Samples of Visibility Graph Analysis (VGA) for three traditional courtyard houses located in Syria, produced by DepthmapX software (Authors)

Figure 6

Aspects added to the justified graph as a representation to formal and social realities (Authors)



Model workflow and the user interface

The model depends on generating the layout of historical cases according to a 'space partitioning' mechanism (Knecht and Konig 2010). It is about splitting a region into sub-spaces (cells). This geometric representational technique, using non-manifold topology (NMT), defines topological relations between adjacent spaces without any void (Jabi 2016).

The first step requires users to draw the overall layout boundary for the building (as polyline), internal partitions representing shared surfaces between spaces (as lines), and doors (as rectangles). However, thicknesses of walls are ignored. Once these features are obtained from a 'selection' component, the partitioning process is executed accordingly using NMT. A unique legend number is assigned automatically to each cell. This process could be applied on any layout that is composed of regular or irregular geometries.

The second step involves typing a function label for each cell, and then selecting spaces from lists ac-

cording to two criteria: hierarchy of spaces (public, semi-public, semi-private, private, or intimate zone); and type of enclosure (open or covered area). A tag component is implemented for each cell. The model, then, computes the following values, which are also delivered on the form of Excel spreadsheet (see Figure 7):

1. The area of each space, and the percentage from the total area of the house;
2. The total area for each hierarchical zone, and the percentage from the total area of the layout;
3. The distance from the centre of each cell to the centre of the main courtyard; and
4. Colour-coded syntactic values for each space, which include:
 - Integration value: describes the average depth of a space to other spaces in the system;
 - Control value: measures the degree to which an area controls access to its immediate

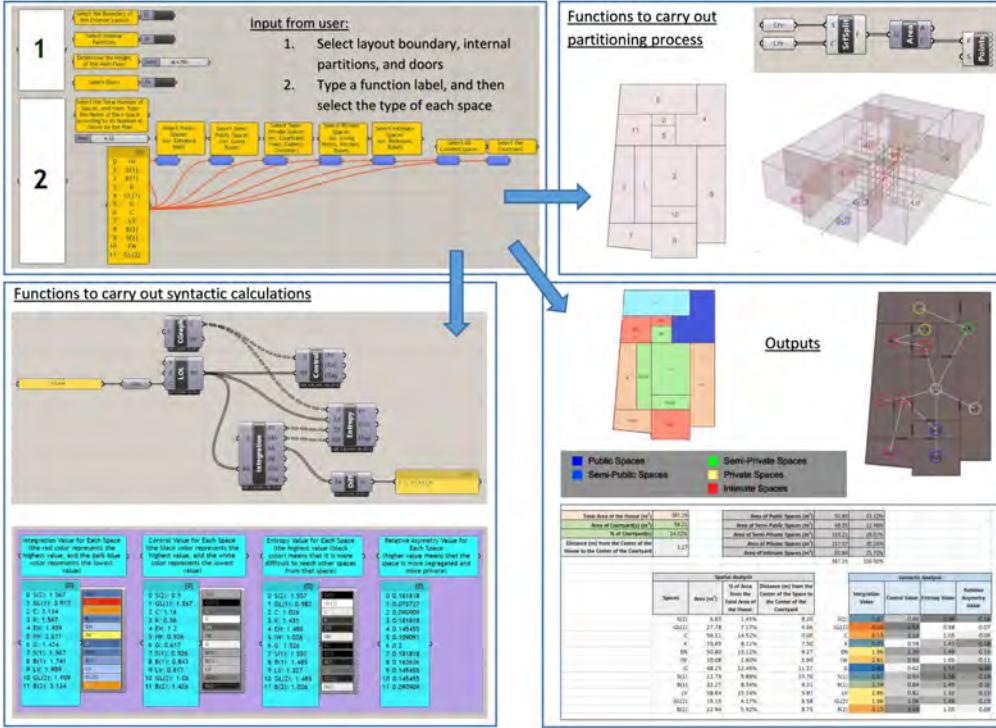


Figure 7
Model workflow and the user interface, showing input data from the user, sample of functions to carry out the partitioning process and the analysis, and the output tables and diagrams (Authors)

neighbours taking into account the number of alternative connections that each space has;

- Entropy value: the difficulty of reaching other areas from that space;
- Relative asymmetry: values that are closer to 0, means that spaces are more integrated, more accessible, and less private (minimum depth of spaces). In contrast, higher values that are closer to 1, indicate that spaces are more segregated, more controlled in movement, and more private (linear sequence of movement, and maximum depth of spaces); and
- Difference factor: values that are closer to 0

mean that spaces are more structured, while higher values, i.e. closer to 1, indicate that spaces are more integrated.

Visually, four types of diagrams are generated:

1. Orientation of spaces: based on the coordinates of the centre of each cell in relation to the centre of the layout, a unique coloured circle that indicates the location is assigned to each space;
2. Node-and-connection syntactic diagram, showing links between spaces. Each link means that there is a door/access between these two cells;
3. Hierarchy of spaces, with a colour code for

- each zone; and
- 4. Distances between the centre of the courtyard and the centre of other spaces.

READINGS FROM SPATIAL AND SYNTACTIC ANALYSES

When the results of syntactical-discursive analyses were examined, the following spatial features that affect the social life of occupants were observed. The traditional house consists of different hierarchical zones (public, private, and intimate spaces). The courtyard is the largest space in the house and the most accessible and connected function. Other functions are controlled and accessed through the courtyard and follow its geometric pattern with a symmetrical layout arrangement. Moreover, the depth between private areas and the courtyard provides a protected and comfortable atmosphere for family members to move inside the house easily.

The Isovist analysis and the Visual Graph Analysis (VGA) show that the privacy of the household is protected from public and semi-public spaces (the entry hall and the guest room). Different mechanisms are used for achieving this result, and to strictly limit access to the courtyard by guests. These features include the bent entrance, the use of partitions in front of the main entrance, and the size and the location of windows for guest rooms. Moreover, the spatial configuration shows that reception rooms are shallow spaces that are suited off the courtyard next to the entry hall. In contrast, findings reveals that intimate spaces (bedrooms), which have a lower integration value, are more integrated with private spaces.

CONCLUSION

Achieving social sustainability in residential buildings requires a holistic approach for clarifying spatial qualities that affect the social life inside houses. A spatial reasoning approach is presented to understand such topologies. For instance, studying the location of each space, and measuring distances between functions, are useful for analysing accessibility and movement. Moreover, defining connections between spaces, and describing their geometry and scale, offer information about their hierarchy, the degree of social interaction that takes place within them, and their ability to provide comfort to their occupants. Analysing these factors creates a database that can be used to improve the social qualities of future developments.

The proposed automated model of analysis, offers an alternative method for extracting topological relations and syntactic calculations. This tool could be easily used to analyse floor layouts that have any size or geometry, in a short time of execution. Moreover, users do not need to know exact procedures of syntactic calculations, or draw the justified graph for the system, as the model provides them automatically. Translating such qualities into rules and parameters leads to the construction of a socio-spatial grammar that is related to the local context. This grammar will be used in the next stages of this ongoing research for the emergence of vertical residential developments that are socially sustainable, and respect the culture and the needs of its users.

ACKNOWLEDGMENTS

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Computation in Architecture

Subtitle: The Handling of Computational Devices in Buildings

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The common point of view in architectural design regarding computation states, that in architecture computational aspects of a building's design are ignored once a building's design is finalized. Computation beyond the completion of a building does not belong into the realm of architectural practice. The undeniable existence of computers in buildings should not only be regarded as addition to a building's design. Architects have to deal with computational devices and their functionality in buildings and they have to design both form and function of them. An integrated design approach as part of the holistic concept of designing buildings needs to be established, because computation will become an essential component in the architectural design process.

Keywords: Programming, Computational architecture, smart buildings, cloud computing

TOPIC(S)

- Design Concepts &Strategies
- Human-Computer Interaction
- Smart & Responsive Design
- Spatial Reasoning & Ontologies
- VR, AR & Visualisation

INTRODUCTION

Computation in architecture, as it is well described in the conference's theme, "spans from the virtual representation of space to its physical making" [Spaeth & Jabi 2016]. This common point of view in architectural design inherently states, that in architecture computational aspects of a building's design are ignored once a building's design is finalized and the building is erected. The finding correspondences

with the typical job profile of an architect that after the architectural production has ended the work including the work the engagement of computers is done. It looks like a perfect fit.

The shortsighted assumption that computation in architecture is only part of the process to enhance and ease the design introduces the limitation that after fulfilling the promise of a design the computational elements therein are not any longer part of its architecture, if they have ever been. Computers inside the finished and established building are usually not regarded as part of architecture, because computation beyond the completion of a building does not belong into the realm of architectural practice.

This is reflected by the naive attitudes of not handling computation by simply ignoring computers in buildings, like as the conference's theme, refusing

them, neglecting, denying and even fighting it in a sense, that buildings cannot be 'smart' (Koolhaas 2015).

It is obvious that these strategies are leading to a dead-end. Theoretical and practical computational applications in architecture cannot be left out at will. They are everywhere and buildings are no exception. Instead computers as part of buildings should be considered as valid parts of the architectural design and taken as chance to the ongoing quest of improving architecture.

COMPUTERS IN ARCHITECTURE

Computational machines and applications can be essentially divided into two groups, computers in the hand of a user within a building running specific software, like mobile device with a navigational software or an AR-system (Augmented Reality) and computers as part of the building itself, usually small embedded computers with limited capabilities and especially no dedicated user interface, commonly assigned to home automation or 'smart buildings'.

Mobile devices

For a decade now mobile devices with their touch-screens have silently infiltrated the perception of our reality, meaning that the sole focus on our world is vanishing in favor of a more connected and networked surrounding. Any activity like a simple tweet or an SMS on a smart-phone is related to a location, the place where the users gets distracted and shifts the focus from the environment to a small display.

Designated applications on mobile devices for certain buildings or locations are already known, like apps for museums or exhibitions, often based on augmented-reality technologies, or specifically designed navigational applications for particular localities.

What is lacking is an integrated design of both the application and the building. By pretending that programmers are not designers and designers can not write code a building's environment delivers only the static context where the app is fitted in. The us-

age of the app should not interfere with the architectural design, even though apps are already doing it all the time by mixing realities and changing the architectural appearance. This ostensible arguing becomes more and more outdated.

Computers mounted in building

Unlike walls, doors, windows, handles, locks or else computers are not considered as part of a building. Instead they have become part of them as accessories. Computers merged inside building parts, typically some electrical and mechanical items, as embedded systems are regarded as component of that part of the building. Computerized outlets deploy an integrated relay as switch, locks are motorized and so on. The upcoming question here is, if e.g. an automated door is still a door with a lock and some mechanism or a temporarily opening which appears to be permanent, because only the absence of users made it close. Hence in theory nobody never will notice that particular spatial separation. Just an aspect here, which will not be discussed any further.

The point is that while the relation between mobile devices and buildings are only established through the simultaneous perception of their users the relation between computers mounted in buildings and the building itself are even more tight, and hence is the design.

TERMS AND DEFINITIONS

The utilization of embedded computers in buildings has lead to some interesting wordings like 'home automation', 'smart devices' and IoT (Internet of things). Before discussing them in detail at first these terms have to be acknowledged as technical terms. Otherwise philosophical issues and similar will become overwhelming. Neither can a device be taken as smart, nor a complete home automated (What does it do?) nor reality be augmented and so on.

Smart Devices

Adding an embedded computer, eventual some network interface and commonly some sensors and

some actuators to some part of a building assumably makes them 'smart'. A window with a computer is a 'smart window', an outlet with a computer a 'smart outlet' etc. Usually such computerized entities act to some degree on their own without direct user control, hence sensors and actuators are usually integrated.

Besides the inflationary usage of 'smart' which causes a lot of irritations (Koolhaas, 2015; Lonsing, Smartness and Interactiveness, 2016) the real functionality of the computer is disguised. It is not about smartness or intelligence, it is about control. Modern embedded systems establish controlling, timing, supervision, regulations etc. in a quality that have been unthinkable only a few years ago. With servos, colorful lighting and modern networking technologies attached to it new types of installations can be created inside computerized buildings making them interactive, responsive and more flexible.

Home Automation

Home automation slightly differs from smart devices as it includes more sophisticated machines like a coffee-maker or a dish-washer. Already computerized those machines have become interconnected and may now are messaging their status and also accepting orders from authorized users elsewhere, although strictly an Internet connections according to the concept is not mandatory.

Surprisingly one special consideration in home automation is the wide variety of technologies, platforms and protocols. Some of them are standardized, some of them are open and a lot of them are still proprietary. However, essentially the usage of different protocols and frequencies is simply an implementation detail.

IoT

The 'Internet of Things' is defined by its status, where all devices are expected as connected through the Internet regardless of their functionality. It can be literally everything.

One point to mention is the ubiquitous usage of speech recognition, which depends on the Inter-

net. All major provider, Apple with Siri, Amazon with Alexa, Microsoft with Cortana, and Google with its refreshed Assistant are performing cloud-assisted speech recognition as their services.

Common Pattern

Needless to state that the terms and definitions and their related technologies are not a major concern. The main problem is that in architecture a kind of yet unknown flexibility and control of the built environment has been established. With the introduction of computation in buildings, this may include networked access, new concepts are requested to integrate computers into a building's design process. The apparent sprawling installations more than indicate this as a consequence.

A look at the simple example of smart outlets from the supermarket, which can be triggered wirelessly, may demonstrate the issue. There are a lot of different vendors, each of them uses specific technologies and probably different frequencies, each of them has its own cloud and its own app. These device are not designed for integration and their users' experience is less than optimal. But what really matters, even for otherwise technology-resistant architects, is their appearance. Although the look of common outlets is not always pleasant, these kind of extensions are distinguishable well designed in all different forms. Plugged into a normal outlet on a wall they look like pimples, just ugly.

Then there may be different types of outlets, because they were once on sale, with different protocols of course. In addition there maybe are those typical cylindric sometimes blinking devices for speech recognition, dominating a room because they should always listening, and there maybe other devices to come.

If as architects we otherwise do not care about computers and have no opinion regarding computation whatsoever, this is a point we have to address.

THE TASK

To prevent a building's design from electrical clutter has become the challenge in modern architecture. The related task is to do it by design. It implies rethinking the concept of buildings like it has been done before when new technologies were introduced like e.g. the usage of steel or glass.

Therefor the computational infrastructure as part of buildings should be laid out during the design process. A special type of installations are central computers or a network thereof in buildings. They establish an informational grid and a local cloud bound to the location eventually effecting the ownership of data, reliability, security and other issues of modern computation. A holistic view of a network as integrated part and as a specific element of the construction of a building, when a building provides connectivity like shelter, is the focal point of this task. Designing a layout for computation needs special consideration on its own during the design process.

Computers in public spaces

Architecture is not limited to buildings and therefore computation not bound to their physical presence. Public spaces as part of urban planning are also about to be computerized. One example are much more flexible public lighting concepts based on smart street lights.

Some Projects

Instead of theoretically elaborating on design issues some projects are introduced. They have in common that they are all deploying a micro-controller based on the Arduino-platform. While the genuine Arduino does not provide connectivity the specific type of controller from Particle here in use are connected. Their different types of boards are interchangeable and can offer connection either through WiFi, GSM or Bluetooth with the same code-base. In addition they can access either the company's global cloud or a cloud locally installed on a small server, typically a Raspberry Pi.



Figure 1
Lighting with a color changing lamp.

The project related to deliver some new computational supported functionality in buildings are more or less all related to lighting. As technology artificial lighting simply provides the best cost-benefits ratio. User interfaces on the other hand may already cut costs and do provide some savings. By substituting wall switches and their really expensive high-current power lines with connected and programmable custom made switches the switch panels on walls could be eliminated altogether with something like e.g. integrated touch areas made from concrete.

Empathic Lighting. Empathic lighting as project (Lonsing 2016, Empathic Lighting) explores the usage of computers, sensors and actors to illuminate a scene. With moving RGB-LEDs a fast responding lighting system is developed to not only defy the impact of changing daylight conditions but to answer the environmental light intake on the fly and even anticipate a viewer's acting. Still at a model scale the working system comprises two specially designed lighting units and a smart phone as both as camera input and user interface.

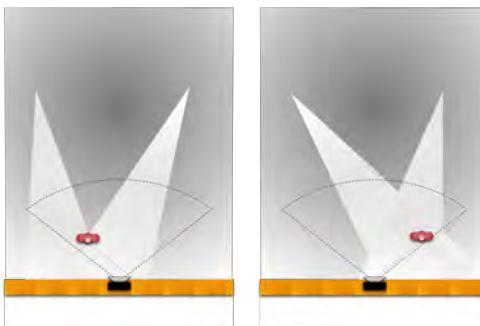


Figure 2
Concept of empathic lighting, the lamps are moving according to the position of a user.

Figure 3
User-interface on a smart-phone to control a single lighting unit.



Figure 4
Complete system, colored LEDs mounted on pan-tilt-brackets with servos and micro-controllers.



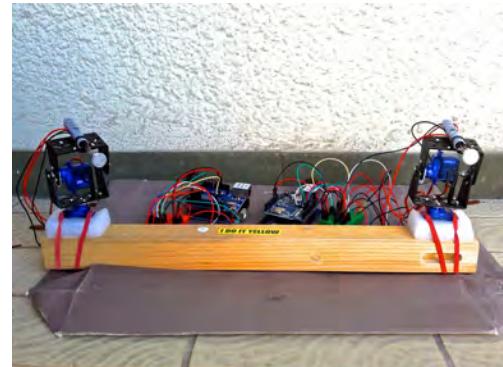
Figure 5
Projected socket with designed parts.

The lighting units are spot-lights with RGB-LEDs mounted on pan-tilt brackets. They are individually controllable: color, brightness and the direction can be changed on demand. Each lighting unit deploys its own computational controller, a common Arduino-board with an Ethernet-shield for connections.

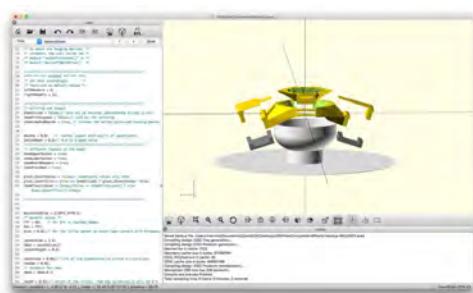
To determine the actual illumination a camera is used, which is already part of a mobile device. By means of image processing the immediate visual appearance is analyzed like the presence of users and the ambient lighting. An overall color value is detected by summarizing all pixels and calculate a mean value thereof which is used for corrections. Then the detected color components of the LED are lowered and the opposite color components are raised. As result the scene should always appear in

a constant light regardless of environmental inputs whatsoever.

An additional feature is the usage of the built-in face detection to anticipate the viewing direction of a user in order to illuminate only the area of interests the user is looking at.



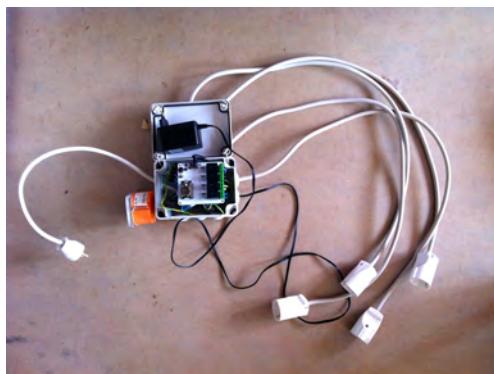
Fado Lamp. The Fado-lamp is a simple self-made RGB-lamp similar to common mood lamps. It utilizes 3D-printed parts to mount the LEDs and the micro-controller on top of the socket of the then removed light bulb. The chosen Pixie-LEDs have the advantage, that they can be daisy-chained, hence a variant with three LEDs is already projected.





To create the printed parts the socket was measured and virtually rebuilt to design the mounts. The micro-controller then were virtually placed as winglets and mounted using the physical pin layout of the boards. Due to the small size of the pins the fitting of the winglets still has to be worked out.

Outlet Spider. The outlet spider is a smart remote switch which is built around a micro-controller mounted on a power shield. The shield including AC/DC converter is inserted inside a typical junction box from a hardware store in order to simulate a typical building situation, where the installations are sunk into walls.



The concept avoids any unnecessary devices, like smart power bars or smart outlets to be plugged into conventional outlets.

Smart Street Light. The Smart Street Light project (Lonsing 2016, Smart Street Light) was designed as a common street lamp with added colored lighting allowing for new concepts of public spaces with integrated lighting installations.



As project it enters the realm of urban planning. The prototype of a street light is made from a common mushroom shaped enclosure, wherein different types of light sources as high power LEDs, one RGB- and three white LEDs, sensors and the electronic devices, micro controller, shields and a power converter are integrated. It combines ambient and directed lighting as result of environmental stimuli detection and an animated installation as well.

Figure 6
Printed parts and the real lamp.

Figure 8
Concept of a smart street light.

Figure 7
Outlet spider with micro-controller and relais inside a junction box.

Figure 9
Inside of the street light.



Figure 10
Projected switch to control a complex lamp with a rotary button and a small display as UI.

Figure 11
The same functional switch with micro-controller on a breadboard.

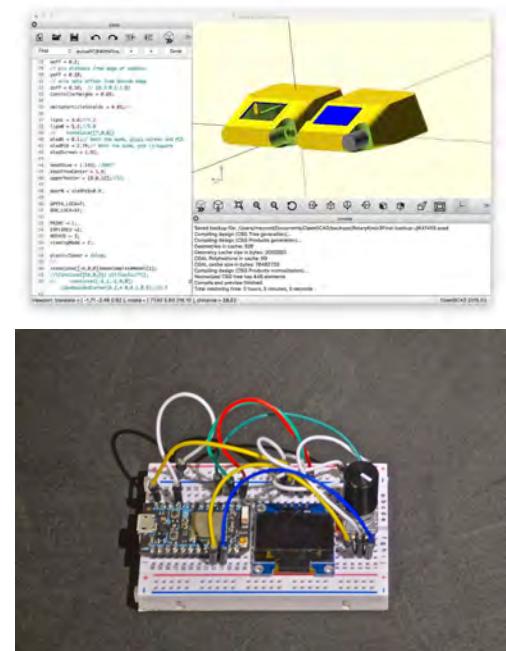
As a street light the power can be supplied through the pole. A remote control is not yet installed. The usage of higher voltages here simply requires more attention and extra care.

User Interfaces in Buildings

Regardless of the functionality of their corresponding computational devices common user interfaces in buildings are following only two patterns, and both are relying on the Internet comprising remote data processing and storage.

Either connected embedded computers are controlled through mobile devices or by speech recognition. Both use cases are not as intuitive as they could be. Focussing on some small display and wiping through screens is always distracting and almost as cumbersome as the time consuming verbal communication is .

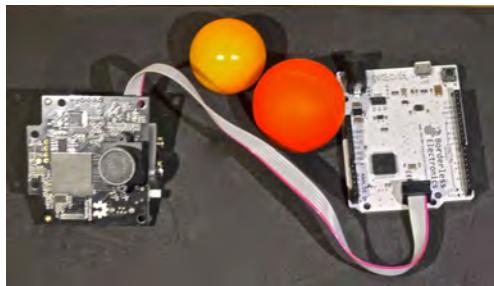
Flexible Switch Pad. The switch pad combines an OLED-display, a push-rotary-button and a micro-controller. The button provides the input to display a little menu on the the display, walk through it and select some functions, while the push-button is an on-off switch. One application is to control the colors of the LED of the Fado-Lamp and simply switch it on or off.



The provisional implementation is hard coded, but it is contemplated, that all devices, once connected, may deliver their menus and related functions, hence this small pad (Weiser 1991) is capable of controlling more than one and different types of devices.

Wand. The wand is a colored ball on a stick, which can be visually traced. A camera with integrated image processing detects the ball and its color and sends the detected features as values to the controller like e.g. what color has been chosen, is the ball raised or lowered and so on. Various colors may invoke differ-

ent functions.



The controller then acts according to the installed functionality.

Push Button. The push button is a simple all-purpose button with a big push button, a rotary switch to select a specific functionality and the micro-controller. Based on the idea to create a simple and easy to use emergency button the actual implementation is mounted inside an off-the-shelf button, which has been produced to some office entertainment application making random comments.



The button itself offers little degree of freedom. Once the up to twelve different functions are assigned, the button can be placed anywhere, and it can be pressed by hand or foot.

Touchable Pad from Concrete. The concrete pad is still highly experimental. Goal is to establish a touch-

able surface made out of concrete without any mechanical components. Using concrete as material with some electrically conductive additive and probably some reinforcement permits almost any form and kind of integration in buildings made from concrete.

Right now the pad can execute only one function, because there is only one single touch area. It is connected to the micro-controller by only one single wire.

It is contemplated that more touchable surfaces can provide more functionality. Then every touchable area is connected by a dedicated wire, increasing their number significantly.

Other parameters may be arranged similar to other usages of concrete, it can be colored by using pigments, the surface can be to some degree structured and so on, as long as the electrically functionality is maintained.



Figure 12
Camera with
micro-controller
and two colored
balls

Figure 14
Pad made from
concrete with wire.

Figure 13
Simple push-button
with integrated
rotary switch.

COMPUTATION AS PART OF THE DESIGN

In architecture computers are already bound to the design process: whatever kind of building and construction is imagined, it is developed as data, at first a virtual model, than as integrated building model. This widely accepted approach ignores the computational statements done within a building. In other words, handling the undeniable existence of computers in buildings is not the task of an architect. This

has to be changed.

At first, it has to be acknowledged that architects have to deal with computational devices and their functionality in buildings. As consequence they should secondly design both form and function of those computational devices and finally their should be an integrated design of them as part of a holistic concept of computation in buildings.

The role of programming

The question is, how and to what degree architect should and can handle computers in buildings. There is no answer yet except that some programming skills are required, because programming is an essential part of computation and no computer is running without software. Programming will become part of the design process the one way or the other.

Then a question remains: Can architects acquire and maintain an in-depth knowledge of some specifically designed architectural SDK (software development kit), programming language included?

This question is not simple to answer, but there are some aspects worthwhile to mention:

- Architects are already programming. They are writing C-sharp or Python scripts as executable code for computers to enhance their drawing software-packages.
- Programming itself is changing dramatically and has become diversified. The old model of a desktop-computer running some software now competes with mobile-, cloud- and embedded computation and even more.
- New technologies are evolving. Tools like visual programming or cloud-compilation detach the programmer from a specific platform and its IDE.

Other issues, like if there will be any support for a standardization from an industry or a major supporting governmental entity like ANSI (American National Standards Institute) or ISO (International Organization for Standardization) then will be resolved almost automatically based on needs.

CONCLUSION, KIND OF

Computation will become an essential component of architecture, there is no question about it. By closer looking at buildings it becomes evident, that the upcoming task here, if taken seriously, is nothing less than injecting a nervous system into pre-existing structures, like the modernization of buildings, or historic concepts as building designs.

The standard phrase, that the introduction of new technologies will sooner or later lead to new forms of design applies here, too. It has happened before. The difference to those events from the past with the introduction of new materials and structures is only, that structures and materials are already in place as static elements. With computation the next kind of architectural style will become dynamic, flexible and responsive. Buildings will change from an almost immutable state to a collection of mutable objects in control by the buildings' inhabitants.

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Digitizing the Unexplored

Bridging the Concrete Experience and Abstract Geometry Through Physical Experiments

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Ways of promoting creative approaches in the context of embedding digital design approaches in education are increasingly becoming a popular topic in architecture schools. On one hand, digital design methods, approaches and tools are diversified, while on the other hand, the danger for students losing control over the design process by appears as a new phenomenon. We argue that experiential dimensions of empirical observation conducted with physical experimentation might be helpful for students to comprehend digital topics creatively. With a particular emphasis on engagement of physical experimentation and computational thinking, this study aims to present a pedagogical model which has been applied from 2014 to 2016 within a postgraduate course. The potentials and limitations of the introduced pedagogical model are investigated through students' bottom-up and top-down algorithm development processes and the outcomes of the digital modelling exercises.

Keywords: *pedagogical model, dynamic process, physical experiment, computational thinking*

INTRODUCTION

Theoretical debates on chaos, complexity and non-linearity have resulted in a series of well-established computational models of dynamic processes such as computational fluid dynamics, self-organisation of living organisms, swarm behaviour, various optimization models and physics engines. As a consequence, emerging models and approaches were introduced to researchers of different fields such as engineering, natural sciences, design, art and architecture.

As the basis or components of these computational models; mathematics, geometry, algorithms, programming languages or representation of space in digital environment can be all considered as a product and reflection of human thought. Regarding the relationship between reality and abstraction, Einstein (1921) used the term "axiomatic". In the first emergence of concepts, theories and axioms, there might still be relationship among the experienced world, inference and assumptions. After gaining a logical structure, axioms and signs start to perform

autonomously and independently of their sources. When it comes to computational models, they usually depart from original sources at least two times, being interpreted and reduced by the theoreticians and by the computer scientist. This reduction process makes it difficult for architects to understand, comprehend and generate new assumptions in relation with the original intuitive content.

Although architects have adapted various computational models to design processes, many architects still tend to approach CAAD possibilities via assumptions of Cartesian space in relation to the ontological crises of the digital age. There is a necessity to explore new relationships in the transitions among 2D, 3D and 4D information beyond Alberti's perspective. With Lonsway's (2002) words, the computational complexity is reduced to the Minkowskian Space in the usage of CAD software. Kolarevic (2000) also emphasizes the dynamic, open-ended and unpredictable characteristics of digitally driven architecture as a new potentiality. However, in difference to other debates, Lonsway (2002) clearly pointed out the differences between visual complexity and computational complexity by asserting Greg Lynn's (1998) blob still does not embody complexity beyond Minkowskian Space conception.

On one hand, ways of thinking, concepts, and vocabulary of conventional approaches dominate how one might comprehend and approach the potentials of digital tools. However, new concepts have been emerging while they effect the improvement of understandings. As a consequence, the emphasis on the concepts such as typology, form and geometry has been replaced by the focus on topology, formation and geometrical relations in the field of architecture. Moreover, new concepts and results are expanding the research area and innovative design processes.

In this study, we focus on how and in which ways it might be possible to introduce computational thinking logic to design students as a way of thinking beyond well-defined software packages and algorithms. With this concern in mind, we examined both

bottom-up and top-down approaches of algorithm development. What we mean with bottom-up is related to generating algorithms based on an iterative abstraction and diagramming process. In contrast to this, the top-down algorithm development process refers to the demystification of well-structured algorithms by changing parameters or components.

This study aims to propose a pedagogical model for introducing digital modelling approaches to architecture students with the focus on developing a better understanding on computational thinking. The scope of this study will examine the proposed pedagogical model which has been applied to post-graduate students from 2014 to 2016.

ALGORITHMS IN DESIGN - DESIGNING ALGORITHMS

"Algorithms, software, hardware, and digital manufacturing tools are the new standards that determine not only the general aspect of all objects in a nonstandard series, but also the aspects of each individual product, which may change randomly or by design" (Carpo, 2011, p.99).

In a world in which algorithms replace the visuals and physicals with an increasing speed, it is unavoidable for architects to engage with theses on new faces of representation. Carpo (2011) defined this transformation as "shift from mechanical to algorithmic reproduction" which affect both the way architects design and the role of architects in design processes. In this case, the question of how architects employ invisible and immaterial algorithms in design arise, while constitution of physical spaces and qualities has been most closely concerning architects. The encounter of architects with algorithms leads a dialogue crisis between a structured language and the perceived and designed world of the architect.

The compilers execute programming codes line by line, in a linear order. The expressions, and the relations among different expressions enable a recursive flow, in other words syntactic and semantic relations make a linear text work as hypertext. Developing an algorithm is similar to an attempt to trans-

Figure 1
Examples from
studies on
condensation (Hill,
2006, p.101); fluid
dynamics Kaijima et
al. 2013, p.121);
magnetic fields
(Bello Diaz & Dubor,
2013, p.239); fluid
crystallization
(Url-1)

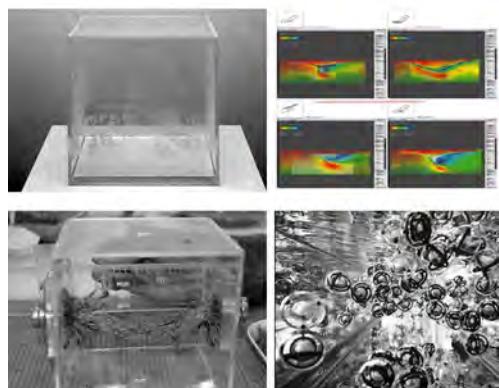
late any process including nonlinear ones into a finite number string-like lines. As Terzidis (2004) underlines, an algorithm as a computational procedure covers processes such as deduction, induction, abstraction, generalization, and structured logic. In this sense, developing algorithms involve several multiplicities of translation, transformation and conversion of different information types amongst each other, and constitution of new relationships among different domains and dimensions.

In a broader sense, this study focuses on seeking pedagogical approaches which might accelerate students' usage of digital modelling environments more creatively with respect to gaining computational thinking skills. This focus brings out another embedded contradiction: whether it is possible to encourage algorithmic ways of thinking for architecture students while keeping a critical distance to the existing commercial software and tools.

The pedagogical approaches to facilitate creativity in computational thinking, and the tool-independent teaching strategies have been on the agenda of many educators from different fields (National Research Council, 2011; Nickerson et al., 2015). One of the related topics which has been mentioned in "Pedagogical Aspects of Computational Thinking" Workshop was that: "Learning and teaching computational thinking should be contextualized" (Wolz in National Research Council, 2011).

In our study, physical experimentation process is considered as a source of intuitive context and contextualization of variables, expressions, loops and functions. Exploration new relations based on students' empirical observations and constitution of new links between the explored relations and existing computational models, in other words defining new problems took priority in our study different than other problem solving based approaches which has revealed problem solving based strategies might invoke students learning motivation. Moreover, findings similar with the literature (National Research Council, 2011), working collaboratively had an advantage over individual learning environments.

We aim to make a particular emphasis on expanding and utilizing the potentials of computational complexity towards a dynamic understanding of the things and the world instead of merely representing cartesian space. In this regard, we attempted to constitute a cyclic connection between well-established computational models on dynamic systems and the empirical research based of simple dynamic and changing environments. Related notions of flow such as flow as an abstract concept, flow as a particular feature of elements, flow as an observable phenomenon of dynamic systems have triggered the emergence of various research environments in the field of computational design. Usage of dynamic systems as a source for intuitive explorations is not new in architecture.



In Figure 1, top-left, an image of condensation is shown, which was introduced by Hill (2006), as a part of immaterial aspects of computational design. Dubor and Diaz (2013) presented a material behavior driven form-finding approach based on observation of magnetic behavior in different scales and scopes (Dubor&Diaz, 2013). A part of Dubor and Diaz's (2013) experiment setup is shown in Figure 1, bottom-left. One of their remarkable contributions is the workflow associated with digital fabrication process (Dubor&Diaz, 2013). In Figure 1, bottom-right an empirical study focusing on crystallization of fluids is

shown (Url-1). Implementation of a well-established computational fluid dynamics in architectural design is shown in Figure 1, top-right (Kajima et al. 2013).

In his 2006 book entitled "Immaterial Architecture", Hill pointed out the potentials of the dialogue between material and immaterial, concrete and ephemeral, conception and perception. Hill (2006) contributed to theoretical debates on exploring new meanings for creativity in design. Hill (2006) quoted from Moholy-Nagy that: 'A definition of space which may at least be taken as a point of departure is found in physics- "space is the relation between the position of bodies" (Moholy-Nagy, 1947, p.57; Hill, 2006, p.67). Giving the experience its due in early 20th century, Moholy-Nagy's expression can be considered as a manifestation of space-self-time interrelationship towards a new and dynamic understanding of geometry. In respect to the priority of experience, this study is an experimental process which involves attempts to multiplicate the viewpoints of the perceiving subject looking to static geometry via one-to-many model. In addition, many-to-many model which is explained in detail in the next section aims to accumulate the singular abstractions of the subject who observes dynamic process

PEDAGOGICAL MODEL

In the scope of the study, two models that we call one-to-many and many-to-many were tested in post-graduate courses. Duration of the implication of each model was 4 weeks. The course involved introduction of the sample studies, theoretical discussions, and readings separate from the experimental process. The implementation was repeated 3 times in different semesters. The one-to-many and many-to-many models included explorative, experimental and structured exercises. The physical experimentation, digitization of the observed information derived from experiments, and the outcomes of the modelling exercises were evaluated.

One-to-Many

This model was considered to depart from an initial static geometry. The source of the initial geometry was changed in different semesters, and the changes included things such as a part of a body or a part from the built environment preferably involving rich topological relations or complex geometrical information. The students were expected to depart from the initial geometry and gain experience in exploring generative and behavioural relations while generating a series of digital and physical models. The four-week module included but was not limited to the following phases:

- Measurement and 3D scanning. Extraction of geometrical relations from a given context.
- Generation of the same geometry in digital environment through a systematic topological investigation (Eg: sequentiality, repetition, in/out, near/far, etc.)
- Exploration of performative relations based on fabrication with different materials.

The modelling exercise shown in Figure 2 consisted of 3 steps. First, the data were collected with a 3D scanner. Subsequently, the lines of the layers were manipulated and surfaces were created inside the layer curves. Finally, joints' details were optimized and a 1:1 scale model was prototyped.

Figure 2
Digital and physical head models by
Aren Semerci

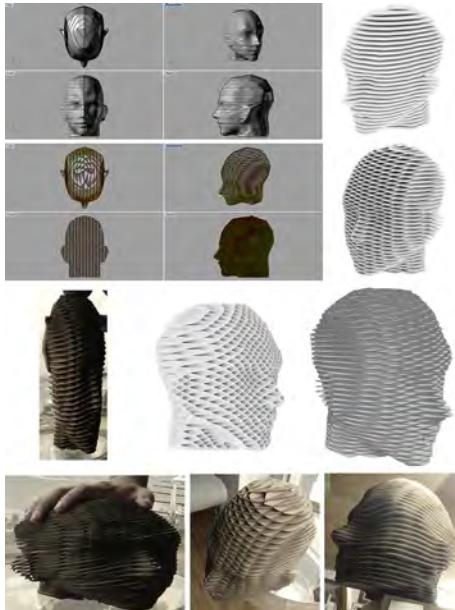


Figure 4
Muqarnas analysis
and computational
interpretation by
John Bogren

In Figure 4, an existing muqarnas geometry is modelled with a conventional 3D modelling tool. Reproducing the geometry with a parametric tessellation. A non-continuous form was generated with Voronoi. The new form was filled with a simulated cloth. The digital model was prototyped with the combination of plaster and cloth. Hang points and length of the strings were calculated in Grasshopper.



Figure 3
Generation of
column heads with
folding and
subtraction
operations by Gülcé
Kirdar

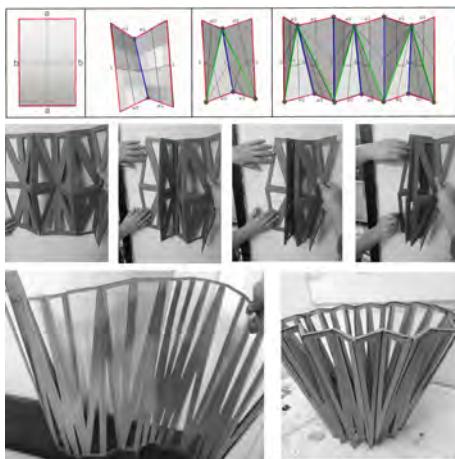


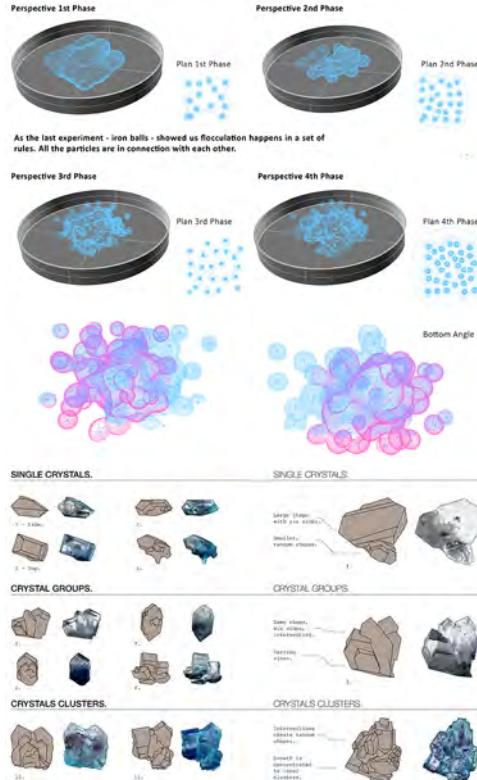
Figure 3 illustrates a process in which the column heads can be varied by different modelling techniques.

Many-to-Many

The main difference between one-to-many and many-to-many models was the assumption of initial source. Instead of a static geometry, a dynamic physical, biological or chemical process was selected for examination. This model included:

- Explorative experimentation: Selection of a dynamic process such as movement-based behaviour (magnetism), or particle behaviour (liquid behaviour - fluid dynamics, crystallization, etc.).
- Trial-Error: Repeating the same experiment through a series of structured experiments. Therefore, this phase involved a design experiment setup. The emphasis was on the exploration of qualities and parameters.
- Documentation: (Video record and time-based framing, phenomenon-based framing, etc.)
- Analysis: The students were asked to extract information from the experiments that they did. Although extracting information in most cases depended on visual analysis of the video records, this phase might cover various analyses such as phenomenon-based, event-based, and threshold-based ones.

- Developing algorithms for digital modelling: This phase involved both bottom-up algorithm development and top-down merging and adaptation of the existing algorithms. In the first case, the process was more important than the end results. The final outcome did not need to be a precise working model. However, it needed to be a new insight which can be improved by others in a long term. The second case focused on merging, manipulating, adapting and re-compiling different algorithms and samples on purpose.



Observed Phenomenon	Materials Used in Experiment Setup	Parameters	Bottom-up (analysis, abstraction, algorithm development)	Top-down (usage and adaptation of existing algorithms)
Magnetism	principle toner, motor oil, elec. acid, metal balls, magnets, ammonia	amount of metal balls, ratios of materials, coordinates of magnets	polarization; milling	swarm behavior; metropolis
Diffusion in Liquid	water, oil, ink	density of liquid, temperature, time		computational fluid dynamics
Mineralization in Liquid	sulfuric acid, ammonia, sodium carbonate, wood extract	speed of shrink, height of shrirk, viscosity		dynamic site diffusion, computational fluid dynamics; particle-based physics simulation
Fizzing in Liquid	water, oil, food coloring, effervescent antacid tablet	amount of materials, time		cellular automata, fluid dynamics, Physics
Condensation	liquid, planar glass, water	temperature, time	circle based analysis of bubbles	voronoi
Crystallization	sugar, water, food coloring	density of liquid, shape, temperature, time	shape based analysis and adaptation, growth analysis, gravity related behaviors	voronoi, agent based behavior

Table 1
Selected student experiments of many-to-many approach

FINDINGS, OUTCOMES AND EVALUATION

This part evaluates the common aspects and the differences of the student works, which were derived from implementation of the proposed pedagogical model between 2014 and 2016 in postgraduate courses. The selected student works of the many-to-many model were based on experimentation of viscosity, magnetism, ferro-fluid behaviour, cracking, diffusion and crystallization processes. The gaps and connections between the information extracted from the physical experimentation and the top-down examination of the existing algorithms are explained.

CONCLUDING REMARKS

The foundations of computational thinking are rooted in abstraction, translation and transformation processes. These processes conducted with physical experimentation might be considered as one of the core experiences for gaining a better understanding on the potentials of computational complexity. In other words, physical experimentation, documentation, abstraction and digitizing would lead to perceptual knowledge, which is different than well-established closed computational models. Therefore, we argue that revisiting the empirical research by architects will be important in the digital age to explore new and open-ended relations beyond well-established algorithms. In this sense, this study may be considered as an attempt to explore new ways of

Figure 5
Flocculation of iron balls related to the generated magnetic field by Yiğit Can Ülküçü

Figure 6
Analysis and interpretation of sugar crystallization by John Bogren

Figure 7

Flow diagrams of experimentation and images from experiments by Taylan Kılıç.

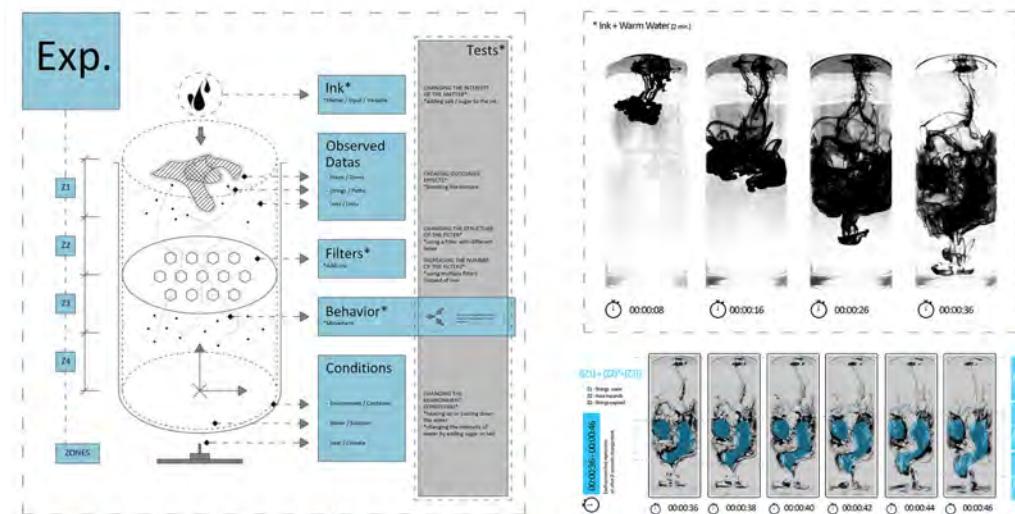
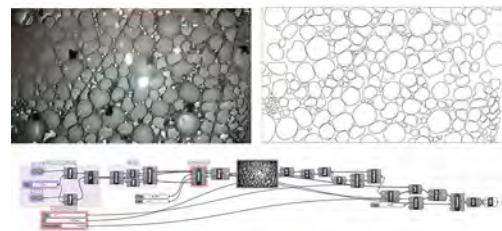


Figure 8

Regeneration of the pattern of condensed water on glass surface via image sampler by Ahmet Onkas

introducing computational models to architecture students with the aim of supporting students in developing personal reflections on the existing and also unexplored computational design models.

One of the findings of this study is that, in the case of the bottom-up processes where algorithms introduced explicitly as a foreign language involving vocabulary elements, syntactic rules and logical operations, it might be difficult to integrate the experience of developing algorithms with different scopes and contexts. On the other hand, gaining experience in algorithmic thinking depending on particular and digestible contexts might lead to tacit learning. We argue that the context-based tacitly acquired knowledge has the potential to be transformed into different problems.



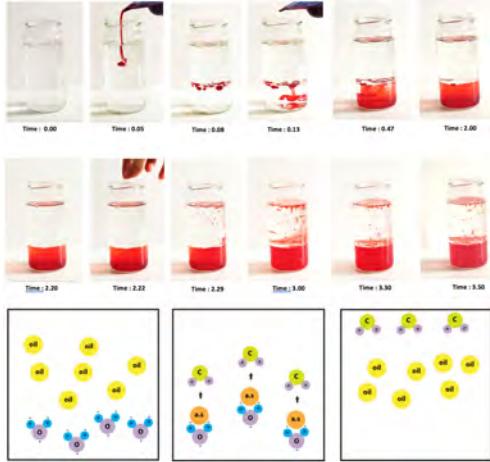


Figure 9
Sequential photos of experiment and diagramming the outcomes by Begum Moralioglu

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Building Performance Computation

Architectural space quality, from virtual to physical

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The adoption of digital design has offered new computational methods improving and deepening the morphological dimension of architectural production.

Algorithmic and parametric design associated with new fabrication technologies have made generating increasingly complex shapes possible, forming the basis of non-standard architecture. Such approaches raise many interesting questions like the qualitative and functional dimensions of the provided architectural spaces, which remains a very fiercely debated topic in the field of CAAD. This paper looks for the qualitative and functional spatial requirements that ought to be taken into account in these practices to accompany the quantitative data on which models are currently founded, thus providing the possibility of a more complete vision of new space, recognising that space is perceived as a reading of many factors, both measurable and un-measurable.

Keywords: BIM, Architectural space, Requirements, Spatial quality, Topology

INTRODUCTION

The continuous development of digital design tools has been concentrated in recent years, especially on the morphological side of architectural production, leaving the functional and qualitative aspects of provided spaces barely explored. Architectural production is based on spatial requirements determined at an early stage of the design process. These requirements are given in the form of geometrical constraints (e.g. length, width, ceiling height, etc.), but also and mainly in the form of non-geometrical ones (e.g. ambiance, accessibility, relation between spaces, visibility, communication, etc.). Current BIM practices do not take those non-geometrical spatial requirements into consideration since they are based on the use of measured standards and codifications,

which transform all building information into quantitative data. Thus, only constructive information is taken into account during the design phases (Siala and al. 2016). The qualitative and functional dimensions of architecture, on which the whole design depends in most cases, are not considered. The main question which therefore arises is how exactly to take into account and represent information about spaces within BIM tools. This concerns information on the scale of the space itself as an empty, invisible and immaterial building entity. It also concerns information on the scale of the properties of space, especially non-geometrical ones, like qualitative and topographical (or functional) requirements. Non-geometrical information can ensure the transition of the design model, from a set of design requirements expressed

by the future user (owner) of the building (described space) to a finally constructed space (physical space), going through the design phases (virtual space).

In our approach, we discuss the concept of architectural space as a key concept allowing the integration of qualitative and topological spatial requirements in current collaborative practices. If those non-geometrical parameters could influence the evolution of the design model according to the future user's needs, their presence in BIM tools would be crucial. So which are the relevant non-geometrical requirements that should be taken into account and what could be their form of representation in BIM tools? Regarding these matters and based on an investigative and analysing work, we propose identifying and representing relevant non-geometrical requirements necessary to describe spaces during the design phases. This restructuring approach aims to take into account non-geometrical spatial requirements, especially qualitative and topological ones, in current collaborative usages. The overall goal of this study is to enable designers to measure, predict, assess, comprehend and manage the layout of spaces and their quality, respective of new requirements, defined at an early stage of the design process.

In this paper, we first focus on the status of architectural space information in recent research works to identify the need for space representation. Then, we look for the relevant non-geometrical requirements that should be taken into account in current collaborative uses. Afterwards, we try to provide a restructuring approach for the identified requirements to allow for their integration and management in current BIM tools as spatial parameters. By the end of this paper, our space model inclusive of relevant qualitative and topological spatial requirements will be demonstrated. A discussion dealing with our future work will explain how to guide current digital design tools towards the qualitative and functional dimensions of architecture.

INFORMATION ABOUT SPACES IN RECENT RESEARCH WORKS

When performing design tasks, architects give space not only a form (geometrical properties), but also a sense (non-geometrical information like ambiance, quality, relation between spaces, etc). Based on a requested program, they provide design models that tend to satisfy the future user requirements. User requirements are usually given in terms of spatial quality and topology (e.g. the intentions required by a house owner might be *"The living room has to enjoy a maximum of sunshine with visibility on the garden. It must be close to the bathroom and communicating directly with the kitchen"*). To identify how space is described in recent research works, several works dealing with space data modelling have been investigated. Between the investigated models, we emphasise the following:

- The IFC model [1]
- KIM model (KIM 2015)
- Ekholm model (Ekholm 2000)
- Bjork model (Bjork 1992)

Based on this analysis work, we noticed that most of the investigated space models focus on the quantitative properties of spaces (e.g. geometric properties, position, quantity, etc. IFC, Ekholm and Bjork models include partial descriptions of topology of spaces, since they allow a space to be decomposed into sub-spaces and admit that a space can belong to a larger spatial structure (zone, floor, etc.). However, none of the analysed models dealt with the possible topological requirements on a space. Proposing a method for automatic updates of spatial requirements, Kim focuses especially on quantitative ones (geometrical requirements, quantity requirements, etc.). Between all the observed works, only the IFC model includes an aspect of qualitative spatial requirements (e.g. whether the space requires artificial lighting, whether an external view is desirable, the activity type of the space, etc). All the remaining qualitative spatial requirements possible are not supported by all investigated models. Qualitative spa-

Table 1
Example of
Accessibility
Requirements
Categorisation

tial requirements consist of descriptions about the intended whole ambiance of a space (e.g. acoustic, thermal, hygrometric, lighting, safety and coating requirements).

IDENTIFICATION OF SPATIAL REQUIREMENTS

Our purpose in this section is not only to illustrate the different requirement types on a space, but also to discern relevant ones to integrate into current BIM usages. Our method is based on the content analysis of written descriptions of design requirements. This analysis work was organised around three chronological phases, as structured by Wanlin (Wanlin 2007), the pre-analysis work, the tools exploitation, as well as the results treatment, inference and interpretations.

The pre-analysis work

The preliminary work concerns the first phase of intuition and organisation in order to operationalise and systematise the initial ideas to arrive at an analysis schema. To represent the possible concepts describing requirements on spaces, we focused on architectural programming studies developed by specialised agencies in architectural programming. From the available and accessible ones, those having the most detailed descriptions of spatial requirements were privileged. To collect the maximum amount of data, we selected several representative types of real public construction works. Among investigated public works, we emphasise the following:

- The schooler and extracurricular group of Vany, Fance (2013)
- The elementary school of Saint Antonin, France (2016)
- Elsa Triolet College of Thaon Les Vosges, France (2017)
- The emergency Center of Dieulouard, France (2013)
- The nursery and parental care center of Laxou, France (2015)
- The multidisciplinary health center of

Montchanin, France (2015)

In the first empirical step, we started by acquainting ourselves with the collected documents. This allowed us to limit the investigation scope letting impressions and certain orientations come about during the reading and re-reading of each programming study. Spatial requirements are described in explanatory texts, tables and diagrams. We proceeded by gathering the close or similar words (lexical words) used to qualify spatial requirements and joining them with their relating descriptions. The identified words and descriptions have constituted the basis of the second analysis step.

This study focuses only on objective spatial requirements, which have factual referents. Requirements like 'pleasant space,' 'cheerful space,' and 'warm space' are completely subjective requirements and cannot be considered in this study.

Title	Heading	Word
Accessibility	Access	Access
		Accessible
		Accessibility
Entrance	Entrance	Entrance
		Entry
		Entree
Exit		Exit

The hardware operation

This second phase consists mainly in carrying out the coding, counting or enumeration operations according to the specifications previously formulated. It involves in turn two steps:

The first step concern the categorisation operations, in which we elaborated a grid of categories, is the first step. We started associating each identified word used to qualify a space with the related adjectives. For example, the word lighting was associated with natural or artificial, direct or indirect, zenithal, controlled, etc. Then, words belonging to the same family (having a common cardinal) were grouped under a generic heading. For example, the words Access, Accessible, Accessibility, etc. were grouped

TOPOLOGICAL REQUIREMENTS

Title	Heading	Frequency	Description	Frequency
Relation	Relationship, Connection	544	Visual / Physical	51
	Pathways, Traffic,		Direct/ Indirect	17
	Distribution,		Frequent / Occasional	13
	Communication,		Horizontal / Vertical	12
	Separation		Main / Secondary	10
			Clean / dirty	4
Accessibility	Access, Entrance, Exit	499	Principal / Secondary	114
			Access constraints	103
			Interior / Exterior	72
			From / To	69
			For	43
			Direct / Indirect	21
			Easy	19
			Private / Public	13
			Close to / far from	7
			Secure	6
Arrangement	Arrangement, layout	380	Close to, next to, near	151
			A part of, a corner of	28
			Contiguous	8
			comprises	3

under the generic heading *Access* (table 1). Next, headings were gathered in turn, by synonyms and/or antonyms under the same title, in order to provide a condensed and simplified representation of the raw data. For example, the headings *Access*, *Entrance*, *exit*, etc. were classified under the title *Accessibility*. Finally, titles were classified by type. For example, titles *Accessibility* and *Relation* and *arrangement* were classified as Topological requirements, where *Accessibility* gathers requirements concerning the access to space and the exits, *Relation* groups requirements about connection between spaces (relationship, pathways, traffic, distribution, communication, separation, etc.) and *arrangement* gathers the adjacency requirements (proximity, layout, etc.).

This step has allowed us to identify and apprehend the different types of spatial requirements. Il-

lustrated spatial requirements are classified into five types, namely: **geometrical requirements** (shape and dimensions), **quantity requirements**, **occupancy requirements** (Equipment, number of occupants, occupancy duration, activity type, etc.), **topological requirements** and **qualitative requirements**. Among these requirement types, we are primarily concerned with non-geometrical requirements, in particular topological and qualitative ones.

The second step involves filling the grid according to the identified words and their descriptions with the related usage frequency. Software supporting qualitative and combined research methods were used to systematise the coding and counting works (NVivo [2]). The topological and qualitative requirements condensed grids of categories are shown in Tables 2 and 3.

Table 2
Topological requirements condensed grid of categories

Interpretation, inference and validation

In this last phase, the raw data is treated using simple statistical operations (based on percentages) to be meaningful. The results are summarised in diagrams (Figure 1) that condense and highlight the information provided by the analysis work. A final step in this analysis work focused on the results verification. Our approach was verified by statistical tests on a new real public work programming study. This verification was carried out on a project that falls within the educational framework since half of the analysed programming studies belongs to educational institution projects. The selected programming study concerns the kindergarten of Jean Jaurès, Libourne -France (2012). We noticed in this final

step that results were very close and in some cases even statistically identical. It should, however, be noted that slight differences which do not exceed 6% were found in certain descriptions . The verification work has enabled this study to identify new families of words synonymous with those presented in this analysis work.

DISCUSSION

Topological requirements are described in texts, diagrams and functional flow charts, which explain the required arrangement between spaces, the relationship between them and accessibility constraints. Topological descriptions are almost fixed and recurrent in all analysed programming studies. Figure

Table 3
An excerpt from qualitative requirements condensed grid of categories

QUALITATIVE REQUIREMENTS				
Title	Heading	Frequency	Description	Frequency
Coating	Coating, peinture	826	Type (marble, tiles, parquet, plinth)	506
			Finish (anti-slip, washable, easy to clean, waterproof, Resistant to friction)	127
			Of (wall, ground, ceiling, ...)	79
			Complies with (standards)	16
			Adapted (Space type)	1
Hygrometric	Hygrometry, Ventilation, Extraction, Air renewal	628	Natural / Mechanical	77
			Reinforced, powerful, ...	52
			Type (nitrogen, oxygen, ...)	39
			Adapted (Space type)	15
			Rate, flow, type, diameter	15
			Day time / Night time, Time, date, season	4
			Complies with (standards)	3
			Primary / secondary	2
Acoustic	Acoustic, Noise, Phonic	611	Complies with (standards)	27
			Adapted (Space type)	16
			Performance (dB)	13
			Reinforced, of quality, ...	9
Thermal	Thermal, Air-conditionning, Heating, refreshment	611	Will/will not be, Air-conditionned/ heated	76
			Temperature (°C)	66
			Complies with (standards)	29
			Time, date, season	9
			Required	3
			Efficient	3
			Adapted (Space type)	1

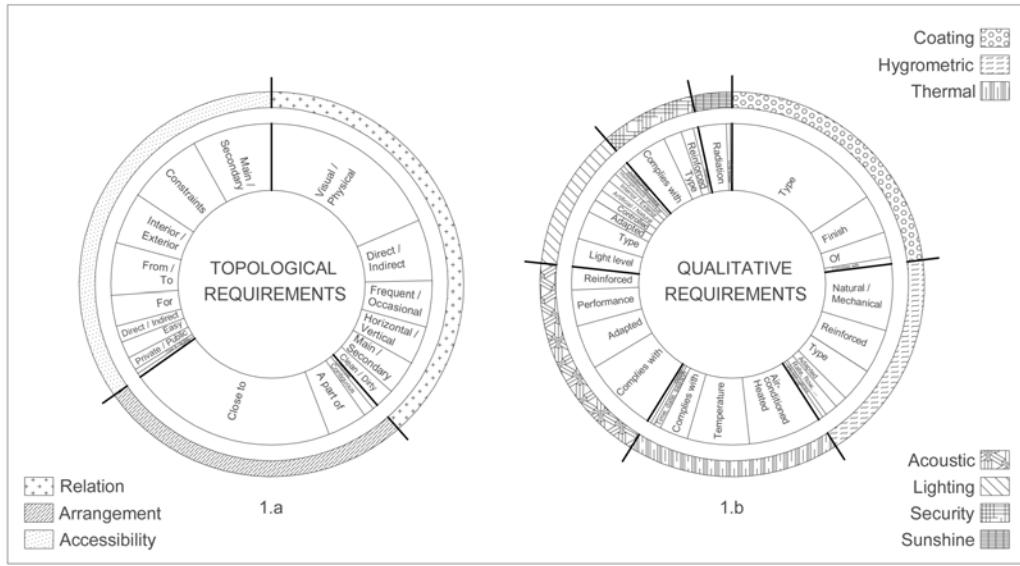


Figure 1
Topological (1-a)
and qualitative
(1-b) requirements,
descriptions and
related use
frequency.

1.a shows that the must used topological requirements are: the arrangement of spaces (close to, next to, near, etc.), the type of communication relation between spaces (visual or physical), the accessibility type (main or secondary) and constraints (width, height, etc.), the type of connection relation between spaces (direct or indirect), etc.

Figure 1.b shows that much of the qualitative descriptions are indicated to raise awareness about the importance of certain qualitative aspects of space (e.g. air-conditioning, heating, ventilation, noise, etc.). For example, 42% of acoustic requirement descriptions revert to existing standards and regulations (complies with, conforms to, standardised, etc.). 25% of these descriptions revert to the space type of the activity type in which they will be housed (an adapted treatment, the attenuation will be adapted accordingly, etc.) and 14% describe the desired acoustic quality (reinforced, optimal, of quality, etc.). Only 20% of the acoustic description are quantitative (attenuation: 60 dB, 43 dB, etc). Thus, 80% of the acoustic requirements refer to standards and en-

gineering.

Qualitative requirements gather descriptions that define the overall ambiance of a space. This analytic work has enabled this study to identify qualitative descriptions very commonly used in the programming phase. These descriptions concern: the coating type of a space or space-type (marble, tiles, parquet, etc.), the acoustic attenuation (which must complies with standards), the thermal needs (must be air conditioned, will be heated, etc.), the required ventilation (natural or mechanical), among other things.

It should be noted that qualitative and topological requirements include essentially qualitative descriptions, which are generally given in binary and opposite representations (e.g. interior exterior, main secondary, direct indirect, artificial natural, etc).

Topological requirements include only qualitative descriptions. Qualitative requirements are more important than topological ones as 71% of the descriptions relate to spatial quality. They include not only qualitative description, but also some quanti-

tative ones (e.g. the required temperature ($^{\circ}\text{C}$) in a space, the ventilation flow (m^3/h), the sound attenuation (dB), the solar radiation (wh/m^2), etc) along with other typological descriptions, like types of coatings, spot lights, stores, among others.

All these descriptions are useful during the design phases to assist the design evolution process in taking into account both measurable and non-measurable requirements. To further illustrate our results, the diagrams presented above were summarised in a single diagram (Figure. 2) based only on significant percentages. To descry the relevant descriptions of spatial requirements, we have defined a percentage threshold (10%) below which descriptions were not taken into consideration. Based on this final diagram, the next section consists of the representation of the identified relevant requirements in a space data model.

Figure 2
Topological and qualitative requirements summarised diagram



A SPACE MODEL INCLUDING NON-GEOMETRICAL QUALITATIVE AND TOPOLOGICAL REQUIREMENTS

This section presents our view of how relevant spatial requirements can be accommodated in the same

schema and how can they be related to spaces.

In addition to <Geometrical> spatial requirements (area, width, ceiling height, etc.), <quantity> requirements and <Occupancy> requirements, our space model (Figure 3) includes also <Qualitative> and <Topological> requirements as classified in the previous section. Proposed space model consists of two instances: the Requirements Model and the Design Model.

In the Requirements Model, a <Space> should satisfy a set of requirements according to its <Space Type>, <Space SubType>, <Activity type> or <Activity SubType>. For example, in a university, the space "Pedagogical depot-003" should satisfy topological qualitative descriptions imposed by its <space type> as a "Depot" (All depots will have direct access from the common traffic). It should also satisfy those required by its <Space SubType> as a "Pedagogical depot" (Pedagogical depots for the storage of teaching materials must be contiguous to classrooms and accessible directly from them). Thus, the space "Pedagogical depot-001" must satisfy both of those requirements. Its final topological requirements would be as follows: contagious to a classroom, access from the classroom, and access from the common traffic. Thus, requirements with qualitative descriptions are cumulative.

On the other hand, a <Space> should also satisfy a set of requirements according to the <Activity Type> or <Activity SubType>. For the same example of a college, the <SpaceType> "Classroom" should satisfy requirements imposed by its <Activity type> "Having Class" (a natural lighting is required) and those required by its <Activity SubType> "watching projection" that necessitates stores to minimise the natural lighting. The resulting requirements here will be: natural lighting, equipped with stores.

In the Design Model, architectural <Space> has three types of data classified as follows: <General> data, which indicates general properties of space (e.g. ID, GUID, name, etc.). <Geometrical> data, which groups geometrical properties of space (e.g. length, width, ceiling height, position, etc.) and <Quantity>

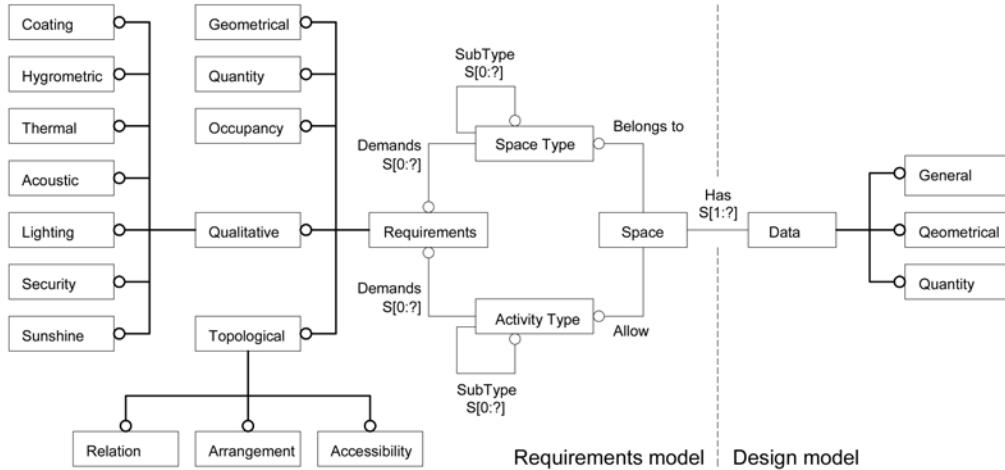


Figure 3
Schema of space data model, including identified qualitative and topological requirements

data, which gives the location of space in the entire model.

CONCLUSION

The overall goal of this research is to assist designers in providing architecture that satisfy non-geometrical requirements described during the programming phase, especially topological and qualitative ones. Those requirements are implicitly known by designers and architects in current collaborative usages, since the absence of qualitative information within BIM models is currently evident.

We have attempted in this paper to provide a structural approach of the relevant topological and qualitative requirements necessary to be taken into consideration in collaborative usages. This approach had allowed us to propose a data modelling all information about spaces, their requirements and properties. A future work will focus on new collaborative usages allowing designers to add and manage topological and qualitative spatial requirements during the design phases.

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[1] <http://www.buildingsmart-tech.org>

[2] <http://www.qsrinternational.com>

Architects' use of tools for low energy building design

Methodological reflections from Ethnography and Philosophy of Technology

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Design practitioners face an increased pressure to design low energy buildings because of the need to reduce the carbon emissions of the built environment. As a response, building performance simulation tools (BPS) have been created for designers to facilitate the decision-making and help them to propose low energy buildings. This paper is based on a research that adopted ethnographic research to conduct a case study comparison and explore how BPS tools were deployed by designers during real-time design process. The research adopted a constructivist approach informed by philosophy of technology and human computer interaction theories to reveal what designers were doing during the design process as opposed to what they should be doing according to best practice advice. This paper focuses on the application of ethnographic methods and brings attention to the advantages, challenges and limitations of adopting ethnographic research to investigate the 'context of use of tools'. The discussion of the method brings attention to the context of use of tools as the departure point to develop a range of solutions for design support.

Keywords: *building performance simulation, design tool, design process, energy performance, ethnography, social context*

INTRODUCTION

There has been a rapid growth in the number of BPS tools that fit all the stages of the design process (from early to advanced design), to be deployed by different practitioners: architects, building services engineers and energy specialists. While the benefits of using BPS tools in the design process are widely recognised, building designers face several challenges to incorporate BPS tools in the design process (Zapata-Lancaster and Tweed 2016; Alsaadani and Bleil de

Souza 2012). The use of BPS tools in routine design process is likely to be limited and their potential impact as design-aid remains latent (Clarke et al., 2008), suggesting a gap in the practical use of BPS tools by designers (Macdonald et al., 2005). Research on performance gaps (discrepancy between the as-designed intentions and the actual building performance during operation) suggest the failure of as-designed performance calculations to represent the performance of the building in use and discrepancies

due to different factors (Van Dijken et al 2016). The study of design support tools for practitioners has been carried using questionnaires, interviews and focus groups. Despite the important contributions of those approaches, they are limited in providing an in-depth analysis of the context where designers operate. The context of use is likely to affect the way BPS tools are invoked in the design process, as highlighted by the Zero Carbon Hub (2010): "...performance issues are more much more concerned with the processes and cultures within the industry than with the model that is used to predict carbon emissions". Therefore, the purpose of this ethnographic study was to reveal in detail the context where designers operate and how they inform the low energy building design; including design process aspects, knowledge aspects and tool deployment aspects. The study aimed to investigate in detail how BPS tools were used in the real-time routine design process (do design teams use BPS tools as recommended by best practice advice, as expected by the BPS tool developers ?) and more importantly, why were BPS tools used that way (understanding that can inform the development and improvement of tools, identification of design support needs that could translate into tool improvement and/or the identification of features and capabilities as perceived by the users). This paper discusses the use of ethnographic methods to investigate the 'context of use of BPS tools'. The reflection about the application of ethnographic methods as a way to engage with the users aims to encourage the debate about how the researcher and tool development community engage with the anticipated users to understand their needs and solutions for design support.

LITERATURE REVIEW

Philosophy of technology and human-computer interaction perspectives question tool-centric approaches that reduce human action and problem-solving to deterministic models where the tools fit into processes regardless of the features of the context where they are incorporated. Winograd and

Flores (1987) argue that technologies become part of the pre-existing network of human interactions. Therefore, the context should be considered to understand how technologies fit and change the network where they are used (Winograd and Flores, 1987). Conventional ways of thinking that assume that technologies fit as forecasted by the tool developers are likely to be misleading because they neglect the interaction between tool and user in the context of use (Borgman 2004). In this sense, Gibson's concept of affordances is relevant to highlight the potential of an object to enable action (Gibson 1979). Affordances relate to the inherent characteristics of objects, to the ways that users perceive the potential of objects to enable or deter action and the enactment of different sets of actions. Affordances are latent and their realisation requires the 'association of objects and situatedness' (Hodder, 2012). In other words, whilst objects have the potential to facilitate action; the user and the context of use play a role in the ways objects are deployed.

The affordance of objects and the situatedness are part of the relativity of the relations human-technology and culture-technology (Ihde, 2004). While technologies provide a 'framework for action'; they are defined by existing patterns of use, intentions and preferences. Ihde (2004) uses the term 'double ambiguity' to refer to the dichotomy between 'trajectories of development' and the 'instrumental intentionalities' of objects. The trajectories of development are the ways how users use the tool while the instrumental intentionalities are the uses anticipated by tool developers. Ihde argues that the intended uses of tools outlined by their developers have little effect on the subsequent history of the tool because the user can develop a variety of uses including ones that might not have been anticipated by the developers (Ihde, 2004). Ihde's argument does not negate the technical properties of objects; it simply draws attention to the idea that tool's properties are part of relativity of the human-technology relationship.

In architectural and engineering research, a

number of precedents have addressed the use of tools from a perspective that acknowledges the human-tool juncture. For instance, Bucciarelli (2002) suggest that artefacts facilitate the communication, negotiation, learning and living the language of engineering. Bucciarelli (2002) argues that tools are part of the construction of common understandings and praxis. Similarly, Berente et al. (2010) point out that new tools are introduced to old systems and routines, leading to new configurations of practice while Coyne et al (2002) use the 'evolutionary metaphor' to highlight the dynamic nature of devices and the complex ecology of devices to refer to notions such as derivation, improvement, survival, suitability to purpose, adaptation, inheritance of features, and recombination. Those arguments suggest that tools are part of complex processes and the relationships they establish as individuals within groups. Tweed (2001) looks at the early introduction of CAD in design practice and suggests that the stereotypical and totalising view that represents the end-user as a single type of designer fails to consider the beliefs, norms, values and history of end-users that fall outside the ideal type. Simplified assumptions about the way practitioners engage in problem-solving may be limited because they are prone to focus on a typical or rational 'ways of doing' that could overlook (tacit) features of practice. This aspect has been addressed by Chastain et al (2002) and Harty (2008). Chastain et al (2002 p.239) suggest that the properties of tools are inferred from the tool developers' assumptions of praxis so when a new technology is adopted, a dysfunctional relationship might emerge between tools and tasks. Tool developers embed assumptions and constraints about the intended users which enable and deter the ways how tools are used (Harty, 2008).

These literatures contest the idea of 'ready-made' tools and suggest that tools are used in relation to their cultural and social dimensions beyond their inherent capabilities. In spite of the artefactual properties of tools, the users are prone to manipulate their properties in use, deploying the tools for purposes other than those anticipated by the tool developer.

Tools for low carbon design are in this sense no different to any other tools and could be similarly affected by the social context. The term 'social context' refers to the physical and social location where people interact and develop as part of the group. It comprises the beliefs, paradigms, motivations, attitudes, habits, repeated patterns of action that unfold during the interactions between individuals (Berger and Luckmann 1967). This research acknowledges that the concerns emerging in the design process could influence the potential and perceived affordances of tools, their roles and their patterns of use as compared to what is expected by best practice advice and by models that recommend the 'correct' use of BPS tools by designers.

RESEARCH METHODOLOGY

In order to investigate what people do in real time design process, the study adopted a theoretic framework based on propositions from philosophy of technology and human-computer interaction theories (section above) and develop empirical work using an ethnographic approach. Ethnography is a qualitative research method that enables the study of meanings and experience engendered in the social milieu of a group (Hammersley and Atkinson 1995; Silverman 2005; Bryman 2008). The locus of the ethnographic analysis is culture. It allows the exploration of 'the social issues and the behaviours that are not clearly understood' (Angrosino 2007 p.26) by considering the influence of the social context in the creation of meanings, attitudes and beliefs held by a group (Lecompte and Schensul 1999 p.58).

In design research, ethnography has been used as methodological approach to study practitioners in design and construction; for example, Bucciarelli 1998; Lloyd and Deasley 1998; Baird et al 2000; Ball and Ormerod 2000; Button 2000; Gorse and Emmitt 2007, to cite few. In the ethnographic study about migrant construction workers, Pink et al (2010 p. 658) argue that 'ethnographic research can make visible informal (or unofficial) worlds of action, interactions and ways of knowing that can easily slip under the

industry (or official) horizons of notice.'

The study analysed in-depth the design processes of six non-domestic buildings located in England and Wales by four sustainable architecture practices. The study investigated how designers used tools to embed energy performance during routine design process. Building upon the principles of qualitative research (Denzin and Lincoln 1998; 2008; Silverman 2006; Creswell 1998), purposeful sampling was done based on communities of practice criteria. The investigation analysed the conceptual and detailed design phases. The delivery and construction phases were outside the scope. However, the aspects related to delivery, construction and operation were considered in that they overlap to the design process. The main research participants were the architects. Other design team members were included to depict the dynamics and richness of the process.

The ethnography study was conducted for twelve to twenty-one months per case study. It comprised an average of seventy five hours per architecture firm distributed in eighteen to twenty five visits per firm. The data collection methods included interviews, non-participant observation (ie in meetings, design team exercises), document analysis, shadowing of work, visits of construction sites. The performance targets and BREEAM credentials of the case studies are described in table 1.

ETHNOGRAPHIC FINDING RELATED TO BPS TOOL USE DURING THE DESIGN PROCESS

COMPLIANCE V PERFORMANCE-BASED PROCESS

The use of ethnographic research enabled the identification of challenges faced by designers to use BPS tools as recommended by best practice advice (further reading: BSRIA Building Services Research and Information Association 2009. BSRIA BG4. The Soft-landings framework for better briefing, design, handover and building performance in-use. Retrieved from <http://www.bsria.co.uk/services/design/soft-landings/>). The data suggests that BPS tools were

not consistently deployed as recommended by best practice advice. BPS tools were not consistently deployed as expected by BPS tool developers (ie in early design stage, to compare design options, etc) (For further details, see Zapata-Lancaster and Tweed 2016). All of the research participants were working in sustainable architecture firms and designing low energy buildings; yet, the project drivers such as cost, construction time and buildability featured as priorities for decision-making, compromising the energy performance intentions of design teams in some of the case studies. The project drivers of the wider stakeholders (ie. client and construction team) affected the prevalence of the energy target and the use of BPS tools during the design process. As illustrated, by the following quotes, energy performance is unlikely to be an explicit requirement even in low energy buildings:

Building Services Engineer 2: 'the client could not confirm whether cost, quality or time was of most importance'

The client referring to low energy design targets: Client 1: 'if it is not a compulsory requirement, we do not want it'

The ethnographic work enabled the continuous observations of the different ways that BPS tools were invoke in the design process in the context of routine design process. In the case studies (projects designed by architects with experience in sustainability), there were two types of engagement with BPS tools for energy purposes: use of BPS tools prompted by compliance (namely, compliance-only process) and performance-based use of BPS tools (pervasive and consistent use for design decision-making). The level of engagement was observed in the long-term non-participant observation and discussed with the participants during follow-up interviews. The real-time use of BPS tools in relation to the deliverables and the project drivers was a key ethnographic finding that illustrates a facet of the processes and cultures within the building industry.

Table 1
Energy performance targets and BREEAM credentials in the case studies

Case study	1	2	3a	3b	4a	4b
Roof	0.15	0.18	0.18	0.15	0.15	0.10
Walls	0.15	0.26	0.26	0.18	0.16	0.16
Glazing	1.20	1.60	1.60	1.60	1.60	1.50
Floors		0.32	0.19	0.21		0.12
Airtightness	3	1	3	5	5	5
EPC	31	40	19	40	40	28
% LZC tech	10	20	30	15	15	10
BREEAM Rating	Excellent	Excellent	Outstanding	V Good	Excellent	V Good
BREEAM Energy	52	16.00	19.00	14.00	14.00	15.00
BREEAM Credits total	71.85	81.70	89.00	64.00	73.00	66.00

BPS IN COMPLIANCE-ONLY PROCESS-CHALLENGES

The aim of the compliance-only process was mainly to produce as-designed estimation models to demonstrate that the energy regulatory requirements were met. In this situation, BPS tools were invoked only in the light of policy requirements (planning application, building control application) to produce the evidence to estimate the as-designed performance. In that situation, BPS tools were not used to inform the decision making. BPS tools were used fine-tune an already designed building. In the compliance-only circumstance, the use of user friendly design tools was irrelevant because rapid decision making during early design was done on the basis of experience and heuristics (ie rules of thumb, adopting design strategies that were used in previous designs). The main challenges in the use of BPS in the context of compliance only, as perceived by research participants:

1) BPS tools did not afford quick estimation in early design.

2) BPS tools were too time consuming in detailed design to be deployed in parallel to decision mak-

ing (ie. effort for modelling input and computational time for calculation).

3) BPS tools were perceive as an 'investigation exercise of energy performance' rather than an aid for decision making when the priorities are reducing capital cost and time on site.

BPS, A COMMUNICATION TOOL IN THE PERFORMANCE DIALOGUE

In the performance-based process, BPS tools were used to inform the performance dialogue as recommended by best practice advice. BPS tools and their results were part of the design negotiations and the decision-making throughout the design process. The as-designed estimation informed the design strategies from early design to detailed design.

Interestingly, there was a communication role played by BPS tools to facilitate the dialogue about energy performance within the design team and between the design team members and other stakeholders and decision-makers in the process:

1) Communication within the design team: the energy expert/simulationist conducted the as-designed estimation and took the results to codesign

sessions with other design team members ie. architects, acoustic engineers, architectural technologists in order to decide how different strategies affected different requirements (ie specification of windows in relation to glare, sound protection, heat gains)

2) Communication (education) of the wider stakeholders: the design teams used the as-designed estimations to illustrate the potential benefits of low energy strategies in relation to metrics/aspects that clients were concerned about for example, operational cost. The following excerpt illustrates the BPS use to communicate with the client:

Building Services Engineer 3a: 'They [the clients] wanted to have the PVs on and all those things. They [the clients] wanted to know how much it would save them potentially off their bills because they get just a set budget every year to run and maintain the school, so obviously the more we can reduce the energy consumption, the more they can spend on text books and things like that for the kids.'

This communication aspect with the clients, suggests that the energy metrics obtained by BPS tools are 'translated' to concerns that are more relevant to the stakeholder. For example, the designers in one of the case studies had developed a tool, the energy bill saving estimator. It was a spreadsheet that calculates the weekly costs associated to the energy consumption for space heating, water heating and lighting. The weekly costs were aggregated and compared to the basic income of the user to determine the percentage of basic income likely to be used to pay the energy bills. The clients were more compelled to support low energy strategies if they could link their benefits to potential savings during operation.

3) Communication between the simulationist/energy expert/design teams and the contractor: to link the as-designed performance intentions to actions required from the other team members to facilitate the achievement of as-designed intentions. The BPS results were used to produce evidence about the need of certain performance specifications in building materials and standards on site:

Architect 4b: 'There's a reason why the building

is like that, you know. And I think [achieving a low carbon building] it's about educating people. I feel that contractors don't understand what [architects] we've been doing, to the depths that we've taken it. So you have someone, like well, we can do a frame in steel because it's cheaper. Hang on a sec, no, no, the frame isn't just there to support the building, the frame actually has other parts to play in the whole environmental model of what the building is. Yeah, and I think that's shown when we get the questions going, can we use this as an alternative? And you go, well it doesn't work for this reason, that reason and that reason. I can see you want to use it because it looks the same, but that's where the similarity ends. So it's about educating them [the contractors] to really understand ... being more attentive to things like that.'

USERS OF BPS TOOLS

In alignment with Lawson's notion of the designer's problem solving preferences (Lawson 1997) -preference for quick understanding over numbers-, this work found that no architect in any of the case studies used BPS tools or any quantifiable method to estimate performance. User friendly 'early design' tools were not used to inform decision making:

Architect: 'It's about basic principles; do you need software to tell you that?'

Even the Building Services Engineers acknowledged using experience and heuristics for early decision-making:

Building Services Engineer: 'We sort of start talking about the low carbon strategies quite early with them without any calculation so it is quite experience-based in a way. We look at the orientation, the form, the massing, the things that you could do without the calculations, the things that you know that will work. It is done in that way, it is more qualitative than quantitative..'

Another interesting aspect is that the estimation of energy performance was perceived to be a duty for the energy specialist. Generally, there was an energy specialist or simulationist in the design team who de-

ployed BPS tools as requested (either only for compliance or throughout the design process for decision-making). Even within the building services engineering field, it was suggested that the increasingly ambitious energy goals required by legislation were leading to the creation of a 'sub-expertise' in BPS tools:

Building Services Engineer 2: 'Even in our discipline [building services engineering], there is sub-expertise with people who can produce models and worry about Part L and the other engineers who have not been trained in producing models who will rely on the modelling group...'

These aspects bring attention as to whether the move towards the widespread use of BPS tools by practitioners is bringing to question the knowledge and expertise of different practitioners within the design team . (further reference, see Dreyfus (2004)

AS-DESIGNED PERFORMANCE ESTIMATION BY BPS TOOLS AFTER DESIGN PHASE

There were mixed views about the extent to what the results of BPS tools represented the performance of future buildings. There was a generalised concern among research participants that the as-designed estimations did not reflect the in-use performance and that there were connections between the as-designed estimation and the building performance in further stages of the building lifecycle process (construction -as-built performance; operation -in-use performance). This resulted in conflicting views where the designers perceived that BPS tools were theoretical or compliance-only instruments. The as-designed performance estimation was regarded as an uncertain representation of performance unlikely to be met during construction and operation. In other words, the BPS tools were seen as limited for the appraisal of performance due to the uncertainty embedded in the as-designed evaluation in relation to as-built and in-use performance.

Architect 2: 'How reliable is the use of advanced simulation tools?'

Architect 4b: 'You'll never reach the [energy] target; it's some kind of false target really. It's uncon-

trollable, because you can't control people. You can control lights to a degree; you can obviously control heating and ventilation. But on the modeling we've managed to reach the target and that's completely right if no one is going to switch a plug.'

Building Services Engineer 2: 'Sometimes I strongly disagree with simulation and its pretty pictures... is this helping to understand or just generating pretty pictures, images of performance that can't be mapped against actual energy use?'

REFLECTION OF THE METHOD

The discussion few of the ethnographic findings of the main study presented in the previous section reveals the challenges in adopting BPS tools in the relation to the context of use ie. project drivers (reducing cost more important than energy performance during operation). In situations where energy performance was not an explicit project requirement, the designers could use BPS tools for compliance-only purpose (no/minimum use of BPS tools to inform decision-making) or to support the performance dialogue between stakeholders (using BPS tools to communicate within the design team and beyond). The ethnographic research enabled to identify some of the solutions devised by designers to 'align visions' of different stakeholders in performance-based process. In cases where BPS tools were used to mediate the communication with the 'non-energy expert', BPS tools were used to provide evidence and to 'translate' energy metrics to concerns that were relevant to different stakeholders who participated in the decision-making process ie. cost savings in operation can be invested in other expenditures (client-user's concern); buildability and standards site needed to meet as-built energy performance (contractor's concern). Yet, there is a generalised concern about the credibility of as-designed estimations (and BPS results) in relation to discrepancies with as-built and in-use performance.

The key advantages of the ethnographic approach is that it enabled the comparison of case studies of design in action to identify the commonali-

ties and differences in the design process enacted by designers, including how BPS tools were used in everyday design process (bottom up understanding of the circumstances that facilitate and that interfere with the use of BPS tools by designers). The use of theoretical informed propositions from philosophy of technology and human-computer interaction allowed the focused investigation of design processes without imposing any research agenda. Yet, the use of these theories enabled a focused constructivist investigation to identify the participant's views and experiences in real-time design process. The ethnographic engagement helped the researcher to avoid out-of-context interviews, observations, retrospective accounts, self-accounts and snapshots of the process so the use of BPS tools was linked to the concerns and drivers of the different stakeholders in the process (within and beyond the design team)-cultures and processes-.

The disadvantage of ethnographic work is the resources need to conduct the investigation: length of the immersion, access to the research setting, time/budget constraints, commitment of the research participants, asymmetry of data collected across the case studies (specific to comparative ethnographic studies). Qualitative research methods where the researcher creates scenarios and prompts problem-solving situations which prompt comparisons and consideration of real circumstances are alternatives to ethnographic work; for example board games, scenario setting during focus groups. These methods can help to identify situations, challenges and solutions that build upon the participants' experiences, requiring less resources in terms of time and access to participants than ethnography.

CONCLUSIONS

The ethnographic method enables an in-depth understanding of how processes unfold (behaviours, actions) as experienced by participants; and, more importantly, why that happens. In relation to this work, the detailed field data is relevant to illustrate the complex practices that surround the adoption of

BPS tools in building design. The field data suggest that the project-specific circumstances, the drivers of the process, the regulatory panorama determine how the design process develops over time; and, how the design teams engage with BPS tools during the design process.

However, the reader should be cautious in transposing these findings to other situations. Transferability of the field finding is one of the potential limitations of ethnographic work. The specific circumstances and processes are not prescriptive or predictive of other case studies. The findings are specific to the context of analysis, to the specific case studies. Yet, in reporting in detail the circumstances of the case studies, participants, research design and analysis, the reader can understand the research circumstances and what it means to the wider context. Ultimately, the detailed descriptions of how BPS tools are used and why it happens in such way have a global relevance in generating insights aligned to HCI propositions: BPS tools are not 'ready-made tools', the designers use tools in unexpected ways in relation to the context of use. Ultimately, this ethnographic work has identified some of the challenges faced by design teams. It illustrates existing problems and solutions which can be the source of inspiration for the provision of design support, whether that is realised by low tech or high solutions.

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Investigating Spatial Configurations of Skycourts as Buffer Zones in High-Rise Office Buildings

Coupling building energy simulation (BES) and computational fluid dynamic (CFD)

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Skycourts are attracting widespread interest in the contemporary construction of high-rise commercial buildings. Due to their remarkable function as public realms and transitional nodes, those spaces could introduce alternatives to the vernacular courtyards/atriums in high-rise buildings. This paper outlines the methodology that was adopted to examine the performance of basic spatial configurations of skycourt in high-rise office buildings in a temperate climate. Significantly, these areas accomplished as buffer zones that are non-ventilated and unheated while accommodating combined ventilation strategy. The study is processed via coupled simulation between a building energy simulation (BES) and a computational fluid dynamic (CFD). The developed coupling approach aims to improve the prediction for skycourt performance that is essential for the assessment of thermal comfort conditions and energy consumption. Results to nominate the optimum spatial configuration of skycourt along the vertical section of the high-rise office buildings are discussed briefly. However, the focus is on the methodology.

Keywords: *Skycourt, Spatial Configuration, Coupling Simulation, Thermal Comfort, Energy Efficiency*

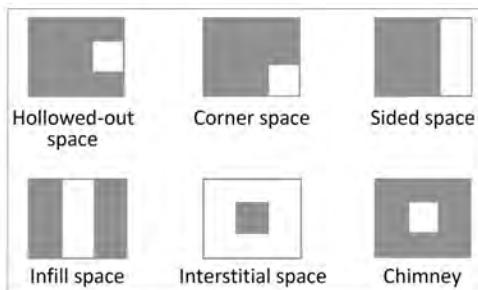
INTRODUCTION

The skycourt, by its various configurations, is recognised as communal areas in high-rise commercial buildings, established from the concept of the courtyards in low-rise buildings. They function as public social void spaces which can provide leisure; well-being for workers, obvious connections and social interaction as hubs. They could perform such as areas

for circulation and transition. Moreover, they could perform as buffer zones between the indoor and the outdoor thus could mediate the climate conditions, provide thermal and acoustic protection to the interior and reduce heat loss. Furthermore, skycourt can offer a contemporary alternative to the vernacular courtyard or atrium in high-rise buildings due to its potential to allow natural light and ventilation to

enter deeper into the interior of the high-rise building and avoid unwanted solar gain (Goncalves and Umakoshi, 2010; Pomeroy, 2008, 2007; Yeang, 1999).

Therefore, these areas could play a promising role in conserving energy and improving the thermal comfort for buildings (Alnusairat and Elsharkawy, 2015; Pomeroy, 2014). The perspectives of obtaining significant reductions in energy consumption besides enhancing the thermal comfort of users in these areas are considered in this study. The paper is part of research seeks to investigate the energy saving potentials associated with the modification of the sky-court design. This objective could be achieved by demonstrating skycourt as an integrated buffer element in high-rise office buildings and exploring its consequence on reducing demand for heating and cooling, besides potential advantages on occupants' thermal comfort at the skycourt, in temperate climates such as London.



Skycourt may be classified on the basis of position in the midst of the high-rise building into sky-entrance, sky-terrace, sky-court and sky-roof. The sky-entrance is the open or void space located at the lower floor(s), whereas the sky-roof is located at the top of the building. The sky court is the open or void space between floors, and finally, the sky-terrace is the space located at the corner(s) of the building. These spaces are two or more floors height linked directly with the surrounding indoor and outdoor areas by open walls or indirectly through enclosed walls.

However, the space configuration or form geometry of skycourt can be divided into several pro-

totypes: hollowed-out space, corner space, sided space, infill space, interstitial space and chimney space (Pomeroy, 2014). See figure 1. This paper focuses on the first three configurations because these spaces are widely constructed in the study context. Also, these configurations reveal useful models to test the research's hypothesis that sky-court could function as a buffer zone that is non-ventilated and unheated space intermediate between the inside -the office zones that combined controlled air temperature- and the outside- the external environment-. These glazed void areas could be connected with the outdoor by one edge, two edges and three edges. See figure 2. The hollowed-out prototype (A) represents the one edge connection. The corner prototype (B) displays the two edges connection and finally the three edges connection illustrated by the sided prototype (C).

COUPLING STRATEGY: BUILDING ENERGY SIMULATION (BES) AND COMPUTATIONAL FLUID DYNAMIC (CFD)

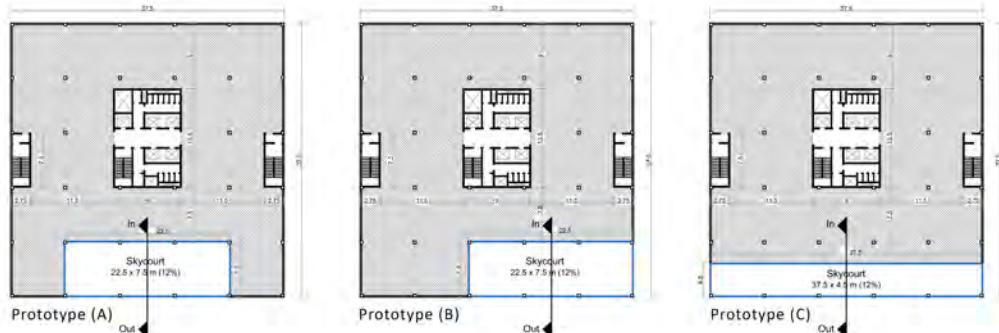
A large and growing body of literature has argued that simulation plays an important role as an intermediate point of knowledge for developing design solutions in construction. It is a useful technique for developing and testing theory, in addition, it could be used as a design tool for generating design alternatives, predicting performance and defining the optimum solution that improves performance. This technique could be conducted for analysing the effect of space(s), the system(s) or device(s) at several scales to inform more details (Groat and Wang, 2013).

However, methods for modelling the ambient conditions concerned for investigating thermal comfort, air containment and energy efficiency could be divided into two groups: physical models and numerical models. These differ in the base of modelling techniques and level of details for the input data. The physical (reduced scale) models could represent or reproduce the characteristics of the full-scale physical context or system, such as materials and products that are readily manipulated by exper-

Figure 1
Diagrams for the spatial configuration of skycourt in high-rise office buildings (the white coloured zone represents the skycourt)

Figure 2

The spatial configurations of skycourt (the white shaded zone) floor plans considered in the study: (A) hollowed-out, (B) corner, and (C) sided prototypes



menters and difficult to be obtained in full scale. On the other hand, numerical (mathematical) models are recommended when dealing with questions of scale and complexity. These use numerical approximation to predict the thermal, airflow performance inside and outside the buildings, and energy consumption, in various constructions such as atrium and glazed buildings due to cost-effective and efficiency (Wang and Wong, 2008). In this model, mathematical problems are formulated so that they can be solved with fundamental arithmetic equations of heat transfer and fluid dynamics (Prajongsan and Sharples, 2012). However, the most powerful modelling is the computer simulation, which offers a useful tactical tool that could produce a large body of accurate information in short periods for determining the thermal and energy performance (Ali and Armstrong, 2008; Groat and Wang, 2013). Computer programs could replicate the real-world contexts or events ("virtual world") for the purpose of studying dynamic interaction ("synthetic elements") that resulted of manipulated factors within the setting (Groat and Wang 2013). Therefore, numerical simulation model technique was selected to investigate the thermal, air performance inside the skycourt, and encounter the most affordable spatial configuration of skycourts in high-rise office buildings.

Recently, the new direction of building thermal and energy simulation has been established is

in which, two models could be interrelated. This method is known as the "coupling models" that is widely used in ventilation studies. Simulation methods in the construction are classified into two major modules: the building energy simulation and the airflow method. In recent years, many literature has recognised the Computational Fluid Dynamics (CFD) as the most accurate and detailed model among the airflow models (Zhai and Yan, 2003). Barbason and Reiter (2014) concluded from reviewing several simulation studies that computational fluid dynamics simulation has been accepted as an appropriate simulation to investigate all kinds of aero-thermal phenomena in buildings. For example, it can predict the full distribution of air velocity, air temperature and air quality. In addition, it can inform the performance of both the natural and mechanical ventilation, the contaminant dispersion, the internal and external airflow, and the heat islands. Moreover, CFD is sophisticated for the current architectural style, which characterised by glazed facades and atrium configurations (Barbason and Reiter, 2014). On the other hand, fully CFD simulation requires long calculation times. Further, airflow models require thermal and flow boundary conditions that can be obtained from the BES (Zhai and Yan, 2003). CFD stands on numerical techniques to solve the equations for the fluid flow, the mass of containment species, the thermal comfort and indoor air quality analysis. It can

solve the equations by dividing the spatial continuum into cells among grid, which requires iterations to achieve a converged solution (Zhai et al., 2002). In contrast, the Building Energy Simulation (BES) stands on the principles of energy (heat) balance equations that considers the internal heat transfer between the space air and surface. These include energy balance equations for a space air, for a surface (e.g. wall and window) and for the radiative heat flux (Zhai et al. 2002). Therefore, BES could provide thermal, energy analysis for the whole building and the HVAC systems. The output of this simulation includes mean (average) air temperature, heating, cooling, ventilation, solar gain, fabric and incidental loads. BES could be obtained on an hourly basis for the whole year. Unfortunately, this type of simulation assumes air as well-mixed. Therefore, it is unable to provide detailed predictions of the spaces' indoor air properties such as the distributions of air velocity and temperature, the relative humidity and the contaminant concentrations (Zhai et al. 2002; Zhai and Yan 2003). Therefore, it is argued that integrating BES and CFD together can produce complementary information for the energy consumption and the indoor thermal comfort for buildings. Furthermore, it is agreed that the coupled simulation can predict more accurate, detailed and quick results compared to the separate simulation (Barbason and Reiter, 2014; John and Yan, 2005; Wang and Wong, 2008; Zhai et al., 2002; Zhai and Yan, 2003). The coupling approach stands on providing the interior surface temperatures and the heat extraction rate that are obtained from BES to the CFD model so the airflow simulation could calculate specific air thermal conditions (Zhai et al. 2002). Therefore, the CFD model can receive more exact and real-time internal thermal conditions thus can predict the dynamic indoor thermal conditions. This significance is essential for the assessment of indoor air quality and thermal comfort. Moreover, the BES can obtain more accurate convection heat transfer coefficient from the boundary envelope. This process produces a more precise calculation of energy demand and full thermal behaviours of the building enclosure

(John and Yan 2005). In addition, using this mechanism of integration can eliminate few assumptions that handled via each separate application, reduce the computation time of CFD (Wang and Wong, 2009; Zhai and Yan, 2003).

There are two major approaches for coupling thermal and CFD simulation to reduce computing time-cost: the static coupling and the dynamic coupling. However, Zhai et al. (2002) distinguished a third key strategy for coupling simulation. That is the bin coupling. The static coupling process includes one-step or two-step data exchange between BES and CFD programs. The process can be performed manually with a few coupling iterations and does not require hard modifications of individual ES and CFD programs. While, the dynamic coupling process requires continuous coupling between the BES and the CFD at each time step. This method may occur in one-time step, quasi-dynamic or full-dynamic. The one-time-step focuses on the coupling at one specific time step of interest. At that point step, the iteration between ES and CFD is carried out to reach a converged solution. However, coupling might happen without iteration at each time step in a period such as in the quasi-dynamic. That is the CFD simulation obtains the boundary conditions from the previous BES calculation at the specific time step, then returns the thermal information of indoor air to BES of the next time step. The full dynamic coupling involves iteration between BES and CFD to reach a converged solution at each coupling time step before moving on to the next step. In the bin coupling process, the BES receives info that is pre-calculated by the CFD and saved it in the bins to be used for subsequent energy computation (Zhai et al. 2002).

Generally, the approaches of exchanging data between the BES and the CFD modules may be classified depending on the type of data transfer into three methods. In the first method, the indoor surface temperatures transfer from BES to CFD, then convective heat coefficient and indoor air temperature from CFD to BES. The second approach considers transferring indoor surface temperature from BES to CFD

and then convective heat flux from CFD to BES. The third method includes transferring interior convective heat flux from BES to CFD and then returns convective heat coefficient and indoor air temperature gradients from CFD to BES. Method one is considered the most appropriate one due to its stability. However, method two is the most expensive one since it requires explicit in BES and implicit in CFD. Whereas, method three is not recommended since it is unable to control air temperature (John and Yan, 2005; Zhai and Yan, 2003).

The next section describes the coupling simulation approach that is adopted in the study.

INTEGRATING HTB2 AND WIN AIR FOR THE SKYCourt ANALYSIS

HTB2 and WinAir are used in this study. The HTB2 software version 10 is used to inform the thermal performance and energy efficiency while WinAir Version 4 is adopted as a CFD simulation to inform the ventilation performance inside the skycourt. The input data required for the HTB2 comprises information of both the regional climate data and the building, including info regarding the building size, construction materials, small power, building services (heating, lighting, ventilation and occupancy) during the occupation and avocation periods and the diary of application. The output data includes thermal conditions represented by air temperature, air humidity, mean radiant temperature, element surface temperature, and mean surface temperature. Furthermore, energy performance embodied by space gains and losses from heating, cooling, incidental, solar, ventilation and fabric loads. The output information could be in the form of power (W) or energy (kWh). This information could be based on the hourly, daily, monthly or yearly database. On the other hand, the WinAir software requires knowledge of the building size, inflow and outflow rate in case of fixed flow rates (mechanical ventilation), pressure boundaries in case of varying flow rates (openings -natural ventilation), internal heat gain and heat loss and pollutant conditions in the event of source of contaminants. See

figure 3. The climatic data considers specific time at the specific date. The study investigates the performance of skycourt in summer, winter and transitional seasons emplacing the hottest hour, the coldest hour and mid-temperature hour. The output data comprises graduating information of air temperature, air velocity and air concentration showing the airflow pattern.

The paper aims to predict the indoor air temperature, and the air velocity at the occupancy level of the skycourt under the assumption that these zones are buffer areas do not consume energy for heating neither cooling. However, constant air supply that exhausts from the adjacent offices' zones is assumed to modify the internal environment of the skycourt. Similar conditions are conducted for the three spatial configurations to perform the fair comparison. External coupling is adopted in this study to ensure accurate prediction of the indoor environment for the skycourt, and to eliminate time cost. Therefore, two models should be built separately in the HTB2 and the WinAir. A schematic model was developed in the energy simulation to predict the thermal conditions inside the skycourt space and the energy consumption for heating, cooling and ventilation, considering that the skycourt space consists of three zones; lower, middle and upper zone. Furthermore, a grid model was built in the WinAir to investigate in details the airflow phenomena - air temperature and velocity. Data exchange for boundary conditions is needed to bridge the two programs. The static coupling strategy is chosen to couple the two simulations. The thermal conditions for the CFD (WinAir) simulations are obtained from previously calculated values from the energy modelling software HTB2. These include the surfaces' heat transfer, the inlet -air supply, the outlet -air exhaust and the internal heat gains involved inside the skycourt. Then, the resulted temperature from the CFD simulation was compared with the average skycourt temperature from the BES to find the predicted temperature difference. The temperature difference was small (approximately 1°C). That little difference is usually accepted for venti-

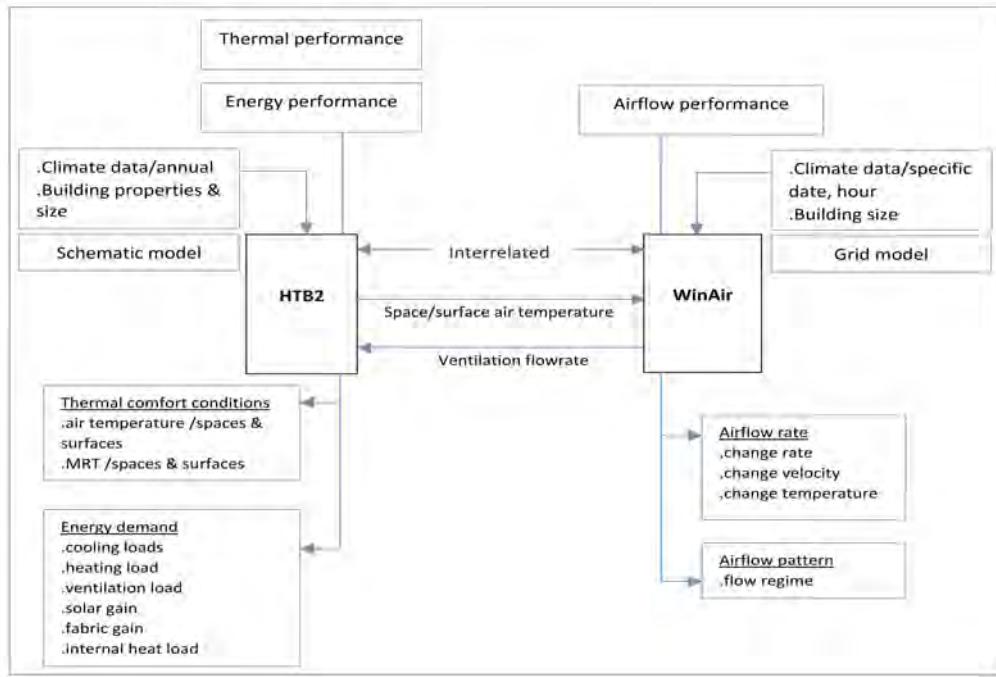


Figure 3
Diagram shows the HTB2 and WinAir coupling models

lation cases to continue the simulation for the next time step (Wang and Wong 2008). Therefore, one-step data exchange was adopted in the study.

RESULTS AND COMPARATIVE ANALYSIS

Results from the energy simulation for the annual energy demand for heating and cooling the buildings are represented in Figure 4. The difference of energy demand for heating and cooling in the building between the selected prototypes is small. Detailed monthly heating, cooling, solar, fabric, ventilation and power loads for the sky courts are shown in Figure 5.

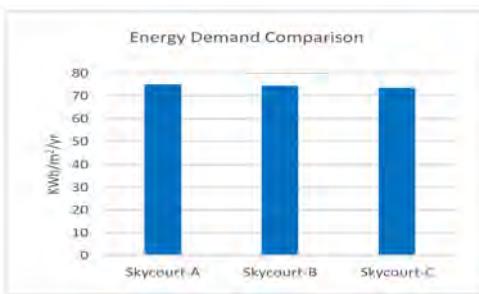


Figure 4
Results from BES of annual energy demand for heating and cooling for the buildings

Figure 6 provides an overview of the thermal conditions including air temperature, mean radiant temperature and the external air temperature, further, it presents the heating, cooling, ventilation, incidental, solar and fabric loads at the lower zone of the sky court in the hottest week in summer for the three prototypes (A), (B) and (C).

Figure 5
Results from BES of monthly heating, cooling, solar, fabric, ventilation and power loads for skycourts

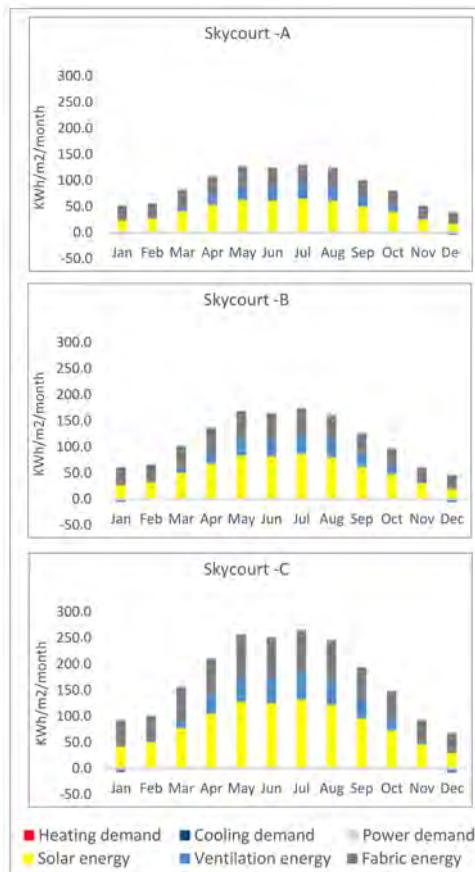


Figure 7 illustrates the specific gradient thermal conditions -air temperature and air velocity obtained from the CFD simulation for one case simulation at 14.00, 28 June.

The results from the BES and CFD simulation are highlighted in Table 1. It is apparent from this table that CFD simulation can provide accurate information at the occupancy level of the skycourt related to the comparison criteria, while the BES provides an average temperature for the whole skycourt space. The table shows that there is a small temperature differ-

ence (nearly 1 °C) between the two models. This provides strong evidence of the efficiency of integrating both the HTB2 and the WinAir programmes. Overall, the results indicate that skycourt prototype A is the best among the three prototypes in terms of thermal comfort- air temperature and air velocity and energy consumption reduction for the building.

CONCLUSIONS

The paper has described a method to explore the thermal performance and the energy consumption of several spatial configurations of skycourt in high-rise office buildings in a temperate climate. The coupling simulation system of integrating BES and CFD is recommended for studies that examine the thermal performance of spaces in details at specific zones within the whole space. Significantly, studies that use simulation as a design tool. It can be seen from the simulation results that the method shows efficiency to study the thermal conditions at the skycourt space. Therefore, this approach could be applied to investigate spaces that are humongous and tall such as skycourt, atriums, courtyards and plazas. However, to further improve the accuracy of the results, segmentation of the skycourt space in the BES model into more than one space to obtain more specific results to feed to the CFD model is recommended.

It is anticipated that the coupling of HTB2 and WinAir programmes produce minimum temperature difference (nearly 1 °C). This result acknowledges the corresponding and compatibility between the two programmes. Therefore, the technique described in this paper to couple HTB2 and WinAir programmes could be applied to predicting the indoor environment of other spaces.

The comparison between the three spatial configurations of skycourt (A, B and C) regarding thermal comfort- air temperature and air velocity- and energy loads shows that prototype A is the recommended configuration.

Figure 6
 Results from the
 BES of thermal
 conditions and
 loads in skycourt -A,
 B and C models at
 summer

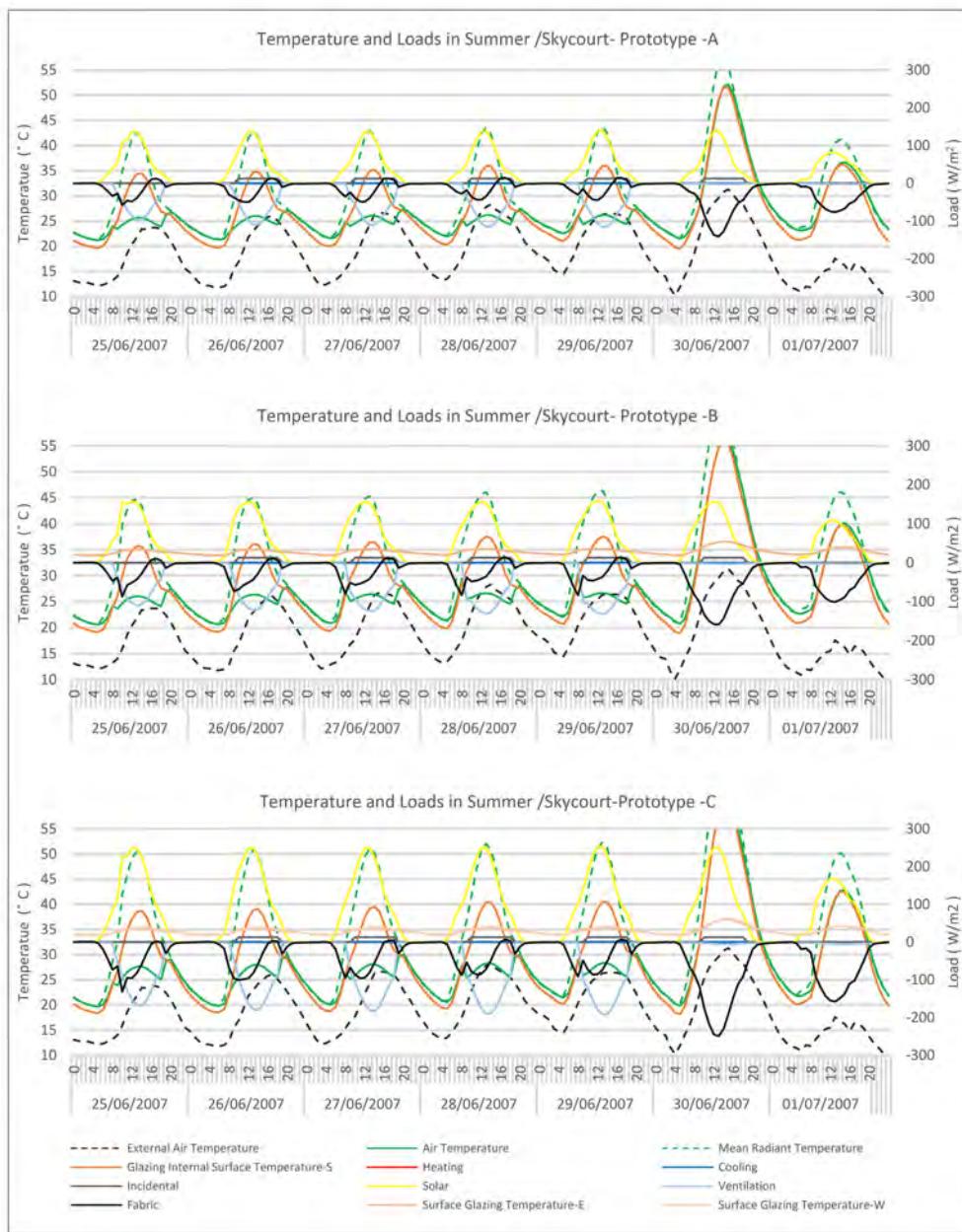


Figure 7
Results from CFD of the thermal conditions -air temperature gradient ($^{\circ}\text{C}$) and air velocity (m/s) in skycourt -A, B and C models at 14.00, 28 June, summer, External air temperature is 28.3°C , RH is 42%. Location of cross sections is shown in figure 2

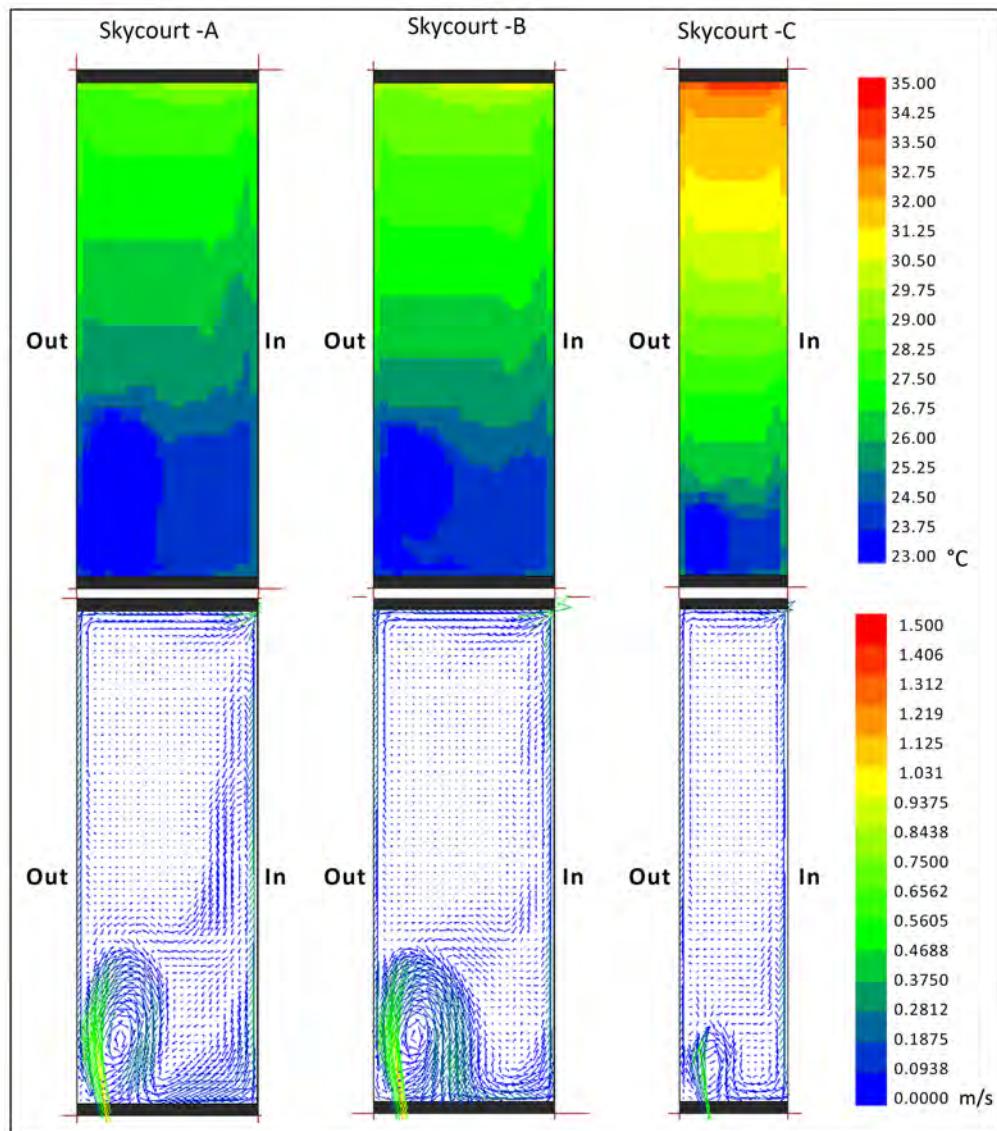


Table 1
Summary of coupling results from BES and CFD

Skycourt	Simulation	Air temperature (°C)	Airspeed (m/s)	Air temperature (°C) at occupancy level*	Airspeed (m/s) at occupancy level
Simulation at hot day at summer/ 28 June –14.00, external air temperature: 28.3° C, RH: 42%					
A	BES	27.8	-	-	-
	CFD	23.0-30.2	0.114	23.0-26.0	0.20
B	BES	28.4	-	-	-
	CFD	23.0-31.5	0.114	23.0-27.0	0.22
C	BES	31.0	-	-	-
	CFD	23.0-35.0	0.066	23.0-27.7	0.15
Simulation at cold day at winter/ 7 December –09.00am, external air temperature: -5.1° C, RH: 95%					
A	BES	14.7	-	-	-
	CFD	13.4-19.0	0.323	14.0-19.0	0.34
B	BES	14.1	-	-	-
	CFD	11.6-18.9	0.336	12.5-19.0	0.35
C	BES	12.8	-	-	-
	CFD	11.1-18.8	0.436	11.0-18.8	0.51
Simulation at typical day at spring/ 19 April –09.00am, external air temperature: 13.2° C, RH: 91%					
A	BES	20.5	-	-	-
	CFD	20.0-21.6	0.198	20.0-20.7	0.17
B	BES	20.7	-	-	-
	CFD	20.0-22.2	0.191	20.0-20.9	0.18
C	BES	21.0	-	-	-
	CFD	20.0-22.5	0.094	20.0-21.0	0.13

ACKNOWLEDGEMENT

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Computational Fabrication

A robotically-driven additive construction planning process using an ecological material

The introduction of 3D clay printing for large scale construction

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This work presents an additive construction approach based on robotic manufacturing and ecological material principles. Through a robotic automated process, the construction planning of a small size shelter is developed in respect to functional, environmental and structural design criteria. The latter plays fundamental role in the process of construction planning since it influences decisions in regard to the way the overall structure is erected using robotic mechanisms. Within this frame, clay is used as the ecological material, influencing the design development of tool paths followed by the robot during construction. In parallel, the functional and environmental criteria are directly related to the construction planning aspect of the process and are cross-examined to adequately respond to the initial design parameters of control. Aim of this work is to achieve the additive construction planning of the proposed design and to discuss limitations and potentials of the application of 3D clay printing technology in the computational design and construction of large scale structures.

Keywords: *Additive construction, ecological material, robotic technology, computational design, 3D clay printing.*

INTRODUCTION

The latest developments in the field of rapid prototyping especially towards the establishment of Additive Manufacturing (AM) techniques for three dimensional production of objects in large scale, lead to the introduction of different procedures that are implemented in various industries including architectural and construction. In general, AM procedures make use of gantry and mounted nozzle, to deposit ready-made mixtures through computer controlled processes. The methodology requires the de-

velopment of a three-dimensional model, which is then split into several layers executed by the additive mechanism. Following this process, specific tool path is created that automatically adjusts the nozzle position, movement, and material flow (Lim et al, 2009) according to the material capabilities. In the literature review a number of AM processes targeted at the design and construction of architectural products in large scale through additive layering (Wu et al, 2016) can be found, pioneered by the Contour Crafting technique (Khoshnevis and Dutton, 1998), and

followed by other approaches like D-Shape [1], Concrete Printing (Lim et al, 2012), Additive manufacturing of concrete (Bos et al, 2016), etc. Such processes are based on similar principles however differences can be found concerning the use of material, their manufacturing logic and their applications. For instance, Contour Crafting (CC) is a layered fabrication technology that uses computer control to exploit the superior surface-forming capability of trowelling to create smooth and accurate planar and free-form surfaces (Khoshnevis and Dutton, 1998; Khoshnevis et al., 2006). Similarly, Concrete Printing is a procedure which makes use of a gantry and a mounted nozzle, to deposit a readymade mixture using a computer controlled algorithm (Lim et al, 2012). In comparison, D-Shape has a different approach to the construction procedure. Similar to inkjet powder printing, this process uses a powder deposition method and a binder to harden the selected area of each layer [1]. In all the large scale AM processes, the nozzle responsible for the material deposition is mounted either on a crane, a frame (gantry) or a robot. In the cases under consideration all nozzles are mounted on frame structure, allowing the deposition of material to be made freely in x-y-z axes. The selection of the machinery used for the construction procedure is directly correlated to the other factors of the process, such as the toolpath followed for the completion of the product, the scale of the finished product as well as the material used.

The use of AM techniques in architecture and construction industry could potentially give rise to new construction capabilities that might include the resolving of complex design issues and complex assemblies. Also, might offer the possibilities for on-site manufacturing, less labour and construction time as well as might promote the local and ecological aspect of material use. According to specific project requirements, appropriate technique can be used. Concerning issues such as materiality, product shape or speed any of the discussed AM procedures could be further explored to be implemented, or even a new concept technique could be studied.

This work, utilizes an AM procedure similar to the

Contour Crafting and Concrete Printing techniques where layer by layer construction in actual scale together with the deposition of specific mixture are implemented. The proposed methodology employs a standard industrial robotic arm instead of a gantry as the delivering mechanism, with a custom-made nozzle mounted on it, and it uses clay instead of concrete. The application of robotic technology and the use of clay material formulate the two important aspects of current research investigation. Within this frame, an approach for the robotically-driven construction planning of a shelter is suggested. Functionality along with the environmental aspect and the ecological behavior of the structure, all are examined simultaneously offering an additive manufacturing planning solution.

At first, the research is focused on materiality and experimentation on the clay mixture. In the second stage of analysis, the selected material is tested in small scale physical prototypes, with mixture, shape and deposition affecting one another, in order to reach a desired and complete outcome. To add another layer of sophistication to the structure, an innovative deposition method is utilized in order to reduce time and material used during the large scale construction process by creating gaps in the thickness of the shell, which at the same time provide air gaps to help insulate the interior. The capabilities of the robotic arm are cross-examined by toolpath investigation that is carried out in respect to the geometry of prototypes and the material limitations. Finally, the additive construction planning of a small-scale structure is presented as a case study.

PROPOSED METHODOLOGY AND EXPERIMENTS

The core of investigation lies on the tool path planning development that formulates the overall structure driven by functional and environmental parameters. In order to achieve an effective methodology for the robotically-driven additive construction of the shelter, the material mixture and its static behavior as well as the tool path planning are investigated

Figure 1
Initial experimentation on different mixtures

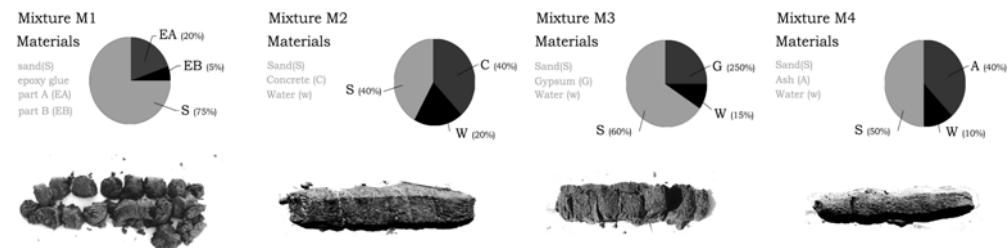


Table 1
Material components of clay-like mixtures

Material\ Mixture	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Soil	60	70	70	80
Straw	10	5	10	5
Water	30	25	20	15

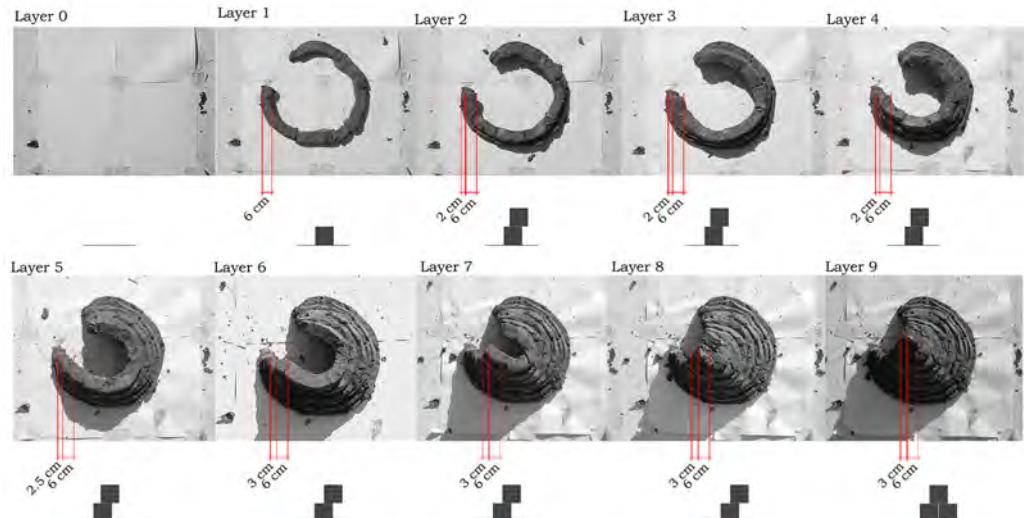
All numbers are in percentage of the whole mixture.

through extensive experimentation. Aim is to find the limitations and potentials of selected material towards appropriate pre-design and pre-construction decisions for the development of structure in actual scale.

Experiments on material properties, static behavior and tool path planning process

In order to successfully support our hypothesis an initial and ongoing investigation into material properties, static behavior and tool path planning process is

Figure 2
Vertical stacking of layers of filament



exemplified in this part of the paper. The materiality aspect is directly connected with the decisions for on-site construction and the use of local material, aiming to promote an ecological approach to the process. Using a local material with no or as few as possible additives for construction, the process enforces minimum disruption to the environment. After the life cycle of the constructed structure the material disintegrates and returns once again to its original state. That being set, the base material is a granular material found in the ground, in the form of sand or soil.

Different mixtures are created and tested for their efficiency (Figure 1). In order to satisfy the stability of the product, as well as the ecological aspect and the extrusion process requirements, both sand and soil are combined with epoxy glue, water, clay, ash, or even concrete. Several quantities and analogies are made and documented. Multiple combinations give rise to various different mixtures, but none of the results are able to provide the necessary properties that can fit the aim of this case study. For example, while giving stable results, the mixture with epoxy glue is hard to handle during the extrusion process. Likewise, further experimentation proved that concrete or gypsum do not merge very well with sand, although they are strong binding agents. On a final note, none of the above is able to hold the mixture together, destroying the product.

These initial observations lead to the selection of water and soil as the main materials. The mixture contains mostly soil (80%), while water acts as a binding agent. Although, this combination is easily prepared and dried, it produces unstable results and for this reason the mixture is combined with straw to create a mud-like mixture, mostly used in the creation of adobe bricks (Table 1). Water acts as the binding agent and straw is used for the consistency of mixture. The result is a clay-like mixture, easily extruded through a nozzle in the form of a hose with square opening 4cm x 4cm. Important aspect taken into consideration is the stability of material so that shape and overall design can be kept steady during layering process. After an appropriate curing time period (30

minutes approximately), the material dries enough and is able to withstand the addition of another layer on top of it. As long as the environmental conditions are kept constant, it takes about three days to dry completely, leading to its hardening. In this work, a number of in-house clay mixtures and material compositions are presented and their static properties are further discussed.

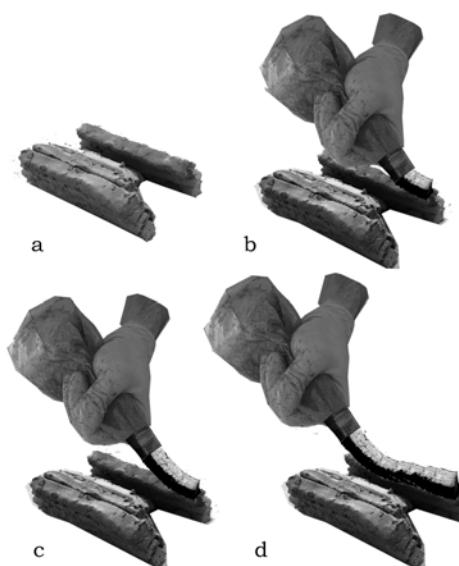
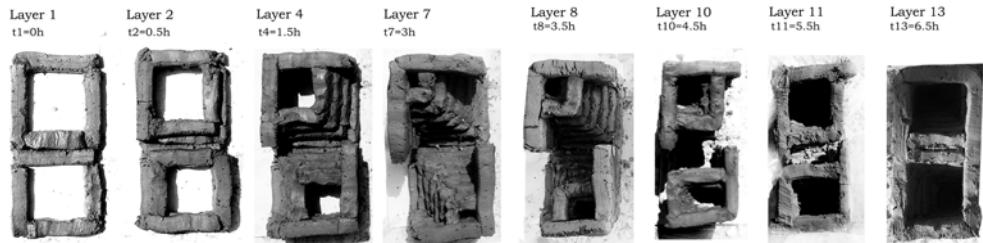


Figure 3
Deposition of material in the example of horizontal building elements

The mixture 1 is almost in liquid form and as such is easily extruded from the nozzle. However, it has limited structural abilities and it hardly keeps its square form and for this reason is rejected. Mixture 2 has better characteristics and is able to remain in a square form after extrusion. Nevertheless, the analogy of the straw is very low and the material started cracking during the curing period. Mixture 3 presents the best quality result due to the relatively easy extrusion through the nozzle and the adequate structural capabilities, strengthening through the curing period into a solid mass. Mixture 4, due to its low

Figure 4

Thirteen layers of filament for vertical elements construction



moisture, becomes very hard and rigid, making it almost impossible to be extruded. Consequently, mixture 3 is selected as the construction mixture to be used for further experimentation (Table 1).

By using the custom-made hose, the selected mixture is deposited in layers of filament. The vertical stacking of layers of filaments are cross linked and remain for certain curing time period, giving enough time to the previous layers to dry and solidify so that stresses of the next layer of material can be preserved (Figure 2). Specifically, in this work the additive construction of three representative building prototypes is investigated, focusing on the tool path development in one or two axes, together with the respective static behavior of each component.

The prototypes reflect the morphology examined in the part of case study and include horizontal surfaces, inclined surfaces and vertical surfaces with dual-aspect openings. In addition, the prototypes are designed to incorporate gaps in the interior of the walls to minimize material and also provide units with as less weight as possible, without compromising stability and structure.

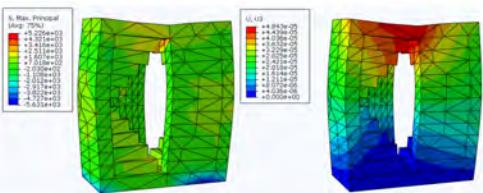
Firstly, the 3D clay printing of horizontal building elements is created by a double pyramid deposition of material in a number of vertical layers of filament with one less stripe in each layering. At the middle of the structure, the reversed procedure is being followed, until the prototype is completed (Figure 3).

Then, the vertical elements with dual-aspect openings are defined in a similar way using the double pyramid construction logic but with an eccentricity in the far corner. Two of these shapes, in symmet-

rical position, create the diamond-like shape of the opening. In general, the prototype is developed by thirteen layers through the deposition of material in a form of a square-like shape, whereas in each layer, the length of the perimeter is reduced by the thickness of a single stripe. This continues until the middle of the structure, when the procedure is reversed (Figure 4).

Finally, the inclined surface is developed using again a double pyramid shape, yet in a form of cantilever. The pyramid is created in a ninety-degrees rotation in comparison to the other prototypes and in an offset shape. In this way, the connection to the exterior and interior surface is maintained, although an inclined logic is followed. Similarly, with the horizontal element, the inclined surfaces are consisted of parallel stripes of material deposition.

The three prototypes determine the limitations and potentials of material and static behavior as well as the effectiveness of tool paths design. This is done in a bidirectional manner from design to physical additive construction and vice versa until the appropriate design and construction rules are defined.



In addition, preliminary studies in regard to the static

Figure 5

Initial numerical simulation results of the second prototype

behavior of the second prototype is conducted. Figure 5 shows a finite element analysis example of the second prototype that is simulated in Abaqus [2], using information derived from the work done by (Illampas et al, 2014; Illampas et al, 2017) in the area of design and production optimization of adobe bricks in Cyprus. Models show maximum principle stress and displacement distribution in the z-axis. The results are used as the foundation for the next phase of experimentation that is the robotic execution.

Experiments on robotics and automation

Within the framework of robotically-driven construction and in an attempt to proceed with the actual construction of the suggested prototypes in future stage, initial experiments in regard to the use of robotic and automation mechanisms and particularly the application of appropriate material extruders and end-effector tools are conducted. In regard to the material extruders, air pressure machines, plungers and augers are investigated. A difficult issue under consideration is the continuous flow of material, which is correlated with the mixture's properties; the softer the mixture is, the more constant the flow. On the other hand, the softer the material is, the less it could hold its extrusion form. So, the most adequate balance is found that would allow steady flow and even form to be developed. The machine extruder selected for further experimentation is based on an auger propeller that pushes material through a hose and off the nozzle.

In regard to the end-effector tool applied, a custom made end-effector tool made of square opening (4cm x 4cm) is used following the manual experimentation. For study purposes the end effector is attached to an industrial ABB robot, model IRB2600-20/1.65 (Figure 6). In comparison with the manual construction of prototypes, the robotic automation requires the establishment of a procedure to incorporate an interrupted flow of material but also its control when this is necessary. Towards this direction, initial experiments to identify appropriate mechanisms and material control are examined.



Figure 6
Material extruder and end-effector tool mounted on the robot

CASE STUDY

Based on the results derived from the experiments as regard the material and static behavior as well as the tool path planning process, in this section a comprehensive design of the robotic tool path is described, providing an additive construction planning solution for the development of the suggested small size shelter in actual scale. The pre-design and pre-construction development is also influenced by functional and environmental criteria formulating the overall morphology of the structure.

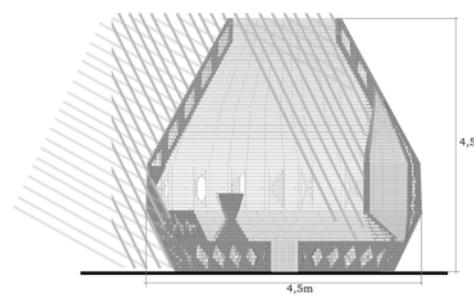


Figure 7
Conceptual study of natural lighting entering the shelter

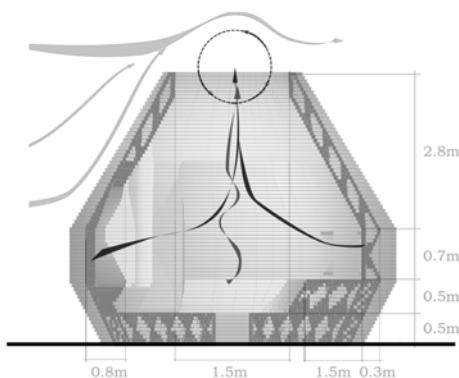
The shelter is a symmetrical, rectangular structure, 4.50m width and 4.50m height. A hole 1.50m width on the rooftop aims to enhance the environmental conditions in the interior space.

As regard environmental aspects involved in the design of the shelter, openings at a height of 1.08m provide ventilation and allow the light to enter the

Figure 9
Three basic parts of the shelter according to the construction logic applied

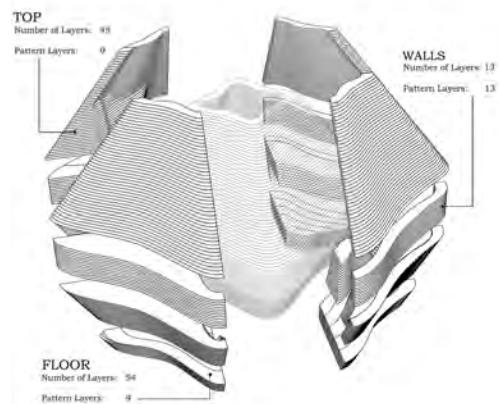
interior space. Even though these openings are relatively small, their number and repetition pattern provide adequate environmental conditions in the interior and prevent the direct insolation and wind. In combination with the hole on the rooftop, a breeze is created, providing enough sunshine to penetrate the room (Figure 7). The hole at the top creates a vacuum, strong enough to push the warm air from the inside and prevent exterior wind from directly penetrating the interior (Figure 8). The shelter creates a small interior, sufficient for a couple of people to temporary inhabit the space for a short time period. It provides bed, sitting spaces, table and fire pit, which acts both as a heater and a stove. As shown in Figure 7 and Figure 8, everything revolves around the fire pit in the middle, creating four different functional areas in the interior: resting area, sleeping area, eating area, and the entrance.

Figure 8
Conceptual study of wind flow in the exterior and interior space



The construction system is distinguished into three basic parts, regarding the material deposition method (Figure 9). These parts are related with the three representative building elements studied in the methodology section of this paper. In the lower part, horizontal construction logic is applied to serve the need for floor and functional area creation. Adjust to that, the vertical construction logic is examined, aiming to provide adequate space in terms of height

and to host the openings of the structure. Finally, the inclined construction logic is applied, in order to develop the roof of the shelter.



For the additive construction planning of the horizontal part, which functions as the foundation and the floor of the structure, the first prototype is used as reference. In the same way, two parallel horizontal surfaces in the logic of incorporating a double pyramid system is applied. Keeping the design technique same, the scale is modified to fit the occasion. Nine different layers of material patterns are completed in order to fully construct the floor. The pattern creates a shape resembling of two opposing pyramids, which form air gaps between the upper and the lower part of the floor. The height of the floor is 50cm, sufficient to create distance from the ground, providing in parallel structural stability to the whole system. In the upper level where functional areas exist, the technique remains the same and the procedure is repeated due to the same horizontal orientation of construction system. Directly above the horizontal part, the additive construction planning of the vertical part is implemented. In this part, the deposition process is adjusted to follow a rotated double

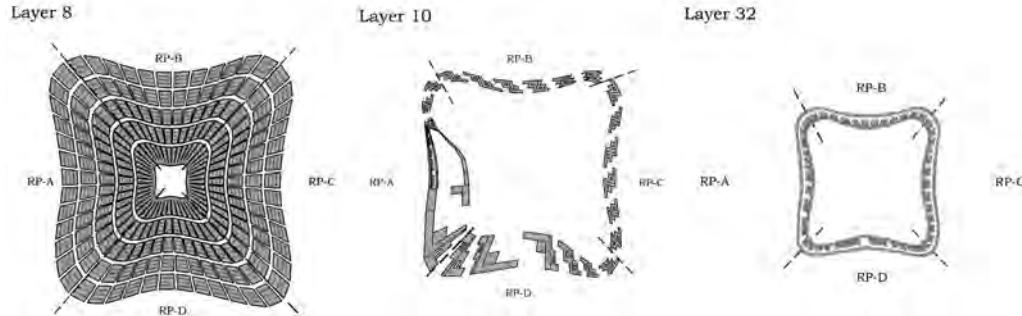


Figure 10
Three characteristic layers of the additive construction logic that correspond to the horizontal, vertical and inclined parts of the construction system

Shelter part	Lift hinge	Number of Layers	Pattern Layers	Height	Pattern Differentiation
Floor	0	18	9 (floor part) 9(functional area)	108 cm	door, toilet
Walls	0	13	13	74 cm	door, toilet
Top	0-1.5m	45	9	268cm	door, toilet (up to layer 18)

pyramid system, as achieved based on the second physical prototype. Using this method, the openings and the extended vertical wall in the height of 0.74m are developed, allowing enough height for an accommodating space in the interior. Following the vertical additive construction planning, an inclined part is created to act as a roof of the shelter, using the inclined construction logic. Five layers in a repeated pattern provide an adequate height of the shelter to be covered (Figure 10).

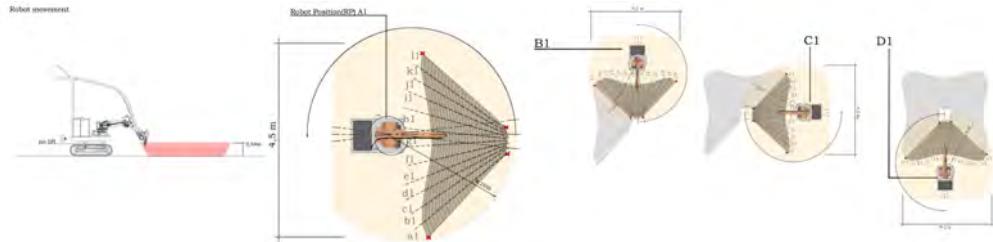
The shelter consists of 50 topologically similar segments that are repeated in a polar array around the central point. Due to the curvilinear design, each segment is partially distorted. The distortion occurs in one direction, which help to maintain a topological continuity of the structure. The width and length are the only parameters affected, which can be compensated by using longer filaments (length) or more rows of filament (width). A parametric algorithm using Grasshopper software [3] (plug-in for Rhino [4]) controls the maximum distortion, checking the pa-

rameters of transposition between layers. The segment with the largest distortion reaches dimensions of 40cm x 25cm, while the smaller one is 25cm x 10cm. For the construction of each segment, firstly, the lower layer is created, with as many deposition filaments as necessary, and then, for each layer the amount of filaments is reduced by one. When the procedure reached the middle stage is reversed with two filaments the minimum. Table 2 demonstrates parameters of additive construction planning in respect to the different parts of construction system.

An indispensable part of additive construction planning process is the robotic scenario implemented. The robotic construction system consists of two separated parts, the service robot and the main robot, which are detached upon reaching the construction site. The service robot is deposited, remaining on-site until the project is completed. The purpose of the service robot is to provide support to the main robot by collecting resources from the environment; it collects material (soil) and power (sun). Thus,

Table 2
Parameters for the additive construction planning of the structure

Figure 11
Mobility capabilities
of the robot during
additive
construction
execution



the main robot is lighter and more flexible to carry out the given tasks and to complete the construction of the shelter. To accomplish this, the main robot has to overcome certain obstacles that include the required height and width of structure. The robotic arm IRB4600 can reach up to 2.5m, which is by no means enough to cover the 4.5m height of the structure. Certain limitations in regard to the capability of main robot (IRB4600) to reach vertically the total height (4.5m) of structure are overcome by a hydraulic lift system that is implemented under the base of the robot, adding an extra 1.5m height. In terms of horizontal reach construction capability, the main robot is also limited and for this reason is programmed to move around the shelter, alternating between 4 different positions. Mobility of the main robot ensures effective construction of the whole area. In parallel, the deployment of flexible cables and pipes connected with service robot allows uninterrupted construction process.

An example of robotic construction scenario is demonstrated in Figure 11. In case of floor construction, the robot is placed at the middle of each side with the capability to reach from one edge to the

other. As the structure is divided into 50 segments, each side consists of 12-13 divided parts, that are completed one layer each time. The robot has to alternate 9 times between 4 positions (RP), before 50 segments of the floor are completely constructed. The height of the floor is within the main robot's reach, and therefore the lift hinge mechanism is not necessary. The same procedure is repeated until all 50 segments of all 9 layers are completed. In a similar way, all the different parts of structure and the layers of shelter are constructed, each time by lifting the main robot upwards when the structure is getting higher. Figure 12 shows three representative steps of the construction simulation. Through the digital simulation, one can comprehend the construction procedure and the continuum between layers, starting from the first layer at the bottom of the shelter and gradually reaching the top at a height of 4.5m.

CONCLUSION

This work is concentrated towards the investigation of the appropriate material mixture and properties so that morphological and construction demands can be effectively executed using robotic technol-

Figure 12
Three
characteristics steps
in the simulation of
construction
sequence



ogy. Aim is to development an additive construction planning process, implemented through 3D clay printing in actual scale. In addition, the work aims to raise awareness in regard to the limitations and potentials of the suggested technology, offering a first inside into the feasibility of additive construction solutions in the production of large scale objects.

This initial experimentation and respective results show possible limitations and potentials of 3D clay printing technology applied within the general framework of additive manufacturing process. Considering the large amount of parameter and criteria that are involved in the suggested methodology, further investigation and deepening into different directions is necessary to be developed. Materiality, static behavior, design of toolpath, robotic and automation mechanisms applied, all are involved and are necessary aspects for further examination. In this paper, an introductory and a general overview of our suggested 3D clay printing process has been demonstrated, opening the ground for future experimentation and development that will take into account possible criteria involved.

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- [3] <http://www.grasshopper3d.com/>
- [4] <https://www.rhino3d.com/>

Before and After NURBS

Investigation of Changes in the Material and Fabrication Processes of the Monocoque Structures

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It is possible to define monocoque structure as a system which the structure and the skin work together. The earlier examples of monocoque structures, which effects of form and material on structural behaviours can be clearly observed, are seen in the automotive, ship and aircraft industries. From the early 20th century onward, many pioneering construction engineers and architects have worked on monocoque structures to seek alternative paths to space construction. With the use of NURBS (Non-Uniform Rational B-Splines) based programs, free forms of curvilinear and complex surfaces are facilitated both in the virtual and physical environment. At this point, relatively basic geometries have left their place to mathematically more complex geometries. In this study, an interpretation has made based on the analysis and comparison of selected samples in the context of material and fabrication strategies. This study can be considered as an attempt to understand the impacts of NURBS on monocoque structures.

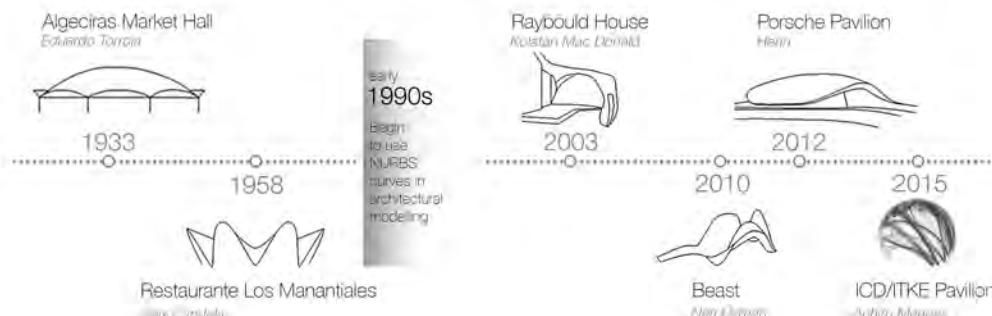
Keywords: monocoque structure, structural skin, form-material-structure relationship, digital fabrication

Introduction

When the monocoque word is examined etymologically, it is seen that it was comprised of using the mono (single) and coque (shell) words together. Thus, it is possible to infer that the bearing feature is integrated into the shell and there is no need for a separate load-bearing system. From the early 20th century onward, monocoque systems, which are frequently encountered in the automotive, ship and aircraft industries, where form and material directly determine structural behavior, have been worked by many pioneering engineers and architects.

In the 1950s, work on the NURBS curves was initiated in order to make the curvilinear bodies of cars and boats identifiable (Burry and Burry 2010). These developments for monocoque systems in other industries also affected architects, and NURBS curves started to use effectively in modeling programs for architecture since the beginning of the 1990s. NURBS curves allow curvilinear surfaces with continuity to be edited with control points in certain fracture zones so that all curves forming the surface are not identified as a point sequence. Furthermore, the data load is minimized to create surfaces with an exact mathe-

Figure 1
The timeline of
considered samples



matical definition. In this case, as much as the computer representations of the structures were affected, the production logic was also affected. Therefore, It is possible to say that the communication between the design tools and the production tools is strengthened. The constructability need of designed structures and their communication with fabrication tools have laid the groundwork for interrogating existing fabrication methods, the use of materials with different performance characteristics in line with new fabrication tools and structural needs have also come to the fore simultaneously.

The impact of NURBS-based programs on the design and production phase of monocoque structures has been tried to be understood and discussed through selected samples which were constructed before and after the early 1990s. The period during which the NURBS-based programs were started to be used in the architectural drawing programs was determined as a threshold. Since the new digital production tools and designed free form structures refers the search for new materials, the samples were handled in terms of materials and production systems in the working process. Because of the symbiotic interaction of form, material and structural requirements with each other, and the relationship with NURBS curves can be clearly observed, monocoque structures were decided to work on.

In the scope of the study, 6 samples were se-

lected considering the criteria such as completion date, material variety, production methods and form (Figure 1). These examples are, Algeciras Market Hall by Eduardo Torroja (1933), Restaurante Los Manantiales by Felix Candela (1958), Raybould House by Kolatan-Mac Donald (2003), Beast by Neri Oxman (2010), Porsche Pavilion by Henn (2012), ICD/ITKE Pavillion by Achim Menges and Jan Knippers (2015).

Differentiation in Production Methods

The creation of free-formed curved surfaces in the digital environment has become possible with the use of NURBS-based programs in design. In progress of time, the relationship of the designed form with the structure became analysable with simulations or related plugins installed in the programs, and at the same time, the feedback received could be interfered with. While the use of NURBS-based programs allows flexibility in the design process and support for new geometry searches, this freedom has come with various challenges in the construction phase. For instance, sometimes subdivision surface modelling is preferred to NURBS due to the necessity of post-rationalizing process for panelization (Hudson et al. 2015). Nowadays, as constructability is considered one of the primary objectives of computational design, the need for realising designed free-forms geometries in a digital environment, has led to a questioning of existing production methods. Pottmann

Figure 2
Porsche Pavilion
2012 perspective
view and twisting
detail [1].



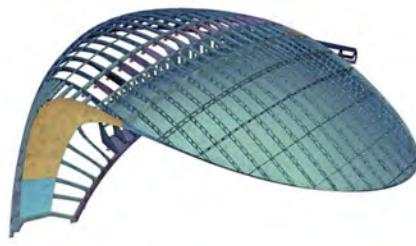
(2007), also mentioned that complicated freeform shapes require advanced methods of geometric definition to make them constructible. Over time, the production methods of curved surfaces that are frequently used in the automotive, ship and aircraft industries have begun to be used in architectural construction scales. In addition to the questioning of existing production techniques and adaptation to architectural scales, suitability of NURBS-based programs for the operation of computer-aided production tools has led to developing these tools, produce new tools, and use digital tools with different functions at a later stage.

It is possible to say that the involvement of the designer in the whole process from the concept phase to the production of the design is supported by the research groups formed in the design offices. With these interdisciplinary groups, material research and the use of digital production systems have become part of the design. In the case of the Porsche Pavilion (2012), designed by Henn, the design and production process was similarly completed under the control of the architectural office (Figure 2). The

shell, which is structurally challenged by being a cantilever, is constructed in two layers using stainless steel plates, which then work together structurally, without losing the monocoque character [1].

"Generating doubly-curved structures from initially planar elements is of major interest in the field of architecture, as double curvature is highly beneficial to the structural behaviour, while the planarity of the elements facilitates fabrication" (Bechert et al. 2016). In the case of the Porsche pavilion, metal plates were cut directly by transferring the digital model into digital production machines and then bent at the desired angle at the shipyard. The process was completed by mounting the modules created by combining the layers (Figure 3). By using prefabrication possibilities production process was accelerated, at the same time, planar steel plates were bent at different angles. Likewise, most of Coop Himmelbl(l)au's steel parts of buildings were produced in shipyards, because geometrically complex steel plates could be made directly from the computer model efficiently and precisely [2]. Also, the thickness of shell was controlled by using structural simulations and related

Figure 3
Porsche Pavilion 3D
model and the
production phase
of units [1].



plugins. Thus, considering the tensile and compressive forces at different values applied to different zones on the shell surface, the shell thickness varied throughout the structure.

The shell thickness is fixed in the early 20th century examples of monocoque structures, which were constructed with reinforced concrete. Because the main purpose was reaching the larger spans with thinner structures than the traditional masonry structures by taking advantage of the mechanical properties of the material. In this period, the design and the constructability of the curvilinear shells were tested with physical models over a long period of time, because the related digital tools have not yet been developed. In the direction of the material, the construction of shells was completed by in-situ mold method. It can be interpreted that the thickness of the material is kept constant throughout the entire shell, in order not to extend the long construction period any longer by changing the molds, and to avoid the disrupt total behavior of the system against the loads. The implementation of a new material in certain forms with a new technique has created a process to experience the direct structural behavior of the material.

Although Candela placed great importance on form studies, in most of his projects hyperbolic paraboloid was selected as a base unit and 90% of his works are the results of rotation and intersection of this geometry in diversely (Cassinello et al. 2010). It can be seen that the shell samples designed by the use of hyperbolic paraboloids, which

form a more dynamic and complex perception than the domed forms, are considered as structural art in many sources. Contrary to the visual impression that it has created, symmetrical forms and mold making suitability have caused these forms to be repeated for a long time. Restaurante Los Manantiales (1958), one of the most significant works of Candela, is an example of a monocoque structure formed at the intersection of the centers of four circularly arranged hyperbolic paraboloids. The preferred symmetry to ease construction process can be also clearly observed from drawings (Figure 4).

William Mitchell observed that architects can draw what they can build and build what they can draw, and that observation now seems to be valid, it is possible to come to the conclusion that the possibilities offered by new digital production techniques and the capacities of these tools are beginning to be influential in shaping the designed forms (Kolarevic 2003). The ICD / ITKE Pavilion (2015), designed by Achim Menges and Jan Knippers, can also be traced as a final product of a process between digital design and production tools.

In ICD / ITKE Pavilion, air supported ETFE was used as a mold and the carbon fibers were adhered to the inner surface of the mold by the robotic arm, which is left in the air supported mold (Figure 5). The form has been developed using structural simulations and computational design tools in line with the constraints imposed by the robotic arm to be used in production. An agent-based program has been developed so that the path to be followed by the robots,

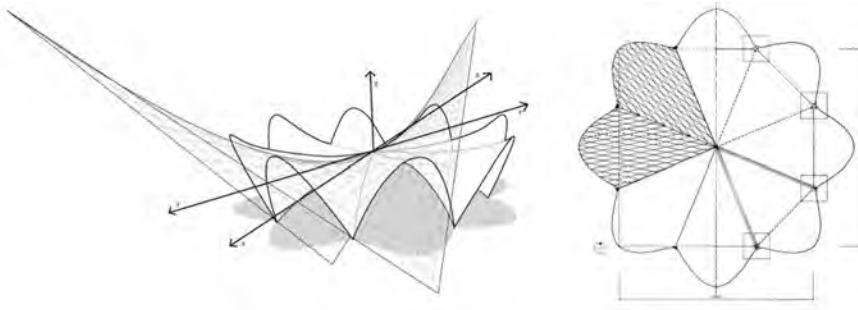


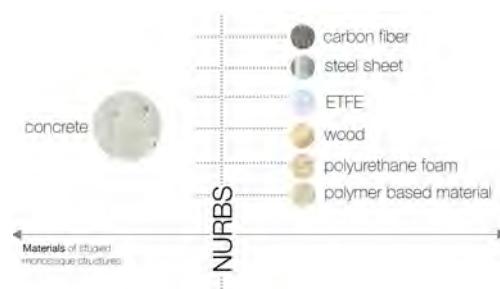
Figure 4
Restaurante Los
Manantiales form
diagram and roof
plan 1958 [3].

Figure 5
ICD/ITKE Pavilion
2014-2015
production process
[4].



and therefore the locations where the fibers will be placed can be determined. The deformations that occur in the form during bonding are also included as a parameter and feedback is continuously obtained by using an embedded sensor system. In this respect, the production of new robot control codes is allowed digitally in accordance with the notifications received simultaneously with the actual production conditions [4]. When the whole process is considered, it can be deduced that the design and the production are integrated and the density of the used material, turns the system into a monocoque structure by gaining a load-bearing character step-by-step during construction.

Figure 6
Material variety in
monocoque
structures
before/after NURBS



Both the conditions of constructibility and the responses of continuous surfaces to loads and stresses, lay the groundwork for the re-evaluation of the structural shells and tectonic concepts. While the load-bearing feature of the shell provided the environment for the production of new forms, these new

forms referred to search for new materials (Kolarevic 2003).

Material Process

Historically, NURBS invented for progression requirement in computational surfaces for CNC tools. Thus, it can be deduced that the roots of NURBS surfaces lie in its connection to material systems, different than other approaches act without consideration of material characteristics (Cabrinha 2005). As a result of the use of NURBS-based programs in architecture, the complex curvilinear surfaces became analysable and transformable with featured plugins. These features encouraged architects to test new materials' structural behaviors in different form alternatives before construction phase. Besides, new fabrication techniques and enhanced communication with production tools broadened material variety that can be used with these tools (Figure 6).

The materials used in the monocoque structure samples were investigated under the headings of (i) single, (ii) layered and (iii) compound in the study. In the first examples of structural shells, concrete was used as a single material. At the beginning of the 20th century, the structural behavior of the new building material has been emphasized for a long time, and it has become possible to construct very thin structural shells compared to the traditional masonry construction. Putting it another way, since the concrete was a new building material, the possibilities offered by material and new construction tech-

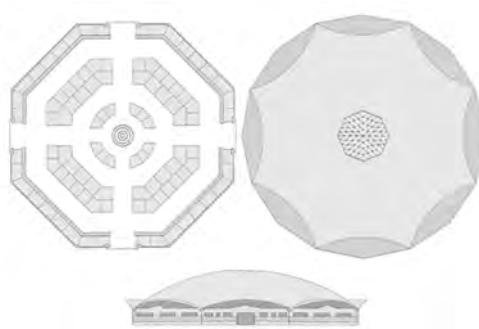


Figure 7
Algeciras Market
Hall 1933 [5].

niques have been evaluated during this period. Also, it proceeds from the possibilities and limitations offered by the material, rather than form search. Additionally, considering the duration of static analysis and construction phase, a large number of reinforced concrete shells have been constructed for quite a long time without searching for different materials.

Forms, that were generated by simple combinations and transformations of defined geometries, had been tried to improve and complexify in time. However, It is seen that basic defined geometries were not disappeared entirely in reinforced concrete shells. Eduardo Torroja designed a shell, formed by the intersection of a hemisphere, and seven smaller spheres, for the Algeciras Market Hall (1933) (Figure 7). Although such a form is quite simple and has a very basic mathematical description, it has been distinguished from the conventional masonry by using concrete and it has been possible to construct a very thin shell of 8 cm, compared to the masonry. Then the reinforced concrete shell thickness was decreased to 4cm, and the minimum thickness was reached in Restaurante Los Manantiales (Figure 4), designed by Candela.

This process followed by the structural shells of Heinz Isler. By experiencing the compressive strength and weakness against tensile loads of the concrete and tensile strength and weakness against compression loads of the textile materials, Isler has a new approach to form search and constructability.

At this point, it is possible to deduce that the performance characteristics of the materials are beginning to play an active role in form generation as well as the production process. At the same time, it can be said that such experimental processes and the problems faced by them constitute a basis for digital simulations used today. At the International Association for Shell Structures (IAAS) conference in 1959, Isler presented 39 applicable form alternatives for structural shells, tested with textile materials, and stated that these forms are only selected from the infinite variations possible to produce (Chilton 2000). The requirement to build reinforced concrete structures in-situ, prolongs workmanship and production processes. Therefore, when considering the advantage of prefabrication, a material which is totally working in unit logic as compared to the construction of a holistic material with a mold, is decreased assembly and accordingly construction duration. At the same time, the operations that can be applied to the separately produced units will be much more practical than intervening with the mold to create a continuous surface. When considered in this context, it is possible to investigate the monocoque structures formed by using various metal sheets and wooden plates also under the title of the single material.

From another point of view, the need to meet a structurally different tension and compression value at each point on the shell surface can be considered a sign of the heterogeneity of the nature of the sys-

Figure 8
Beast 2010 3D
model and material
- pattern detail [7].



tem. When this heterogeneity is interpreted through the material, it can be concluded that the structure can be formed by using different materials together instead of a single material. Raybould House (2003), designed by Kolatan Mac Donald Studio, is a proposal of using polyurethane foam to cover a prefabricated cage, preferably a layered material instead of a single material. Unlike concrete, the cage has a digital pre-fabrication process. At this point, in order to preserve monocoque character, it is important that the layers that make up the structure act like a single element, against the loads on it.

Accelerating in the search for new materials, it is possible to say that composite materials are handled with a different approach in terms of layering properties, and they are one step further from the single and layered materials. Neri Oxman's experimental studies on monocoque structures in 2007 using the multi-material 3d printer, which can combine multiple materials, can be seen as the first examples of the use of a compound material in this area [6]. Oxman (2015) mentions a variety of methods and tools that incorporate computational design, material science, engineering, and advanced digital production systems that they have developed in their research. One of the products of such interdisciplinary processes can be seen as Beast (2010), the next step in experimental work on monocoque structures. In the project, an organic form consisting of curvilinear surfaces was produced by using a continuous surface consisting of a combination of five materials and allowing this skin

to act as the structure of the form (Figure 8) [7]. The materials that differ according to their rigid / elasticity levels, which are marked with colors from black to white. Then, structural requirements were met by adjusting the frequency, flexibility, and strength of the compound material. The design has advanced over the possibilities provided by the combined use of materials in different flexibility, besides generating and structuring the form has been completed by prioritising the material (Oxman 2012).

The material-fabrication-design (MFD) model described by Rivka Oxman (2015) is defined as the design of the tectonic relation between the structure and the material within the framework of production logic. When assessed in the context of this model, the mentioned integration and process orientation of production can be clearly observed both in Beast and ICD / ITKE Pavilion examples.

Concluding Remarks

In all of the samples considered in the study, material behavior and production methods are seen to be prioritised as an effect of the being monocoque of the case studies (Table 1). Therefore, the triggering between new materials and new production techniques can also be read through examples. Considering the reinforced concrete shells studied, it is possible to talk about the continuation of a long period of experimentation before the construction phase. In these examples, problems and difficulties that may arise in the construction process have led to the pref-

Table 1
The information about materials and fabrication processes of considered samples.

		General Information	Material	Fabrication Process
	1933	Algeciras Market Hall <i>Edmundo Taracena</i>	Concrete	Mould In-situ
	1958	Restaurante Los Manantiales <i>Felix Candela</i>	Concrete	Mould In-situ
	2003	Raybould House <i>Kieran Mac Donald</i>	Polyurethane foam Wood	CNC Assembled on site
	2010	Beast <i>Neri Oxman</i>	5 different polymer based material	Multi material 3D printer
	2012	Porsche Pavilion <i>Henn</i>	Steel sheet	CNC Preproduction in shipyard Assembled on site
	2015	ICD/ITKE Pavilion <i>Actum Merges</i>	ETFE Carbon fiber	Robotic arm On Site

erence of simple geometries and symmetry, even though the form decisions have been made according to load-bearing characteristics and material properties. The thickness of the shell, which is held constant along the form, can also be read as an indication of this condition. With the use of NURBS-based programs, surfaces can be mathematically defined in the level that they can communicate with the production tools. In other words, instead of applying basic mathematical forms due to production constraints, complex forms have been mathematically explained. By solving the problem of communication with the means of production, the generated forms are able to be freed from the basic geometry and became editable freely. Nevertheless, in the case of reinforced concrete shell case studies investigated, the experi-

mental progression can be interpreted as proximity to the present computational design process basic logic, by shifting the focal point to the behavior of materials and the structural requirements rather than the form search. Especially in Beast and ICD / ITKE pavilion samples, it is seen that the design and production process is integrated with each other and the form has become an outcome of this integrated process. Therefore, production methods, as well as materials, continue to be one of the leading factors of the process. It can be said that minimizing the labor hours and workmanship faults in the concrete shells became possible by replacing the material in the Porsche Pavilion, on the other hand similar requirements have been provided by the selected production method for the ICD / ITKE pavilion.

It is now possible to observe that the production methods and materials used to participate in the design process and play an active role in shaping the design instead of gaining importance during the construction phase of the structure. Beginning to use NURBS-based programs and supporting these programs with related add-ons and simulations over time allowed for a more detailed account of the relationship between material, structure, and form. The demand to produce digitally designed forms required improvement in production tools, on the other hand, the materials used and the structural requirements have begun to influence form simultaneously. Although all studied examples have continuous experimental processes as a common feature, the concern of form, which is formed by the constraints of constructability, has gradually begun to leave its place to the developing process in the centre of specific materials and fabrication tools.

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Visual Thinking Through Model Making

Between the preferred and desired

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Emerging technologies of the twenty-first century are drastically changing the way designs are produced, and adjusting the very processes of common architectural practice. This creates uncertainty amongst architects as to their current methods of designing and the effectiveness of those methods in a profession now driven by technology. This paper gives context to such design methods from a visual thinking perspective, addressing digital and physical model making and various other design tools. Previous studies have investigated sketching and its use by many designers as a tool for conceptualisation, before developing that concept through digital models.

Keywords: *Working model, 3D Physical model, Digital modelling, Visual thinking*

INTRODUCTION

Through the current 'technology age', the place of architects in the construction industry is ever-shifting - perhaps due to our accessibility to digital modelling software, perhaps due to its generally clear user interface and ease of use. In certain areas, it is believed that many people have lost sight of the importance of the architect in design. This, alongside many other factors, has led to an increase in the amount of self-build projects, and large-scale development companies and volume housebuilders 'designing' our built environment. From a personal point of view, the architectural model should be a rough tool for discovery, and there is only so much discovering that can be done of a 3D model on a computer screen, demarcated by dimensions (Lawson and Loke, 1997). There are, however, two types of architectural model: "the

study model and the presentation model" (Sutherland, 1999). These two types compose a certain craft in architecture. Yet has this craft of physical model making in the architect's practice been replaced by a new digital one? The answer to that question is essential in defining the role of craft in practices today. On that point, this paper will consider the architect's place in the construction industry with regards to their skills in model making and staying relevant in a world of ever-advancing technologies. This paper intends to reinstate the importance of that phrase 'design process', and redirect the focus of designers back to that very process amidst the current upsurge of technology. This continued rise in new technology presents the great variety of modelling processes that impact the design process today. A study into this topic would delineate the place of models in the

21st century design studio and discuss the importance of visual thinking through physical as well as digital modelling processes. "The variety of design processes that inform the fabrication of architecture is now greater than ever" (Dunn, 2012). A huge player in this is Building Information Modelling (BIM). This - alongside various other types of digital media - have the potential to radically shift the way designs are created in the industry, not to mention the ways in which they could greatly support and extend creativity in architecture. "As a term and method that is rapidly gaining popularity, BIM is under the scrutiny of many building professionals questioning its potential benefits on their projects" (Barlish and Sullivan, 2012). Thus, this paper will provide a balance of both physical modelling and digital modelling, informing current and future decisions of whether or not to adopt such digital design tools.

Aim and Objectives

A computer screen is only ever 2½D. So when you make a 3D model from it, there is always something you are not expecting. "(Løddesøl, 2014). Snøhetta Architects utilise a constant process of 3D modelling and 3D printing as an approach to visual design thinking: discussing, sketching and investigating spatial form. Do physical models allow greater autonomy in this design development than 3D models? Is there more freedom to think visually through a rough conceptual model before it has dimensions? This study aims to investigate these questions through the subject of 'visual thinking' whilst examining various processes of model making. For clarity, this paper will refer to handmade models as "physical models" and computer generated models as "digital models". First the research will cover physical models, described as "a vehicle for process, idea and reflection" (Voulgaridis and Morkel, 2010), of which there are two genres: the "working model" and the "presentation model" (Sutherland, 1999). This study will then investigate digital (computer-generated) models, before comparing the two types and discussing which is more effective with regards to that which is of con-

cern to this paper: the "working model". As a subject of great personal interest, a study into architectural model making would delineate the place of working models in the design process. The time-frame of this paper also lent itself to the completion of a study in the Stage 5 Architectural Design Studio at Robert Gordon University investigating various students' use of this and other mediums in their design process. The overall aim of the paper is to compare these two methods of modelling with regards to design development at a conceptual level. This carries two objectives, each of which has an element in both physical modelling and in digital modelling. The objectives are:

- to investigate, through a process of design reflection and visual thinking, which one method of model making is more pertinent to designers (final year students) at a conceptual level.
- to establish to what degree alternative design tools are being used in design conceptualisation before being presented through physical and computer-generated models.

Both objectives will be addressed initially through the studio-based project study and practice based survey.

REVIEW

What is visual design thinking?

The creative process described in this section suggests a back and forth movement between the brain and the medium, and is highly reminiscent of Donald Schön's description of the way an architect 'holds a conversation with the drawing' (Schön, 1983). In the Review of Educational Research journal, a useful description is given: "design thinking is generally defined as an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" (Razzouk and Shute, 2012). This activity is further emphasised in the paper 'Problems, frames and design perspectives on designing', where Schön

states that “when [design] moves function in an exploratory way, the designer allows the situation to ‘talk back’ to him, causing him to see things in a new way - to construct new meanings and intentions” (Schön, 1984). Offered here is an essential process of the designer, which engages the brain through a critical progression of design and redesign, but is this process being used in twenty-first century model making? Moore (2003) laments a similar idea that “the concept of the visual [also] hinges on the idea that there is a direct connection between what we are looking at and the manner in which we think, that ‘external things’ are the causes of our ‘inner’ experiences” as “the mind takes the form of the object perceived, without its matter” (Putnam, 1999). Salman, Laing and Conniff (2006) “A designer’s ability to solve design problems depends on his/her ability to create a virtual world where visual thinking becomes possible and helps to externalise ideas of the different design situations. This design world includes sketches, diagrams, drawings and physical models”. When tackling a design problem, it is possible to connect with this world through a design conversation (Schön, 1991) with one’s preferred mediums and design tools. Thus, through the designer’s use of physical models to help solve that design problem, he/she interacts with a 3D world (Mitchell, 1990).

Visual Thinking in Physical Modelling

What exactly is the craft of physical modelling? physical models and their description act as “a vehicle for process, idea and reflection”. Vouglarelis and Morkel (2010) also observe that “the cognitive focus of the physical model is that it enhances dialogue. Not only does the model talk back, but it is an easy graphic form to access visually and verbally for both student and lecturer”. This creates a clear contrast to model making on the computer, and its lack of ‘accessibility’ and engagement of the senses. Although 3D printing has more recently changed this, digital modelling was previously only accessible “within a ‘live’ computer where students can show the whole model with ease. However, students tend to print out

views that hide problematic issues - this is not possible to achieve with a physical model.” These views established by Vouglarelis and Morkel reminisce the work of Schön, regarding the ‘conversation’ that the designer holds with the medium. It is recognised that all mediums ‘talk back’ in different ways (Schön, 1989; Breen et al, 2003; Lawson, 2015; Mitchell, 1990; Salman, Laing and Conniff 2014). Another observational study (Akalin, 2003), stated that “when concept models or muck-ups are considered, such tasks involved in modelling may be regarded as a way of reasoning just like sketching”. This quotation suggests an analogous back and forth motion between mind and medium. There is no function of a design tool, unless it aids critical analysis and communicates to the brain feedback of the design created with that tool. This in turn begs the question of the effectiveness of model making as a creative tool for design development. Undoubtedly it will depend on the studio, and the designer (Lawson and Loke, 1997), but is there a better balance that can be found in the architecture profession today than sketching a concept before developing and representing it through physical and computer-generated models? This paper aims to act as an instrument in striking that balance, but research must first be done into the digital realm.

Visual Thinking in Digital Modelling

“Visual design thinking is performed through three-dimensional digital models. Designing in a three-dimensional digital environment might be described as sketching in space” (Abdelhameed, 2004). Although this type of model making suggests one with more complexities, it also suggests one with less boundaries and more liberty. Is there anything we can take from physical modelling into the new digital craft? Jordan Brandt writes in the book ‘Persistent Modelling’ that “craft is marked by the mind relating the purpose of the work to the motions of the hand” (Ayres, 2012) and concludes by saying “the use and creation of our technology could well be informed by the process of craft. So instead of authoring a

deterministic model, how do we craft the modelling process to accommodate a persistent continuum?" This suggests that digital modelling systems should be ever-advancing, meaning at a design level such a system should enable us to expand, through a process of imagining, what we can do in the digital modelling realm."Tools in the more literal sense, like pencil, compasses and ruler, say next to nothing about the designs devised with their assistance" (Gänshirt, 2007). The same could be said about Building Information Modelling (BIM). It could be said that at the end of the day it is the end product that determines the effectiveness of that tool, not how it was arrived at. There is, however, an evident increase in the various avenues that a design may take, and that is where potential lies for further exploration of visual design thinking. Bearing in mind that each designer designs more effectively using particular tools, a notable area for investigation is whether or not this digital exploration is, or can be, for everyone. It is argued by Lawson and Loke (1997), however, that "present CAD tools do not support the kind of vagueness and uncertainty that those manual conceptual sketches allow and thus often prematurely fixate or crystallise developing design concepts." Or, in using the language of Donald Schön, "such CAD drawings are insufficiently conversational but seem more like imperative statements made by the computer leaving little or no room for further contributions from the designer" (Lawson and Loke, 1997). With regards to design exploration, Peter Rowe (1987) notes that "there are many different styles of decision-making, each with individual quirks as well as manifestations of common characteristics". Goel (1995) further describes the design process as being a task of complex cognition. It is evident then, that this process is different for every designer and his or her understanding of the medium, as Abdelhameed (2004) observes that "what an architect can conceive and comprehend depends on what this architect can visually perceive through the media used". Designers have and will always have different skills and capacities; therefore it is unlikely that digital modelling will be-

come customary to architectural design. However, in an attempt to accommodate personal preference, alternative mediums of design are offered through programs such as Google SketchUp, Adobe Photoshop, and Autodesk AutoCAD. Breen (2004) informs us such software has allowed students and practices alike the opportunity to personify working methods (Achten 2003; Achten and Reymen 2005) according to their styles, preferences and abilities.

Craft and Technology

"Computer-assisted design might serve as an emblem of a large challenge faced by modern society: how to think like craftsmen in making good use of technology" (Sennett, 2008). There are such architects as Greg Lynn, who seek to expand the use of computers in design, through research, education and practice. Such acts are essential to the existence of a 'digi-craft', and perhaps also essential to the relevance of architects throughout the 21st century. In his article, 'Design Course Goes Digital'; John Marx emphasises that "recent advances in computer hardware and software have opened opportunities for a digital design process that does not diminish but rather enhances creativity" (Marx, 2000). This outlines a point essential to the formation of a digital craft; creativity. But is that creativity using physical or digital design tools? 'The word 'tool' might invoke the mechanical, rather than the digital age. Yet 'tool' was used for representing both action and thinking, as in 'thinking tool', and therefore the notion of conceptual tools covered both physical and cognitive activities" (Jonson, 2005). These conceptual tools have always stretched design exploration, whether physical or cognitive. The architect started out designing using the pencil (the design tool) to create sketches (the medium), forming the gesture that produces a concept for the rest of the design to follow. Then as technology developed, his design tools changed to perspective drawings, to physical models, and now to 3D modelling. Regardless of the development of new design tools, software etc., the architecture industry would still be designing and making, using whatever

tool or media is available to them. With regard to the range of new design tools available to architects today, Nick Dunn (2012) offers a strong background to historic digital modelling processes and their more recent proliferation in architecture in his book titled 'Digital Fabrication in Architecture'. "CAD/CAM processes have been used in engineering and industrial design for over 50 years in the development and fabrication of cars, aeroplanes and smaller consumer goods. Components are usually designed and developed with three-dimensional modelling software, and then scale models are produced using a rapid prototyping process that translates digital information into physical object" (Dunn, 2012). However, with regard to these computer-generated models which were discussed earlier as being demarcated by dimensions, and hence too rigid to fulfil its function as a development model. It is argued by Lawson and Loke (1997), that "present CAD tools do not support the kind of vagueness and uncertainty that those manual conceptual sketches allow and thus often prematurely fixate or crystallise developing design concepts." Or, in using the language of Donald Schön, "such CAD drawings are insufficiently conversational but seem more like imperative statements made by the computer leaving little or no room for further contributions from the designer" (Lawson and Loke, 1997). How is it that one model inspires a thought in the mind, which in turn creates a 'development' of models? The question is then, are the media and tools in common use today allowing that precision and elegant design required in order to endorse this new digital craft, or are they just equipping us to get the job done faster? It is deemed by some that computing as a tool is unsuitable for conceptualisation (Lawson and Loke, 1997). It has been shown, however, that CAD is actually a conceptual tool used to foster new methods in the perception and conceivability of design (Jonson, 2005). "Arguably, then, the view that CAD is inappropriate for conceptualising seems to be based on a preconception of conceptual tools as surface, rather than deep structures" (Jonson, 2005). In the methodology, various con-

tual tools will be investigated with relation to craft in order to determine that which is most appropriate to design ideation. In related studies, sketching has traditionally been considered a core conceptual tool (Schön, 1983; Bilda and Demirkhan, 2003; Jonson, 2005). However, in the last ten years, significant increase has been evident in the use of digital model making at both university level and practice level design studios. Thus, as a new digital craft matures, what is now the norm for conceptual ideation may be significantly different in the architectural design studio than what it was a decade ago.

METHODOLOGY

This paper research methodology aims to observe the conversational aspect of a design "process" (iteration cycles, ideation). Design process acts as a rich source for reflection, which pertains to the reflective aspect of design (referring to Schön's 1987) theory of conversation with the material. At the same time, reflection has a methodological aspect and can be used as a research method in design as well as other fields, whether the investigated setting is practice or education (Salman 2011). Reflection can occur along with designing (concurrently) or after reaching a satisfied result (retrospectively). Design process studies inspired the empirical element of this research to emphasise two paradigms of design research methodology: the constructive and the reflective-practice. Case study research is widespread in social sciences and education (Scott and Morrison 2006). According to Robson (2002) a case study is: "a strategy for doing research which involves an empirical investigation of a particular phenomenon within its real-life context using multiple sources of evidence". Another mentioned feature was its flexibility as an approach to combine quantitative methods and qualitative methods in one study. Moreover, Scott and Morrison (2006) state that the main focus of a case study in educational research is to give the case actors a 'voice' in such a way that the researcher's role may sound passive to the benefit of the case actors.



Sample

With respect to the study context, the choice of sample was (Master of Architecture) final year students. The choice was made to reduce the differences in design cognitive abilities and to have cohesive understanding of the skill level and its impact on the used media (Salman 2011). Using design mediums with no experience seems to reduce the possibilities for designing (Coyne, Park and Wiszniewski 2002; Jonson 2005). However, there is a high probability that this study sample may represent part of a bigger population within UK schools of architecture that embrace a similar pedagogical approach. At the same time, the results would deviate if the same study were to be employed in schools of architecture which embrace digital theories and computation. The sample was final year students (Master of Architecture) cohort 2014-2015, who studied architecture for at least four years and used physical modelling and digital modelling for problem solving and presentation.

Data Collection Method

Design studies previously have maintained a focus on sketching, its impact on designing and have engaged less emphasis on reflection and visual thinking with regard to digital and physical model making, with little concern for design tools in the current digital age. The research instrument was used to collect such data was adapted from Jonson (2005) self reporting study. The study matrix was designed in a similar manner to that of Jonson study (2005),

with students being instructed to select the mediums (or design tools) used in their conceptual stage design process from: sketching [S], words (spoken or written) [W], physical modelling [PM] and digital modelling [DM]. Each time the participant switched to a different medium, a new box was ticked, followed by a brief description of (a) the task undertaken through that medium, and (b) any notable observations, landmark events, or "Aha!" moments experienced through this medium. Any other design tools used, of which there were none, were to be included as a numbered footnote at the bottom of the page. Students were also advised that, due to the nature of the model making study, this matrix was to be completed only when using either physical or digital modelling (in conjunction with another medium). An example is shown in Figure 2. The informants were also asked to tick a box indicating their preferences for sketching (either 2D or 3D), and Modelling (either physical or digital). The data was gathered through their daily studio practices by jotting down the most frequent conceptual tool they had used. Students who made notable observations with relevance to the literature, or had particularly interesting visual design processes were then questioned through follow-up interviews. The collection of their thoughts after the studio study regarding the design process, or "reflection-on-action" (Schön, 1983), provided a rationale for the quantitative data received. In these instances, the self-report became a preliminary to interviewing (Burgess, 1981), revealing points for speculation and helping to regulate the authenticity of the results (Jonson, 2005). These interviews will be semi-structured, using several guided questions. The students selected for these interviews include one preferring digital model making and one who was favourable of physical model making, offering a balanced discussion of the subject area and those mediums concerned within it.

Figure 1
Student
Participation in
Studio Study

Figure 2
Studio Study Matrix
(Adapted from
Jonson 2005)

Design Thinking Study Template

As part of my dissertation titled 'Visual Thinking through Model-making', I would appreciate your cooperation in completing this simple design study. Note: Template only to be completed when using either physical or digital modeling in conjunction with another medium.

Student Name: _____ Age: _____

Nature of Project: _____ Size of Project: _____

Preferred Medium for Designing: Sketching 2D 3D
Modelling PM DM

Please circle new box each time medium is changed. Describe other tools used in numbered footnote.

1. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


2. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


3. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


4. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


Footnotes:
1. _____

Key:
S = Sketching
W = Words (spoken/written + internet searches)
PM = Physical Modelling
DM = Digital Modelling
1 (etc.) = Other Tools in numbered footnote

Figure 3
Sample's preferred
mediums

Design Thinking Study Template

As part of my dissertation titled 'Visual Thinking through Model-making', I would appreciate your cooperation in completing this simple design study. Note: Template only to be completed when using either physical or digital modeling in conjunction with another medium.

Student Name: _____ Age: _____

Nature of Project: _____ Size of Project: _____

Preferred Medium for Designing: Sketching 2D 3D
Modelling PM DM

Please circle new box each time medium is changed. Describe other tools used in numbered footnote.

1. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


2. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


3. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


4. Task undertaken using this medium (e.g. Testing massing forms on site):
Notable observations/landmark events (Aha) experienced through medium:


Footnotes:
1. _____

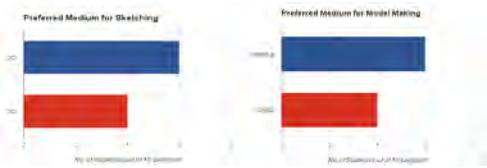
Key:
S = Sketching
W = Words (spoken/written + internet searches)
PM = Physical Modelling
DM = Digital Modelling
1 (etc.) = Other Tools in numbered footnote

Studio Matrix Findings and Discussion

A total of 10 students volunteered in the self-reporting study, providing a round number for subsequent analysis. The study was undertaken over the course of a three-week period, and responses completed by participants when using digital or physical modelling over that time-frame. Then, the self reporting matrix and semi structured reflections were analysed using descriptive statistics and frequency analysis (Field 2005), this is presented in percentages and reported in this section.

Self-reporting analysis in Figure 3 shows that more students (60%) preferred to use 2D sketching over 3D sketching in exploring their early ideas. Similarly, analysis also shows that 60% of students in preference of physical model making over digital. This arguably shows that the majority of final year students are still using a combination of 2D and 3D in physical format rather than digital. But others (40%) have

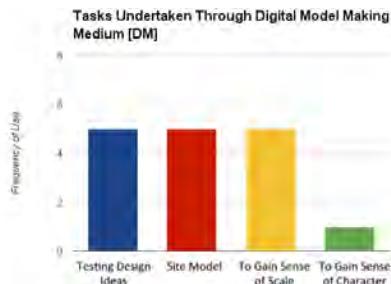
shifted this trend towards 3D digital tools for design thinking. On the level of the individual skills, the findings refer dominantly to participants' habitual design methods as one constraint that affected their use of their digital skills in its full computational capacity.



In brief, whether the produced artefacts (model, drawing) would affect the student design conceptually, students separated what is analytical from what is regarded as a complementary act (drawing activity). In other words, 2D sketching and 3D physical modelling has a strong relation with authorship and identity, bearing in mind that drawing brings understanding, and from understanding students can develop more ideas. However the matrix analysis also revealed that sketching [S] has been identified by the students as the primary conceptual tool . These findings also challenged the view that digital modelling is an inappropriate medium for conceptual design. What has been observed historically in conceptualisation studies is that verbalisation [W], "on its own or in combination with other conceptual tools, emerged as the prime mover for getting started" (Jonson, 2005). It is apparent in this research, however, that conceptualisation in recent years has been somewhat different.

A number of tasks were undertaken by the students who used digital modelling -Sketchup, which was used more prominently for testing design ideas, generating site models and also to try and achieve a sense of scale. On the other hand, physical modelling was most commonly used for creating site models and performing massing studies of existing surroundings and also proposed developments; most seemingly with presentation in mind as opposed to development. The only other instance of its use was in exploring spatial relationships for one

student's precedent study.

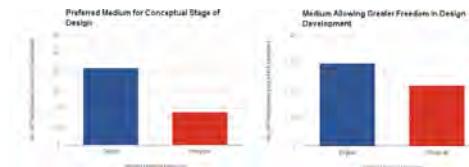


It was apparent that more subjects preferring physical modelling used digital modelling than those preferring digital modelling using physical modelling. This trend, backed up by student feedback, suggests pressures of cost and time upon the students, influencing their decision to use digital modelling, which is said by students to be "quicker and easier to visualise". Various disadvantages of digital modelling were also noted by the students, with one student remarking with regards to speed, "it takes time to compile enough information to gain a sense of character until the model is more developed". Another student also noted that it wasn't very helpful in developing a conceptual idea.

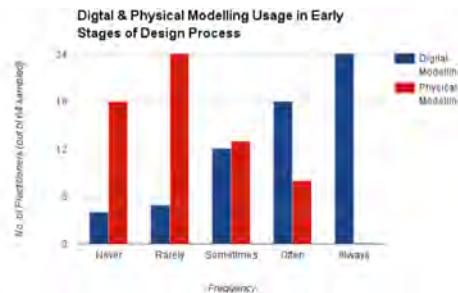
Practitioners Survey Findings and Discussion

This section contained a brief background to the study and a description of visual design thinking. Participants were asked to indicate their model making preference for the conceptual stage of design. It was shown in this study that 70% of the practitioners surveyed preferred digital model making for design in the conceptual stage, and four participants preferred not to answer due to such modelling processes not being used in their practice. Despite the results in favour of digital model making, seventeen practitioners felt that physical models were more assistive for design development, but still used digital due to time and cost constraints, as well as flexibility further along the design process.

A common view was that physical models are greater for conceptual massing, form design and ease of communication to others, whilst digital models have their advantage when it comes to modification, contained information and the exploration of multiple solutions.



With regard to the frequency of modelling use in practice; the first relating to digital (3D CAD) models in the early stages of the design process and the second relating to physical (handmade) modelling. It can be seen how drastically the design processes of architecture practices have changed in recent years, showing that not a single practice in the sample always create physical models, however, 37.5% (and ever-increasing) percentage of practitioners always utilise digital modelling software in the early stages. The two data sets are almost symmetric suggesting that through the increase of digital modelling usage, there is a subsequent decrease in physical modelling usage, showing that practices are perhaps utilising individual specific mediums, rather than a range of design tools.



The findings show that there has been a significant neglect of the craft of physical modelling in the architecture practice in recent years. Respondents of

Figure 4
Tasks Undertaken Through Digital Model Making

Figure 5
Practitioners Preferred Mediums

Figure 6
Digital & Physical Modelling Usage in Early Stages of Design Process

this question outlined similar reasons to those of the 'Frequency of Use' section. The recurring theme of time was recorded primarily, but secondly reasons included factors such as lack of flexibility, cost, lack of portability and storage, as well as featuring a higher quality and more resourceful output.

CONCLUSIONS

A challenge of the future, however, will be in retaining focus on actual design. Undoubtedly many students are pursuing an architecture course with great familiarity of computers, and aspirations of 3D printers and technology, therefore the task for such educational bodies will be to try and develop a hunger for good design first, retaining this as the centrality of the architecture course in the 21st century. In summary, it is important that architects must always progress with ever-advancing technology, but never substitute it for the brain. As a subsequent of the daily challenges faced by designers, their problem solving and resourceful strategic thinking skills are second to none. Therefore, we must use those proficiencies to benefit the world around us today in whatever way we can. By a process of visual thinking and design reflection, we as an industry must continue to imagine and create great spaces and buildings using a range of design tools, and whatever technology helps us do so most efficiently.

Some architecture schools are advancing faster than others, but all operate differently. Therefore, further research should be focused on a wider population to gain more representative inferences and conclusions, perhaps including architecture schools across the UK. This would minimise the subjectivity of such research by allowing comparative studies to take place. A more detailed study may also be beneficial in establishing what must be done in adapting education systems in accordance with changes emerging throughout the new 'digital era' facing architectural practice.

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Modular Mycelia

Scaling Fungal Growth for Architectural Assembly

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This paper covers the findings of a master's level investigation into the potential of fungal-based architecture. The overarching hypothesis of the research is that fungal growth can be scaled for architectural application through the development of a multi-scalar assembly system. This investigation was conducted in three stages. In the first stage, fungal growth patterns were tested on a variety of substrates, at the petri dish scale. In the second stage, findings from these growth tests were used as drivers for the development of an assembly unit. In the third stage, combinations of these units were arranged to produce larger elements. These elements were then used to build a proof of concept prototype. The final prototype demonstrates the strengths of the multi-scalar system, while further outlining the technical challenges of using fungal growth as a means of architectural assembly.

Keywords: *fungal-based architecture, modular mycelia, synthetic biology*

INTRODUCTION:

There are a number of companies currently producing fungus-based materials as sustainable alternatives to conventional building materials. Fungi's capacity to grow on agricultural waste, its low-energy and carbon neutral requirements for production, as well as, its inherent biodegradability make it ideal as a sustainable alternative to current building materials.(Travaglini et al. 2016) Fungi also have a range of mechanical properties that make them potentially well-suited for building technology. (Travaglini et al. 2016) Despite the sustainable, economical, and structural benefits, there is an inherent problem in using fungal-based materials simply as an alternative to standard building materials. The problem with

this approach is that fungus-based materials retain the assembly techniques of their traditional counterparts. Fungal-based bricks are stacked in the same way as conventional bricks; they require just as much labour and just as much mortar. A new method of construction could emerge simply by leaving the fungal bricks alive during assembly, rather than killing the organism after the brick is formed, which renders the material inert. While this approach adds a level of control and consistency to the material, it neglects fungi's capacity for self-organized growth. (Webster and Weber 2007) And, more importantly, it neglects fungi's potential to challenge conventional methods of construction.



The aim of this research project is to investigate the potential of fungal-based architecture through the development of a multi-scalar assembly system. Scalability is a principal characteristic of fungal growth. The processes that determine the interconnectiv-

ity of a fungi's mycelium at the micrometer are the same processes that determine the form of a fungi that stretches kilometres.(Davidson 2007) When incorporated into an assembly system, these same processes could be exploited to manufacture the individual elements of a structure, then exploited again to bind the overall structure together. Despite the scalability of fungal growth, challenges emerge when fungi are grown in large volumes of substrate. Maintaining optimal environmental conditions(moisture, temperature, nutrition) and preventing contamination become more difficult as the volume of growth increases. Given the heterogenous nature of fungal colonization, it is also difficult to maintain consistent growth throughout large volumes of substrate.(Boswell et al. 2007) The overarching hypothesis of the research is that a multi-scalar assembly system could resolve the challenges inherent in exploiting fungal growth for architectural application.

There are a number of opportunities presented by embedding biology processes into architecture.

Figure 2
Different Stages of
Fungal-Based
Multi-Scalar
Assembly System

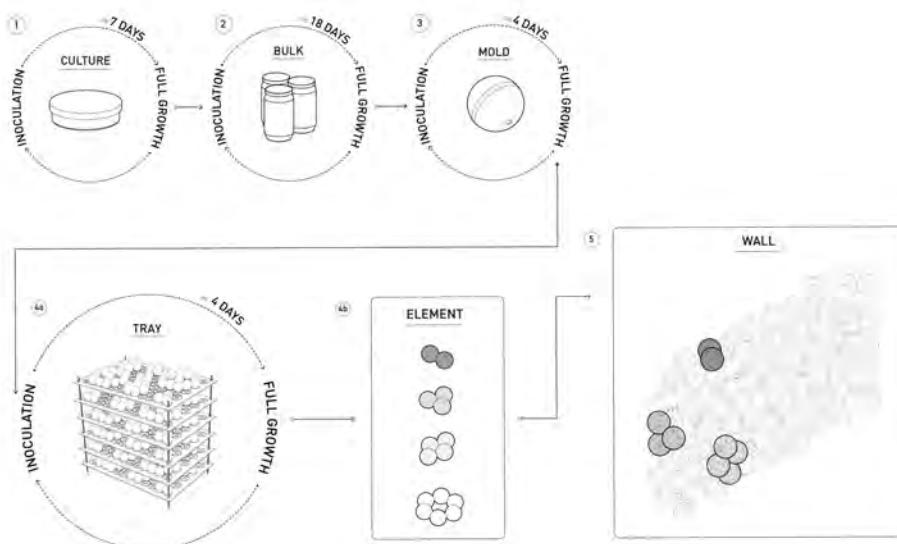


Figure 1
Process Diagram of
Multi-Scalar
Assembly System

Natural systems exhibit a range of functions that are not found in current construction. These functions include adaptation, resilience, self-repair, self-organization.(Imhof and Gruber 2015) Each function represents a novel way to engage the built environment. It is important to note that the benefits of imbuing architecture with natural functions go much further than novelty. Natural systems tend to be very efficient in their use of energy and resources. (Imhof and Gruber 2015) The potential benefits for architecture range from the economical to the sustainable. There are a number of researchers who are currently exploring the potential of engineering biological systems for architectural application. These researchers include Rachel Armstrong, who is credited with projects such as Hylozoic Ground and Future Venice, as well as, Barbara Imhof and Petra Gruber, who direct GrAB (Growing as Building) an ongoing research project that uses patterns and dynamics found in nature and applies them to architecture. Through their work, these researchers are effectively applying the tools of synthetic biology to architecture. Synthetic biology is an interdisciplinary approach to designing biological processes for practical applications, which "offers new ways to combine the advantages of living systems with the robustness of traditional materials to produce genuinely sustainable and environmentally responsive architecture." (Armstrong and Spiller 2010)

The Hy-Fi Tower, by The Living (David Benjamin), Polyominoes, by Mycoworks (Phillip Ross), and Mycelium Tectonics, by Gianluca Tabellini, are three precedents of the current research project. At twelve meters high, the Hy-Fi tower is one of the largest and most resolved fungus-based architectural project to date. 10,000 fungal-based bricks were grown by Evocative, a biomaterials company, for the project.(Holcim 2015) The Hy-Fi tower is an example of a fungal-based project that engages construction at the material, manufacturing, and waste stages of a building life cycle. At the material stage, local agricultural waste (corn stalks) was chosen as a substrate. The shredded corn stalks were the inoculated with

mycelia and packed into moulds.(Holcim 2015) After the mycelia had fully grown through the substrate, it was killed, producing strong, but inert bricks. The bricks were then assembled into the tower using timber scaffolding as form work and mortar to hold the bricks together. The bricks were then composted after the tower was disassembled. (Holcim 2015)

In contrast we have Polyominoes, an ongoing research project by Mycoworks. From an architectural perspective, Polyominoes is a less resolved project than the HyFi tower. As the project title suggests, these blocks take the form of a polyomino, which is a shape made by combining a number of squares edge to edge. Polyominoes are often used for problems or puzzles that involve tiling a plane. Tetris is a popular example. In this project, the blocks are made from a mix of mycelium and sawdust, which is packed into a mould. The shape and scale of the mould is determined by the dimensions of standardized lumber. After the mycelium grows through the sawdust, the blocks are removed from their moulds and are put in close physical contact.(Mycoworks 2015) The blocks then fuse through hyphal bonding, and a continuous object is formed.

The third precedent is a thesis project titled Mycelium Tectonics, which was conducted at the University of Bologna by Gianluca Tabellini. Similar to Mycowork's Polyominoes, Tabellini's research explored fungi's potential to create structures. For the project's final prototypes, Tabellini designed hanging models made with mycelia infused hemp strands. The strands are held by a small frame made from plywood and threaded rods. Cotton balls are also added to the frame after they are soaked in water.(Tabellini 2015) After the cotton balls and hemp fibres are secured in the frame, the prototype is wrapped in plastic to maintain a high moisture level. (Tabellini 2015) As the fungi's mycelia grows through the hemp fibres, the hanging strands become structural. After the mycelium has fully grown through the strands, the supporting rods are removed. Unlike the previous precedents, which tended to grow the mycelium as a homogenous mass, here, fungi's natural growth

processes are used to create a structure with variable material densities. It is also important to note that a mould was not used to determine the final shape of the prototype. Instead, the prototype's final form was determined by the arrangement of the substrate (hemp strands).

These precedents represent three approaches to two important variables in fungal-based architecture: architectural viability and biological utility. The architectural viability of a project is measured by its capacity to function as an inhabitable structure. Whereas, the biological utility of a project is measured by its capacity to exploit the biological processes of fungi. At one end of the scale is the HyFi Tower, which has a high score for architectural viability due to its scale and its capacity to function as an architectural structure for three months before it was disassembled. However, it has a relatively low score for biological utility because the role of fungi in the project was limited to producing a new kind of compostable brick. The biological processes of the fungi did not contribute to the form of the tower or the method of assembly. At the other end of the scale is Mycelium Tectonics, which has a high score for biological utility because fungal growth is used to add structure to a hanging model. However, due the scale of the final prototypes and, more importantly, the inherent issues of scaling the process, its architectural viability is relatively low. Polyominoes falls between the two other precedents in terms of these two variables. While it has not produced an inhabitable structure, the mycelial blocks could easily be incorporated into a functional architectural element. For biological utility, the project is a clear demonstration of how hyphal bonding can be used as a means of assembly, even though the design of the blocks themselves are determined by the dimensions of standardized lumber. The current research will attempt to balance these two variables in a similar fashion. It will also attempt to reach a similar level of resolution. The goal of the current research is not to produce functional architecture made from fungus. Instead, the goal of the research is to demonstrate the strengths of a multi-

scalar assembly system, while outlining the technical challenges of using fungal growth as a means of architectural assembly.

STAGE ONE: GROWTH EXPERIMENTS:

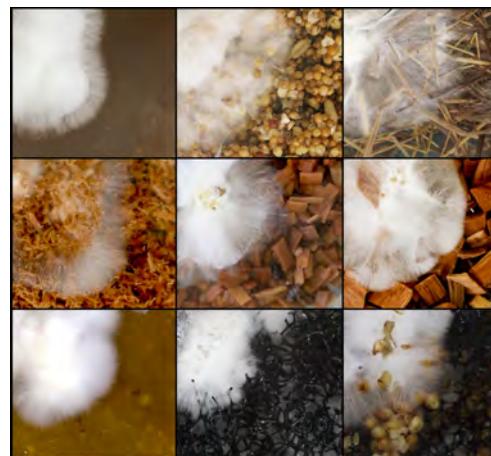


Figure 3
Fungal Growth
Experiments on a
Variety of
Substrates

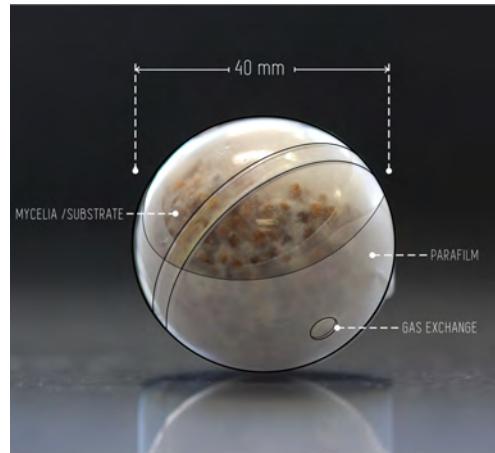
The first stage consisted of a series of growth experiments. These tests were used to gain a more intimate understanding of fungal growth processes. *Pleurotus ostreatus*, a species of basidiomycetes, was chosen for these experiments. *Pleurotus ostreatus* was chosen for its growth speed, its resilience to environmental condition and its adaptability to various substrates. The colonization patterns of *Pleurotus ostreatus* were tested on a variety of substrates. These substrates included organic material, such as agar, seed, straw and wood, and inorganic materials, such as sand and plastic, as well as mixtures of both organic and inorganic materials. The substrates were chosen to test how key parameters, such as nutrient content, moisture content, density and geometry, would affect the colonization patterns of the fungus. Due to the challenge presented by contaminants, after an appropriate substrate has been chosen, it must be pasteurized in an autoclave. The requirements of temperature, pressure and time will all be specific to the substrate chosen. It is important to note that the

Figure 5
Assembly Unit At
Three Different
Scales

substrate will not be fully sterile after it is pasteurized in the autoclave. It will, however, reduce the amount of competing organisms, which will increase the success rate of colonization for the chosen fungus. After the substrate is pasteurized, it is put into a petri dish and inoculated with *Pleurotus ostreatus* at a central point. A HEPA filter was used to remove the contaminants in the air so they will not be introduced to the substrate during the inoculation process. The inoculated petri dishes were then put into a grow chamber. The temperature of the grow chamber is set to 22 degrees Celsius. Though the fungi would grow more quickly at a higher temperature, it would also increase the chances of contamination. The results of the growth experiments were used as design drivers for the assembly unit. The seed substrate was chosen among the other substrates because it produced the thickest fungal growth the quickest. An important observation from these experiments was that despite the differences in geometry and nutritional content of the substrates used, the fungi maintained a radial growth pattern. A spherical shape was chosen for the assembly unit to match these radial growth patterns and to maximize the efficiency of colonization.

STAGE TWO: FUNGAL ASSEMBLY UNITS:

Figure 4
Growth Container
of the Assembly
Unit



A second set of experiments was used to determine the method for production, the design of the growth container and the size of the assembly unit. The inoculation process for the substrate is the same as the process used in the first experiment. The spherical containers were made from a thin clear plastic that was not autoclavable, so the substrate had to be pasteurized separately, then added to the containers once it had cooled. The containers were sterilized separately using ethanol and a cotton swab. Once the substrate was added to the spherical container, it was then inoculated with the fungi from a central point. A hole was added to both ends of the container for gas exchange. The containers were then wrapped in parafilm to prevent competing organisms from contaminating the substrate. The inoculated containers were then put into a grow chamber, whose temperature was set to 22 degrees Celsius. The assembly unit was tested at three different diameters (40, 90 and 220 millimetres). Although assembly units were successfully grown at all three sizes, a diameter of 40 mm was chosen. This choice of scale was predicated by the space available in the grow chamber.

STAGE THREE: LARGER ASSEMBLY:



In the third stage of the research project, the assembly units were combined in different arrangements to produce larger assembly elements. The benefit of creating assembly elements from the individual units is that they produce different functions. For example, where individual units could be used as a pourable infill, a triangular element made of three combined units could be stacked. The use of stackable elements

would remove the need for rigid formwork when creating larger assemblies, as in the case of a wall. To produce these larger elements, the spherical assembly units were first removed from their containers. A HEPA filter was used as a precaution to minimize airborne contaminants, though the assembly units are resilient to competing organisms once they are fully colonized. After they are removed from their containers, the assembly units are arranged on acrylic trays that have been sterilized. The acrylic trays are cut with rows of circles, which are used to hold the spherical assembly units in place while they fuse. After the assembly units are arranged, the trays are wrapped in plastic to create a moisture sealing envelope. Then the trays were stored in a grow chamber (22 degrees Celsius).

DISCUSSION

The speed of growth is pivotal in the colonization of a substrate. Even after pasteurization, substrates will often contain minute amounts of competing organisms. If the chosen fungi grows too slowly, the competing organisms can overrun the substrate. An important factor in the success of the seed substrate was its geometry. When aggregated, the seeds would produce gaps that promoted the transfer of moisture and oxygen through the substrate. These gaps also provide the fungi with a growth matrix. In contrast, the fungi had difficulty growing through denser substrates, like fine sawdust, which became a thick paste after pasteurization.

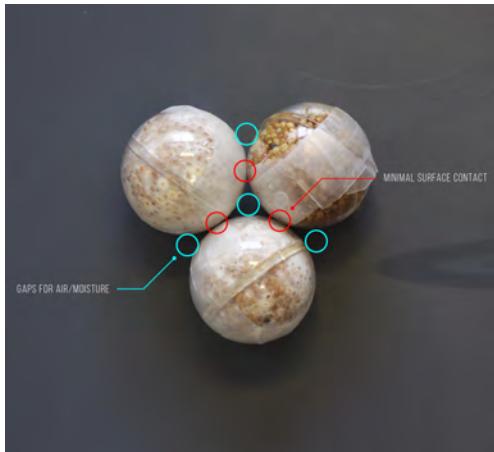
Figure 6
Fused Assembly
Elements

Figure 7
Stack of Assembly
Elements

Figure 8
Acrylic Tray with a
Collection of
Assembly Elements



Figure 9
Collection of
Assembly Units



The use of assembly units effectively discretizes fungal growth. This approach may be a suitable method for up-scaling fungal growth processes for architectural applications. One of the challenges that this approach addresses is the heterogenous nature of fungal growth. Since each assembly unit is inoculated with fungus from a central point, the fungus will be more evenly distributed throughout a larger assembly when the units are aggregated. Much more evenly, at least, than if an aggregation of substrate was inoculated at a single point. Also, by discretizing fungal growth, contaminated spheres can be easily

removed and cleaned. It would be very difficult to control the growth of a contaminant in a larger assembly. Another benefit to discretizing the fungal growth process is that the different growth speeds can be accounted for. The spherical shape of the assembly unit provide a specific benefit for use in larger assemblies. The gaps provided by their geometry act as a growth matrix (much like the seeds did at the smaller scale). These gaps also allow moisture and air to be distributed more evenly throughout the larger assembly. The fungi's ability to grow across these gaps solves the potential problem of minimal surface contact.

It is important to note that the larger elements are produced by the same growth processes that produced the individual units. The network of hyphae that binds the individual unit is the same network that holds the larger elements together. The larger elements are produced without adding new material and with only minimal formwork. Once the individual units are fused into larger elements (which only requires a few days) they have to be removed from the tray or the mycelia will overrun the tray. This excessive growth will make the larger elements difficult to remove from the tray cleanly. The requirement for the prompt removal of the larger elements works to the advantage of the overall assembly system. The need to continually remove fused elements

creates space for new elements on the tray. As new elements are added to the tray, the spherical containers can be reused to produce new units. The required removal of the elements essentially turns the multi-scalar assembly system into a iterative process. (as seen in the overall process diagram) This iterative nature also proved to be an advantage in the last step of the assembly system, when the elements are stacked to form an architectural component, like a wall. Since the elements are stacked gradually, they have time to fuse, making them more stable and solid, before new elements are added. This iterative stacking eliminates the need for rigid formwork. However, a moisture barrier is still required to maintain a high level of humidity.

Contamination proved to be an issue when assembling the final prototype. To add new elements to the prototype, the moisture barrier had to be opened, which created an opportunity for competing organisms to be introduced. The unintentional introduction of competing organisms is a constant challenge when working with fungi. Contaminants will grow in identical conditions, and will generally grow much faster than the intended fungi. (Webster and Weber 2007) Since the assembly elements were fully colonized when they were added to the final prototype, the assumption was that they would be able to fend off competing organisms. And they did, insofar as the contaminants were only able to grow along the surface of the elements. An attempt was made to remove the contaminants using ethanol and a wipe, but it was unsuccessful. Contaminants are also very difficult to contain or remove once they are introduced. In hindsight, this challenge could have been overcome through the design of a more functional moisture barrier.

OUTLOOK:

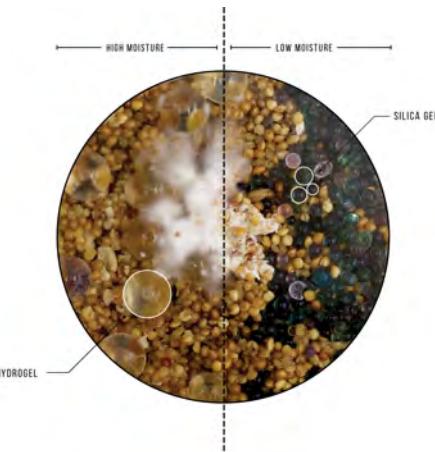


Figure 10
Seed Substrate
Mixed With
Silica/Hydrogel

Fungi have a number of properties that make them a great candidate for a building material. They can absorb nutrients from a variety of substrates, which allows them to convert agricultural waste into a number of useful products. They are biodegradable, once the material has served its purpose, it can be quickly returned to the soil where it will be absorbed and potentially used to create more of the same material. The energy input required for fungal growth is minimal. Fungi will essentially grow in the dark at room temperature with little more input. These characteristics of fungal-based materials make them sustainable and economical. Fungi also have a number of material properties that are particularly suited for building technology. They are lightweight, which increases the ease of transportation and assembly. They will also have lower dead loads. They are durable, and have the capacity to localize vibrations. (Mycoworks 2015) This capacity increases the fungi's ability to absorb impact loads and fail non-catastrophically, unlike masonry or concrete. (Mycoworks 2015) They are flame resistant and self-extinguishing. (Mycoworks 2015) Despite all of these beneficial properties, fungi's true potential as a building material lies in their capacity for capacity for en-

Figure 11
Fungi Grown on a
Mixed Substrate

vironmentally responsive, self-organized growth.

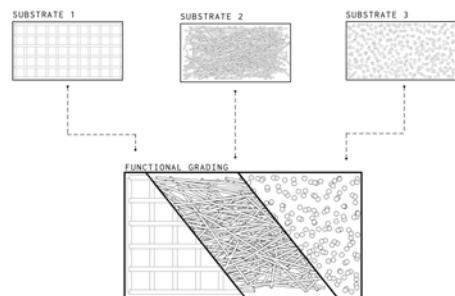
This research project explored the potential of fungal growth as a means of architectural assembly. Despite the inherent scalability of fungal growth, a number of challenges emerge when fungi are grown in large volumes. These challenges include: preserving an optimal growth environment, preventing contamination, and maintaining consistent growth. The overarching hypothesis of the research was that the introduction of a multi-scalar assembly system could not only resolve these challenges, but also guide fungal growth in such a way that allowed for the introduction of design intention. The multi-scalar assembly system that was developed during the course of this research was successful at the levels of assembly unit and assembly element insofar as it balanced the biological utility and architectural viability of the fungi. Even though contamination was an issue that emerged when assembling the final prototype, it does not invalidate the multi-scalar assembly system. Since, it is an issue that could have been resolved through the design of a more functional moisture barrier.

There were a number of potentially fruitful explorations that were abandoned because they did not fit within the stated objectives of this research project. The first experiment dealt with the effects of moisture on fungal growth. In it, silica gel was added to the seed substrate. The addition or removal of moisture had a much more drastic effect on fungal growth than changing the type of substrate. The precision of control over the fungal growth is pretty remarkable. As can be seen on the figure at the top of the following page, the fungus grows toward the hydro gel on the left side, while the initial chunk of mycelia on the dry side never starts growing. Another fruitful exploration was the use of mixed substrates. This kind of experimentation would exploit the fungi's ability to grow on a variety of substrates. The physical properties of a fungal-based material will depend both on the fungi used; as well as, the type, and arrangement of the substrate. There are a lot of opportunities to create different materials properties by mixing

different kinds of substrates. These properties could then be combined to create new materials with integrated functionality, particularly in dealing with different structural conditions.



Figure 12
Using Mixed
Substrates to Create
Functional Grading



Another area of experimentation for fungal based-materials is using mixed types of substrates. This kind of experimentation would exploit the fungi's ability to grow on a variety of substrates. The physical properties of a fungal-based material will depend both on the fungi used; as well as, the type, and arrangement of the substrate. There are a lot of opportunities to create different materials properties by mixing

different kinds of substrates. These properties could then be combined to create new materials with integrated functionality, particularly in dealing with different structural conditions. The reason for choosing structural conditions as the criteria of fitness is because this is the area where the greatest challenges of using mycelia-based materials at the architectural scale currently fall.

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