2016 Proceedings of the
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Edited by
Ramtin Attar
Angelos Chronis
Sean Hanna
Michela Turrin
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Architectural Association (AA) School of Architecture.
On behalf of the Organizing Committee, it is my pleasure to welcome you to the 7th annual Symposium on Simulation for Architecture and Urban Design (SimAUD) in London, UK. SimAUD 2016 marks our inaugural event in Europe bringing together an international group of researchers, engineers, architects and computer scientists.

London has long been an international hub in research and innovation and home to some of the world’s most known academic institutions, architectural practices and engineering offices. We are thrilled to have University College London (UCL) as our academic and venue partner making SimAUD EU possible. We have an excellent program to offer our attendees this year. This includes presentation of peer-reviewed original research papers, work in progress, posters, panel discussion, and keynote speech.

My sincere gratitude goes to my Organization Committee of SimAUD 2016. I would like to thank our scientific committee, Michela Turrin and Sean Hanna, and our program chair, Angelos Chronis, for their dedication to keeping SimAUD’s peer-reviewed process and program to a very high standard. I would also like to thank my colleagues at Autodesk, Rhys Goldstein and John Yee, for their continuous contribution to the production of SimAUD. SimAUD is run in partnership with Society for Modeling & Simulation International (SCS). We really appreciate the efforts of SCS officers, Oletha Darenburg, Aleah Hockridge and their team for conference coordination activities.

Finally, SimAUD’s contribution to research rests upon the hard work of our authors. Thank you for making SimAUD 2016 a success through your contribution. We look forward to your continued participation in growing our research community.

Ramtin Attar

*General Chair, SimAUD EU 2016*

UCL, London, UK
All accepted papers will be published in the ACM Digital Library at the SpringSim Archive. Sponsored by The Society for Modeling and Simulation International.
Keynote

Alan Penn
Dean, The Bartlett Faculty of the Built Environment
University College London (UCL)

Alan Penn (Professor of Architectural and Urban Computing, director of Space Syntax Ltd, the VR Centre for the Built Environment, and Dean of the Bartlett, UCL). Penn’s research spans the fields of architecture, planning and computing. He has a consistent track record in EPSRC funded research, and has helped EPSRC develop the Dongtan Networks.

In 2004 he coordinated the Built Environment theme at the Celebration of Engineering showcase event for the International Review of Engineering. He was Chair of Sub-panel H30 for RAE2008, and a member of Main- panel H.

Penn was also the academic lead for the HEIF3 funded UrbanBuzz programme (5 m), and Chair of an oversight group for the UK-China Task Force charged with developing a Virtual Academy for Sustainable Cities.
Session 1: Building Simulation

Capsule Towers Revisited: Using a Genetic Algorithm for Floor Area and Diffuse Daylight Optimisation
Ricardo Andrade, Angelos Chronis
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RMIT University; University of Oregon. ☑️ STUDENT PAPER AWARD

An Integrated Experimental-Computational Investigation of Connected Spaces as Natural Ventilation Typologies 59
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Iowa State University.
Capsule Towers Revisited: Using a Genetic Algorithm for Floor Area and Diffuse Daylight Optimisation

Ricardo Andrade¹ and Angelos Chronis²

¹Universidad Gabriela Mistral
Santiago, Chile
randrade.arq@gmail.com

²University College London
London, United Kingdom
angelos.chronis.09@ucl.ac.uk

ABSTRACT
The capsule tower typology was a well-known visionary architectural idea during the 1960-70s. However, the few materialized projects were criticised mostly due to their use of standard-size capsules and their lack of adaptability to user needs. A new methodology for capsule tower design is proposed by means of the use of a genetic algorithm, in order to emphasise the generative approach of the original projects; it adds area and light optimisation to secure size variation and light comfort. The results show a set of variations in terms of floor layouts, capsule volumes, front facade areas and interstitial spaces amongst modules, which go beyond the uniformity of the earlier strategies. These early findings suggest that this generative approach has the potential of re-examine old design projects by increasing their feasibility and adaptability; this approach also suggests the possibility of combining this concept with additional algorithmic implementations to study other ideas.

Author Keywords
Generative Design; Design & Optimization; Form-finding.

ACM Classification Keywords
J.5 ARTS AND HUMANITIES (Architecture).

1 INTRODUCTION
The capsule tower typology was a well-known visionary architectural idea during the 1960-70s envisioned by people from groups such as the Archigram in the UK and the Metabolist Movement in Japan. These projects consisted of structures that support housing capsules that could be plugged and unplugged from buildings. The theoretical framework behind these designs was the fusion between architectural design and organic growth. However, the few materialized projects were criticised mostly due to their use of standard-size capsules and their lack of adaptability to user needs. Indeed, the most iconic building, the still-standing Nakagin Capsule Tower (Figure 1), designed by Kisho Kurokawa and completed in 1972, will almost certainly be demolished; in addition to issues such as poor maintenance, the use of asbestos on the capsules and concerns due to earthquakes, this project was designed in the context of a post-war lifestyle: single people of strong urban mobility behaviour, who live in small pods of limited living area and daylight source [10].

2 BACKGROUND
Genetic algorithms (GAs) were created by John Holland, who worked with his students in the 1960s and the 1970s to further develop the concept [7]. His original goal was to implement a computational method to study adaptation in nature: an algorithm in which the original population of chromosomes evolves to a new population by a ‘natural selection’ process, where the fitter chromosomes are selected to reproduce and create offspring by using genetic operators such as crossover, mutation and inversion [11].
These methods have been recently introduced into architectural design, mainly for purposes of design optimisation and form exploration. Both of these uses imply stochastic procedures where the designer is more focused on the set of rules and its parameters than on predefined design solutions.

The optimisation-based approach makes use of GAs’ capabilities for problem solving in design, centring on sustainability and efficacy matters that range from structural needs [13] to environmental performance [2]. Form-finding using GAs entails philosophical implications; inspired by Gilles Deleuze’s work, DeLanda [5] has identified three lines of thought for their emergence in evolutionary design: populational –a population of virtual solutions, which reproduce to find the optimal one; intensive –the evolving elements have to be connected with the whole; and topological –the building as a set of parameters and their inner relations. Therefore, by means of optimisation and form generation, GAs have found their place within the scope of generative techniques in architecture.

This research takes both approaches into account: design optimisation to generate modules with good daylight and comfortable size, and form exploration to develop variation in different iterations.

3 METHOD

This approach departed from the idea of standard-size modules by generating unities in different sizes and proportions. The experiment was performed with an interactive prototype developed in Java-based Processing whose development took into account the following factors.

3.1 Spatial Layout

The block consisted of five floors of 16 modules each, which were combined into pairs to generate eight flats per level. The floor layout had two vertical cores, with each module attached to it by one of seven base points. All changes in volume maintained the location of the module at that point (Figure 2). The predefined area target for each floor was different in order to gain variability and decrease weight of the upper floors.

3.2 Diffuse Light

Natural light was optimised in each flat, according to the formula

$$A_{glazing} = \frac{DF 2A_{total} (1 - R_{mean})}{\tau_{vis} \theta}$$

where DF corresponds to the targeted daylight factor, A total to the total area of all interior surfaces, R mean to the mean surface reflectance, \( \tau_{vis} \) to the glazing transmittance and \( \theta \) to the skylight angle [12]. The window-to-wall ratio was calculated according to

$$wwR = \frac{A_{glazing}}{A_w}$$

where \( A_w \) corresponds to the exterior surface in which the window was located. The size of each flat was optimised according to an ideal window-to-wall ratio of 0.25 – considering the values range from 0.2 to 0.3 for clear glass [9] –, where only the front facade was considered as an exterior surface. The following variables were predefined in order to simplify the process:

1. Skylight angle: each floor received an angle from 60° on the first floor, increasing to 80° on the fifth floor.
2. Mean daylight factor: it was set at 2%, suitable for offices and housing [12], corresponding to the recommended values in the UK [1].
3. Glazing transmittance: glazing clearness was set at 0.9, typical of glasses with good visual transmission [6].
4. Mean surface reflectance: it was set at 0.5, the minimum value for walls [9].

3.3 Genetic Algorithm

The GA managed a set of genes that determined the sizes of the modules on each floor. Having an initial random population of 30 floor layouts, an amount that allowed for fast computation and 5% crossover and mutation rates, capsule dimensions were provided by the genotype, a set of random measures of width, length and height. Each module could vary in length and height only, except for the two flats at the sides of the block that could change their widths as well. Minimum and maximum values of length and width ranged from 350 to 1,050 cm, and from 300 to 900 cm for height (Figure 3).
The fitness factor was calculated by taking into account two variables: 1) the difference between a target and the current total floor area, with the former being different for each floor; and 2) the difference between a target (25%) and the current window-to-wall ratio inside each flat. For both variables, the smaller the difference, the higher the fitness value. In order to avoid inhabitable spaces due to their reduced dimensions, the fitness value decreased when the gene values were lower than the minimum values for width, length and height.

The user interface showed the evolving design in real-time, a 3D-orbit feature controlled by the mouse, a table with changes in target floor area and window-to-wall ratios in each flat, and interactive buttons to change parameters such as population and window-to-wall ratio target (Figure 4).

4 RESULTS

The outcomes were compared according to an optimal floor area target of 495.5 m² and an average optimal window-to-wall ratio of 25%. After obtaining a sample of 20 iterations, whose generative processes started with initial populations of 30 architectural layouts, the analysis showed that the prototype obtained an average floor area of 490.15 m² and an average window-to-wall ratio of 26.55%; these results were close to the initial estimates. Some window-to-wall ratios showed high variations in comparison with target percentages. For example, the 18th iteration reached 35% and the 20th, 32.5%. In spite of those results, most of the iterations (90%) showed a window-to-wall ratio within the optimal range of 20-30%, with no percentages below the 20% minimum. Regarding floor area optimisation, a steady trend for average floor area was obtained (Figure 5).

The resulting designs avoided the uniformity of earlier projects, offering differences in dimensions and structure amongst iterations (Figure 6). One unexpected result was a variation in density, since new spaces, whose areas were sufficient for outdoor activities, were generated amongst the capsules (Figure 7). However, some iterations exhibited a couple of modules whose sizes appeared too small for human use. In this case, the height variable was the issue, despite the initial limitations in the genotypes. However, only 20% of the iterations showed height problems in some of their capsules.
5 DISCUSSION
This paper suggests that a design process led by a genetic algorithm can update the idea of capsule towers by optimising diffuse daylight inside the modules in order to enhance its feasibility for modern standards. Our evaluation shows that the interactive prototype designed for this task was able to generate different iterations of a capsule block, which presented variations in the capsules’ sizes and ensured enough daylight inside the capsules so as to address energetic concerns. The outdoor spaces, which resulted from the evolving procedure performed by the genetic algorithm, have the room to host additional terraces and balconies that were absent in old capsule tower proposals. However, a few cases of out-of-optimal window-to-wall percentages indicated that the small population of floor layouts did not offer enough variability of alternatives in some of the iterations. Linked to that, the generation of small capsules that do not allow for human occupancy seems to imply that the fitness formula, in its effort to obtain the optimal space, tended to forfeit capsule size in such cases. Future work will test whether these issues can be addressed by increasing the population size.

Finally, we support the idea that GA-based designs allow for managing multiple tasks and large amounts of information. Although in a design process like this –based on generative rules and emergent outcomes– the architect’s role could seem restricted to breeding potential solutions, there are three ideas that may open further discussion: 1) the architect is still in charge of creating the set of rules, and selecting the best alternatives created by the algorithm; 2) these tools enhance the architect’s creativity by helping the design process on complex tasks; and 3) it can be related to Darwinian theories of creativity [3], which indicate that ‘blind variation and selective retention’ can be a core part of creative processes. Future work will take into account these implications, which incorporate architectural matters such as structure and construction.

6 CONCLUSION
These early findings suggest that this generative approach has the potential to re-examine the capsule tower idea by adding an improvement in its degree of feasibility according to contemporary standards of comfort and adaptability. Although the initial population has to be increased in future experiments, the results presented in this research have shown the possibility of this approach combining generative design with early ideas of organic growth in architecture. Further development will address the integration of additional data such as the different heights in the nearest context, different climate scenarios that may change daylight conditions, and structural needs. It also offers the chance to revisit other visionary ideas, such as Yona Friedman’s megastructures, by combining genetic algorithms and cellular automata implementations. This approach enables the possibility to contribute to the recovery of other historical ideas that can open alternatives for contemporary architectural design.

REFERENCES
Application of Surrogate Models for Building Envelope Design Exploration and Optimization

Ding Yang¹,², Yimin Sun¹, Rusne Sileryte², Antonio D’Aquilio² and Michela Turrin¹,²

¹State Key Lab of Subtropical Building Science, South China University of Technology, Guangzhou, China
d.yang-2@tudelft.nl, arymsun@scut.edu.cn

²Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands
{r.sileryte, a.daquilio, m.turrin}@tudelft.nl

ABSTRACT
Building performance simulations are usually time-consuming. They may account for the major portion of time spent in Computational Design Optimization (CDO), for instance, annual hourly daylight and energy simulations. In this case, the optimization may become less efficient or even infeasible within a limited time frame of real-world projects, due to the computationally expensive simulations. To handle the problem, this research aims to investigate the potentials of surrogate models (i.e. Response Surface Methodology - RSM) to be used in the building envelope design exploration and optimization that consider visual and energy performance. Specifically, the work investigates how, and to what extent, 1) problem scales may affect the application of RSM, and 2) different ways of using RSM may affect the quality of Pareto Front approximations. Thus, a series of multi-objective optimization tests are carried out; preliminary discussion is made based on the current results.

Author Keywords
Multi-objective optimization; building envelope; surrogate models; design of experiments (DoE); response surface methodology (RSM).

ACM Classification Keywords
I.6.3 Application; I.6.4 Model Validation and Analysis

1 INTRODUCTION
Computational Design Optimization (CDO) is a rising field of research in sustainable building design. It has been applied to many aspects including building envelope design, building service system, and renewable energy generation, etc. [4]. Thus, simulation-based optimization is frequently employed by architects and engineers to assist the early design decisions. However, simulations are usually time-consuming, for instance, annual hourly daylight and energy simulation or computational fluid dynamics (CFD) simulation; this poses substantial obstacles to the application of CDO within a feasible time frame of projects.

Surrogate models (or meta-models) are promising solutions to this problem. They are actually approximation methods that mimic the behavior of original simulation model at a reduced computational cost [9]. Among various surrogate models, Response Surface Methodology (RSM) [7] is commonly used, along with Design of Experiments (DoE) [3]. RSM contains a group of mathematical and statistical techniques used to explore the functional relationship between input variables and output variables; while DoE is used to create a well-distributed sampling of design points, allowing to extract as much information as possible from a limited number of simulation runs.

In the sustainable building design, surrogate models, developed based on RSM, are used for the prediction of energy performance [10] and indoor environmental quality, including thermal, daylighting [6] and ventilation performance [11]. Within these applications, validated surrogate models are used to replace computationally expensive simulations (like dynamic energy and daylight simulation or CFD simulation). Although the potentials of RSM are observed in above-mentioned literature, there are still concerns regarding the advantage of RSM, as reported in [2], because, in some cases, the number of simulations necessary to get a reasonably accurate RSM may be approaching the number of simulations needed for the simulation-based optimization.

This work aims at evaluating the applicability of RSM to the building envelope design exploration and optimization (mainly considering visual and energy performance). Specifically, the work investigates how, and to what extent, 1) problem scales may affect the use of RSM, and 2) different ways of using RSM may affect the quality of Pareto Front approximations. As a research-in-progress, the second part of the investigation is not included in this paper, but only providing a framework for future research.

2 METHODOLOGY
To achieve the research goal, a series of multi-objective optimization tests are arranged based on two different problem scales (i.e. two cases with a different number of design variables) and three different workflows (not included in this paper, but in future research).

(1) By comparing the accuracy of surrogate models in the two proposed cases, possible effects of problem scales on RSM are investigated.

(2) By comparing the quality of (Predicted) Pareto Front approximations of the three proposed workflows within the same time frame, potentials of using RSM (or different ways of using it) will be discussed in future research.
2.1 Problem Scales
To investigate possible effects of problem scales on RSM, two test cases are shaped based on a similar building envelope design optimization problem (Section 3). The first test case is based on a parametric model including two design variables, while the second one includes forty-one.

2.2 Workflows
To investigate potentials of using RSM (or different ways of using it), three workflows will be used based on related literature (Figure 1). Two of the workflows use RSM in different ways, but the remaining one does not. According to Cavazzuti [1], RSM can be utilized in two ways during the design exploration and optimization: (1) replacing the simulations by surrogate models that will be used with an optimization algorithm, i.e. RSM-based or “virtual” optimization, in contrary to simulation-based or “real” optimization; and (2) locating the area in which the optimum is expected to be based on the response surface, it facilitates narrowing down the design space in the neighborhood of the optimum for the further optimization. Therefore, the complete workflows of the two options to utilize RSM are illustrated in Figure 1, and denoted by Workflow2 and Workflow3, respectively. In addition, the typical way for simulation-based optimization that does not use RSM is also illustrated, and denoted by Workflow1.

It is worth noting that running a certain number of simulations is required no matter whether RSM is used or not. It is needed either for training the response surfaces, or for running the simulation-based optimization. The difference between these two scenarios lies in whether “shifting” (instead of eliminating) the computational effort for simulation from within an optimization loop to a prior time, or not. Specifically, in Workflow1, simulations are required within an optimization loop, while in Workflow2 and Workflow3 they are shifted to a prior time (i.e. before the optimization loop, for training response surfaces). Furthermore, the simulations required by Workflow3 are not all in once (as Workflow2), because simulations are needed as well after narrowing down the constraints of design variables, for updating the response surfaces.

2.3 Comparative Study
Comparative studies are/will be carried out according to the schema shown in Figure 2. In order to investigate possible effects of problem scales, the left schema is used; while in order to investigate the potentials of using RSM, the right schema will be followed in future. Moreover, the same timeframe of implementing these tests should be ensured for the sake of comparison. Considering that simulations account for a major portion of time spent in all tests, the number of simulations to be run in a specific test is an important monitoring factor. For the same purpose, the selection of algorithms for DoE, RSM and optimization will be kept the same, as well as the corresponding settings.

3 CASE STUDY DESCRIPTION
For the application of RSM, a simple building envelope design optimization was formulated in Grasshopper [5] – a parametric modelling tool frequently used by architects for exploring varied building configurations. Generally, the aim of the problem is to figure out the optimal roof configuration for visual and energy performance, based on which two similar test cases are created (Figure 3).

3.1 Geometry Generation
The two buildings are assumed to be one-story sports halls with a fixed rectangular plan (40m*70m) and a changeable spherical roof, located in Guangzhou, South China. The skylights are allocated to each cell (40 cells in total) of the roof, respectively. Basically, these two test cases are the same, except for the principle of allocating skylights (i.e. the number of design variables regarding skylights).

Specifically, in Case 1, there are only two design variables, i.e. the height of roof and the window-to-roof ratio (each cell shares the same ratio). While in Case 2, there are 41 design variables in total, because each of the cells has an independent window-to-roof ratio. The design variables are shown in Table 1, as well as their ranges.

In addition, considering that the focus of this paper is the applicability of RSM, other design variables regarding shading devices and/or constructions are not discussed here for the sake of simplicity.
3.2 Simulation Setup

Energy Use Intensity (EUI) and Illuminance Uniformity (IU) are selected as performance criteria, while Spatial Daylight Autonomy (sDA) and Average Illuminance (AI) are chosen as performance constraints (Table 1). They will be used as optimization objectives and constraints in future research.

Therefore, annual hourly daylight and energy simulations are performed by Daysim and Energyplus sequentially, based on the platform described in [12]. The platform couples Grasshopper with modeFRONTIER [8].

4 DESIGN OF EXPERIMENTS (DOE) & RESPONSE SURFACE METHODOLOGY (RSM)

In order to develop the surrogate model, the following steps are followed: 1) Sampling of Design Points by DoE; 2) Data Collection by Running Simulations; 3) Surrogate Model Generation by RSM.

In the first stage, the number of design points (i.e. design variable vectors) and their locations within the design space are defined. A well-distributed sampling is helpful for obtaining a reliable surrogate model. Among all the available DoE algorithms, Uniform Latin Hypercube Sampling is chosen in order to ensure a random and uniform distribution in each dimension.

Numerical simulations are performed based on the selected design points in the previous stage. The simulation time needed for each design point is around 5 minutes, and the affordable number of simulations for each test is assumed to be 300 times (i.e. around 25 hours in total). Among all the simulation data, 270 are collected for training the response surfaces and 30 are used for the RSM validation.

In the last stage, a set of RSM algorithms is used to train multiple response surfaces for each performance indicator (i.e. EUI, IU, sDA and AI respectively). By comparing the fit or quality of obtained response surfaces (i.e. RSM Validation), a final surrogate model is selected for each performance indicator. In this research, this set of RSM algorithms includes “Classical meta-models” (i.e. Polynomial Singular Value Decomposition, Stepwise Regression) and “Statistical meta-models” (i.e. Shepard K-Nearest, Kriging).

5 OBSERVATION OF THE CURRENT RESULTS

In order to investigate possible effects of problem scales, the accuracy of surrogate models in the two proposed cases are compared.

As shown in Table 2, in general, the accuracy of surrogate models in Case 1 appears to be better than that in Case 2. The RSM Distance Charts show the distance between real designs (30 simulation data sets for the RSM validation lying on the blue 45° slope) and virtual designs (computed with the RSM algorithm). By observing these charts, current results suggest that the IU and sDA estimation in Case 1 is much better than that in Case 2. This is also indicated by the R-squared values (i.e. coefficient of determination), which provide information on the goodness of fit of a model. An $R^2$ value of 1 indicates a perfect fit. The Max and Mean Absolute Errors give us information that the errors in the IU and sDA prediction are relatively high compared to the real simulation values in both cases. Moreover, an error message was observed when using Stepwise Regression algorithm to train response surfaces in Case 2, because of the relatively small training set size. It indicates that a larger sample size is needed. Therefore, as the increase of the problem scale, the accuracy of RSM can be lower due to the limited or insufficient sample size.

6 FUTURE RESEARCH

In order to investigate potential pros and cons of utilizing RSM, the quality of (Predicted) Pareto Front approximations of the three proposed workflows will be compared in future research. Besides, further study on the RSM selection and parameter tuning will be carried out in order to ensure the predictive capabilities of the RSM.

ACKNOWLEDGMENTS

This research was supported by the Key Project of National Natural Science Foundation of China (Grant No.
Table 2. RSM validation (270 simulation data sets for training the response surfaces; 30 simulation data sets for the RSM validation)

<table>
<thead>
<tr>
<th>Case1 RSM Distance Charts</th>
<th>EUI</th>
<th>IU</th>
<th>sDA</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Abs. Error</td>
<td>3.31 kWh/m²</td>
<td>0.07</td>
<td>16.97%</td>
<td>13.93 lux</td>
</tr>
<tr>
<td>Mean Abs. Error</td>
<td>0.91 kWh/m²</td>
<td>0.02</td>
<td>2.42%</td>
<td>4.85 lux</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.967</td>
<td>0.932</td>
<td>0.988</td>
<td>0.999</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case2 RSM Distance Charts</th>
<th>EUI</th>
<th>IU</th>
<th>sDA</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Abs. Error</td>
<td>1.71 kWh/m²</td>
<td>0.09</td>
<td>10.38%</td>
<td>21.61 lux</td>
</tr>
<tr>
<td>Mean Abs. Error</td>
<td>0.53 kWh/m²</td>
<td>0.03</td>
<td>2.29%</td>
<td>7.10 lux</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.934</td>
<td>0.233</td>
<td>0.671</td>
<td>0.980</td>
</tr>
</tbody>
</table>

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Solar potential in extreme climate conditions: comparative analysis of two district case studies in Norway and Reunion Island.

Aymeric Delmas¹, ⁴, Gabriele Lobaccaro², Michael Donn³, Marjorie Musy⁴, and François Garde¹

¹PIMENT
Le Tampon, Reunion Island
aymeric.delmas@imageen.re
francois.garde@univ-reunion.fr

² Norwegian University of Science and Technology
Trondheim, Norway
gabriele.lobaccaro@ntnu.no
michael.donn@vuw.ac.nz

³ Victoria University of Wellington
Wellington, New Zealand
marjorie.musy@ec-nantes.fr

⁴ CRENAU
Nantes, France

ABSTRACT
This work aims to investigate the application and replicability of parametric solar design to both existing and future development urban areas in two extreme climate conditions: Øvre Rotvoll in Norway (subarctic climate) and Ravine Blanche in Reunion Island (tropical humid climate). The interplay between urban morphology and its potential for passive and active solar energy strategies has been investigated. The methodology combines the parametric modelling software Rhinoceros-Grasshopper, with two Radiance-based solar simulation tools to optimise the solar potential of a district. The application of a new workflow is studied over the computation of various design scenarios in an existing urban environment at both the district and the building scale. The results show differences and similarities between climate-specific interventions that can be used as supportive instruments for the on-going local planning processes. The study demonstrates how parametric optimisation allows maximising the solar potential of urban areas at different latitudes despite climatic and urban densification constraints.

Author Keywords
Urban Simulation; Design & Optimisation; Parametric Design; Solar Urban Planning, Extreme Climate Conditions.

1 INTRODUCTION
In the current scenario of urbanisation and global warming, an informed use of solar energy in urban planning aims to increase the quality and efficiency of the built environment. In that regards, developing solar active and passive solutions architecturally integrated in urban morphology [1] is one of the key strategies. The numerous urban parameters, the design constraints (i.e. maximum building height, plot ratio, distance from the borders) and the complexity of the dynamic 3-dimensional interplay between solar irradiation and the urban morphology, represent a real challenge for designers and urban planners who need flexible and performative tools for studying these phenomena [2]. In this context, a new approach combining parametric design tools with dynamic simulation software to optimise the solar potential of urban typologies, patterns and building shapes has recently become a pivotal issue [3, 4, 5, 6].

This paper introduces a workflow to fully exploit the solar energy potential of urban settlements. The proposed approach is to maximise the annual global solar irradiation received by the roofs and façades of both new and existing buildings. The developed methodology integrates a scale-flexible optimisation process that limits adverse solar availability reduction over the existing environment. Finally, this work aims to demonstrate the applicability and replicability of the workflow and the methodology, by positive optimisation results of various design scenarios in two extreme climate conditions (tropical and subarctic).

2 METHODOLOGY
The application of the aforementioned approach was tested in two different district case studies situated in extreme climate conditions: (i) a future urban development area, Øvre Rotvoll, located in Trondheim, Norway (latitude 63°36'N); and (ii) a newly renovated neighbourhood, recently awarded 'eco-district' status, Ravine Blanche in Saint-Pierre, Reunion Island (latitude 21°20'S). The two districts are under a significant densification development and comprise new building projects that were planned without taking into account the challenges deriving from solar energy integration and mutual interactions in urban environments. Urban densification aims to reduce urban sprawl by limiting the use of new soil and to improve the energy efficiency. However, most of the time those aspects affect the solar accessibility and the integration of solar technologies in the urban environment by creating overshadowing effects on new and existing buildings.

2.1 Tools
This work uses a solar urban design platform, developed on the software pair Rhinoceros-Grasshopper. Rhinoceros [7] and the visual programming tool Grasshopper [8] allow parametrical control and generation of complex 3D
models. Ladybug [9] and DIVA for Grasshopper [10] as Radiance-based tools developed for the Rhinoceros-Grasshopper platform were selected for their user-friendly interfaces and high accuracy for simulating solar irradiation in complex urban environments [2]. Finally, the evolutionary algorithm Galapagos [11] was used to solve the multi-objectives problem of simultaneous maximisation of new and existing buildings’ solar potentials (both potentials are treated equally in the fitness function of the problem).

2.2 Parametric building model
A unique architectural brief was defined in two extreme latitudes in order to evaluate the influence of the climate over the process of solar potential in urban planning. The defined brief comprises two buildings: a residential block and a media library (respectively (a) and (b) in Figure 1). Both buildings are planned interventions in the district of Ravine Blanche, with assigned land parcels of respectively 1,550m² (a) and 3,700m² (b). These two buildings represent perfect case studies for parametric design optimisation. They were selected in order to test the influences of solar accessibility on the urban surrounding in the tropical climate of Reunion Island and in the subarctic climate of central Norway.

2.3 Simulation parameters
The Radiance and material parameters used in DIVA for Grasshopper for simulating the annual global solar radiation received on the buildings’ envelopes in both Saint-Pierre and Trondheim were validated in a previous study [6] and are summarised in Table 1. Typical .epw weather data files were used in the simulations.

2.4 Design and optimisation process
A global, multi-scale and multi-objectives approach was developed in order to maximise the solar potential at both district and building scale and to minimise the impact on the solar accessibility on the existing urban surrounding. This approach comprises four design stages:

1. From the brief’s footprints and the maximum building height authorised in the district (12m), the maximum buildable volumes of the two buildings are generated (around 63,000m³ in total). They are represented by the blocks (a) and (b) in Figure 1.

2. A solar map analysis is performed in order to identify the overshadowing issues generated by the integration of the new buildings (top picture in Figure 1) in the two climates. The most critical parts of the built volumes in terms of solar accessibility (dashed framed in Figure 1), are subdivided into several smaller volumes representative of the existing buildings of the district ((1) to (6) in Figure 1).

3. Coupling Ladybug and Galapagos, the location of the smaller volumes over the available land (area in dark hatch in Figure 1) is optimised in order to maximise the annual global solar radiation received by their buildings’ envelopes and to reduce as much as possible the overshadowing effect on the nearby buildings (distance < 100m). The other surrounding areas (100m < distance < 200m) are also considered in the analysis.

4. At the final stage, coupling DIVA for Grasshopper and Galapagos, a second set of simulations allowed optimising the solar potential of the generated building shapes through more climate-specific transformations of the façades. The slope of its main façade (from -10° South to 10° North) but also the orientation of the façades (rotation of its roof; from -10° West to 10° East) were optimised in the two locations.

![Figure 1. Annual solar map (South East view) of the initial scenario (top) and solar optimised urban scenario (bottom); climate of Saint-Pierre.](image1)

![Figure 2. Annual solar map of the solar optimised building scenario for Saint-Pierre (left) and East rotated building scenario (right).](image2)

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Ambient bounces</th>
<th>Ambient division</th>
<th>Ambient super-sample</th>
<th>Ambient resolution</th>
<th>Ambient accuracy</th>
<th>Specular threshold</th>
<th>Direct sampling</th>
<th>Direct relays</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>1000</td>
<td>20</td>
<td>300</td>
<td>0.1</td>
<td>0.15</td>
<td>0.20</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Radiance material</td>
<td>Number of values</td>
<td>R refl.</td>
<td>G refl.</td>
<td>B refl.</td>
<td>Specularity</td>
<td>Roughness</td>
<td></td>
</tr>
<tr>
<td>Concrete block</td>
<td>Void</td>
<td>Plastic</td>
<td>0.549</td>
<td>0.549</td>
<td>0.549</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Radiance simulation and material parameters used for analysis [6].
3 RESULTS

3.1 Solar potential of the districts before the integration of the new buildings

The global solar radiation received by the nearby buildings (distance < 100m) on the design site was calculated and used as reference case (initial scenario). In the initial scenario, the district has a solar collection potential of 32,148 MWh in Saint-Pierre and 15,848 MWh in Trondheim. In the conducted analyses, at the district scale only the overshadowing effect between the buildings was taken into account; while at the building scale (section 3.3) the simulations were run by setting 3 ambient bounces in order to calculate the mutual reflections between buildings’ façades and the ground.

3.2 Optimisation of the building blocks’ location in two extreme climates

The maximum buildings’ volumes (a) and (b) led to several critical solar accessibility issues on the existing buildings. Due to close relative positions on the East and West façades, a reduction in terms of solar potential was estimated in both climates (Figure 1). In order to avoid the reduction of solar accessibility of the district, the most affected parts of the new buildings’ volumes (dashed framed volumes in Figure 1) were divided into several smaller volumes by keeping the original distribution’s volume constant. Their positions were optimised within the borders of the available land site by maximising the solar radiation at the district scale. This optimisation process is inspired and adopted from the Solar Dance method, originally developed by Igor Mitrić Lavovski [12]. Additionally, in order to architecturally integrate the new building’s volumes in the existing urban environment, their dimensions were set in order to be representative of the typical local buildings populating the area (small rectangular blocks with average dimensions of 12m height, 12m width and 24m long). This led to the generation of 6 new building shapes.

The total annual solar radiation received by building (a’), building (b’), the new six generated building volumes and their surroundings was calculated over 400 building positions, automatically generated and simulated in both locations by using Galapagos. A cross analysis of the results allowed the identification of the best layout (solar optimised urban scenario) that maximises the total solar potential of the district (aggregation of new and existing buildings’ received irradiation) by 3.6% and 10.1%, in Saint-Pierre and in Trondheim respectively.

The integration of the new buildings generates a limited solar potential reduction over the existing buildings of about 1.7% in Saint-Pierre and 1.9% in Trondheim compared to the initial scenario.

3.3 Climate-specific optimisation of a building

The optimisation at the building scale was conducted by using the morphology of the solar optimised urban scenario as baseline. The buildings’ shapes were optimised in order to exploit the maximum solar potential and to minimise the impact on the surroundings’ buildings’ façades. Surrounded by three buildings, building (b’) was selected as case study. Its shape was twisted along the rotation of its roof (from -10° West to 10° East) and sloped along its main façade (from -10° South to 10° North), independently in both locations. The range of transformations was kept narrow in order to make the final building’s shape structurally feasible, not interfering with the surrounding ones and harmoniously integrated within its urban environment.

The solar radiation was calculated over the façades of the solar optimised building (b’) scenario (Figure 2, left) and its nearby buildings. In both climates, the optimisation of the global solar radiation received by the analysed façades (highlighted in Figure 1) gives relevant improvement up to 88% in Saint-Pierre (tropical climate) and up to 93% in Trondheim (subarctic climate) compared to the solar optimised urban scenario. Regarding the surrounding buildings, whereas in Saint-Pierre the optimisation gives more than 10% of reduction of the solar potential, in Trondheim the process allows reaching an increase up to 2%. The relative transformations for building (b’) are: -10° West rotation for the roof, -10° South slope for the façade in Saint-Pierre (Figure 2); and -8° West rotation for the roof, 10° North slope for the façade in Trondheim.

4 DISCUSSIONS

4.1 Influence of the climate on the design process

At the district scale, the optimised urban scenario shows better improvement compared to the initial scenario for the latitude of Trondheim than in Saint-Pierre. This demonstrates that the building placement optimisation process favours the reduction of the overshadowing effect caused by the low sun angles of a city close to the poles than for a city closer to the equator. Future developments of the current study should correct this feature as well as integrate penalty clauses in the fitness function of the genetic algorithm in order to exclude unwanted generated

Figure 3. Solar potential evolution function of the building top rotation for two extreme climates.
scenarios such as buildings with too close relative positions or with common walls.

From the building scale optimisation, some outcomes are qualitatively confirmed. As expected, the design process of the façades must take into account the influence on the nearby buildings as well as the solar accessibility of the optimised building. In the southern hemisphere, the most optimised solar potential of the façades is obtained for a North sloped façade. On the contrary, in the northern hemisphere, the optimal transformation is for a South sloped façade. From the analysis of the evolution of the solar potential of the analysed façades function of the two separated building’s transformations (Figure 3), similar patterns are observed in both climates. Moreover, whereas the results for the façade’s slope transformation do not present any distinct relationship with the evolution of the solar potential, the roof’s rotation of the building towards the East can have critical effects over the reduction of the solar potential of the buildings between 2.5° and 10° East (Figure 3). This is explained by the fact that in both locations, the East rotation closes even more the gaps between the buildings (b'), (1) and (6). This transformation accentuates the self-shading and overshadowing effects (Figure 2, right), whereas the West rotation increases the North and South gaps by maximising the area of the radiated façades.

5 CONCLUSION

This external solar and geometry-based study demonstrates the great potential that represents the coupled use of the parametric modelling tools Rhinoceros-Grasshopper with Radiance-based simulation tools for solar urban planning. Thanks to their flexibility and accuracy, it is possible to maximise the solar potential of a district at various scales; as well as to analyse the complex overshadowing effects and mutual reflections within the urban environment. The use of evolutionary algorithm tools, such as Galapagos, allows generating numerous design scenarios, identifying optimised ones, avoiding local optima and limiting solar availability reduction. This is a critical aspect in dense areas, where energy need is higher and where ensuring solar accessibility is more complex due to the number of buildings’ interactions. The solar analyses show that maximised solar energy integration for both existing and new buildings is possible throughout simple form optimisations. This study demonstrates that such processes can be successfully applied in extreme latitudes (here in tropical and subarctic climates), where specific climate constraints are relevant. Finally, the advantage of using evolutionary algorithm has been highlighted by its remarkable flexibility to tackle a wide variety of problems. Its degree of interaction with the user, who can compare and explore sub-optimal solutions during the optimisation process, is a unique and valuable feature in multi-scale problems where environmental performance must meet urban design quality. In further developments, such methodology could be used in local planning processes, as urban decision support instruments, by designers and urban planners.

This work is part of a doctoral study dealing with the design of optimised bioclimatic buildings in dense tropical urban areas using generative modelling tools with various climate-based tools. In future works, the scale-flexible approach introduced in this paper will be further developed in order to investigate the use of the urban energy potential through the parametric design of roof and facade modules, for optimising external and internal performance objectives (PV and thermal generation, daylighting level, thermal comfort, etc.).

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Urban Scale Simulations of Solar Reflections in the Built Environment: Methodology & Validation

Ryan Danks¹, Joel Good²

¹Rowan, Williams, Davies & Irwin (RWDI) Inc.
Guelph, Ontario, Canada
ryan.danks@rwdi.com

²Rowan, Williams, Davies & Irwin (RWDI) Inc.
Vancouver, British Columbia, Canada
joel.good@rwdi.com

ABSTRACT
Solar reflections are often unavoidable in an urban environment, however as numerous instances around the world have proven; reflections can pose serious risks to human safety by impairing vision and/or causing undesirable or even dangerous heat gains. The authors have developed a computational tool, which accurately and rapidly predicts reflected irradiance levels at varying temporal and spatial resolutions. This tool allows for high-fidelity simulations of how the visible and thermal energy reflected by a building will impact its environment at the early stages of design. This understanding can then inform decision making regarding façade geometry and materiality. This paper describes the methodology followed in creating the tool and validation of its predictions. The simulation tool shows satisfactory levels of agreement with the measured data both in terms of the peak intensity and timing of the reflections for a situation where a concave façade focused reflections to an intense spot.

Author Keywords
Solar reflections; Glare; Simulation; Validation

ACM Classification Keywords
I.6.4 [Simulation and Modeling]: Model Validation and Analysis.; I.6.5 [Simulation and Modeling]: Model Development – Modeling methodologies.

1 INTRODUCTION
Solar reflections are a fact of life for city dwellers. As architects increasingly employ reflective glazing as the primary cladding of a building, glare impacts become more likely. Ordinarily such reflections are, at most, a nuisance; however, there have been many documented cases where reflections have impaired the vision of drivers [20], train conductors [4] and air traffic control personnel [8] potentially putting lives at risk. More disturbing, are the cases where buildings have concentrated solar energy within occupied spaces leading to property damage [27] and personal injury [16]. Despite the risks associated with solar reflections they are typically given little consideration by designers and governing bodies during the early design and approval stages. This could be attributed to the fact that highly reflective facade materials are a relatively new phenomenon, but also because the methodologies to test for reflections have previously been cumbersome, laborious, and often times inconclusive.

1.1 Existing Tools
There are several options for determining the impact solar reflections will have on their environment.

Geometric Approaches
The most basic approach to determine if reflections from the sun will impact a point is to use simple tools based only on the geometric relationship between the sun, reflective surfaces and a viewer. The earliest examples of such a tool were the so-called “reflection protractors”. Pioneered by Littlefair in 1987 [15], later refined by Hassall [7] and others [19], these protractors are used in conjunction with sun path information, and photographs, hand sketches or computer renderings of the building in question to compute the times and durations at which the sun is in the appropriate position to reflect off of a given façade and impact a viewer with an assumed line-of-sight towards the building. The brightness of the reflection can then be computed using the Holladay formula [26] and compared to the brightness a driver is assumed to be adapted to. This is known as the “veiling luminance” and is related to disability glare (i.e. glare bright enough to impair the ability of a viewer to distinguish other objects due to a loss of contrast). This geometric approach is quite laborious, with each view point needing its own diagram. Curved and/or non-vertical facades as well as non-horizontal lines-of-sight toward the building further complicate the analysis, as does the variability of surface reflectance. Additionally, as the protractor view is taken from the perspective of a potential receptor (typically a vehicle driver) the entire impact that a building’s potential reflections will have on the urban landscape is difficult to quantify. The evaluator will select specific locations that may be trouble spots and test them for potential reflections. This trial-and-error approach potentially lends itself to missed reflection occurrences, particularly for complex façade shapes and urban topographies where intuitive analysis falls short. Protractor based approaches also tend to focus only on the visual impact on drivers, and not acknowledge the visual impact
on pedestrians or the thermal impacts of solar reflections. Locations where multiple reflections may converge are not easy to include, nor is the fact that a glazing system may reflect considerably more thermal energy than visible light.

**Rendering Based Approaches**

One option commonly used for indoor glare analysis is using daylight ray-tracing software such as Radiance [17], either on its own or as part of a package such as OpenStudio or DIVA-for-Rhino. These programs can identify glare sources in a high quality rendering or high dynamic range photograph of a scene and then compute various standard indoor glare metrics. While Radiance has proven to be highly accurate at estimating light reflection for the full range of material surface properties [18], this approach has several drawbacks for exterior reflection analyses. Aside from the often steep learning curves and complex material definitions required for most rendering tools, the primary weakness is that the high quality renderings created by Radiance are typically quite slow to compute. This is due to the highly detailed nature of the lighting calculations and a lack of simple parallelization options. As dangerous reflection scenarios can be very short in duration and can occur far afield from the offending surfaces, high spatial and/or temporal fidelity are needed, limiting the utility of this type of analysis.

**Computational Fluid Dynamics Approaches**

Computational fluid dynamics (CFD) based approaches are also possible. Most CFD packages (e.g. Star-CCM [22], Fluent [3]) are able to include solar radiation and reflective elements in an analysis, yielding temperature predictions, which are then used as an analogue for the intensity of reflections. There are however, numerous drawbacks to this approach. Most importantly, is that surface temperature is dependent on many factors in addition to the reflected heat flux. Ambient temperatures, local wind speeds and material properties all dramatically impact the final temperature of an object. Given the highly complex and transient nature of the wind flows and variety of possible materials found in an urban domain, assumptions have to be made, which if done non-conservatively, can lull designers into a false sense of security.

The intensity at which a material reflects is also highly dependent on the angle of incidence of the incoming solar ray. This important relationship is not always possible to incorporate easily in off-the-shelf, closed-source software. For example, Star-CCM+ assumes a fixed reflectance regardless of solar angle, and Fluent uses a correlation to estimate the angular dependence [1], which doesn’t necessarily apply to all forms of glazing.

As an example, the inset image in Figure 1 shows a schematic view of a double pane insulated glazing unit (IGU). Low-emissivity coatings (which are used to improve the thermal performance of glazing) are typically applied to surface 2, but applying the coating on surface 3 is not unheard of. Figure 1 plots the reflectance at various angles of incidence for both coating locations, as predicted by the Fluent correlation and from the industry standard WINDOW software produced by Lawrence Berkeley National Laboratory (LBNL) [29]. For the more common scenario with the coating on surface 2, the correlation is within 5% of the WINDOW values. Conversely, when the coating on surface 3, the Fluent correlation under-predicts the reflectance by as much as 30%. Similar discrepancies are noted for triple and quadruple pane IGU’s and double pane IGU’s, with atypical air gaps and/or pane thicknesses as well.

Further complicating the use of CFD is the computational effort. Very fine spatial resolution around the areas of interest and the reflecting surfaces is required in order to properly resolve small physical elements such as mullion fins, as well as the thermal and velocity boundary layers on surfaces. Failing to properly resolve these features will significantly impact the accuracy of the simulations. The resulting long computational times limit the size of the study domain and/or the number of solar positions to be examined. For simple building geometries it may be easy to determine the critical solar positions which are likely to cause glare.

![Figure 1. Comparison of glazing reflectance as a function of incidence angle for a typical and atypical glazing unit.](image-url)
problems, but for complex facades, it is much more difficult. Reflections can occur at any time or date so selecting “standard” days and times runs the risk of missing critical events.

**Additional Approaches**

The Solar Glare Hazard Analysis Tool (SGHAT) produced by Sandia National Labs [9] takes a different approach. Unlike both rendering and protractor based methodologies, SGHAT quantifies the impact of a given reflection by computing the retinal irradiance (i.e. the radiative flux impacting the back of an observer’s eye) rather than the luminance of a given source. That value combined with the size of the glare source in the field of view is used to classify glare based on its potential to cause after-images, or in extreme cases, thermal damage to the eye. This web-based tool employs a methodology also developed by Sandia [10] to determine the risk of glare from photovoltaic (PV) solar installations impacting pilots or air traffic control personnel at selected points around the installation. This metric has the advantage of being easy to compute, allowing for very high temporal fidelity (minute-by-minute tests for an entire year) simulations. Also, the fact that irradiance is computed means that the results can also be reused to investigate thermal impacts. This analysis is also required by the Federal Aviation Administration as part of the approval process for PV installations near airports [25].

The main downsides of this tool are that it does not identify the glare source, only that a risk exists, and the simplified geometrical analysis was created for open, unobstructed spaces not for complex urban topographies. SGHAT, like the protractor methods also works on a point by point basis; making understanding glare impacts over a wide area a cumbersome and time consuming process.

Ultimately, the existing methodologies for assessing solar reflections in the built environment fall short in delivering a tool that: 1) can consider complex façade and urban geometries, 2) can accurately model reflection intensities for modern façade materials, 3) can assess the full spatial and temporal breadth of a building’s potential reflections, and 4) can consider the thermal and visual requirements of the locations that the reflections are expected to fall.

**1.2 The ECLIPSE Approach**

The tool presented here, known as ECLIPSE, builds on work presented previously by the authors [2], using the same solar insolation engine to derive reflected irradiance levels. A full description of the OpenFOAM-based calculation engine can be found in the reference text, but in brief; the authors propose a multi-phased approach to assessing glare impacts in a neighborhood.

Typically the interest is the new reflections caused by a proposed development, thus only the reflective surfaces of that building(s) are included in the simulation. The reflectance is defined in a piece-wise fashion based on the angle of incidence of the incoming light ray. It is possible to include reflectance data for surrounding buildings, but obtaining details of their façade construction is often not practical. However, the surrounding buildings do act to obstruct direct and reflected solar energy.

The first step is an initial simulation over a large volume (on the order of a 1000m radius by highest building height) at a coarse time step (typically 1 hour) for an entire year. This highlights the geometric extent of the reflection impacts, the maximum reflected intensities (both direct normal and horizontal) and the frequency of glare occurrences. Two dimensional plots of highest hourly normal intensity and frequency are produced for each grid cell to illuminate these key indicators, as illustrated in Figure 2. This volumetric approach has the added benefit of allowing the visualization of reflection impacts in the surrounding air space.

![Figure 2. Sample peak intensity and reflection frequency plots.](image-url)
Next, specific points are selected based on the results of the preliminary analysis for which a more detailed investigation is conducted. These points are selected based on the frequency and/or peak intensity of reflections, but could also be points with a particular sensitivity to reflected light or heat (e.g. highway on/off ramps, intersections, parks, etc.). For each of these points the intensity and duration of each reflection is resolved at a one minute time step and the impact of each reflection is assessed based on the specific viewing and thermal requirements for each location using internally developed threshold limits.

2 SIMULATION APPROACH

2.1 Input Data
Determining reflected irradiance is highly dependent on building geometry, material properties and ambient solar levels.

Study Building Geometry and Surrounds
To suitably model the reflections emanating from a building, an accurate 3D model of the built environment is required. The surfaces should be resolved to the degree that different material properties can be correctly attributed and construction details down to roughly 30 cm (i.e. fins and reveals, but not mullions) should be represented. Surrounding buildings can be represented with less resolution (roughly 0.5 m) as they are essentially blocks to shade the sun or intercept reflections or viewers’ lines of sight. Larger vegetation (i.e. trees and hedges, but not shrubs) should be considered for key areas, and schedules assigned if foliage levels vary significantly throughout the seasons. It is useful to underlay road map to the site so pedestrian locations and traffic flow directions can be assessed easily.

Surface Reflectance Data
The thermal and visual reflectance of a façade material is typically available from the manufacturer for normal angles of incidence. As mentioned previously, reflectance is highly dependent on angle of incidence thus additional angular increments should be calculated and assigned using a program such as LBNL’s WINDOW software. For a given glazing system, this industry standard software can compute both full spectrum and visible specular reflectance of the glazing for light rays striking at various angles of incidence. In the case of modern high-performance glazing systems, surface coatings can selectivity reflect thermal energy but not visible light. This variability is important to acknowledge; the visible reflectance values, while appropriate for understanding the visible light impacts on people, may underestimate the intensity of the thermal effects in some glazing types.

For other reflective façade materials (i.e. polished metals) some industry test data is available, or can be calculated theoretically by employing the Fresnel equations.

Ambient Solar Data
The foundation of all reflection analyses is the initial prediction of ambient solar conditions. ECLIPSE, like other building modeling programs, requires ambient solar levels to be broken down into the direct normal, (i.e. the flux emanating directly from the sun onto a surface oriented normal to the rays of light), and the diffuse horizontal (the flux emanating from the remainder of the sky dome onto a surface oriented horizontally) components. Ideally, high quality measured ground level irradiance data would be used as the input to the simulation, however such data simply doesn’t exist for many locations around the world. In the absence of measured data, the next best option is to use modeled data.

The most common sources of modeled solar data are the Typical Meteorological Year v3 (TMY3) and EnergyPlus Weather (EPW) files published by the National Renewable Energy Laboratory (NREL) [28] and The United States Department of Energy (USDOE) [14] respectively. These data sets provide hourly records of solar and other meteorological parameters for one “typical” year. Determining what is “typical” for a given month at a given location is determined through a weighting algorithm, in which direct normal solar intensity (the key parameter for solar reflection analysis) is quite highly weighted [23]. While these data sets are convenient and ubiquitous within the building science community, it is important to fully understand the sky conditions that are represented in these files.

To represent a “typical” year, the published solar irradiance levels in these files include the effects of cloud cover, and while cloud cover on a monthly or annual basis is relatively consistent, the change in hourly cloud cover is much more variable. Energy modeling and other building science applications are usually focused on monthly or annual statistics, so hourly variations will balance and thus not impact results. Reflection analyses, on the other hand, are highly dependent on the intensities at a specific time and date. Lower hourly intensities due to cloud cover can’t be guaranteed in reality, and can lead to the under-prediction of the intensity, frequency or durations of reflection impacts.

Therefore, the authors employ a “clear-sky” model [5], to provide an estimate of solar intensity which ignores the impacts of cloud cover; this conservative approach allows the analysis to investigate all possible solar positions and predicts an upper limit on the reflection durations and frequencies caused by the study building.

2.2 Reflection Computation
For each input met record the incident direct normal radiation on each of the surface subdivisions of any surface with a non-zero reflectance is computed [as per 2]. For any subsurface exposed to direct sunlight, the angle of incidence of the light is computed based on the sun’s position and the normal of the reflecting surface using
simple vector geometry. The surface’s reflectance at that angle of incidence is then determined and used to compute the intensity of the reflections [as per 10]. This is repeated for all reflective surfaces and the cumulative irradiance is determined at each test point in the study domain. Attenuation along reflections due to surface obstructions is accounted for using angle of incidence dependent transmission factors, but as a conservatism atmospheric attenuation and the diffusing effects of dirty windows are not. Attenuation due to vegetation can also be included with scheduled attenuation factors, but is often also ignored due to its highly variable shading characteristics.

If a simulated façade element shows a significant difference in reflectance in the visible spectrum compared to the entire solar spectrum, separate simulations are run using both data sets. The results are then used to inform the visual and thermal impact analysis respectively.

2.3 Level of Impact Prediction

The visual impact at a given point is determined using the Ho et al methodology [10]. In short, this algorithm categorizes glare based on the reflection’s potential to cause retinal damage or after-imaging in a viewer based on the intensity and size within the field of view of a reflection. This categorization is combined with knowledge of where the reflection is emanating relative to a viewer to provide an understanding of the degree to which an individual would be affected by the reflection depending on their assumed task (e.g. walking, driving a car, flying a plane, looking out a window, etc.). The results of this analysis for a given location and view are illustrated in Figure 3. Where a convex façade created frequent, short duration glare impacts in the morning and evening hours. The surfaces causing the glare and the angle at which light impacts them can also be identified at this stage to assist with mitigation design.

Thermal impacts are assessed by looking at the cumulative reflected irradiance from all reflective surfaces at a given location and time. Peak and mean reflected irradiance values are computed at each test point and are compared to criteria developed by the authors, to gauge their potential effects on people and property.

3 VALIDATION

3.1 Background

During construction of a new building in the United States, it was discovered that at certain times the concave (inward-curving) curtain wall was focusing reflected sunlight to an intense spot that tracked across pedestrian areas in front of the building. The light spot was found to cause rapid and dramatic increases in temperature of objects in its path and unacceptable visual glare. A 15 week measurement program was proposed to coincide with the period with the highest predicted reflection intensities.

3.2 Equipment

A Kipp & Zonen CMP3-L pyranometer [11] was placed on the roof of the building to record ambient solar conditions out of reflection. Due to the expected unnaturally high levels of irradiance at grade, a Kipp & Zonen CMP10 pyranometer [12] was employed, since it can resolve solar fluxes up to 4,000 W/m². The CMP3 and CMP10 have stated accuracies of ±20 W/m² and ±10 W/m² respectively. The two pyranometers were positioned on stands approximately 1.5m in height so that the readings would be taken at “pedestrian height”. Both pyranometers measure total horizontal irradiance, that is to say the “downward” component of the incoming radiation. For light striking the sensor at shallow angles, this results in the sensors reporting a lower irradiance level than it would if the sensor was oriented perpendicular to the incoming light rays.

Two Kipp & Zonen “Meteon” irradiance meters [13] were used to log the total horizontal irradiance measurements from the pyranometers at one minute increments (rounded to the closest 1 W/m²). The logging was timed to ensure synchronized recordings from both pyranometers.

3.3 Methodology

Ambient Solar Conditions

For a given focal event, the ambient global horizontal irradiance (measured on a nearby rooftop) was converted
into the required direct normal and diffuse horizontal components using the procedure proposed by Skartveit et al [21]. According to the reference text, this method is able to covert hourly global horizontal irradiance into its components with an RMS error of less than 80 W/m² compared to measured data. Because this study would be using measurements at much shorter timescales, this algorithm was further benchmarked by the authors against research grade solar data collected at minute scale intervals by the National Oceanic & Atmospheric Administration (NOAA) [24].

Table 1 summarizes the results of an error analysis for four American cities (the stated uncertainty of the NOAA measurements is ±15 W/m²). Even at very short time-scales, this methodology still provides a reasonably accurate prediction of the solar irradiance components with RMS errors below 145 W/m² for direct normal and less than 100 W/m² for diffuse horizontal. Additionally, the direct normal component (which is what drives the specular reflection intensity), tends to be over-predicted with this algorithm, which is conservative in this context.

<table>
<thead>
<tr>
<th>Location</th>
<th>Dataset Length (years)</th>
<th>Direct Normal Error (W/m²)</th>
<th>Diffuse Horizontal Error (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bondville, IL</td>
<td>21</td>
<td>133</td>
<td>92</td>
</tr>
<tr>
<td>Desert Rock, NV</td>
<td>18</td>
<td>129</td>
<td>73</td>
</tr>
<tr>
<td>Fort Peck, MT</td>
<td>21</td>
<td>110</td>
<td>68</td>
</tr>
<tr>
<td>Penn State, PA</td>
<td>18</td>
<td>144</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 1. Error in solar irradiance components computed using [21]

Measured Grade Level Conditions
The positioning of the grade level sensor was handled by on-site personnel, using both photographs of previous focal events and preliminary simulations to determine the approximate location of the most intense focusing. Limitations in access to the site meant that the sensor was not repositioned regularly in order to capture the movement of the focal spot over the study period. This means that some of the recorded events may not represent the most intense reflections; however the results are still suitable for benchmarking purposes.

Simulated Grade Level Conditions
The minute-by-minute ambient irradiance values are then input into the simulation engine and the total reflected irradiance at grade level at each minute was computed. The predicted reflected horizontal irradiance values were then compared to the increase in horizontal irradiance recorded by the grade level pyranometer. The reflectance of the glazed facades was computed using WINDOW 7.2. The majority of the glazing was determined to be approximately 40% reflective at normal incidence angles; a smaller area was determined to be nominally 30% reflective.

3.4 Results
Over the course of the measurement program, 25 focal events were recorded. Figure 4 illustrates three of the recorded events. All plots illustrate the ambient horizontal irradiance as well as the measured and simulated total horizontal irradiance in the focal area.

Focal Event Timing
In all recorded focal events, the focal area took 20 to 25 minutes to sweep over the pyranometer. The simulated results were generally shorter in duration, typically on the order of 10 to 15 minutes. This indicates the simulation predicts a smaller focal region than what was seen in reality. However the simulation was able to capture within one minute the timing of the peaks. Figure 4B illustrates a situation where a cloud presumably covered the sun just as the focal point passed over the sensor.

The three minute drop in irradiance seen in both the ambient and grade level measurements is captured clearly.
in the simulated results. These results justify the authors’ use of fine temporal resolution in simulations. It also underscores how cloud cover can mask issues related to glare and why the authors prefer to use clear-sky solar models as the input to simulations.

Irradiance Levels
Peak horizontal irradiance levels measured at grade ranged from 1,500 W/m² to over 4,000 W/m². Figure 4A illustrates a typical focusing event recorded during a winter afternoon. Within the focal area, horizontal irradiance levels were over nine times the ambient level. The simulated results predict a more abrupt rise and fall in the irradiance levels; however the peak irradiance predicted by the simulation tool matches quite closely (within 5 W/m²) to the measured peak irradiance. Over the entire course of the focal event, the RMS error is approximately 400 W/m² with the error driven primarily by the underestimation of the size of the focal area. These results are typical of the other focal events. Predicted peak irradiances were all within 30 W/m² and overall RMS errors between 300 and 500 W/m² over each of the focal events, driven primarily by an under-prediction in the size of the focal area.

4 DISCUSSION

4.1 Validity
While the timing and intensity of the peak of each focal event was well captured, the measurements indicate a “wider” focal area than what the simulations predicted. While the limitations of the project prevented a detailed investigation of why this occurred, the authors believe that the most likely reason for the discrepancy is the idealized nature of both the simulated surfaces and the light propagation model.

Slight differences in the as-built condition of the building compared to the architectural drawings (which is what the 3D model used in the simulations is based on), particularly with respect to the orientation of each glazing unit and/or the radius and uniformity of the curvature of the curtain wall, could be acting to create a wider focal area. Similarly, it has been noted in the past that double pane glazing units can deform if there is a difference in pressure between the air gap and ambient conditions [6]. Such deformation could distort how light is reflected compared to the simulation which assumes planar glazing units.

The simulation engine also assumes a fixed beam divergence angle (i.e. the “spread” of the specular reflection as it travels) taken from [10]. For glazed surfaces which are wet, dirty, or otherwise “roughened”, this divergence angle could be larger, which would in turn act to widen the area impacted by the reflected light.

Given the level of agreement seen between the predicted and measured reflection intensities, it appears that in this case, any error introduced by the conversion of global horizontal irradiance into its components is low. Overall the authors feel that this tool yields sufficiently accurate results to provide engineering guidance on the degree to which reflected solar energy from a building impacts its neighbors.

4.2 Computational Effort
The ability to provide feedback on glare impacts in a timely fashion is critical in the fast-paced world of architecture and design. This tool has been applied at scales ranging from parking lots to large (>300 ha) areas of dense urban environments. The ability to parallelize the computations means that an annual analysis of larger domains at hourly time steps, or smaller domains and minute-scale time steps can be completed within hours, and are able to acknowledge small-scale building shading features.

4.3 Future Work
The authors plan to conduct further tests under more controlled conditions to further assess the software’s predictive abilities, particularly with respect to the duration of the focal events. Further research investigating temperature gains caused by reflections of various intensities on common materials in an urban environment, as well as the thermal and visual impacts on people and property is also planned.

5 CONCLUSION
The tool presented here is able to rapidly and accurately predict the cumulative reflected irradiance from the built environment at a range of spatial and temporal scales. For a situation where a building façade was focusing reflections to a significant degree, the predicted reflection intensities, and timings show good agreement with measured data taken on site. The authors have successfully applied this tool to assist architects and designers understand how a building will reflect light and the impact those reflections have on their surrounds.

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Stock modeling and building morphology: a case study of Belo Horizonte, Brazil.

Tatiana Alves¹,², Luiz Machado¹, Roberta Gonçalves de Souza¹ and Pieter de Wilde²

¹ Federal University of Minas Gerais, Belo Horizonte, Brazil
luizm@demec.ufmg.br

² Plymouth University
Plymouth, United Kingdom
pieter.dewilde@plymouth.ac.uk

ABSTRACT

Commercial buildings in Brazil consume approximately 16% of electricity energy use nationwide. The goal of this study is to explore and model the relationship of land use regulation, high-rise commercial building morphology and their energy use intensity in the city of Belo Horizonte, Brazil. The database from the local city council was used to identify and map the high-rise commercial building stock combined with a field survey which investigated prevalent commercial building typologies in the city. Data from this field survey was used to build representative energy models of the high-rise commercial buildings for building performance simulation. The tool selected to evaluate building energy performance of the representative model was EnergyPlus. DaySim was used for dynamic daylighting analysis. The simulation results demonstrate how vertical development and a building morphology produced by land use code affect air conditioning energy use intensity and access to daylight in these representative building models.

Author Keywords
Simulation and Modeling; Building Performance Simulation; Daylight analysis;

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING

1 INTRODUCTION

Cities develop over time and their built environment has long lasting impacts on the energy consumption. The interaction between climate, urban form and building performance has gained substantial attention. Current studies has explored the influence of the Urban Heat Island (UHI) on the cooling demand of buildings [1,2], the relationship between geometry of urban canyons and energy consumption [3] and the effect of building form and urban density on solar access [4,5] and ventilation [6].

Worldwide governments are setting targets to building sector energy consumption. The building sector is among the largest consumers of electricity in Brazil. Currently over 45% of electricity is consumed in building sector and commercial buildings represent a 16% share of the total [7]. Reduction of energy consumption plays an important role in energy conservation programs focused on the built environment. Studies capable of integrating energy building analysis at an urban scale are an important tool for understanding and managing the energy demand of the cities.

The city of Belo Horizonte was chosen as the field study based on the socioeconomic importance of the city in the national context. The objective of this paper is to investigate the interaction between land use regulations, city plans, high-rise commercial building morphology, and the daylighting access and air conditioning energy use intensity of buildings in this city by means of simulations.

2 METHODOLOGY

First, the original city plan and the land use regulation evolution were studied with a focus on commercial buildings. Additionally, the effect of land use parameters, the original city plan and the building construction parameters on the high-rise commercial building morphology has been investigated.

A local city database, the Secretaria Municipal Adjunta de Planejamento Urbano (SMAPU/PBH) database [8] was used to study the high-rise commercial building stock prevalent in the city. The commercial building stock features collected from SMAPU/PBH database formed the starting point to further analyze and map high-rise commercial buildings through a field survey.

The SMAPU/PBH database was used to describe building age, localization, area and height. The criterion used as a filter was the end use office buildings.

The survey followed three steps: Adapted Morphological Diagram analysis, in loco visits and internal floor plan distribution investigation. Data was compiled and used to analyze recurrent urban and building features. Furthermore, evidence of the way original city plan and the land use parameters have influenced the commercial building morphology have been explored.

From SMAPU/PBH database 298 buildings were selected for the field survey. The selection criterion was that buildings had to be representative of the larger share of commercial buildings in the city.

The “Morphological Box” was the method used to summarize the first step of the field survey. The “Morphological Box” developed by Backer et al. [9] and adapted by Amorim [10] is an instrument for morphological analysis of existing buildings from the environmental point
of view. In this research the “Morphological Diagram” proposed by Amorim was adapted and called Adapted Morphological Diagram (AMD). The urban parameters analyzed were: street width and sky view. The building parameters analyzed were: facade reflectance, building orientation, building height, building shape, ground floor feature, window wall ratio, daylighting control, and air conditioning.

The address reported on the SMAPU/PBH database was the starting point for localization of the buildings in the urban fabric using Google Earth®. Images of the buildings and their urban context were captured through the Street View feature and analyzed using AMD. Figure 1 illustrates the potential of the street view tool to collect images of buildings and urban contexts.

![Figure 1. Contorno Plaza Building, example of images collected during AMD analysis. Source: Google Earth throughout Street View](image)

From 298 sample buildings, 12 buildings were selected and a total of 60 work spaces in those buildings were visited. For these 60 spaces data was collected on artificial lighting and air conditioning. Technical information was collected and confirmed with suppliers. Operational schedules of both systems were gathered together from occupants.

Completing the field study, 19 floor plans from the sample buildings were analyzed in terms of internal distribution. The information was categorized into vertical distribution (stairs and elevators), horizontal distribution, technical support areas and workspaces. Data was used to describe the internal distribution of the representative prototypes used during simulation.

Data from the field survey was the basis for the development of representative prototypes used in simulations. The tool selected to evaluate energy performance was EnergyPlus V.8.1[11]. DaySim 3.0 [12] was used for dynamic daylighting analysis. Simulations were performed for the whole year (8760 hours) using the TRY (Test Reference Year) climate file of Belo Horizonte.

### 2.1 Simulations

Prototypes can be used to characterize typical buildings during the simulation process when they are representative of a group [13,14]. In this study a representative prototype of the high-rise commercial buildings was modeled. Building information (area, shape, typical height, construction material, percentage glazing and surrounding built environmental) was based on the field survey. Specific information such as external and internal wall U-value, Roof U-value, absorptance and glass SHGC was collected from Brazilian Standards [15–17] and technical guides [18]. Operational characteristics were modeled based on the field survey information and international standards from ASHRAE [19] and CIBSE [20]. The representative prototype parameters used for building energy simulation are presented in Table 1. The parameters are categorized into four types: building features, envelope features, building systems, building routine.

![Table 1. Representative Prototype input parameters for building energy analysis](image)

Hybrid Ventilation is an important characteristic of modeled prototype buildings. The multi-zone Airflow Network model was used to simulate natural ventilation. The wind pressure coefficients were calculated by EnergyPlus. The windows are operable and the control strategy adopted is based on temperature. The air mass flow coefficients, exponents and discharge coefficient of openings are showed in Table 2.

![Table 2. Parameters for natural ventilation simulation](image)

In order to incorporate the hybrid ventilation, control schedules of air-conditioning and natural ventilation were created using spreadsheets. These schedules cover control settings on an hourly basis for the whole year. The
objective of these schedules is to control the hybrid ventilation strategy considering the thermal comfort. The method to assess thermal comfort was the Adaptive Standard ASHRAE 55 [22] (90% acceptability limit). For each hour, if the value for the control schedule of natural ventilation is set to one (1) natural ventilation would be allowed with no use of air-conditioning, if the value is set to zero (0) then the use of air-conditioning would be necessary, without natural ventilation. The control schedule of air conditioning is the opposite of the control schedule of natural ventilation, which means that when natural ventilation is allowed, the use of air-conditioning is not allowed and vice versa.

DaySim 3.0 was used for dynamic daylighting analysis and Daylight Autonomy (DA) was selected as performance indicator. The DA at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone [12]. Table 3 shows the input parameters used to simulate Daylight Autonomy (DA).

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>DEFINITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectance</td>
<td>Internal Wall 50%</td>
</tr>
<tr>
<td></td>
<td>Floor 30%</td>
</tr>
<tr>
<td></td>
<td>Ceiling 80%</td>
</tr>
<tr>
<td>Radiance Simulation Parameters</td>
<td>Surrounding Buildings 50%</td>
</tr>
<tr>
<td>Operational Schedule</td>
<td>Scene Complexity 1</td>
</tr>
<tr>
<td>Minimum Illuminance Level</td>
<td>(BH+1BH)</td>
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<tr>
<td>Shading Device Mode</td>
<td>simplified shading device model</td>
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<tr>
<td>Occupant Behavior</td>
<td>Active</td>
</tr>
</tbody>
</table>

Table 3. DaySim input parameters for building daylighting analysis

3 BELO HORIZONTE COMMERCIAL BUILDINGS: AN OVERVIEW OF LAND USE AND BUILDING CONSTRUCTION REGULATIONS

The original city plan of Belo Horizonte was developed by Aaron Reis and established a rational and orthogonal grid for the city. The original plan divided the city in three zones: urban, suburban and rural. The Urban zone, delimited by Contorno Avenue, presented regular blocks based on the overall orthogonal grid of the city as shown in Figure 2. The orthogonal original grid of the city is rotated 15 ° clockwise from North. The blocks in the urban zone have three geometric shapes: 120x120m (most common), 120x60m, and a triangular shape that was born of the inserts of some diagonal avenues in the orthogonal grid. These blocks are composed of 24 rectangular plot subdivisions with same size but different shapes: 10x60m, 20x30m and 15x40m [23].

In Belo Horizonte, the first land use regulation regarding buildings volumes was established in 1901. For the urban zone it defined an architecture characterized by low volumes limited to three floors [23].

From 1920s on, the city land use regulation provided specific criteria for vertical construction. In 1930s the desire for a vertical city was affected by the introduction of the height restriction parameter in the urban zone. In 1933 a new code was approved. The city was subdivided in commercial, residential, suburban and rural zones. The new regulation removed height restrictions in the commercial zone, encouraging the emergence of high-rise commercial buildings [23].

In 1940, a building construction code called Código de Obras [24] defined general and specific rules to be followed during building design, construction, maintenance and use. From a building design point of view, this code set rules to minimum room areas, daylight and ventilation levels. Natural ventilation was now required in every room and a minimum window-to-floor area ratio (example: 1/8 of floor surface to end use offices) was prescribed to ensure ventilation and daylight. Another daylighting design parameter was a room depth limit to allow access to daylight. For a room to be considered illuminated this should have a depth no longer than 2.5 its internal height. This resulted in the emergence of light courts and the use of E, H and U plan forms to optimize natural light.

Código de Obras remained effective until the 2009 when it was replaced by Código de Edificações [25] although for those mentioned ventilation and daylighting topics there were no important changes.

The 50s, 60s and 70s were marked by sharp population growth and consequently an intense process of densification of the city.

In 1974, the creation of the PLAMBEL (Metropolitan Planning Authority) allowed the development of global urban studies for the city. The results were the approval Law of Use and Land Use of Belo Horizonte – LUOS/76 [26]. The LUOS/76 established a set of rules for a very regimented use of the urban space of the city. Thus, the permitted uses were defined by zones (residential, commercial, industrial and institutional) and occupation by settlement models. Crossing these two information, the regulation defined land use parameter values.
Among land use parameters established in the LUOS/76 there are two that affect building morphology: Coeficiente de Aproveitamento (CA) and Recuo (R). CA is a land utilization coefficient and R is a perimeter distance requirement. The coefficient CA determines the amount of floor space which will be allowed on that land (example: if a CA is defined as 8.0, means that 1m² of land allowed 8m² of floor space). A high CA coefficient means zone densification. The R parameter is divided in Frontal (RF), Back (RB) and Lateral (RL) and means the minimum distance to be kept from the Frontal, Back and Lateral land borders respectively. Figure 3 illustrates the developable volume allowed in the commercial central zone of the city based on the LUOS/76.

From the commercial building perspective the effects of the LUOS/76 was an increase of vertical construction and building densification in the commercial central zone and along major roads.

In 1985, the LUOS/85 [26] was approved, a revision of the LUOS/76. It added more types of zoning such as Special Sectors (SE) and provided more detail on the end use categories. Generally, the CA and R parameters related to commercial zoning remained unchanged.

The LUOS/96 [26] redefines the city zoning according to infrastructure availability, roads classification, environmental demands, historical, cultural and landscape preservation. In other words, the LUOS/96 allowed any end use in anywhere since end use activity was compatible to the road classification. Related to high-rise commercial buildings, the major change occurred in the CA coefficient. The CA in the commercial central zoning was reduced from 8 to 3 in an effort to stabilize and diminish densification. The R parameter in the LUOS/96 changed as well. The FR parameter for ground floors was now defined in relation to the road classification. RB and RL parameters previously fixed at 5m and 1.5m were now related to building height. The results were lower buildings and larger lateral and backside distances, meaning that vertical constructions demand larger land areas. Figure 4 illustrates the developable volume allowed in the commercial central zone of the city based on the LUOS/96.

Although the legislation allowed commercial activity across the city the high-rise commercial building remained linked to central commercial zones and major roads. Major roads were reinforced in the LUOS/96 as a place of commercial activity and thus led to so-called linear commercial centralities.

In 2000, the LUOS/96 was reviewed. The LUOS/2000 [26] provided once more further detail on the end use categories and their negative impact across the city. For each negative impact a compensating measure must be introduced. In general, the CA and R parameters related to commercial end use in central area and major roads remained unchanged.

In 2010, the LUOS/2010 [26] was approved, which is a revision of the LUOS/2000. The most significant change was a reduction of CA of 10% across the city. In other words, the LUOS/2010 kept the search for a balanced densification throughout the city. The LUOS/2010 is still effective.

### 4 RESULTS AND DISCUSSION

#### 4.1. Stock and Building Morphology Modeling

Based on the SMAPU/PBH database information, Belo Horizonte city currently provides about 4,577,000m² related to office buildings. The age of the stock is shown in Figure 5. A sharp growth can be seen from the 70’s reaching its apex during the 90’s, coincidently joining Brazilian economic stability and high land densification allowed by the LUOS/76 and the LUOS/85 regulations.

Mapping the office building stock across the city shows commercial building centralization in downtown area and along major roads. The area inside Contorno Avenue, firstly known as the Urban Zone, shows the highest amount of office building areas of the city, approximately a 75% of the total. This can be understood as a response to the desire of transforming this area in a place of attraction for trade and urban services since city foundation.
The Figure 6 shows based on the SMAPU/PBH database that a great part of the office building stock is composed by high-rise buildings. Among high-rise buildings, the database shows the predominance of cellular office buildings (70%) and total building area about 5,000 m².

![Figure 6](image)

**Figure 6.** Office Building Area Stock (m²) per Building Height

Building selection for the field survey was based on the larger share of commercial buildings in the city. The AMD was used to organize and synthesize the data and the results are shown as follows.

In terms of street width, 99% of the total buildings are located on streets wider than 10 meter (64% located on streets between 10 and 20m, and 35% on streets of over 20m). This situation historically reflects the city land use regulation that links commercial zones to major traffic roads [26].

![Figure 7](image)

**Figure 7.** Image of the urban context of Belo Horizonte Source: Google Earth.

The urban context indicates that the office buildings are located on vertical density areas. The sky view angle (Figure 7) from lateral and backside façades are inferior to 30° in 45% share of the total sample buildings.

In terms of building façades color, 63% share of total front façades display diversity of materials and colors intensity, 79% share of the total side and back façades display light colors intensity.

Regarding solar building orientation, there is no prevalent solar building orientation and 15 floor height is the average height of the sample buildings;

The most common shape found in the sample is the rectangular shape (64%), followed by square (12%) and triangular shapes (11%). A correlation between rectangular plot subdivision and building shape could be understood as a result of a renovation process over an existing area.

In terms of wall window ratio, front façade prevalent glazing percentage account for 50% of the total while side and back facade prevalent glazing percentage account for 25% of the total.

Regarding ground, 1st and 2nd floor features, 73% share of the total buildings use ground floor for commercial proposals. The 1st and 2nd floor occupy 100% of land perimeters in 73% of the total buildings. These features are illustrated in Figure 8. Ground, 1st and 2nd floor prevalent shape is known to be linked to land use parameters from LUOS/76 onwards.

![Figure 8](image)

**Figure 8.** Images of ground, 1st and 2nd floor features Source: Google Earth throughout Street View

In terms of environmental conditioning, 98% of the buildings allow natural ventilation. Hybrid conditioning systems (natural ventilation and Split/window equipment) occur in 74% share of the total buildings and 18% of the buildings are conditioning by central systems. Figure 9 illustrates the images used to identify air conditioning systems.

![Figure 9](image)

**Figure 9.** Images of conditioning environmental features Source: Google Earth / Street View

In terms of daylight control, curtains/blinds placed inside office rooms are the most common daylight control found (90%). Daylight control components such as brises-soleil are present in less than 10% of the buildings.

Continuing the field survey, there were 60 office rooms visited and the results are shown as follows. The predominant artificial lighting system is the tubular fluorescent lamp (78%), followed by compact fluorescent lamp 15% and LED lamp 7%. Among the tubular lamp systems dominate the 40/20W lamp power (62%), followed by 32 / 16W (30%) and the 28 / 14W (8%).

The predominant air conditioning system is the window equipment with 58%, followed by Split equipment 25%. Among those conditioning systems the predominant energy efficiency classes are B and C respectively [15].

In terms of lighting routine, 47% of the work spaces visited there are no lighting circuit subdivision, meaning that the whole lighting system remaining ON during room operation. The remaining 53% shows lighting circuit subdivision but no integration with natural lighting.
The survey also indicates the prevalence of hybrid ventilation. In 82% of the office rooms visited, users only switch the air conditioning on when they feel the room thermally uncomfortable.

Completing the field study, 19 floor plans were studied in terms of dimension distribution. The space distribution can be summarized as follows: 15% of the plan floor is related to vertical and horizontal distribution (stairs, elevators, and halls), 5% to technical support areas and 80% to workspaces. Those dimensional proportions were used to describe plan floor on the representative prototype used during simulation.

4.2 Building Energy Simulation and Daylighting Analysis

Table 1 summarizes all parameters modeled to represent high-rise office building prototype. The simulation considered specifically the office room tower. Detailed description of the energetic interactions was analysed considering the subdivision: bottom floor, intermediate floor and roof floor as shown in Figure 10. Each floor is divided in five office rooms and one horizontal/vertical distribution as presented in Figure 11.

The surrounding built environment was modeled based on front, back and side perimeter distances required by the LUOS/76 once the 80’s and 90’s are predominant on the commercial building stock. Surrounding building height was considered the same of the representative model as identified in the field study and the street width was estimated 20 meters. Front façade orientation was south which means 195º from North considering original city plan. Figure 12 shows the urban canyon simulated.

An overview of Energy Use Intensity (EUI) indicates the influence of floor position on the EUI. The roof floor presents the higher energy use intensity, followed by intermediate floor and bottom floor as shown in Figure 13. The EUI difference between roof and bottom floor is about 12%. The difference among floors could be explained as the difference of thermal loads in to the HVAC system once equipment power density (12 W/m²) and light power density (19.04 W/m²) were set equally for all floors. The equipment power density value was set based on CIBSE[20]. The light power density value was set based on the correlation between the predominant artificial lighting system of 40W fluorescent lamp and the lighting system efficiency classification suggested by Technical Regulation for the Quality Level of Energy Efficiency in Commercial, Service and Public Buildings -RTQ-C [17].

Variation of the HVAC energy consumption on the same floor is observed to be related to solar orientation. Office rooms positioned on backside façade facing North are the greatest HVAC energy consumers. The percentage difference among zones on the same floor may reach 4% in the roof floor, 5% in the intermediate floor and 4% in the bottom floor.

Analysing thermal loads, the non-uniform solar access is the main explanation for EUI difference among floors. The urban canyon simulated has an impact on floor solar heat gains as shown Figure 14 and 15. Figure 14 and 15 illustrate the total heat gain rate through window, internal and external surfaces of a room facing North. The day
simulated is the typical summer day. Comparing both, it is possible to identify during operational time a sharp influence of the window and external surfaces on heat gain rate of the roof floor room.

Figure 14. Roof floor room surfaces total heat gain rate

Figure 15. Bottom floor room surfaces total heat gain rate

The energy end use distribution analysis indicates that the artificial lighting system is the biggest consumer of electricity. It is representative of approximately 65% share of the total, followed by office appliances (20%) and HVAC (15%) as illustrated in Figure 16. The impact of artificial lighting is explained by lighting routine (switched ON during operational period), no daylight integration and inefficient artificial lighting system (LPD = 19.04) modeled base on the field survey. Hybrid ventilation is observed to reduce thermal heat loads and consequently air conditioning energy consumption which explains low EUI related to HVAC on this simulation.

Figure 16. End use percentage contribution to EUI

A study of daylight considering the dynamic parameter Daylight Autonomy (DA) was simulated using Daysim 3.0. The floor subdivision is presented in Figure 11. In general, every room shows regions with low illuminance as illustrated in Figure 17. Comparing rooms on the same floor, the highest percentage and uniform distribution occurs in front façade rooms due to the influence of street width. Rooms located on the bottom floor present lower illuminance and non uniform distribution. These characteristics tend to invert when the floor position is closer to the building roof, showing the influence of the surrounding built environment on daylighting access and consequently DA distribution. Rooms with only one window (the west rooms in Figure 17) show reduced illuminance and uniformity.

Figure 17. DA distribution comparison among rooms

The surrounding built environment, the street width and the glazing percentage are observed to have impact on the DA distribution.

5 CONCLUSION

This paper investigates the relationship of land use regulation, high-rise commercial building morphology and energy use intensity in the city of Belo Horizonte, Minas Gerais, Brazil. Stock modeling based on the SMAPU/PBH database and the field survey allowed identifying prevalent building morphology and its relation to the original city plan, land use regulations and construction codes. This prevalent morphology was the starting point to build a representative prototype model to study energy interactions.

Better understanding of building interactions is a key to improve building energy performance. This study shows evidence that the urban canyon and high-rise building
features could affect HVAC energy use intensity and daylighting access. Although vertical density may represent mutual building shading, reducing surfaces exposed to heat exchange leading to a reduction in HVAC systems; on the other hand, vertical density may represent a reduction in the access to daylight resulting in increased demand for artificial lighting.

High-rise buildings are noted to be strictly linked to their urban context. Being aware of this influence is a way of understanding high-rise building energy use intensity which could lead to interesting insights about energy saving opportunities that effect the built environment.

Encouraging building retrofits might be decisive for a timely energy use reduction in consolidated cities, where slow growth and an old building stock elevate the importance of existing building retrofits. Investigating energy-efficient retrofit measures focused on the Belo Horizonte existing building stock is the next step of this research.

ACKNOWLEDGMENTS
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ABSTRACT
This paper examines the impact of selected design parameters of a new community on its environmental performance. The design parameters include the type of the neighbourhood, its density, the location of the commercial center relative to the residential areas, in addition to energy efficiency of the overall neighbourhood. The environmental impact is considered in terms of the energy performance of the neighbourhood and its carbon footprint. Energy performance is measured as the balance between energy consumption, including building operations and transportation, and solar energy generation potential, assuming the integration of PV panels on all available roof surfaces.

The results indicate that while adopting high-energy efficiency measures can reduce the buildings’ impact by up to 40%, transport still has a large impact on the environment. Both the design of the neighbourhood and the distance to the business center have the largest impact on transport energy use and associated GHG emissions.

This study relates to a specific location and a range of design assumptions, however the methodology employed can serve as a template for evaluating design alternatives and their environmental impacts of new sustainable developments.

Keywords
Mixed-use communities; energy consumption; transport; building operations; GHG emissions; electricity generation potential.

1 INTRODUCTION
Building and transportation sectors account for large portions of energy consumption in urban areas, and for the associated Green House Gas (GHG) emissions. Buildings are responsible for more than 40% of global energy consumption, and about third of the overall greenhouse gas emissions, in both developed and developing countries [1]. On the other hand, the transport sector plays a central role in world energy use and emissions of GHGs. For instance, in 2004, transport energy consumption accounted for 26% of the global energy use [2]. This was associated with GHG emissions that constituted about 23% of world energy-related GHG emissions [3].

Current urban form, especially in North America, works against decreasing energy consumption by the transport sector. For instance, the total vehicle miles (kilometres) (VMT) in the US is expected to grow by 2% in the next 25 years, if the current pattern of urban expansion continues [4].

Travel pattern is dependent on many factors including distance to destinations (home, work, transit, green spaces/nature, as well as for daily activities (e.g. shopping, schools etc.). The distance factor affects significantly the decision of people to use a car or public transportation [5]. For example, in neighborhoods located farther from downtown, people tend to choose private transport over public transit due to shorter automobile routes, less developed transit infrastructure, and other factors such as time travelled or passenger comfort [6].

Car dependency reduction is an important and, in many situations, a feasible strategy to reduce cities’ overall material and energy flows [7]. Several studies were conducted to understand the effect of various neighborhood patterns on the mode of transportation. For instance an extensive study of 370 large American cities [8] shows that VMT can be reduced with compact communities, decreased number of roads, increased options/infrastructure for active transportation and community-based retail with restricted parking lots. In addition, land use coupled with transportation choices, have the potential to shape travel behavior and reduce the dependency on fossil fuel [4].

An extensive literature survey indicates that most of the existing studies concentrate on one or the other of these sectors (i.e. transport or building operations). Those research that tackled the two sectors, do not explore the effect of various parameters of buildings and neighborhood design on the overall energy consumption (e.g. [9, 4, 10]). There is need therefore to understand the effect of design parameters of a neighborhood on the energy usage for building and for transportation, and to quantify this effect, to serve as a guide for future efforts and policies.

This paper explores the effects of some design parameters on the energy use and GHG emissions of a large-scale solar community. The studied parameters include: The energy efficiency of the buildings, the location of the central business district (CBD); density of the community, and the nature of the neighborhood (residential as
and roof insulation of 7 m²k/W and 10 m²k/W, compared to a mixed-use). The response variables are energy performance of the neighborhoods and GHG emissions. Energy performance refer to the total energy consumption (for buildings’ operation and for transport) and renewable energy production potential of the neighborhood. The paper aims at giving an insight on the most significant environmental impacts of different variables, and to understand how modes of transportation compare to energy use in various community types.

2 METHODOLOGY

The paper studies a large-scale neighborhood assuming a land area of 64 hectares. This hypothetical neighborhood is specially designed for the purpose of this study, based on various design considerations as described below (section 2.1). The design takes into account the density in term of number of people and number of residential units per acre. The pilot location of the study is Calgary (Alberta, Canada; 52° N) representing a mid-high latitude, cold climate zone.

A total of 24 scenarios are designed and studied to analyze the effects of various parameters on energy performance (energy consumption and energy generation), and GHG emissions. As mentioned above, those parameters include the density level, the type of neighborhood, the energy efficiency of the neighborhood and, the location of the central business district (CBD).

A low density is first designed, according to the commonly used density in the area (outskirt of Calgary), around 6 units per acre (u/a). The density is then doubled for the second alternative. Doubling the density allows only reaching the minimum population to support a mixed-use community (e.g. jobs and business) [11], and therefore is still not conductive to high-density community.

Two performance levels are designed, both of them assume higher efficiency measures than prescribed by the Canadian national code. The advanced performance level assumes residential building designed for R2000 standard [12]. R-2000 Standard homes are about 30 percent more energy efficient than conventional new homes and must achieve a minimum energy efficiency rating of 80 on the EnerGuide rating scale [12]. Energy loads of commercial buildings are based on reference commercial buildings developed by the US department of Energy [13]. The input parameters for the building models are derived from several sources, some of which are determined from ASHRAE Standards 90.1-2004, 62.1-2004, and 62-1999 [14, 15, and 16] for new construction.

For the high energy efficient scenarios, buildings are designed with the objective of achieving net zero energy status [17]. High performance building envelope (wall and roof insulation of 7m²k/W and 10m²k/W, respectively; triple glaze, low-e argon fill windows, and airtight construction) is assumed in all types of buildings. High performance building envelope can significantly improve the energy efficiency of buildings. In addition, the design of residential units assumes optimal passive solar principles [18]. Commercial buildings assume the same building envelope characteristics as residential, while energy consumption is determined based on lighting and electrical specifications of the National Energy Code of Canada for Buildings [19].

Two neighborhood types are analyzed, for each of the density levels and the performance level mentioned above, a mixed-use development (mixed of residential, commercial and institutional) and a residential neighborhood consisting of houses and apartment buildings.

The effect of the average distance to the central business district (CBD) is also analyzed. Two different scenarios are studied according to the type of the neighborhood. For the mixed-use neighborhood, the CBD is within the community, at the center, or at the edge of the development. For the residential neighborhood, four average distance are studied, 5km, 10 km, 20 km and 30km. The location of the center is expected to affect the number of kilometers traveled per day and the transport mode (i.e. use of car as compared to public transport) and therefore the energy used by the transport.

2.1 Neighborhood Design

Overall design considerations

The neighborhood is designed based on guidelines of traditional neighborhood developments (TND), on CMHC fused grid, and various design guidelines of shaping sustainable neighborhood. A TND, known as a village-style development, includes a variety of housing types, a mixture of land uses, an active center, a walkable design, and often a transit option within a compact neighborhood scale area [20]. The site layout is based on the CMHC fused grid [21]. The fused grid can be a good basis for the design of a new energy efficient sustainable neighborhood, because it is designed to allow mixed use, densification, and efficient public transportation.

The land partition employs a mixture of fused grid and TND designs. The built area constitutes 64% of the land, streets use about 28%, and the remaining 8% represents the green area. Residential area forms about 80% of the total built area, with the remainder (approximately 20%) assigned to viable commercial space and civic functions. The residential buildings include single-family detached houses, attached houses, and mid-rise apartment buildings (3 to 5 floors). The main commercial amenities include office buildings, retail area and grocery store, and a primary school. Figure 1 presents the overall neighborhood design associated with a low-density scenario.
Figure 1. Low-density neighborhood design (a) Isometric view, (b) Perspective showing the CBD.

Buildings design assumptions

Residential Buildings

- Houses
  Two types of houses are designed, a detached house of a total of 180m² and attached houses of 120m². The area is based on average detached and attached houses in Calgary [22]. Two-story house design is adopted for both attached and detached houses, accommodating a single family of 4 members. The houses are designed to optimize passive solar design. For instance the ratio of south façade to the east and west façades is about 1.3, shown to be within the optimum range for passive solar design in northern climate, to maximize passive solar gains in winter [18]. The South windows form about 35% of the south wall.

- Multistory
  Low-rise multistory buildings (3, 4 and 5 stories) are considered in this study. Apartments have a floor area of 110m² (average apartment size in Canada). A family of four members is assumed to occupy these apartments. Similarly to the house designs, an aspect ratio – ratio of equatorial-facing façade to perpendicular façade – of about 1.3 is employed in all apartments. This ratio is relevant only for the equatorial-facing apartments; however it is generally adopted in this study to simplify the design and analysis of the multistory buildings.

Table 1 summarizes the type of residential buildings, their unit area as well as the total area associated with each of these types, for the low-density neighborhood.

<table>
<thead>
<tr>
<th></th>
<th>Detached</th>
<th>Townhouse</th>
<th>Duplex</th>
<th>Apartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Units</td>
<td>160</td>
<td>296</td>
<td>72</td>
<td>796</td>
</tr>
<tr>
<td>Total Area (m²)</td>
<td>28800</td>
<td>35520</td>
<td>7920</td>
<td>87560</td>
</tr>
</tbody>
</table>

Table 1: Residential unit distribution in a low density neighborhood

Commercial buildings

The total area allocated for commercial buildings is around 20% of the total built area. Below is a summary of the main design considerations for each of the commercial buildings employed in the study. Table 2 summarizes the commercial buildings distribution and areas in the low density neighborhood.

- Office Buildings
  No guidelines are available to assist in determining the office area needed in a neighborhood with a given population. This is due to the large number of factors that should be considered in planning office areas for a development (e.g. type of business, area required for a business, local employees, etc.). For this neighborhood three mid-size 3-story office buildings of 3200m² each, are assumed, for the low-density neighborhood.

- Primary school
  The single story school building is designed to specifications for a primary school serving a population of 2500 persons for the low-density housing and 5000 persons for the higher density. This is based on an estimated number of pupils and an average area of 11 m² per pupil [11].

- Other commercial buildings
  The supermarket and retail buildings are designed as single storey buildings. While average retail in Canadian cities can be estimated on per capita base, there is no documentation on an acceptable size of a supermarket or retail area for a specific population.

<table>
<thead>
<tr>
<th></th>
<th>Office</th>
<th>Retail</th>
<th>Supermarket</th>
<th>School</th>
</tr>
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<tbody>
<tr>
<td>Total Units</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total Area (m²)</td>
<td>9600</td>
<td>4800</td>
<td>2400</td>
<td>4000</td>
</tr>
</tbody>
</table>

Table 2: Commercial buildings distribution and areas in a low density neighborhood

Roof Design

The roof design of houses (both attached and detached) consists of a gable roof, with 45° tilt angle. A building-integrated photovoltaic (BIPV) system is assumed to cover the complete south facing roof surface. The tilt angle of 45° is selected for being within the optimal range.
for the studied location (Calgary, latitude 52°N) corresponding to latitude ±10° [23].

The roof of multistory and commercial buildings is designed as saw-tooth, where PV is integrated on the south areas, at a tilt angle of 45°. The saw-tooth design is assumed to limit the roof height of buildings of large plan area. North facing slopes are specified to allow a distance between panels, which reduce shading on the PV integrated areas (i.e. ca 1.5 times the height of shading panel [18]).

2.2 Simulations

The neighborhood energy performance is simulated using EnergyPlus [24] and Openstudio [25]. EnergyPlus enables to take into account the effect of neighborhood design on energy performance such as mutual shading between buildings. SketchUp/OpenStudio is employed to generate geometric data for EnergyPlus. Each residential unit is modeled as a single conditioned zone. Heat pump and chiller are assumed in all scenarios, to supplement the heating and cooling for all buildings. All models account for the variation of performance with outdoor air temperature and partial load. The weather files of the building simulation program EnergyPlus are used for the simulations (EnergyPlus, Weather Data Sources). The weather data file, which is based on CWF/C – Canadian Weather for Energy Calculations, provides hourly weather observations. The data collected for this year includes hourly values for solar radiation, ambient temperature, wet bulb temperature, wind speed, wind direction and cloud cover.

2.3 Transport analysis

The analysis of energy consumed by transportation and resulting GHG emissions should take into account various socio-economic and geographical characteristics. The analysis is conducted using a spreadsheet-based model developed by CMHC’s IBI group [26]. The model allows estimation of the household automobile daily personal vehicle km traveled (VKT) and transit passenger km traveled (PKT) based on a number of household and geographical inputs. In addition, the tool calculates the yearly GHG emission (in kg CO₂) associated with each mode of transport.

Inputs variable include the number of residential units, type of neighborhoods, length of streets and their types, number of intersections and distance from the central business district (CBD).

2.4 GHG Emission

GHG emission is employed to measure the environmental effect of the neighborhood. GHG calculations for buildings are based on the annual net electricity balance (electricity use minus renewable electricity generation). GHG emissions by transportation constitute a part of the transportation analysis, below. The GHG factors for the Alberta electricity grid (the pilot location of this study) are calculated based on the total electricity production by utilities in the province, total fossil fuel use for electricity generation by utilities, and energy and carbon content of the fossil fuels combusted [27, 28]. The electricity generation system in Alberta is currently heavily reliant on fossil fuels (coal and natural gas). The GHG intensity of average electricity generated in Alberta (in the year 2013) and natural gas are 0.71 and 0.19 kg CO₂ eq/kWhₑ respectively.

3 RESULTS AND ANALYSIS

Total energy use (electricity) is determined for each building type, and then for the neighborhood as a whole, taking into account the effect of mutual shading among buildings. These results are compared with the overall potential of the neighborhood to generate its own electricity using integrated PV systems on available roof surfaces. The energy performance is established for each of the scenarios detailed above.

The energy use associated with various mode of transport is estimated in kWh/VKT and kWh/PKT based on the available data [29, 30]. GHG emissions by building operations associated with each of these scenarios are assessed. In addition, GHG emissions by transport is estimated, employing Tools spreadsheet [26].

Results are presented below, in terms of energy use and GHG emissions and the effects of the design parameters on these response variables, are analyzed.

3.1 Energy consumption

Figure 2 presents the energy use for transport and for buildings operation of the mixed-use communities, for the scenarios combining level of densities and energy efficiency. The graph shows that communities of high-energy efficiency buildings require 40% less energy for building operations as compared to those of lower efficiency standards (based on R2000 standard, which consume 30% less energy than traditionally built houses). In all cases energy use for transport exceed significantly the building energy consumption.

The change in density, for the studied scenarios, has no significant effect on the overall energy consumption of the neighborhood. For instance, the energy consumption for building operation and for transport, on a per capita basis is not significantly changed (less than 3% difference). This can be attributed to two main reasons: 1) the increase in density is not substantial as to render the development into a highly densified urban area and 2) the number of vehicle per household is remained unchanged.

Energy generation potential for the low-density, high performance community can cover around 90% of the energy used for the buildings operation. This potential is less for all other neighborhood covering about 50% for the higher density, lower performance community.
Figure 2. Energy performance for building operations and transport for the MU communities, associated with a central CBD.

Figure 3 presents the energy consumption for transport for all residential communities, with the CBD located at various distances from the residential areas. The purpose of the residential neighborhood is mainly to detect the effect of distance on transport. The MU scenario with the central CBD (located at a distance of 0.5km) is also included for the sake of comparison.

The graph establishes that the energy consumed for transportation is increased significantly with increased distance from the CBD. The transport energy in a neighborhood with large distance from the CBD (at 30 km) is almost double of that needed for a mixed-use community (where the CBD is at the center of the development).

3.2 Greenhouse Gas Emissions

This section presents the GHG emissions in (CO₂ kg eq) for the studied scenarios, and summarizes the impact of the design parameters on the emissions.

Overall GHG emissions

Figure 4 presents the overall GHG emissions of all the studied scenarios, plotted according to the location of the CBD. Distance from CBD has a significant effect on the daily distance traveled in private and public transport (VKT and PKT) and therefore on the GHG emissions. This is discussed in more detail below.

As expected higher performance neighborhood has the least GHG emissions, independently from the location of the CBD. The graph shows that emissions by the mixed-use community are not much affected by the location of the CBD (within the community), since the average distance is still less than 1 km. Moreover, the mixed-use community performs similarly to the residential community with a close CBD (of 5 km).

The comparison between high density and low density does not take into account the values on a per person basis. In fact GHG emission per person does not change significantly between higher and lower density scenarios.

Figure 4. Overall GHG emissions of all the studied scenarios, according to the location of the CBD

Figure 5a presents the comparison of GHG emissions by the total neighborhood for each scenario, to the GHG of the mixed-used scenarios with central CBD, which serves as control. The reason the high performance neighborhood has higher ratios is due to the fact that buildings operation energy in these scenarios is reduced by 40% as compared to the lower performance neighborhoods. This make the GHG emissions by transport more significant, as compared to lower performance neighborhoods.

Figure 5b presents the comparison of GHG emitted by transport as compared to the MU central CBD scenario. The comparison is made only for the low-density neighborhoods. It is noted that in term of GHG emissions by transport, the comparison to the MU central CBD scenario is similar, across all scenarios.
Moreover, a comparison of the performance of various neighborhoods in terms of building operation GHG emissions is conducted. The impact of PV electricity generation in mitigating the GHG emissions is also considered. The comparison indicates that, considering the effect of PV generation in mitigating the impact of building operations, the GHG emissions of high efficiency, low-density MU communities are only 17% of that of the same community but with lower building efficiency.

Effect of density on GHG emissions

Figure 4 above shows that density has significant effect on total GHG emission, obviously because of the larger population. The comparison of the results on per person basis indicates however that density has no significant effect.

Effect of CBD on GHG emissions

In the mixed-use neighborhood, the CBD is located within the community, with 2 different scenarios: in the center of the development and at the edge. The average distance from the residential area to the CBD is 0.5 km for the central CBD and 1 km for the other MU scenario. Consequently, the VKT and PKT for these two cases do not change significantly, and so is the level of GHG emissions associated with transport (see Table 3).

The residential neighborhoods are studied at various distances from the CBD (5km, 10km, 20km and 30km). This has significant effect on the VKT and PKT per household (hh). For instance, the daily distance traveled is increased by 40% when the CBD is at a distance of 30km from the neighborhood, as compared to a close CBD (at 5km distance) (see Table 4). Consequently, the GHG emissions associated with this travel behavior are increased significantly. Table 4 summarizes the daily distance traveled for each of those scenarios, and the corresponding GHG emissions.

3.3 Effect of transport relative to building operations

The study shows that transport has an important effect on the neighborhood capacity to limit CO₂ emissions. For instance, buildings in high-energy efficiency communities reduce carbon emissions by about 40% as compared to those communities designed with upgraded energy measures (R 2000). In addition, high energy performance residential buildings can offset 95% of the total GHG emissions by buildings through the generation of electricity from PV systems. Transport behavior, and associated emissions, are still however unchangeable, especially if compared on per person basis. Figure 6 shows the comparison between GHG emissions corresponding to high and lower energy performance neighborhoods, associated with transport and building operations.
This factor presents an influential parameter and therefore requires a systematic investigation, as well. Another important factor is the average distance to transit, which in this study is assumed unchanged. The number of jobs within a specific distance (5km, as specified in IBI 2010’ Tools), has an important effect on the distance traveled, and therefore requires a systematic investigation, as well. Another important factor is the average distance to transit (distance from home or work to nearest rail station or bus stop). This factor presents an influential parameter and has an important impact on the mode of transport [30]. The tool provided by CMHC [26] enables to determine the effect of this parameter. The main conclusions found in the study are discussed in the following.

Mixed-use communities, which include residential, employment, and retail/services in close proximity to each other, has the potential to reduce significantly the distance traveled per day and therefore the energy usage and associated GHG emissions.

For the residential neighborhood, the effect of the distance from the central business district (CBD) is very significant. The increase in GHG emissions of a neighborhood with a distant CBD (30 km) can reach 40% more than a scenario with the closer CBD option (<5 km).

Comparison between energy use for transport and for building operations indicates energy consumption for transport is much more significant than the energy required for the operation of commercial and institutional buildings in a mixed-use neighborhood. This is especially due the possibility of reducing energy consumption significantly by adopting various energy efficiency measures.

The effect of density, in this study is not very noticeable, especially on per person basis, due to the fact that the increase in the density is relatively not substantial (as compared to highly urbanized areas). As mentioned above the threshold density at which the individual transport is reduced should be investigated. Another factor that will affect the density analysis is also the number of vehicles per household, which in this study is assumed unchanged.

Energy usage and GHG emissions are greatly affected by the mode of transport, and the design of neighborhoods. Although net zero energy neighborhoods are within reach, when only considering buildings design and operation, transport can change the whole equation, when it is taken into account. Therefore a substantial change to the methods of transport, and /or to the fuel used in transportation should be targeted in order to reach net zero emission communities. This should be coupled with adopting design strategies that increase walkability, while increasing potential of building to generate their own energy from renewable sources.

Although the study presented in this paper relates to a specific location and some design assumption, the methodology employed can serve as a template for evaluating design alternatives of new sustainable developments.

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Simulating natural ventilation in large sports buildings.

Prediction of temperature and airflow patterns in the early design stages.

Antonio D’Aquilio¹, Rusne Sileryte¹, Ding Yang²-¹, Michela Turrin²-¹

¹ Faculty of Architecture and the Built Environment, Delft University of Technology
Delft, The Netherlands
{a.daquilio, r.sileryte, m.turrin}@tudelft.nl

² State Key Lab of Subtropical Building Science, South China University of Technology
Guangzhou, China
D.Yang-2@tudelft.nl

ABSTRACT
In large sport’s buildings, a big part of energy can be saved by providing natural instead of mechanical ventilation. However, additional challenges arise while controlling airflow and temperatures in different zones. These measures highly depend on the shape, construction and ventilation openings, which are mostly decided in the early design stages. Computational optimization can support these early stages of design, but needs to be performed in efficient ways. In this respect, the project proposes rapid assessment of temperature and airflow patterns using customized Grasshopper components, which would be able to evaluate a given model using CONTAM and EnergyPlus software as simulation engine. The proposed method integrates these simulations within an environment, which is familiar to architects and is largely used for parameterization of design in its early stages. A case study (Jiangmen Sports Center, Jiangmen, China) is used to test the developed process for a large indoor sports hall.

Author Keywords
Natural ventilation; early design stage; large volumes; sports buildings; rapid assessment; CONTAM; EnergyPlus; Passive cooling, Building Envelope, Building performance and simulation, Thermal comfort.

ACM Classification Keywords
I.6.4 SIMULATION AND MODELING (Model Validation and Analysis).

1 INTRODUCTION
Based on the emerging climatic changes, reducing energy consumption of buildings has become an important issue within the last decades. Large sport buildings such as indoor stadiums, swimming pools, arenas etc. are hefty consumers of energy used for ensuring high comfort levels for both athletes and spectators. While a big part of energy can be saved by providing natural instead of mechanical ventilation, in case of large volume buildings additional challenges arise when it comes to controlling airflow and temperatures in different zones. These measures highly depend on the shape, construction and ventilation openings of such large envelopes, which are mostly decided in the early design stages. Therefore, availability of rapid simulation of temperature and airflow patterns may lead to informed decisions, which tackle important issues related to both indoor comfort and energy performance.

Detailed assessment of natural ventilation, such as Computational Fluid Dynamics (CFD) analysis, can give detailed information on the airflow and temperature patterns in large indoor spaces, but require long computational time to achieve convergence; while faster calculation methods such as Airflow Network (in software like CONTAM) often lack thermal analysis. On the other hand, energy simulation software mostly assumes constant ventilation rates, which do not reflect known dependencies on indoor-outdoor conditions and ventilation system operation [1]. However, output for both air temperature and airflow rates are necessary for determining the passive control of indoor comfort and the related energy saving potential. Especially, in the early stages, this optimization needs to be performed in a fast way.

This project proposes rapid assessment of temperature and airflow patterns using a series of customized Grasshopper components, which would be able to evaluate a given model using CONTAM and EnergyPlus software. The building model to be analyzed is divided into smaller zones in order to retrieve detailed temperature and airflow results. The proposed method integrates these simulations within an environment, which is familiar to architects and is largely used for parameterization of design in its early stages.

The swimming pool of the Jiangmen Sports Center, in Jiangmen (China) is used as case study to test the proposed method for a large swimming pool. The outcomes of rapid simulations are validated using alternative software commonly used for assessing natural ventilation within buildings.
2 PROPOSED METHOD

The proposed method has been developed by an interdisciplinary team at TUDelft, composed by staff members from the Chairs of Design Informatics and Climate Design at the Faculty of Architecture and the Built Environment. The need for a fast assessment of the indoor thermal environment in the early stage of design led to the development of a method for coupling thermal analysis and airflow calculations. The goal is to retrieve results of the indoor microclimate in large volumes, when passive conditions and natural ventilation need to be simulated.

Standard energy simulations based on thermal analysis only investigate the indoor temperature assuming well-mixed air temperature for an entire volume (thermal zone) [2]. When designing large volumes, this assumption cannot be reliable, especially if the goal is to optimize the indoor comfort in specific parts of the volume (i.e. where spectators and athletes are). Therefore, ways to predict the indoor microclimate of large volumes were investigated, with a focus on the subdivision of a large space in sub(thermal)-zones.

A thermal zone is defined as an indoor space with similar thermal requirement, where transient calculations for the heat balance of both internal and enclosing surface temperatures are calculated and solved for each time step [3]. These calculations of the heating and cooling loads are affected by the rate at which air is infiltrated into the zones. This rate is normally set as parameter dependent on the building program. On the other hand, ventilation rate in naturally ventilated building is highly dependent on the relationship indoor-outdoor thermal environment.

The method proposed in this paper tries to quickly balance the airflow and temperature calculations. It is based on the well-known “onion” approach for convergence between thermal and airflow analysis [4]. In the onion approach, for each time step, the thermal analysis results are used for the airflow calculations. This process is iterated for every time step until convergence is found. However, differently from the typical onion approach, the proposed method iterates for the whole analysis period. During the first step, the thermal analysis runs for the whole analysis period (e.g. hourly month simulation), and the results (air temperatures for every zone) are used to calculate the airflow rates. In the second step, the new air temperatures are calculated based on the first airflow simulation. This process is iterated until the new iteration has small difference from the previous one. The major difference between the two approaches is that the computational time needed to achieve convergence in the proposed approach is shorter compared to the onion approach used in other simulation software, such as EnergyPlus [5].

Commercial software embed this approach. For example, the Design Builder software (DB) calculates airflow rates by setting an airflow network simulation and coupling the flow results with thermal results. The limitation is that the results are not related to specific locations within the indoor environment. In order to simulate the internal temperature distribution, it is possible to run a CFD analysis of the design, based on the airflow rates and the other boundary conditions calculated by other software[6].

2.1 Choice of software

The overall purpose of creating a rapid assessment tool for evaluating design in its early stages requires tools to be easy to use and integral to a platform, which is familiar and comprehensible for architects and allows evaluations of various design options without rebuilding the models in a different software. Moreover, the proposed framework needs to be easily adjustable for specific cases. Therefore, Grasshopper plugin (GH) for Rhino has been chosen as an intermediary between parametric modelling and simulation software.

CONTAM 3.1 has been chosen as a software for calculating airflow rates to assess the adequacy of natural ventilation based on income airflows, exfiltration, and zone-to-zone displacements in building systems driven by wind pressures on the exterior of the building, and buoyancy effects induced by air temperature difference [7]. The software is able to determine the ventilation rates over time and distribution of ventilation air within building zones. The software was also chosen due to the straightforward control possibility while launching a simulation through command-line interpreter. It is free of charge and available for Windows and Linux platforms.

The part of thermal simulation has been commended to EnergyPlus (E+) due to its high level of calculations, with the possibility of performing transient heat balance simulations, multi-zone modelling and hourly time steps [8]. Moreover, its input and output data structures are specifically designed to facilitate third party modules and interface development, which makes it easier to integrate into the generic workflow of Grasshopper. The software is free, open-source and cross-platform.

The connection between GH and E+ is done through the Honeybee Plugin for Environmental Analysis (GPL) started by Mostapha Sadeghipour Roudsari, which also connects GH to Radiance, Daysim and OpenStudio for building energy and daylighting simulation [9].

2.2 System framework

The overall scheme of computational system framework can be seen in Figure 2. It is explained in details hereafter.

The process starts with the definition of a simplified model of the design, which is then used to construct zones for thermal and airflow analysis. Outputs of both analysis are then coupled until convergence (balanced airflow rates and temperatures) is reached. Finally, the results can be used for the assessment of thermal comfort performance.
Simplified model

The overall iterative computational process for optimizing comfort levels based on temperature and airflow predictions is performed on a 3D model of the building. Such model is highly simplified as compared to the complexity of the building, even in early design. Simplification is needed in order to ensure reasonably short computation time. In particular, the computation time is pertained to the number of faces in the simplified geometry – the lower amount of faces, the shorter computation time. Curved surfaces need to be approximated as much as possible to keep the balance between running time and oversimplifying geometrical features, which have impact on performance values. The relationship between the number of faces and overall computation time can be seen in table 1.

Thermal analysis

In order to perform thermal analysis, building volume needs to be separated into thermal zones based on zones of interest (e.g. spectator zone vs. playground), physical barriers (e.g. walls and floors) and educate guess on different thermal conditions. The partitioning is performed manually.

The thermal zones besides the simplified geometry hold provided or intended material properties, including glazed surfaces. Thermal analysis is performed by E+, providing an average temperature (to be considered to be in the middle of the zone) in each of the zones for the desired period on hourly basis (or other step size defined by user).

Airflow analysis

Airflow analysis is based on an airflow network simulation, i.e. the model is restricted to a single forced air system. Similar to thermal analysis, an analyzed building is represented by a network of zones connected by airflow paths. Zones are discrete volumes of air within which mass is conserved with uniform temperature and pressure values. Air moves between zones along airflow paths with pressure-dependent resistance to airflow [10].

Modelling of airflow zones are based on a different simplification method than thermal zones, however, influenced by the latter as well. The general differences between the two are conditioned by the different size and shape. Airflow zones are modelled as equal size voxels composing the whole building volume. Each voxel inherits its thermal properties (temperature) from the thermal zone it belongs to and is aware of its neighboring voxels and possessed openings (airflow paths). Openings are modelled either as fixed size physical openings towards outside, provided by the user, or virtual openings between neighboring voxels which have the size of an entire voxel face.

Voxel size is decided by the user bearing in mind the balance between desired resolution of the results and computation time, since smaller voxel size yields longer computational time. Smaller voxel size means more accurate geometry definition and therefore more accurate

Figure 1. Left: Thermal zones colored according to temperature values, arrows showing airflow directions and relative amount of air in between neighboring thermal zones. Right: Airflow zones colored according to temperature values, arrows showing airflow directions and relative amount of air in between neighboring airflow zones.
results. When complex shape buildings are simulated, the voxel grid definition is important in approximating at best the shape of the building envelope, and therefore getting more accurate results, in terms of airflow.

The relationship between the number of voxels and overall computation time can be seen in Table 2. The voxel grid is generated automatically using a customized Grasshopper component. The airflow simulation is performed by CONTAM software and provides the air exchange rate between all neighboring voxels and the outside environment in kg/s (then translated in m³/s). Air change rates are calculated as the total flow of outdoor air into the building divided by the floor area. As the process is still under development, the effect of wind façade pressures on ventilation performance now is not taken into account (but possible future implementation).

Coupling of thermal and airflow analysis
As mentioned previously, common thermal analysis assumes constant ventilation rates, which do not reflect an actual situation for ventilation, while airflow analysis is based on provided temperatures. Since indoor temperatures are influenced by the air exchange within the building and outdoor-indoor environments and the air exchange is determined by the air density, (i.e. temperature differences in different zones), both systems need to be coupled and analyzed simultaneously. In order to achieve this, the values are looped in between both until convergence is achieved.

The loop starts with thermal analysis assuming constant ventilation and air mixing between the thermal zones. The simulated temperatures are then provided for the airflow analysis. Whereas airflow simulation provides air exchange rates between the thermal zones. Since airflow zones are of different geometry than thermal zones, the obtained values are aggregated to express air exchange rates between them and ventilation values for the zones, which possess openings towards outside. Figure 1 shows the difference between thermal and airflow zones of a simple rectangular volume. The transmission of values between the airflow and thermal simulations is performed until convergence of desired tolerance is reached. Alternatively, a fixed number of cycles can be chosen dependent on the desired accuracy of the results.

In order to loop them, the thermal and airflow simulations have to be consistent with each others. Specifically, though zone areas and the number of zones may be different between the thermal and airflow models, the total building area is consistent between the two. Moreover, both thermal and airflow simulations share the same weather data for the specific location, which contain outdoor temperature, outdoor humidity, and wind direction and speed. The weather data is obtained from the E+ weather file online database [11].

Performance values
The method allows obtaining values relevant to assess thermal comfort.

Specifically, the output from the natural airflow analysis can give an overall estimate of the airflow behavior inside a large space, predicting the capability of the design to deliver a sufficient amount of air changes (ach) in relation to the specific micro-zone requirements within the indoor space. For example, for a sport building, the requirements for air changes per hour related to indoor air quality differ between the spectator area and the area where the athletes perform.

Moreover, the thermal analysis of the macro-zone is done by considering the ventilation rate within the zone, and therefore the performance of passive cooling of a design can be assessed. The useful outputs of this analysis are operative temperatures (°C) and relative humidity (%). Operative temperatures, together with air speed (m/s), for each macro-zone can be used to predict the thermal comfort level. This further assessment can be done by using a thermal comfort model, in which these parameters play a role in defining comfort. Since the focus of this research is the way of delivering a computational process for indoor microclimate simulation, the final assessment of estimating thermal comfort levels is not tested on the case study.

2.3 Computation time
As mentioned, the method aims at rapid assessments of temperature and airflow patterns for early design. Computation time is highly dependent on the accepted level of simplification and required accuracy. Since the tool supports the identification of the preferred design direction and the ranking of chosen designs according to their performance values, rather than deliver detailed assessment. Therefore, high accuracy is generally a less important factor than short computation time.

<table>
<thead>
<tr>
<th>No. of faces</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>26</td>
<td>47</td>
<td>82</td>
</tr>
<tr>
<td>No. of voxels</td>
<td>1636</td>
<td>845</td>
<td>455</td>
</tr>
</tbody>
</table>

Table 2. The relationship between the number of voxels and the computation time for a single airflow simulation. Numbers are based on the case study described in section 4.

<table>
<thead>
<tr>
<th>Voxel size(m)</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time(s)</td>
<td>798</td>
<td>216</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 1. The relationship between the number of faces and the computation time for a single thermal analysis. Numbers are based on the case study described in section 4, where four thermal zones are calculated.
The tables show dependencies between the level of simplification and computational time required for one simulation. The tests were run with an Intel® Core(TM) i5-330M CPU @ 2.80 GHz, 8 GB RAM, 64-bit OS.

The overall computation time for the performance assessment is also dependent on the number of cycles required for the convergence between the results simulated by CONTAM and E+.

### 3 VALIDATION

In order to test the reliability of the proposed computational method, a test on a simple design case was performed and compared to the results from the same case modelled in the DB software, known as a reliable tool for design performance assessment [12].

Specifically, the comparison was made on two levels. One is the overall airflow rates and temperature of the design case along the whole simulation period (averaging the zones temperature and total results from the developed process). The other is on detailed level, for one snapshot of the simulated period. The results are compared against the CFD module within the DB software, looking at the temperature and airflow distribution within the indoor space. In this way it is possible to tell to what extent the results coming from the proposed method can be used for design evaluation.

The design case used for validation is a “box-like” space, with a 6x6m floor, and height of 10m. The bottom part of this construction is completely glazed in all façade orientations. Two ventilation openings are modelled, one at the bottom part of the west façade, the other one at the roof. The constructions of the design case were set the same as in the DB model. The design case was divided into 6 horizontal sub-zones for thermal analysis and 200 sub-zones for airflow network analysis. The simulation period was set for the whole month of May, with no closing hours for the ventilation openings. The number of coupling iterations was set as 10. The outdoor condition was set on Guangzhou (China). In order to account for hourly temperatures, the thermal analysis derives this data from the E+ weather data file (EPW).

#### 3.1 Temperature results

In Figure 3, the results of the proposed method and the ones from DB are compared hour-by-hour. As it can be observed, the difference between the temperature results from DB and the average temperature of the sub-zones defined in the proposed method, is generally small (max 2°C). Moreover, it is clear that the general trend of the indoor temperature under natural ventilation conditions has convincing results. In Figure 4 the temperature distribution within the design case is compared to a CFD analysis done in DB. The boundary conditions (average indoor temperature, surface temperatures, airflow rate) were set as the ones retrieved from the E+ model. The comparison shows similarities in terms of temperature gradient. Temperature distribution of the upper part has slightly higher magnitude in the developed approach. The results, especially at the zone close to the inlet opening shows a good match with the CFD analysis.

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**Figure 3.** Left: CFD analysis done in the DB software. Right: Zone temperatures and airflow distribution with the developed approach.
3.2 Airflow results

In terms of airflow simulation, the following graph shows the comparison of the total air mass entering and leaving the space (ach).

As for the temperature fluctuations, also the airflow rates can be comparable with the ones retrieved from DB. The overall behavior of the two methods generally has similar results, with small distances in some cases (max 0.4 ach).

However, at the detailed level, the flow pattern appears to have relatively greater distance from the CFD analysis, apart from the flow pattern at the ground level.

The main conclusion that can be derived from this comparison is that the proposed model is able up to a certain extent to predict the thermal behavior of the microclimate inside a large space, while not able to completely predict the airflow pattern (apart from a general trend). The reason behind this is that CONTAM does not take into account complex turbulence problems, which can however be accurately simulated by CFD.

More testing is needed to entirely assess the extent at which this approach can lead to reliable results to be used in early stage of design.

4 CASE STUDY

The method is being tested also on a real project (currently under detailed development) located in Guangzhou (China). This case study has been developed together with team from the State Key Lab of Subtropical Building Science, South China University of Technology and from Sun Yimin Studio. The case study is a building of the Jiangmen Sports Center, a large swimming pool that will be used for sport events of national level.

The idea of this test is to retrieve results from the analysis that can be used to improve the early design concept for natural ventilation and thermal comfort goals.

In this case, the relationship between building shape and ventilation opening size is investigated and the results analyzed.

4.1 Design concept

Indoor thermal comfort in sport buildings is a complex subject, depending on the level at which the building is used and on the related requirements that need to be satisfied. For high-level sport events, the most used strategy to deliver indoor air quality and thermal comfort is the use of mechanical systems for cooling, heating and ventilation. The main reason for this is the generally strict normative in terms of sport events and human comfort. However, the strategy adopted in this case study, is to improve the design in terms of passive climate control, in case of low level events (e.g. times during the year when the building is only used for small competitions and training). Passive cooling and passive ventilation would be an efficient way of delivering comfort for this type of occupancy level.

The main goal is to investigate the indoor microclimate in which both spectators and athletes would be standing, according to the specific (passive) design. The building, located in a hot and humid climate, is naturally ventilated during the day (from 8:00 to 20:00). Ventilation occurs thanks to the operable windows located on the sides and the operable skylights. All openings can be completely open for ventilation.

For this investigation, the number and size of operable skylights are the parameters that were set in order to investigate two different design proposals.

The main air displacement principle used in order to deliver natural ventilation is the stack effect, induced by the shape of the large roof.

In order to retrieve a faster feedback of the design efficiency, the simulated period was set as 31 days (month of May).
4.2 Model simplification

The building model (built in Rhino/GH) is simplified in order to have faster results for thermal analysis. The double curved geometry of the roof and the curved facades were meshed in a medium mesh size.

The building is divided in sub-zones for thermal analysis. Since the focus of this design exploration is the zones where spectators and athletes share the same space, and since the neighboring zones are not consistently affecting the energy balance of the main zones, the rest of the building was cut-out of the simulation (Figure 7). The surfaces shared with the excluded zones were set as adiabatic. The total number of mesh faces of the simulated zones is 245.

4.3 Results

The results of the investigation done on the case study are reviewed separately for the two simulated design options. In the investigated case study, the number of iterations used to achieve convergence was 6, as it was observed that no major changes (airflow rate and temperature values) would occur for the specific case after the 6th iteration.

Design case 1

The first design configuration has 4 operable skylights and operable openings with height of 1.5m on both side facades. This first thermal and natural airflow analysis show an uneven distribution and potential differences in comfort levels within the large indoor volume.

As it can be observed in Figure 8, the zone close to the south facade (right side in figure) shows the highest temperature among all the zones. Generally, the sub-zones show high temperatures, especially considering the south zone and related thermal comfort level for the spectators.

The reason for this is the number of skylights and their dimensions, which allow for a large amount of solar radiation, causing local overheating. The buoyancy driven natural ventilation, entering the side facades and leaving at the top roof, is not sufficient at lowering the air temperatures in every zone, as it might be expected.

Design case 2

In this design option, the building shape and constructions are kept stable, while the number of skylights is decreased to 3 and their dimensions reduced by half. The total openable area of the roof is therefore also reduced by half, while the total ventilation openings at the sides are left unchanged.

As expected, the thermal distribution appears to be generally similar to the first case, with the south zone having higher temperatures than the others.

The airflow result (shown in Figure 9 with vector magnitude) shows a reduction of total mass flow rate. This is due to the decrease in gains, resulting in a lower pressure difference between the indoor and outdoor environments.

In this case, it might be expected that the overall air temperature would be increased because of a reduction of natural airflow rate (since the outdoor air temperature is at 28°C). However, the overall temperature levels are lower than the previous case (ca.1.5°C). This is mainly due to the reduction of the total skylights area, drastically reducing direct solar radiation.

5 DISCUSSION AND FUTURE WORK

The process has shown very promising results. Future research is required in order to completely verify the level at which the developed process can be used in early stage of design optimization and investigation.

A challenge to overcome is the limitations of the E+ software in calculating solar distribution with a high number of thermal zones. Beam solar radiation is transmitted as diffuse radiation only to the first zone, neighboring the zone with glazing on its external surfaces. Thermal analysis of the sub-zones is highly affected by the

Figure 7 Thermal sub-zones division and meshing.

Figure 8 West elevation, thermal and airflow patterns for design case 1.

Figure 9 West elevation, thermal and airflow patterns for design case 1.
way solar radiation is distributed in the indoor environment. A possibility for this is to test ways of approximating thermal stratification in natural ventilated buildings. This solution would result in a higher level of detail for microclimate investigation and possibly in more convincing results, especially in terms of natural airflow pattern within a large indoor space.

As for the time being neglected, another possible implementation within the CONTAM software is the effect of façade wind pressure, which would lead to more accurate ventilation performance results.

Finally, more investigation needs to be done in order to better assess the way levels of simplification affect the model accuracy, in terms of thermal sub-zoning.

6 CONCLUSIONS
In the paper, a method has been presented for fast assessment of the indoor thermal environment in the early design stage, by coupling thermal analysis and airflow calculations. A validation of the method has been presented for a simple case. Moreover, the application of the method in a complex case study has been also presented. For both cases, the results have been discussed and future work has been addressed.

The research is currently under development and the results shown in this paper are only partially assessing such a developed computational method. However, it is possible to state that the results gathered so far show an interesting match in terms of overall thermal and total airflow behaviors, compared to a reliable commercial simulation software.

The case study shows that this type of simulation in early design stages can lead to higher future performance of buildings in terms of indoor microclimate. This is especially true when the design needs to satisfy different thermal conditions within the same space, such as in case of sport buildings.

Interesting to notice is the way this process can steer the design decisions in early stages towards unexpected solutions. This is shown in the application on the case study, where correlations between even simple design parameters leads to partially unexpected results that might not be directly foreseen by the designer.

Since the procedure is highly automated by a set of GH components, the developed approach can be reused for many different cases.

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REFERENCES
Air Flow Visualisation Towards the Design of Breathing Skins

Manuel Muehlbauer¹, Nancy Y. Cheng², Mehrnoush Latifi Khorasgani¹, Jesse McCarthy¹ and Jane Burry¹

¹RMIT University
Melbourne, Australia
{manuel.muehlbauer,
jesse.mccarthy,
latifikhorasgani.mehrnoush,
jane.burry}@rmit.edu.au

²University of Oregon
Eugene, Oregon, USA
nywc@uoregon.edu

ABSTRACT
How can the geometric modification of surfaces affect airflow and enhance the thermal performance of ventilated facades? This study is an initial investigation into how surface articulation can affect air movement in a plenum between the shaped surface and the building, as a step toward the design of climate-specific ventilated facades, termed “Breathing Skins”.

The research method describes how physical and digital procedures can play complementary roles in the understanding of complex environmental phenomena for architectural applications. Initial wind-tunnel tests measured the pressure change from the inbound side to the outbound side of a cavity with a variable shaped surface on one face. They allowed comparison of the frictional properties of a variety of folded surface forms, that could be used for façade siding or screens. Subsequently, the patterns were simulated with Computational Fluid Dynamics (CFD).

Results show that a solid sheet with concertina folds parallel to the wind revealed a greater loss in pressure and a Miura-Ori pattern a smaller loss in pressure than a flat sheet. These findings are shaping further research into the phenomenon by indicating useful avenues for the development of climate-modulating outer building skins.

Author Keywords
Computational fluid dynamics; folding surfaces; physical and digital simulation; patterned skins; ventilated facades.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING

1 INTRODUCTION
This research is a part of on-going research to investigate the potential of employing surface articulations or patterns for improving the thermal performance of building skins. It focuses on the consequences of a folded surface pattern on the movement of air close to the surface and within a cavity immediately behind the external layer of the Rear-Ventilated Façade. The primary intention is to modulate temperature and potentially provide both heating and cooling under different ambient conditions. Previous experiments [1,2] demonstrate that the surface shape can influence the passive heating of buildings’ skins and alter the immediate external microclimate through self-shading.

Those studies were focused on developing empirical methods of investigating heat phenomena through engaging with the parallel physical and digital platforms along with employing a comparative scientific approach. They reveal the impact of surface articulations on reducing the amount of radiation received by the folded surfaces and changing amount of heat distribution on the double skin façade [2].

This study focuses on the application of folded continuous surfaces for improving the thermal performance of double skin facades by revealing the dynamics of air around them. This paper reports the results from the early experiments on observations and visualisations of the airflow in the cavity of ventilated facades by applying a similar hybrid physical-digital experimental method and framework.

2 BACKGROUND
Various experimental and numerical studies in engineering confirm that ventilated facades provide the opportunity of enhancing building energy efficiency by removing the heat inside wall plenums through air circulation and convection [3]. These thermodynamic and fluid dynamic studies reveal how the thermal improvement in such systems can be achieved by providing better air circulation inside the cavity.

They highlight the necessity of improving the cavity air flow to enhance the efficiency of the system. Summer Heat stagnation inside the cavity during summer can be prevented by altering the air density, leading air to flow upward, removing heat from the cavity [4]. This process reduces the amount of heat transmission from the cavity to the building [5].

Architectural studies explore different material applications for improving the efficiency of such systems [6]. However,
few studies have considered the impacts of parametric geometrical modification of surfaces within thermodynamic and fluid dynamic studies for architectural applications. Accordingly, our earlier research focused on heat conduction, convection and radiation in such building skins for their thermal performance optimisation through shape studies of surfaces [2, 7] and airflow measurement in porous screens systems, in which parameters such as surface roughness and porous shapes were manipulated parametrically.

The investigations were carried out in several software packages and physical platforms such as a small wind tunnel [2,8]. This current study is focused on the design of origami surfaces towards improving the thermal performance of ventilated facades by having the better understanding of the relation between the form of external shading devices and the airflow around them. The key aspect is to reveal the relationships between surface patterns and airflow changes around them that consequently affect heat exchange and convection in the cavity between the two layers of the façade.

2.1 Architectural Context
Understanding how a 3D surface relief pattern mounted on an exterior building wall can affect the airflow in the cavity behind it, requires review and evaluation of similar structures under different climatic conditions. In hot climates, a lightweight canopy is commonly used as a seasonal parasol, keeping direct sun off the roof of a building, and shading screens can be attached to the faces of an existing building. Opening the top of the cavity creates ventilation. We speculate that by manipulating geometries, we could maximize the chimney effect, potentially drawing cool air from an earth duct. For wet climates, shaped surfaces acting as rain screens could also benefit from enhanced cavity ventilation to reduce wood rot and fungal growth, a major source of asthma irritation.

In cold climates, a dark surface added to a sunny façade can collect heat and transfer it to the enclosed cavity between the added skin and the façade, so that warm air can be collected. Research on solar collectors is relevant because optimal flow in the cavity behind the solar radiation-absorbing surface is needed to facilitate the efficiency of the solar module. In the 1980’s and 90’s, Charles F. Kutscher of the National Renewable Energy Lab developed a solar collector that used a dark metal surface with perforations to allow a small volume of air to be slowly pulled by a fan through a heating chamber, known as an Unglazed Transpired Collector (UTC). This has been scaled up into the Conserval Solarwall (http://solarwall.com), a perforated metal second skin that is used for preheating intake air or crop drying.

Reviews of (UTC) research [9,10] examine the impact on efficiency of factors such as porosity, airflow rate, perforation pitch and diameter, wind approach velocity and material absorptivity and emissivity. While surface geometry is not directly addressed, Shukla [10] explains that the strongest factor influencing Heat Exchange Effectiveness (HEE) is the Reynolds number, created from the geometry and proportion of a flow cross-section. This research shows that the impacts of the surface geometry and perforations on flow efficiency have not been fully explored (Fig 1).

This study takes advantage of the fact that compared to a smooth plane, a textured surface causes more turbulence close to the plane, reducing drag. This study aims to explore how specific folding patterns affect airflow, and how we could adjust the folding and perforations for specific thermal comfort goals. This would be the first step in understanding how we can use folding and perforations 1) to maximize convective currents for cooling in hot climates and drying in wet climates and 2) to make UTC more effective for cold climates.

![Figure 1. Active UTC wall & Passive continuous surface](image-url)
4 METHODS

4.1 Analogue Experiment - Wind tunnel testing, gap cavity and geometry as explored variable

In order to understand how a folded screen mounted in front of an exterior building wall would affect air currents in the space between the screen and the wall, initial experiments were undertaken in an analogue wind tunnel. A number of experiments were done with both horizontal and vertical set up, to determine the effective parameters and further simplifications in the experiments.

A transparent acrylic “drawer” system 28 cm (11”) wide x 61 cm (24”) long x 15.3 cm (6”) high, allowed for easy adjustment of cavity depth, with substitution of different screens to form the top surface parallel to the direction of wind travel. The surfaces were inserted into the drawer set up, sealed along the edges to allow airflow only over the surface and through the cavity.

The experimental configuration for the first series of experiments, using the same variable cavity depth system and card surfaces, was to mount the surface vertically, with a gap at the base and open to the top, and heat the surface from the front with a heat lamp (Fig. 2).

Temperature and pressure measurements were taken at the base and top of the cavity to determine whether there were detectable convection currents set up by the surface heating and whether the differential self-shading in different patterns influenced the measurable magnitude.

Because convective buoyancy induced by solar radiation or heat lamps on a dark screen in a vertical position was too subtle to measure consistently, efforts were focused on examining flow through a horizontal chamber in a wind tunnel. Visualizing the flow using smoke and light sources (Fig. 3) helped identify the relevant parameters involved in the modelling turbulence in the cavity between screen and wall.

The flow behind surfaces with different fold patterns (Fig. 5) was benchmarked against flat sheet panels by taking pressure measurements at the leading edge and at the exit point of the cavity for four different wind speeds.

The focus was a consistent experimental setup for comparison of different shapes, rather than for absolute metrics. First flat, then concertina folded, and then more complex folding patterns, created from white and black cardstock were tested.

Variables were: cavity depth for a particular surface shape (2.5, 5.0 and 7.5 cm or 1”, 2” and 3”), depth of folded surface for a particular folding, different surface patterns for consistent cavity and surface depth. The wind tunnel experiment was repeated several times, improving the data gathering technique each time.

The analogue experiments revealed the need for more continuous data and higher-resolution visualisation of the turbulence.
4.2 Computational Fluid Dynamics
Computational Fluid Dynamics (CFD) is a numerical tool utilised to simulate fluid flows and other fluid-related phenomena such as heat transfer, magneto-hydrodynamics, aero-acoustics, and Fluid-Structure Interactions (FSIs). It has typically seen widespread application in engineering disciplines involving fluid physics [13], but is now rapidly becoming a useful tool in the architectural design process [14-18].

The core purpose of any CFD code is to arrive at a numerical solution of the governing equations of fluid dynamics over a discretised domain – commonly known as a mesh, representing the geometry and flow conditions of interest. A key advantage of CFD is the ability to interface with CAD packages, which can permit quick parameterisation of geometric variables of interest while allowing a wide exploration of the design space in a relatively small amount of time.

Turbulence is present in almost every realistic flow in nature and may be either modelled or resolved in CFD. Resolving the turbulent flow structures in a representative flow requires both stringent grid resolution requirements, and depending on the method by which the turbulence is resolved, orders of magnitude higher computing expenditure than if the turbulence were modelled using a suitable turbulence model. Refer to such works as Wilcox [11] for a more elaborate explanation of turbulence modelling.

4.3 Preliminary CFD Analysis
CFD analyses utilising a Reynolds-Averaged Navier-Stokes (RANS) model were performed to correlate with the analogue experiments. They replicated the horizontal analogue setup to visualise the air pressure and velocity, again ignoring the buoyancy impacts for simplicity and consistency. The CFD code employed was ANSYS® Fluent, which is commercially available and has been extensively validated for many canonical flows including those with turbulence and heat transfer mechanisms. Full-scale CAD geometries of the wind-tunnel specimens were meshed with structured grids that were each tested for mesh independence of results. The boundary conditions for the flat-plate setup are shown in Fig. 6, with the flat plate being replaced by the folded or concertina plate in the other two cases. Reynolds numbers for the CFD were similar to the 5 cm cavity depth experiment at 4 m/s.

At this stage of the investigation, the purpose of employing CFD was to rapidly explore the design space through parameterisation of the CFD models. Three geometries – flat sheet, concertina and Miura-Ori pattern that had been tested in the wind tunnel were then simulated with CFD. Here the realizable k-ε RANS turbulence model was chosen for its good performance in wall-bounded flows with pressure gradients [12], and was used to predict the turbulence levels throughout the computational domain. Because heat transfer mechanisms were not taken into account in this stage, only the flow mass and momentum equations are solved.

5 RESULTS
5.1 Reporting Results of Analogue Experiment
Horizontal pressure drop measurements taken at 5.0 cm screen height reveal that the concertina folds create a great deal of friction in the chamber, whereas the Miura-Ori pattern creates less friction than a flat screen (Fig. 7).
Outside of the pressure measurements, working in the wind-tunnel provided an intuitive sense of turbulence. Smoke pencil trails revealed qualitative aspects of the airflow at the chamber entrance. Due to smoke dispersion, a different configuration would be needed to capture downstream behaviour.

5.2 Reporting Results of Preliminary CFD

The pressure distribution contours for the geometries are shown in Fig. 8-10, along with the calculated pressure drop. The gauge pressure is plotted, which is defined by:

\[ P_{\text{gauge}} = P_{\text{absolute}} - P_{\text{atmospheric}} \]

where \( P_{\text{gauge}} \) is the gauge pressure, \( P_{\text{absolute}} \) is the local absolute static pressure and \( P_{\text{atmospheric}} \) is the atmospheric pressure.

Immediately noticeable is the disparity in pressure distribution with the Miura-Ori geometry, as compared to the other two geometries. This is due to the variation in cross-sectional area along the length of the geometry, which changes the pressure gradient of the flow. As the cross-sectional area decreases, the flow velocity increases and subsequently the static pressure decreases. The opposite is true when the cross-sectional area increases. This becomes an important consideration when introducing porosity into the geometry; depending on location, outside air may either be entrained into the duct, which would occur in areas where the local static pressure is lower than atmospheric, or air could be expelled from the duct in places where the local static pressure is greater than atmospheric pressure.

Interestingly, the medium concertina plate exhibited the greatest pressure drop. This is most likely due to the increased viscous losses occurring near the apexes of the geometry. Conversely, the Miura-Or shows the least pressure drop, likely due to the varying cross-sectional area of the duct, preventing boundary-layer development. This is a somewhat similar phenomenon that is exploited with golf balls; that is, the dimples delay boundary-layer growth and subsequent separation, reducing drag and allowing for a longer trajectory. This result is visualised in Fig. 11-13,
which compares the velocity distributions in the three geometries. It can be seen that the Miura-Ori geometry does not allow for steady growth of the wall boundary layers, in contrast with the flat plate and medium concertina geometries.

![Figure 11. Velocity distribution for flat sheet](image)

![Figure 12. Velocity distribution for concertina](image)

![Figure 13. Velocity distribution for Miura-Ori](image)

6 DISCUSSION
The range of experiments provided insight into how the analogue and digital tools complement each other.

The small wind tunnel used is not as accurate as a large-scale wind tunnel experiment, but it allows designers to get some quick initial insights into airflow. An accessible wind tunnel and heat lamp allow sensory perception of environmental phenomena such as lift and heat absorption that might not be evident in a digital simulation. But the analogue experiments accrued some measurement errors. For example, closer observation revealed that the outbound measurements for the 2.5cm height were affected by the location of a support bar, so the 5.0 cm measurements were more reliably compared. In addition, the reliability of the measurements might have been affected by the close proximity of the wind-tunnel walls.

6.1 Limitations of the study - CFD as Approximation
CFD provided insights on the turbulence pattern inside the façade cavity. It is important to recognise that at its core, CFD is a mathematical model that solves the governing equations of fluid dynamics, which in turn are subject to conservation laws of fluid physics. But a mathematical model is only as good as its inputs and simplifying assumptions. One of the major assumptions made in the realizable k-ε turbulence model (and two-equation turbulence models in general) is that the turbulence viscosity is isotropic, which is not strictly true [20]. However, this assumption still holds well for a number of technical flows, such as the wall-bounded flows analysed in the present study. A synopsis of the relative complexity of CFD models is summarised in Fig. 14.

![Figure 14. Complexity of Navier-Stokes Equations](image)

Here, a RANS model was employed to visualise the flow-field within the three plate designs. However, in future studies, where detailed analyses of turbulent structures in a particular facade design are required, a turbulence resolving CFD model such as an FNS model will be used.

6.2 Major Findings - Parameters and decision variables defined and explored
During the series of experiments, we explored different wind velocities, cavity depth and surface geometries as decision variables. With typical Reynolds Numbers for experiments being around 9,500, fully turbulent flows are expected inside the cavity for all three categories of geometry. Furthermore, the optimal façade cavity was determined experimentally at about 50mm for the flat sheet
and at the average cavity depth for the other geometries respectively.

First insights from the preliminary CFD study reveal the potential for strategic positioning of perforation in low-pressure areas with potential flow entrainment into the façade cavity. The Muria-Ori pattern showed the lowest pressure drop and will be further investigated, as the air can pass through the cavity less restrained in case of forced convection. This case is likely, regarding the position of the façade, where the top edge aligns with the leading edge of the façade. The impact of this position and inlet/outlet conditions are different geometric decision variables that will be explored in further experiments. Based on the results it is predicted that applying a folded pattern on the inner layer of the cavity could also change the results – one area for further study.

7 CONCLUSION
The described experiments show ways to study how surface geometry influences the flow of air in a plenum between the surface and the building. Both wind tunnel and CFD studies show that shape of surfaces significantly affects airflow: the impacts can be measured in both low fidelity analogue airflow testing and high fidelity digital simulation. Specifically results showed that a solid sheet with concertina folds parallel to the wind revealed a greater loss in pressure and a Miura-Ori pattern a smaller loss in pressure than a flat sheet. They provide initial evidence for developing optimisation strategies for such variables as cavity depth, surface shape, and angles of folding.

The work also illustrates the value of a cycle of analogue and computational experimentation, each informing the development of the other without the need to close couple numerical results in each context.

The results have provided the evidence and direction for further refined studies, progressively adding to the complexity of the models by introducing different materials, surface finish, and controlled and differentiated perforation for porosity, as well as examining how the sun’s heat changes the flow dynamics. The Computational Fluid Dynamics environment will continue to provide an extensive iteration and versioning cycle as a means to narrow down the most fruitful areas for further analogue experimentation.

8 FUTURE WORKS
The presented research is a significant step in solving the question of how turbulence in the cavity of ventilated facades influences the thermal convection inside the cavity. Multi-Criteria Optimization used in various engineering applications [21-23] has the potential to further improve the design of façade surfaces.

For example, in a holistic optimization strategy, the façade surface geometry could be targeted towards summer interior comfort through self-shading and cavity ventilation, along with sheltering passing pedestrians from excessive wind (Fig.15).

![Figure 15. Venn-diagram of optimization strategy](image)

Currently, more complex morphologies than isolated buildings in an open field, such as, surface effects and porosity influencing turbulence, generally require detailed, computationally heavy and time-consuming simulations [7]. Future directions for the research include investigating the development of lightweight CFD simulation to accomplish meaningful results for façade optimization processes in early design.

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An Integrated Experimental-Computational Investigation of Connected Spaces as Natural Ventilation Typologies

Ulrike Passe1, Mirka Deza2, Baskar Ganapathysubramanian2, Shan He1, Kyle Vansice1, Songzhe Xu2

1 Iowa State University, Architecture
Ames, Iowa, USA
upasse@iastate.edu

2 Iowa State University, Mechanical Engineering, Ames, Iowa, USA
mdeza@iastate.edu

ABSTRACT
This paper investigates the impact of spatial composition on the effectiveness of passive cooling by natural ventilation in a comparative study of the conical roofed Harran houses in Turkey and a passive solar home in the Midwest of the United States. While the projects are distinct and are situated in two extreme climate zones (hot and arid and continental humid) both projects have in common open variable configurations of multiple interconnected spaces. Computational fluid dynamics (CFD) simulations using OpenFoam were used to investigate the fundamental airflow characteristics and the resulting interior temperature and velocity profiles. The simulations were initialized as well as validated with measured field data. Subsequently, we tested the impact of the interconnected spatial composition of the buildings on their cooling potentials. This was accomplished by simulating variations of the spatial connections with reduced flow path connectivity compared to the original validated cases. Preliminary results regarding changes in temperature and air velocity show higher temperatures and lower velocities in the less connected cell-like spaces and indicate the importance of spatial connectivity for effective cooling by natural ventilation based on variable interaction of vents and flow path.

Author Keywords
Natural ventilation; computational fluid dynamics, spatial composition; climate design, vernacular building types.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING; I.6.4 Model Validation and Analysis

1 INTRODUCTION
Natural ventilation strategies use the building fabric and composition of vents and flow path to mediate the outdoor climate. These free cooling strategies will be essential to meeting the cooling needs of a warming planet. Spatial composition and building design can have a transformative impact on cooling potential for extreme climates as encountered in vernacular building types in the hot and arid Middle East as well as the continental humid climate of the US Midwest. Our overarching research goal is to enhance the utilization of naturally occurring energy flow through, within, and around buildings through the ordering of spatial composition as a means for reducing thermal energy consumption while retaining appropriate parameters for thermal comfort. The long-term research objective is thus the development of a knowledge base for passive ventilation strategies using CFD simulations validated by measurements for potential integration into contemporary sustainable high-performing building design. For the pilot project presented here, spatially enhanced natural ventilation strategies were simulated for two inherited building types using validated measured thermal air and surface temperature, as well as local weather data. The two building types are the Harran Houses in Southern Turkey and the Midwestern bungalow with its shaded porches. They have in common locations with extreme climates: the American Midwest and southeast Anatolia in Turkey and provide intricate spatial responses to the challenges provided by these climates. Clues for appropriate design strategies are embedded within many historical building types. These two typologies use a combination of buoyancy and wind driven ventilation strategies and a flow path across interconnected spaces.

This project is part of an architectural research endeavor to reveal the importance of architectural space for sustainable design and thus to reduce costly technical equipment to an effective minimum without compromising comfort. Our research team monitors the energy performance of a passive solar house and compares measured data with design predictions based upon whole building energy and CFD models. These analyses provide beneficial insights into spatial composition for new construction, building operation strategies, and their controls.

Considering air movement in natural ventilation is one of the most complex problems in developing passive design strategies, and design methods have yet to be fully computationally validated at the building scale as multiple previous publications have noted [Stoakes et al 2011a, 2011b, Passe 2007, 2008]. We hypothesized, that a significant key would lie in the space composition and materials of historical structures built in extreme climates utilizing locally available materials [Deza et al, 2015]. This work presents the preliminary results of this endeavor.
2 CASE 1: THE INTERLOCK HOUSE

Iowa State University’s Interlock House was built in 2009 for the US Department of Energy’s Solar Decathlon and has been installed in Iowa as a community laboratory for energy efficiency research (Figure 1 and 2). The house dimensions are approximately 11.8 m x 5.3 m with an inclined ceiling that rises with a 23 degree slope from 2.5 m to 4.7 m. The overarching goal of this project is to research the interaction of passive and active design strategies, and to develop sensible and delightful home prototypes for this challenging climate. The house provides one example of how net-zero energy living can be affordable today. It has been occupied in the Iowa landscape for the past four years while researchers study its energy base line and comfort parameters. By transforming to accommodate the extremes of the Iowa seasons and interlocking with the outdoors, this house balances a reduction of energy consumption through spatial composition and a tight, efficient envelope, with thermal and electrical solar power production.

The spatial composition of the Interlock House can be seasonally adapted by reconfiguring the Hall and Sun Porch. The Sun Porch, with added thermal mass in the floor, mediates light and heat and encourages convective loops to heat and cool the house. A louver system spanning the south façade also mediates light and heat and reduces the active cooling load in summer months. The louvers allow occupants to manipulate light and heat according to activities and privacy needs. The house requires active manipulation of its doors, windows, and exterior louvers to influence airflow and to maximize or minimize heat gain and loss. This reliance on several basic passive solar and ventilation techniques reduces the energy demands for the active systems [Passe 2012].

Spatial continuity is achieved in section and plan by careful volumetric composition of six proportional modules. On the south side, the Sun Porch can be opened and closed to suit the seasons and become a sunspace in winter, a shaded porch in summer or be fully opened for a breezeway in the interim seasons. High clerestory windows on the north façade are spatially connected to the southern spaces across the auxiliary rooms for natural ventilation. [Passe 2011].

3 CASE 2: THE HARRAN HOUSES

The corbelled domes of the Harran Houses (Figure 3 and 4) are a historic building type in the southern Anatolian region of Sanliurfa, Turkey, the base is built of large natural stones, plastered with adobe and the dome is built of mudbricks and outside adobe plaster. They are known by locals for comfortable cool temperatures in the very hot arid summers. Conversely, the interior spaces remain fairly warm in winter, when the outdoor conditions are cool. The key reason for the balanced performance of the Harran House is its sectional shape and construction materials as several authors have noted [Basaran et al 2011, Gomez-Munoza et al 2003, Faghih 2009]. Mutti [2014] has revealed that their strategically placed ventilation holes on walls and roof, and the connectedness of the corbelled spaces play a strong role in this condition while he reports measured interior temperatures of 29°C with outside conditions at about 42°C.
Preliminary measured and simulated data by Mutti (2014) was the basis for this research project. The overall project [Passe et al 2014] validates spatial typologies of these traditionally inherited passive heating and cooling strategies with computational fluid mechanics (CFD) models.

![Figure 4: Case 2: Harran house axonometric showing the interlocking spatial composition on top (Case 2A); the separation for the alternate cellular modelled case 2B.1 and 2B.2 bottom.](image)

4 METHODOLOGY

The overall Computational Fluid Dynamics (CFD) models have been validated with measured performance data taken from the Interlock House using approximately 50 air sensors and 60 surface temperature sensors (thermistors) [Deza et al, 2015] (Figure 5). Outdoor temperature and radiation conditions were also recorded. In addition, a collaborative pilot project studied the fundamental energy flow characteristics observed in the conical roofed Harran houses (Figure 3 and 4) in Turkey [Mutti 2014]. The surface and air temperatures were recorded in the Harran House, and compared with the aforementioned simulations.

Once the observations of these case studies were complete, our team modelled heat transfer and air movement within the Interlock House and the Harran Houses for summer conditions to understand what makes them effective spatial typologies for natural ventilation cooling. In both cases, we first simulated and validated the measured interconnected spaces with the complex interaction of spatial compositions, material properties, solar radiation and natural ventilation as a function of passive cooling. Then we used the same validated model to simulate the spaces without their connections and ‘closed off’ the opening between the rooms to shorten the flow path. The following sections describe the simulation parameters used and results obtained.

5 CFD ANALYSIS AND SIMULATION BACKGROUND

Computational Fluid Dynamics (CFD) was used to model the impact of spatial geometry on the flow pattern and distribution of air. For both the Interlock House and the Harran Houses a buoyant heat transfer numerical model with shear-stress transport (SST) k- omega turbulence model was used within OpenFoam to predict the combined cross- and stack natural ventilation flow using a 3D model of both house geometries and interior composition. This model was selected because it captures the physics of natural ventilation. Given the temperature difference of the flow (incoming and internal), there will be density differences. Therefore, some of the movement will be governed by buoyancy effects. Steady-state was selected to have an approximation on the flow behavior during an approximately uniform 10-minute period from the experiments. The measured and modelled data points show good correlation even with a coarse CFD grid (Figure 5) where the air is being modelled while the measured wall temperature data points were taken as boundary conditions.

![Figure 5: Correlation of measured data in the Interlock House with fine, medium and coarse CFD grid resolution.](image)

The equations were discretized using a finite volume method and cell-centered variables. PIMPLE, a combination of SIMPLE and PISO algorithms were used to couple pressure and velocity for steady-state and transient simulations. Specifics about the solver, buoyantPimpleFoam is located in the OpenFOAM user guide [OPENFOAM 2015]. Time derivatives use a first-order Euler method while spatial derivatives are a blend of first- and second-order.

Two Cases were simulated for each building. Interlock Case 1 and Harran House Case 2 were the original measured cases, while Interlock Case 1B.1 and 1B.2 and Harran House Case 2B were the modified cases.

Results for the Interlock House are obtained for domains of approximately 1.3 million cells. Simulations were run in 128 processors for a total of 9.1 million unknown parameters. The total gross CPU time and wall times for each case 1A are 71 and 72 hours and for case 1B are 50 and 62 hours.
For the Harran house, a transient conjugate heat transfer numerical model (that integrated CFD of the interior volume with heat transfer from/to the thick walls) was used to predict the natural ventilation flow in the Harran house using a 3D domain of the walls as well as the interior of the house. The solver, couples the temperature of the solid at the interface from the solid region to the fluid region. Results were obtained for total combined domain of solid and fluid of approximately 3 million cells. Simulations were run in 128 processors for a total of 27 million unknown parameters with total CPU time and wall time of 44 and 48 hours for case 2A; 59 and 72 hours for case 2B.

Inlet velocity, wind direction, and temperature in the room were used to determine a 10-minute period with the smallest variation by calculating the standard deviation of these parameters. All measurements were averaged over that given period and used in the simulations as boundary conditions for the inlet and walls. The incoming air velocity is 1.12 m/s at 45° with the façade and the air temperature is 11°C. The simulation of this Case Interlock 1A is visualized in Figure 6 – 8.

**Figure 6:** Interlock House floor plans indicating inlet position

**6 CASE 1A: SIMULATION OF MEASURED CASE**

The condition for Interlock Case 1A was modelled based on experimental measurements for a typical fall configuration with a combination of cross ventilation and stack ventilation present. One outward awning window was opened as inlet on the south façade and one clerestory outward opening awning window was opened as outlet on the north façade. Windows facing the opposite side of the wind direction can act both as inlet and outlet, because surrounding flow on the opposite side of the wind direction will be turbulent and eddies will form next to the window. In this case, the southern windward window dominantly acted as inlet, while the northern leeward window acted as outlet. In this case only the interior of the house was simulated and the flow patterns were calculated based on the measured boundary conditions.

**Figure 7:** Interlock House Case 1A: Original case of the Interlock House as connected space with one as inlet acting window on the south façade (front) and one as outlet acting window on the north façade (back). The longitudinal plane shows temperature across the original space composition showing the lower temperature of 289 K and a moderate difference of 2 K across the plane.

**Figure 8:** Interlock House Case 1B.1: Temperature slice of the detached case showing 3 to 4 degrees higher temperatures than in Figure 7

**7 INTERLOCK HOUSE CASE 1B: SIMULATED CASES (1B.1 AND 1B.2) OF DISCONNECTED SPACES**
Figure 9: Interlock House Case 1B.1: Velocity streamlines are shown for the detached case.

Figure 10: Interlock House Case 1B.2: Temperature gradient in the closed-off Eastern side of the building showing 4°F to 5°F higher temperature than in the connected space simulation.

Then we created a model for the second case based on the Interlock House with a configuration which divided the house into two independent disconnected spaces each with one inlet and one outlet (see Figure 2). The same boundary conditions for inlet velocity and temperature were replicated in the second space, but the flow path reduced due to the different spatial configuration. Results of this fictive simulated case are visualized in Figure 8 – 11.

Figure 11: Interlock House Case 1B.2: velocity gradient in the closed-off Eastern side of the building.

8 HARRAN HOUSE CASE 2A: SIMULATION OF MEASURED CASE

The Harran Houses are composed of multiple interconnected square spaces each with a corbelled dome. Mutti [2014] studied two connected spaces, which create the bases for the spatial composition studied here. Their dimensions are 3m x 3.3m x 4.3 m. The domes are approximately conical in the interior with a height of 3.75 m and an approximate wall thickness of 0.63m and 0.57 m for each room. The open-faced mudbrick interior surfaces of the domes are characterized as discrete blocks to represent the mud brick better in opposition to smooth surfaces. The side of one dome is punctured by seven openings of 0.14m x 0.14m while the second dome has four opening of 0.15m x 0.17m. The top openings are circular with 0.10 m and 0.20m diameter and domes have a wall thickness of 0.22 m. Each space has a rectangular opening at person height as entrance (Figure 2 and Figure 12).

Velocity at dome openings were measured and used as boundary conditions and vary from 0.4 to 1.9 m/s. Outside measured temperature was available for March 24, 2014 at 1pm and 284.45K (11.3°C) was used for all the opening inlets. Air temperature of door openings and openings located at the top of the domes as well as outside wall temperature of the domes and lower structure was measured and used as boundary conditions. Conductive and radiative thermal and physical properties were specified for both solid and fluid regions.

The Harran House Case 2A simulates the spatial composition as measured with the two spaces interconnected by a door opening with an additional door opening to the building exterior, located in one of the spaces. Results of this base case are visualized on Figure 13-15.
Figure 12: Harran House floor plan indicating measured rooms

Figure 13: Harran House Case 2A: Original case with connected spaces based on measured air and wall surface temperature.

Figure 14: Harran House Case 2A: Temperature gradients for connected spaces are fairly moderate at about 2k which induces a moderate upward flow.

Figure 15: Harran House Case 2A: Velocity streamlines for connected spaces with high velocity of 2.2m/s only at the right outlet, while the left dome acts as inlet. The simulation also shows a cross current from the right to the left dome which slightly increases the velocity at person height.

9 HARRAN HOUSE CASE 2B: CFD SIMULATION OF DISCONNECTED SPACES

The Harran House Case 2B configuration divides the house into two independent spaces by closing the large opening that interconnects the volumes, and introduces one additional door opening to the outside for each space. The punctured holes in the dome remain at the same location as in Harran Case 2A. Results for Harran Case 2B are visualized in Figures 16 – 18.

Figure 16: Harran House Case 2B: Simulated second case of the Harran house run with two separate spaces within the structure.
In the Harran House case, a similar trend is perceived between Case 2B and Case 2A. The change in temperature and airflow performance is marginally more significant in the case of the Harran House (Case 2A Fig. 13, 14, 15). The simulation results of the two separate domes in Figures 16, 17 and 18, show that the velocity is approximately 0.5 m/s lower while the temperature is approx. 3K to 6K higher at the level of the occupant than at the occupant level of potential occupants (~1.2m above ground) in the original case 2A where the spaces were connected. Even more noticeable is a significant increase in velocity at the connecting passageway between the two domed spaces, which obviously cannot be observed in single spaces. This location of high air velocity between spaces at occupant level is important for further spatial research as it highlights the potential for cross flow with multiple dome opening configurations depending on wind directions. These increased velocities improve comfort conditions at the level of the occupant without the need for lower temperatures. While a change of 2K has only a slight impact on thermal comfort, a change in 4K or even 6K will have a significant cooling effect impact, especially with an increase of air velocity from 1 m/s to 1.5 m/s and 2 m/s at the inlet/outlet (ASHRAE 55-2013).

11 CONCLUSION AND NEXT STEPS
The comparison of the two original verified CFD simulation cases, which were based on measured observations from experiments with cases where the spaces had been disconnected, provides initial indications that natural ventilation and passive strategies are directly influenced by spatial layout according to a number of factors including proportions, connectedness, and placement of inlet and outlet openings. The design of the flow path between the openings is thus as important as the opening size and placement themselves. The presented simulated and measured cases show preliminary results that connectedness of spaces can improve the effectiveness of natural ventilation strategies for free cooling. The cooling strategy in the Harran House relies also on the material properties and structural assembly of the building walls and roof as Mutti [2014] has shown. The material properties of the walls as well as the high outdoor temperatures outdoors might thus have also contributed to this effect.

As next steps we will develop a parametric model refining the proportional knowledge to develop a refined typology catalogue, which will support designers to develop more effective and validated natural ventilation strategies based on spatial proportional relations. The modelled cases provide first evidence that the interconnected spaces can be more effective for cooling and ventilation air exchange. This knowledge can have a transformative impact on building design in hot arid climates of the Middle-East, the continental humid climate of the US Midwest particularly with a changing warming climate and thus contribute transformative knowledge based on passive cooling.
strategies to engineering of sustainable high performance buildings through dynamic building information modelling

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Additive Manufacturing for daylight_Towards a customized shading device

Lemonia Karagianni, Michela Turrin, Ulrich Knaack and Truus Hordijk

Delft University of Technology
Delft, The Netherlands
lemkaragianni@gmail.com
{M.Turrin, U.Knaack, G.J.Hordijk}@tudelft.nl

ABSTRACT
The design of sun-shading systems for facades has a large impact on daylight control and on comfort in the built environment in general. Depending on different climates, functions and user preferences, it requires a variety of customized solutions. However, the current options for customization are limited due to restrictions in geometry and fabrication methods. The research focus is customized sun-shading systems to tailor daylight effects based on the needs of an individual customer. It was developed at Delft university of Technology for a MSc thesis. We discuss a digital workflow, which allows generating different geometric configurations of various sunshades, by means of parametric modelling; verifying their daylight effects by means of performance simulations; and producing the customized solution by means of additive manufacturing. The workflow makes use of the direct relation between geometry, fabrication and light control performance.

Author Keywords
3D printing; Customization; Parametric design; Daylight performance; Product design; Fabrication

ACM Classification Keywords
Design, Experimentation, Performance, User interface

1 INTRODUCTION
Standardization implies production of uniform products available to consumers by limiting personal choice, as well as addressing the individual as a passive participant. Customization implies the creation of items according to user’s needs and preferences. Therefore, customization can change the way we design and manufacture goods for common users and products for the building environment, both from an engineering point of view and a user point of view.

Facades represent a thermal and visual border between indoors and outdoors. They require a technical challenge because they combine many functions, which depend on the indoor comfort and the outdoor external conditions which in turn differ based on the unique context of every case. Facades are the visible part of a building from the outside, which means that not only do they have to fulfill technical aspects, but also aesthetics. Both the technical approach and the aesthetics of the envelope lead to unique design solutions for each building. The research focus is the scope of non-standardized solutions for daylight and shading.

Current computational tools and fabrication techniques open new opportunities to address non-standardized solutions for daylight and shading. Parametric modelling allows generating multiple design solutions; performance simulations allow assessing the performances of each design solution; and Additive Manufacturing (AM) allows fabricating complex and unique shapes. This research takes advantage of the potential, in order to connect the performance-oriented parametric design of personalized shading devices with the production of customized products by means of additive manufacturing.

The aim of the study is to explore the relation between digital modelling, digital manufacturing and performance through the paradigm of a product, that is, an external sunshade. The specific goal of the study is to propose a product by exploring different geometries for efficient and aesthetically pleasant shading systems for facades. Based on these objectives, the project proposes and partially implemented a digital workflow to design changeable solar shading devices according to every user’s needs; the outcome should lead us to different aesthetic proposals which are environmentally efficient. Using the digital workflow, the sunshading devices can be customized by each individual according to their needs, by exploring different facade geometries, from both an efficient and an aesthetical point of view. What connects the fabrication process to the performance oriented design of external window shading devices is parametric design. Thus, the combination of user preferences and climate location parameters is the design driver; the performance of the sunshade is regulated by its geometrical characteristics; and the way to use material form and technology is the key factor behind a successful customized daylight device.

The study introduces an interface, where users can choose one of the specific geometries existing in a library of designs. Then they can adjust the geometry by changing the parameters given by the interface, in accordance with their own individual situation, and they can finally 3D-print the sunshade from their printer or submit the object to be
printed from the web. Lastly, they can assemble the object with snap-fit connections and install it to their window frame.

Ultimately, the study suggests a new direction for product design, based on AM and on-line users generated content. AM has the potential to become a mass market product giving the opportunity to consumers to save money when it comes to buying common household objects [10]. Since AM permits digital designs to become physical products at any location worldwide (i.e., “design anywhere, build anywhere”) and web 2.0 [2] is able to propagate product ideas and designs fabricated through AM, it is obvious that the combination of the above -Web 2.0 with AM- can start a new approach of product design and new models of entrepreneurship.

The paper is structured as follows. First, the digital workflow is presented, with focus on parametric geometries translated into sunshade requirements and daylight performance analysis through computer models. Secondly, a show-case is presented, including the physical models fabricated by 3d printing. This part also addresses the material selection for the specific application; the fabrication of several models through the FDM process to define crucial properties and the structural performance of the final object; and the daylight measurements. A final discussion summarizes successful and critical points.

2 DIGITAL FRAMEWORK

During the project, the workflow and the technological concept of the digital framework were developed in accordance with the findings of a literature review about shading systems functions and user requirements. The resulting framework is based on a parametric library of design options; on performance evaluation tools; and on options for additive manufacturing. The library considered the boundary conditions and the variables that the user would be able to change regarding their needs, in order to create their own-efficient sunshade. These variables serve for the shape generation, through parametric design, of several sunshades and screens to create an available library of patterns of the interface accessible to the users. The performance evaluation tools help users assess whether the design option meets their preferences and their daylight requirements or not. Once a choice is made, the geometry can be 3d printed.

2.1 Parametric library

The library was parametrically designed in Grasshopper, a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools developed by David Rutten at Robert McNeel & Associates Grasshopper. To form the library, a large variety of patterns was designed. Patterns included linear, rectangular, rhombus or honeycomb patterns, voronoi diagrams, panels forming specific logos, advertisements, famous paintings, photos and designs of famous buildings facades and other options. All patterns were parameterized in order to adapt to external conditions (climate-location variables) and user requirements (user based variables). In order to do so, the patterns were based on dynamic grids that enable users to change their dimensions, density etc. Moreover, the library can be expanded by including new patterns eventually generated by the user.

The parametrization of the patterns relates to contextual options for application, (such as dimension of windows,) and performance aspects. Specifically, as the devices are aimed at different contexts and users with different necessities and preferences, general sunshade’s functions and requirements and how they can be achieved have both been translated into design principles for the patterns and into parameters for the parametric script of the designs. The orientation of the window affects the design, as the patterns following the principles of horizontal protection in the south and vertical protection in the east-west projecting horizontal or vertical shields respectively [7]. The specific grids (linear, rhombus, honeycomb, voronoi, rectangular, etc.) are the boundary conditions of the design, while location, date, density, perforation, attraction and dimensions are the parameters that affect the parametric patterns.

Figure 1.Translation of design variables into parametric structure (rectangular, rhombus and honeycomb grid).

Figure 2. Examples of output grid geometry from a rectangular grid input. a) projections for protection of overeating, b) opaque-perforated ratio, c) distorted grid, by using attractors in Grasshopper to control views to the outside, d) density for glare protection.

2.2 Performance evaluation

The performance evaluation process utilizes existing plugins like Diva for Rhino and Grasshopper. The performance evaluations include the possibility of assessing: levels of daylight; and daylight glare probability and other indicators meaningful to assess the effect of the shading on the indoor daylight conditions. The assessment tools can be used to predict the daylight conditions for various options of the customized shadings. In order to do so, a perspective view of the model room is proposed to appear on the screen, and different design variables can be tried in order to observe
how they affect the design and its shading effects, until a final decision is taken. The perspective view that appears on the screen gives information about shading effect that occurs inside the room with a false color image, black and white (fig.5), illustrating with white color the bright parts of the room and with black the dark ones. This false color image is an illustration of the amount of Illuminance (lux) inside the space which is translated into colors in order to be readable by a common user. However, there is potential for more sophisticated ways to estimate daylighting performance through optimization tools, but this is not the scope of this research. If no detailed performance study is required, this image can be used as a map of the brighter and darker parts of the room. The system is meant to support full customization of the daylight effects, based on the customization of the shading device. The parametric variables (density, perforation dimensions etc.) of the shading device can be changed as many times as suitable. Each change provides updated geometries based on the input, which can be assessed iteratively, until the desired output is achieved.

Figure 3. Performance customization. Rectangular space divided in different uses with different shading performance and brightness.

2.3 Setting for Additive Manufacturing

Once the desired output is achieved and a shading device is identified as suitable, the device can be printed. In order to print it, the workflow requires additional choices regarding the production. This step includes the AM process and material selection, according to the accuracy of the final object, the cost and the mechanical properties of the device. In order to develop a guidance for the user, research on available materials and physical models was carried out. The current guidance is limited as well as AM technological developments imply the need of constant updates. However, temporary results include some recommendations regarding the 3dprinting process, material behavior, printer settings, tolerances for correct modeling and assembling of the parts. These partial recommendations were formulated upon preliminary examinations of the engineering requirements of the final product, including: structural performance, assembly of physical models and the engineering test of the joint.

Figure 4. User scenario.

2.4 Overall Workflow

In this research, parts of the modules mentioned above have been implemented as digital workflow for the user. The overall workflow is meant to begin when the user visits the interface. Once (s)he chooses the desired pattern from the parametric library, (s)he can settle on the inputs. After defining the orientation of the window, the sun latitude and the season that (s)he wishes sun protection, the right file opens on the screen. Then the definition of his/her preferences may occur. These are, the dimensions of the window and the room, the density of the pattern which aims the glare control and the dimensions of the projections of the sunshade which aims to the solar protection. The user can define all the above items by writing on the screen specific numbers or words, or moving sliders to see the direct reaction of the design. Once all the required fields are completed, a front and a perspective view of the model...
appear on the screen, informing the user about the shading output inside the room. If a more detailed performance study is desired, interior images of the space illustrating the expected shadow and glaring probability are available. Similarly, the location sunpath is illustrated in order to present an impression of the sun altitude for the specific date and location given by the user. As the last step, the users can finalize the process by using the AM facilities and material selection, taking into account the accuracy, the strength and the price of the final object.

3 CASE STUDY

In order to test the process, the sunshading and the daylight effects of the device, a case study was developed. A specific pattern - a rhombus grid one- and its alternatives were tested for South, West and East orientation, in the summer. The case study is located in Delft (the Netherlands). The climatic profile corresponds to an Energy Plus Weather file (EPW) for the city of Amsterdam, which is similar to the climatic data for Delft (figures developed by the U.S. Department of Energy). The aim is to provide the workplace of an office with sun protection in the summer.

3.1 Parametric design

Among the possible options, a rhombus grid was chosen as a pattern. A perforated rhombus shading pattern was designed. The perforation could change gradually from the top to the bottom of the window with the objective to create useful illumination to the indoor space (useful daylight illuminance levels for a working space are more than 100 lux and less than 2000 lux [5]). The rhombus pattern followed the principle of vertical protection, for the west and east orientation, with the vertical protection on the right and left side of each module (rhombus) respectively and horizontal protection, for the south orientation.

3.2 Performance assessment

In order to assess the daylight performance, the summer solstice: 21st June was chosen as reference weather condition.

The performance was assessed by illuminance levels for all the designed patterns and by DGP (daylight glare probability) factor for the patterns that performed better during the illuminance evaluation. The illuminance levels for three orientations were defined for an office box with and without sun screen, while in the south orientation different densities of the sunshade were tested. Additionally, for the west orientation different levels of perforation in the sunshade were examined with holes of radius, R=3mm, R=4mm and R=5mm, in order to define if there is any difference in illuminance levels when the sun screen is opaque - blocking the sun- and perforated - filtering the sun.

Figure 6. Logic of the overall definition.

Figure 5. Example of user scenario. Perspective view of illuminance levels.

Figure 7a. Illuminance performance for South orientation.

Figure 7b. 1st Graph: Illuminance levels along the room, both with and without shading device. 2nd Graph: Illuminance levels along the room with different types of shading devices. DGP factor for: 06/21, camera located in the middle and on the side of the room / Camera height: 1.65m. South Orientation.
As shown in figure 7a,8a and the diagrams (fig.7b,8b), there is a big difference in illuminance numbers between a shaded room and a non-shaded one. For a non-shading window, the difference in contrast inside the room is supposed to be disturbing as the overall illuminance ratio is 1/100 for the south orientation and 1/83 for the west orientation, while the ratio improves with the application of the sunshade: 1/6 for the south orientation and 1/9 for the west orientation, respectively. (Useful ratio = 1/5 to 1/10)

According to the above illuminance levels, the patterns which performed the best for each orientation were examined afterwards, based on Radiance evaluation tool “evalglare” in DIVA-for Rhino, in order to calculate the Daylight glare probability (DGP) at 9:00, 12:00 and 15:00 o’clock, from the middle and towards the back of the room, and also on the eye level of a person sitting on a desk.

As it is illustrated in figures 7b and 8b, the DGP factor presents numbers which perform lower than 30%. This means that the daylight glare probability is imperceptible; however, glaring is still probable for a person sitting on a desk on the side of a room, at 1.2m height of the eye, when the sun is in a very low position. Thus, the designed sunshades do not solve the glaring problem at all when it comes to a position next to the window, especially in a west orientation scenario, in which the sun comes from the side.

Apart from placing the working desks in a minimum distance of 1 m from the glass pane, another solution to the glaring problem mentioned above lies in sunshades made of translucent material, which should minimize the contrast caused by the shadow of the pattern.

3.3 Process for Additive Manufacturing
The fabrication process developed for this case study does not represent a standard fabrication process as envisioned for the final production in the workflow. Instead, during the research this fabrication was used process to iteratively test a number of aspects of the printed product. In the following section, the tests are presented and discussed as part of the research.

4 FABRICATION PROCESS
The fabrication process of the case study considered a number of aspects, especially the selection of the materials to be printed, the assembly methods and the structural behavior. Additionally, the printed device was also used to perform physical tests on daylight.

4.1 Material selection:
The selection of the materials was conducted based on materials data, 3D printing techniques and tests as well as. CES Edupack 2014 software, information collected from manufacturers (Sculpteo, Taulman, etc.) and discussions on related websites [13] were used in order to check the mechanical and thermal properties of the available 3d printed materials, [11,12] according to the requirements of exposed-to-weather-conditions sunshading device. Despite the fact that Selective Laser Sintering (SLS) is more accurate and professional process, Fused Modeling Deposition (FDM) process was chosen instead because it is more affordable. However, FDM has drawbacks when it comes to applying plastics for an outside use, due to printed material properties like a low melting point and thermoplastic behavior. In an extreme condition, fire scenario, the chances are that the majority of 3D printed thermoplastic materials cannot withstand the fire load unless they have an extra protection. Even in a non-fire scenario, a 3D printed thermoplastic material could lose some of its mechanical properties under a heat load in a summer day. For this reason, maximum service temperature (Tmax) and minimum service temperature (Tmin) were applied as a filter for the case of the Netherlands, taking into consideration the extreme temperatures to which a material is exposed in a sunny summer day in this European country. The maximum temperature of a roof surface in the Netherlands is about 80 degrees Celsius and the minimum temperature is about -30 degrees Celsius [4], and that is why these figures have been introduced as a filter to the CES software. According to the filtration of mechanical properties through CES Edupack, the cost factor and its recyclable properties as well, PET filament was selected as the proposed material for the FDM process. However, an additional protection from fire should be considered; to this respect, coating the final object with a flame retardant or modifying the filament itself before the printing process are both good options.
4.2 Assembling

The fabrication method and the material used not only affect the price and the durability but also the accuracy of the assembling method. As the dimension limitations of the AM processes happen to be very specific, the assembling of the parts of the sunshade has to be taken into consideration. For both easier and faster assembly and disassembly aimed at common users, snap-fit connections were selected, as they offer the opportunity to disassemble a broken part, to perform maintenance and even have potential of recycling the product after the end of its life.

Several alternatives of linear and non-linear connections were first modeled in Rhinoceros [6]. Later on, there were fabricated in the design Informatics department, TOI (Technisch Ontwerp en Informatica), of Delft University of Technology. FDM was the selected fabrication process and PET was the selected material filament, as they were accessible from TOI. TU Delft University of Technology provided us with a 200x270x200 mm building chamber Leapfrog 3D printer. As for the size, it obviously affects the design of the module, as the highest possible dimensions for one (rhombus) module are 200x270x200mm.

Tolerance of the to-be assembled small parts of the modules was also tested with the appropriate machine settings, in order to confirm the correct ones. Barbed leg snap-fits, cylindrical snap-fits and clamp joints were modelled according to literature. [8] This, in combination with the fabrication tests, led to the final connection detail.

According to the results, non-linear connections resulted more preferable than the linear ones, as the latter are weaker when located on the top of the device. The stresses caused by the weight of the sunshade are gathered on the actual snap-fit joint when it comes to the linear connections, making them bearing more load than compared to the non-linear connections. In addition, non-linear joints are easier to be disassembled for maintenance, in case there is a need for broken element-module to be replaced. The angles between the male and female part of the connection define whether the joints are permanent or detachable. For a detachable snap-fit, a considerable amount of force has to be applied deliberately in order for the joint to be successfully disassembled. [8] Finally, when the fabrication process used is FDM, the layering way of building the object has to be taken into consideration. The fact that the surface after FDM 3d-printing is not very smooth, but layered, increases the coefficient of friction between the printed parts, resulting in difficulties in assembling. Therefore, post-processing after fabrication (eg. sanding) may be necessary.

Regarding the modules-assembling, the 3D-printed snap-fit connection tests showed that joints with integrated “clamps” are the most efficient ones in comparison to the other types of joints, when it comes to this application. The four edges of the rhombus have either holes-female or clamps-male parts that can be assembled together. The modelling of the connections should be taken into account in this step, as the settings of the machine affect the correct tolerance between the assembling parts and play an important role when avoiding loose connections. The machine setting is a crucial factor for the structural performance of the final object as well. The assembling process consists of i) the assembly of the modules, ii) the assembly of the modules with the connectors and tubes to create the whole panel (device) and iii) the attachment of the device to the window frame.

![Assembling of modules. Perspective view of snap-fit joint/ Male and female snap-fit connection.](image)

4.3 Structural behavior

The structural performance of the selected module connections was examined both through manual calculations and experimental techniques. The fabricated connections were tested under load in the laboratory of Mechanical Engineering and Materials Department of Delft University of Technology. First of all, the proposed snap-fit joint was modeled and 3D printed with FDM method and with PET material, having a rectilinear infill of 100%.

The joint was modelled in that way in order to test the axial force, caused by the wind to a façade panel and as a result to the snap-fit joint. The male and female parts of the connection were 3Dprinted with the layers positioned vertically to the direction of the expected failure, due to the fact that the printing material presents “clear directional behavior in the way that tensile strength parallel to the grain is significantly higher than perpendicular to the grain” [9]. 3D printed objects have sometimes unpredictable behavior when it comes to their mechanical properties. The snap fit joint calculations were carried out after taking into consideration a shape factor of 1/2 for both the permitted shear and yield strength of PET. [9]

The results showed that the most sensitive part of the joint is the female one, as it was the first that broke at the first and second specimen. The male part of the second specimen withstood a load heavier than 697.7 N, which is more than the estimated load that the joint withstand according to the hand calculations (360 N). However, the third specimen broke in both the male and female part
under a load of 545.9 N, which is again more than the previously calculated one (360 N). This means that the 3D printed modules made out of PET and printed according to the settings used during the experiment; can form a sunshade panel of 2m height and 2m width, if all the joints are built with the layers positioned vertically to the direction of the expected failure.

Figure 10. Setting up the machine in order to test the axial force applied to the snap-fit joint that causes the failure.

Figure 11. 3D printed models, scale 1:1. Testing flexibility and translucency.

4.4 Light and shading device
Tests were run on the on 11th of May in TU Delft faculty of architecture and the building environment (52°01’N, 04°22’E). For the experiment, a calibrated digital camera, Canon EOS 35OD, with a lens SIGMA DC 18-50mm ex macro, was mounted on a tripod at a height of 33 cm from the floor of the scaled box (eye level) to the back of the room in order to measure luminance levels inside the room for the southwest orientation.

As it is observed from the performance analysis of the shading device for all the orientations the designed shutter improves the illuminance levels inside the room and protects from glaring most of the hours of the day. However, as this is a fixed shading device whereas daylight is a dynamic phenomenon, it does not protect from glaring during the entire day, for instance when the sun is in a very low position. For this reason, a translucent material like PET would be ideal to avoid disturbing contrast between bright and dark pots inside the room. Thus, the broad sector of materials could also be explored in order to test different levels of transparency and translucency of the device, leading to interesting effects and patterns inside the room.

5 CONCLUSIONS AND FUTURE DIRECTIONS
AM and product design is a potential field for exploration. This study exemplified how the combination of parametric tools and AM can be suitable in supporting customized products. In the scenario of this study, a user can explore options by changing different parameters of the design on the computer screen (file) and then fabricate it directly through 3D printing technology (factory). For this, a digital workflow was proposed and described in this paper. The study developed and tested the workflow locally. However, it is suggested that the commercial potential can be increased when using the Internet. In this case, a new product design approach can be developed transforming individuals to a dynamic part of the design and fabrication process, changing the existing facts of the industry market.

In addition to this general consideration, the study allowed also to draw conclusions on the specific aspects presented here. The daylight analysis has shown high potentials in customizing daylight effects based on customized geometries of the shading devices. The parametric models have shown high potentials in allowing for design explorations and customization. It is suggested to include more variables into the parametric scripts of the patterns that may meet more user needs and fulfill both daylight and thermal performance. Optimization tools could also be considered. Currently, the major limitations are faced in the 3D printed items, as explained in this paper.
5.1 AM and shading device

Materials: searching available thermoplastics in the market for common users, it is obvious that (apart from aerospace applications) so far there is no affordable and appropriate material producing end-use parts for outdoor use in buildings.

As for PET, it needs extra coatings to improve its thermal performance against fire. Therefore, recycling a coated printing object in order to transform it to new filament is not possible, unless a coating removal by mechanical or chemical processes can be implemented. However, there are advanced engineering materials for end-use parts with improved properties for specific applications, mostly in the aerospace industry.[11,12] Another option is to produce modified filaments by adding fire protection coatings before printing takes place.

Mechanical properties of the printed objects from FDM method are challenging. The fact that it is a layer building process leads to a non-uniform built object with lower mechanical properties, in comparison to an object produced uniformly by the same material and another fabrication method. Normally, a shape factor of 1/2 has to be considered for the mechanical properties of the final object. [9] Another factors that also affect the structural performance of the 3D printed object are the settings used (bed temperature, extruder, speed), the nozzle for extrusion and the infill pattern of the object. For a stronger connection, the layers have to be positioned vertically to the direction of the expected failure (break).

Future recommendations related with the exploration of new materials for the AM processes have a great potential. Exploration of materials with better mechanical and thermal properties is very important when it comes to products exposed to outside weather conditions. According to materials field, an important aspect to be considered is the potential of some printers to extrude two or more materials in the same printed object. This feature leads to an object with different properties in its parts. Therefore, when it comes to a product like the one proposed in this research, different materials could be used for the connections of the parts and other materials for the main body of the device itself. The materials to be used for the joints could be more flexible than the ones for the main body of the device, in order to be more resistant to applied loads. With a flexible material used for the joints, they will show higher levels of deformation to the point of failure, compared to rigid parts. With regard to rigid parts, joints, which are the actual critical points, are recommended to be positioned that way in order for the layers to be vertical to the direction of possible break.

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Figure 13. Exterior view of proposed facade

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Towards a Novel Prediction Model for Visual Interest in Daylit Renderings

Siobhan Rockcastle, María Lovísa Ámundadóttir, and Marilyne Andersen
Interdisciplinary Laboratory of Performance-Integrated Design (LIPID)
School of Architecture, Civil and Environmental Engineering (ENAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland
siobhan.rockcastle@epfl.ch

ABSTRACT
In spaces where daylight is a primary source of illumination, our visual perception of architecture is largely influenced by the ephemeral composition of sunlight and shadow. To evaluate these perceptual effects, the authors will apply quantitative contrast measures to HDR renderings for a series of existing contemporary architectural spaces under variable sunlight conditions. These measures will then be compared to subjective ratings of visual interest, collected through an online survey designed to test the influence of spatial and temporal parameters. The objectives of this study assess the impact of sunlight dynamics on subjective ratings of daylit architectural renderings and compare the relationship between these subjective ratings and existing quantitative metrics. The results show that one modified contrast metric can be used to predict factors of visual interest in daylit renderings. When applied through an annual simulation-based approach, this novel metric reveals human perceptual responses to dynamic daylight conditions.

Author Keywords
Daylight; visual interest; renderings; online survey; contrast

1 INTRODUCTION
The compositional effects of shadow, contrast, and light directionality are essential to the visual performance of architecture, and yet their effects are most often defined as qualitative, and research that seeks to measure the impacts on human perception has been limited. To complicate this issue, variable sunlight and climate-driven sky conditions produce diverse compositions of light and shadow. While electric light can be fine-tuned to achieve a specific visual appearance, the ephemerality of natural lighting conditions can produce un-anticipated and even surprising visual affects over time.

Over the last several decades, daylighting research has gravitated toward the development of task-based illumination metrics to assess general illumination thresholds [1]. Visual comfort metrics, specifically those pertaining to glare, have also gained momentum as daylight integration as an energy efficient alternative to electric light has led to an increase in glazing and shading systems that can trigger occupant discomfort in workplaces [2]. Performance indicators for the visual appearance of daylight in architecture, such as those presented in this paper, have only gained momentum in recent years due to concerns that existing illumination-based metrics are not evaluating light perceived from an occupant’s field-of-view [3].

In some ways, the idea of evaluating perceptual lighting quality through quantitative measures is somewhat superfluous. Why would we need to quantify the performance of something that we can readily evaluate using qualitative judgment? Although people can observe and assess the visual effects of daylight in a single moment of time, they cannot intuitively comprehend or predict the range of effect that might be experienced over time. As daylight is a highly dynamic source, the complexity of predicting performance necessitates a method that can evaluate a space over time and across diverse sun positions to communicate the variable impacts of light and shadow. Simulation is a powerful tool for evaluating performance dynamics as we can assess a range of temporally-induced effects. Existing tools assess illumination and glare risk, yet there are no dynamic simulation-based methods for evaluating the positive perceptual aspects of daylight composition or its impact on architectural design.

As discussed in Section 2.1, while there are studies linking global contrast measures to perceived impressions of visual interest, more sophisticated local contrast measures exist in vision science and psychology but have not been used to evaluate the perceptual performance of daylit architecture. If we use image processing to quantify contrast-based visual effects within a single rendering and successfully link these values to impressions of spatial composition and visual interest, then we can apply that measure to a series of hourly and daily instances and predict these effects over time. This would help designers to understand where (within a defined view) and when (across hourly and daily moments) the effects of contrast, light, and shadow are likely to produce specific perceptual responses.

In this paper, the authors will apply existing contrast metrics from vision science and psychology to high dynamic range (HDR) renderings for a series of nine contemporary
architectural spaces under 3 different sunny sky conditions that vary in daylight composition. These measures will then be compared to subjective ratings for contrast, uniformity, variation, direction, complexity, excitement, and stimulation that have been gathered through an online survey.

The group of local contrast measures selected for this online survey were identified after an initial proof-of-concept experiment conducted with a small subject sample size revealed a stronger correlation between local contrast measures and ratings of contrast, excitement, and stimulation [20] compared to the global measures also tested. This paper builds upon those findings with a larger subject pool and expanded group of local contrast measures to extract a new model for predicting factors of visual interest.

2 BACKGROUND

Those studies that have assessed the perceptual impacts of contrast on daylit space have relied primarily on subjective surveys to explore the relationship between simple photometric measurements and perceived impressions of interior space [4-7]. Existing research has identified two factors that impact subject impressions of daylit space: average luminance and luminance variation [8]. While average luminance has been associated with impressions of brightness, luminance variation has been linked to visual interest [9]. Studies into subject preference have found that mean luminance and luminance variation (distribution and strength of variation) within an office environment contribute to occupant impressions of preference [6-7, 10-13].

2.1 Existing Contrast Measures

Studies that rely on simple photometric measures such as average luminance and luminance variation do not address the spatial diversity of luminance values within an occupants’ field-of-view. The definition of luminance variation or contrast in these studies is most commonly defined by a global measure, such as Michelson or Root Mean Square (RMS) contrast. Where Michelson computes a ratio from two single points of extreme brightness [14], RMS measures the root mean square of pixel intensities [15] (Appendix A.1). These global contrast measures provide a single value, that existing studies in daylight perception have utilized due to the ease of comparing this value to subjective rankings [5]. Global measures cannot, however predict perceived contrast between two images that vary in the distribution of luminance values [16].

To overcome this limitation, more sophisticated contrast measures have been developed in the fields of image analysis and vision research. The current state of the art in these fields would define two types of measures that are commonly used to quantify contrast: those that rely on global measures (such as Michelson and RMS) and those that rely on local measures [16]. Local contrast measures overcome the limitations associated with global measures by quantifying the effect of composition on contrasting areas of brightness and darkness. The authors have focused on neighborhood metrics for their ability to quantify the local contrast values between pixels within a neighborhood or sub-region within an image and assign a singular measure that represents the strength of local variation across all pixels. This led them to define Spatial Contrast (SC) measures as the sum of local pixel variations across a single image resolution [17]:

\[ SC = \frac{1}{w} \sum_{l=1}^{w} \sum_{j=1}^{h} \overline{\Delta p}_{l,j} \]

(1)

where \( \overline{\Delta p}_{l,j} \) is the average difference between the four pixels orthogonally surrounding the central pixel \( p_{l,j} \) or

\[ \overline{\Delta p}_{l,j} = \frac{1}{4} \left( |p_{l,j} - p_{l,j+1}| + |p_{l,j} - p_{l,j-1}| + |p_{l,j} - p_{l,j+1}| + |p_{l,j} - p_{l,j-1}| \right). \]

(2)

RAMMG, a contrast algorithm developed by Rizzi et al. [17] applies a multi-level approach to compute mean local pixel variations across a subsampled pyramid structure, taking into account perceived differences in brightness across multiple image resolutions:

\[ \text{RAMMG} = \frac{1}{N} \sum_{i=1}^{N} \overline{c}_i, \]

(3)

where \( N \) is the number of levels (image resolutions) and \( \overline{c}_i \) is the mean contrast in the level \( l \). The image resolution is halved in each subsequent level, where \( W_l = W_{l-1}/2 \) and \( H_l = H_{l-1}/2 \) are the width and height of the image at level \( l \) and \( c_{i,j} \) is the contrast of each pixel, calculated as:

\[ c_{i,j} = \sum_{k=1}^{K} \alpha |p_{i,j} - p_k|, \]

(4)

where pixels \( p_k \) are the 8 neighbouring pixels of \( p_{l,j} \) and the weight \( \alpha \) applied to each of the 8 surrounding pixels \( k \) is:

\[ \alpha = \frac{1}{4 + 2\sqrt{2}} \left[ \begin{array}{cc} \frac{\sqrt{2}}{2} & 1 \\frac{\sqrt{2}}{2} \frac{1}{2} & \frac{\sqrt{2}}{2} \\end{array} \right]. \]

(5)

Multi-level metrics like RAMMG were developed to assess both small and large pixel. Where large image resolutions (>100,000 pixels) provide the detail to compute small, localized contrast valued between pixel neighbors, small image resolutions (<25,000) provide the opportunity to measure the difference between larger areas of brightness (i.e. larger neighborhoods).

The Difference of Gaussian (DOG) measure, developed by Tadmor & Tolhurst [18], measures local differences between two bi-dimensional Gaussian components with a center radius and a surround radius. In 2009, Simone et al. combined the multilevel approach developed for RAMMG and the DOG measure to create a multi-level measure called Retinal-like Subsampling Contrast (RSC) [19]. These metrics are described in more detail in Appendix A.2.

2.2 Existing Experimental Studies

Existing research into qualitative lighting performance has seen studies which apply subjective rating methods to HDR
photographs [7, 21-22] or rendered images, usually of a simulated office environment [6]. These experiments have asked participants to rate images for pleasantness, contrast, brightness, spaciousness, and/or distribution which [4] are then compared to photometric measurements taken from the digital images.

When using renderings to collect qualitative impressions of daylight related to brightness and contrast, it is essential that tone-mapping algorithms are used to provide the broadest possible luminance range. In controlled laboratory experiments, tone-mapped HDR images have been displayed to subjects using 2D or 3D projection, HDR displays, and conventional low dynamic range (LDR) displays. While there are now backlit HDR screens which can display luminance values up to 4,000 cd/m² [23], a study by Cauwerts in 2013 found that conventional LDR displays of 200 cd/m² (with images tone mapped to 256 distinct luminance levels) could be used as a surrogate for real world spaces to conduct subjective assessments involving contrast and brightness [22]. In 2012, Villa and Labayrade developed a protocol for lighting quality research using digital images distributed through online survey methods. Their study found that 40 subjects were sufficient to measure significant effects despite systematic error due to uncontrolled conditions (variations in display, background, ambient illumination) [24].

In this paper, the authors use an online survey with tone-mapped images, accepting the limitations of conventional displays in order to reach a broader range of test subjects using the method introduced in Section 3.

3 METHODS

The experimental objectives presented in this paper are two-fold: 1) To measure the impact of sky conditions and architectural composition on subjective ratings of contrast-related characteristics in rendered images, and 2) to compare the relationship between these subjective ratings and existing quantitative contrast measurements. The first objective is to test whether subjects agree on ratings of contrast-based visual effects in architectural spaces and whether these ratings are sensitive to sunlight dynamics (sky types). The second objective is to compare existing contrast measurements and subjective ratings in search of a quantitative model for predicting perceptual responses to daylight.

3.1 Architectural Spaces

For this experiment, the authors modeled nine contemporary architectural spaces that display a range of contrast-based visual effects. On the high contrast side of the spectrum, the authors selected the Arab World Institute by Jean Nouvel (arab), the Zolleverein School by SANAA (zoll), and the Serpentine Pavilion by Toyo Ito (serp). The middle of the spectrum contains the Neughebauer House by Richard Meier (neug), the Toledo Glass Museum by SANAA (toledo), and the First Unitarian Church by Louis Kahn (first). Finally, the low contrast holds the Poli House by Pezo Von Ellrichshausen (poli), the Thermal Baths at Vals by Peter Zumthor (vals), and the Menil Gallery by Renzo Piano (menil) (Figure 1).

Each of the selected spaces was modelled in Rhinoceros version 5 sr6 and exported to Radiance using the Diva 3.0 toolbar to produce HDR daylight renderings. The authors did not model temporary artifacts (furniture, people) in order to limit visual obstructions and minimize biases toward space use. The PCOND mapping algorithm [25] was used to compress HDR images down to conventional computer screens (0.5 to 200 cd/m²) as all images in this experiment are displayed on personal tablet, laptop, and desktop screens. The authors acknowledge the limitations associated with a compressed range of values and will use screen technologies with an expanded luminance range in a forthcoming laboratory-based experiment.

3.2 Experimental Design

The experimental design selected for this online study is a repetitive 3 x 3 Semi-Latin-Square which allows for the comparison of three factors – space, subject group, and sky - while limiting experimental fatigue by showing each subject 9 images, rather than the 27 which are required by a full factorial design. The Semi-Latin-Square allows for repetition (in the case of multiple subjects within a given group) and nesting (with three architectural examples per sub category of high, medium, and low contrast – nine spaces in total). Each subject within a group is shown a single rendering for each of the 9 spaces, under one of the 3 sun positions (Figure 1). This methodology was tested in a proof-of-concept experiment using a small subject sample size and limited range of contrast measures to verify the approach [20]. This paper expands that subject pool and range of metrics through an online survey.

To select the dates and times for each rendering within the study, the authors divided half the year (from the winter to summer solstice) into 28 moments which represent symmetrical daily and monthly instances. Each of the nine architectural spaces was then rendered for each of the 28 moments and analyzed in MATLAB R2012b using the RAMMG contrast metric (eq. 3) [17], which was selected to represent the broader group of neighborhood metrics introduced in Section 2.1. From the assessment of RAMMG contrast across these 28 renderings, three images were then selected: the highest, lowest, and mean contrast composition for each space. Based on the mean RAMMG contrast for each architectural space, the 9 spaces were then ordered and divided into three architectural sub-groups: high, medium, and low.

Table 1 shows the contrast measures applied to the 27 renderings selected for this study: both global (Michelson and RMS) and local contrast metrics (SC, RAMMG, DOG and RSC). As DOG measurements are dependent on the center and surround radii of Gaussian components, the authors applied a selection of radii (rc = 1-4 to rs = 2-8) based on past experiments [18,26]. Local measurements such as
RAMMG and RSC are dependent on multiple levels within the image, therefore the authors looked at each resolution level independently. In this study, the original images were 1488 x 1024 pixels and as each subsequent level is halved, we looked at 9 independent image levels for RAMMG (RAMM1, RAMM2,…,RAMM9), and 5-6 levels for RSC, depending on the r_c and r_v.

Table 1 List of contrast measures considered in study.

<table>
<thead>
<tr>
<th>Global Measures</th>
<th>Measure Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michelson</td>
<td>Michelson, 1927</td>
<td>A.1</td>
</tr>
<tr>
<td>RMS</td>
<td>Pavel et. Al, 1987</td>
<td>A.1</td>
</tr>
<tr>
<td>Local Measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>Rockcastle &amp; Andersen, 2014</td>
<td>Eq.1</td>
</tr>
<tr>
<td>RAMMG</td>
<td>Rizzi et al, 2004</td>
<td>Eq.3</td>
</tr>
<tr>
<td>DOG</td>
<td>Tadmor &amp; Tolhurst, 2000</td>
<td>A.2</td>
</tr>
<tr>
<td>RSC</td>
<td>Simone et al., 2009</td>
<td>A.2</td>
</tr>
</tbody>
</table>

3.3 Experimental Procedure

The online survey designed for this experiment was created using Survey Gizmo (http://www.surveygizmo.com/) with a branch logic which allowed for random group assignment upon subject initiation of the survey link. The survey was distributed using multiple diffusion methods: email, Facebook, LinkedIn, and Twitter over a duration of 10 days. Each subject group was asked to respond to some basic demographic questions regarding geographic location and profession and then shown the nine architectural spaces at random, under one of the three possible sky conditions. For example, group 1 (Figure 1) was shown three high contrast spaces under sky 1, three medium contrast spaces under sky 3, and the three low contrast spaces under sky 2. While smartphones were forbidden, we allowed tablet, laptop, and desktop computers. Subjects were asked to turn the brightness on their device to maximum, to ensure the maximum possible pixel range was observed.

For each image, subjects were asked to rate the daylight composition using the following seven point semantic differential scales: low contrast – high contrast, uniform – non-uniform, unvaried – varied, diffuse – direct, simple – complex, calming – exciting, sedating – stimulating (Figure 1). Flynn introduced the use of semantic differential scales to gather subjective assessments of daylight quality in terms of visual clarity, spaciousness, evaluation, relaxation, social prominence, complexity, modifying influence, and spatial modifiers [4]. For the proposed study, the authors have focused on scales associated with complexity and spatial modifiers as well as visual interest.

3.4 Data Management

In total, there were 334 subjects who initiated the survey with 200 complete responses and 134 partially completed, which were discarded. Interestingly, we did see a significant effect on responses from those subjects using tablets. These subjects (4.5%) were discarded as this effect could be due to the smaller screen size (which forced subjects to manually zoom in to view each image) or the default button format which was automatically adjusted in Survey Gizmo on the tablet version. There was no significant effect observed between subjects using a laptop or a desktop computer. Of the remaining 175 subjects, 96% selected their English language capacity as professional, bilingual, or native, with the remaining 4% responding with elementary or limited working proficiency. These subjects were also discarded.

From the remaining 168 subjects, 64% were composed of designers (architecture, landscape, urban, or interior), 36 % non-designers, with 55% reporting their expertise in lighting design as competent, proficient, or expert, and the remaining 45% claiming novice or beginner expertise. There was no significant effect observed between subjects with a design background or expertise in lighting. One subject was excluded from the analysis because 73% of responses were neutral. We normalized the responses (from 1 to 7) for five other subjects, as they did not use either extreme on the rating scale. The remaining 167 subjects were evenly distributed among the three groups (G1: 55, G2: 56, G3: 56).

Figure 1 Subjects are first introduced to basic demographic questions, after which they are randomly sorted into one of three groups (G1, G2, or G3) and asked to rate the selected images as they are presented in fully randomized order.
3.5 Data Analysis
To test the significance of experimental factors on the data from each rating pair collected in the experiment, a 3-way ANOVA was used to test the effects of sky, space, and subject group. As the residuals for each rating pair was not normally distributed, a post-hoc analysis was conducted using Kruskal-Wallis to determine the significance of each group within the factor under consideration. To analyze the relationship between subject ratings and existing contrast measures, the authors calculated the Spearman’s rank correlation coefficient. Using Spearman’s correlation, the authors then selected those combinations of rating-pair and contrast measurement with $\rho_s \geq 0.70$ ($p < 0.0001$). A cumulative logistic model was then applied to fit the subject ratings to selected contrast measures, as the subjective ratings are ordinal response scales.

4 RESULTS
4.1 Distribution of Subject Responses
Figure 2 shows stacked bar plots with the distribution of subject responses for each level of the seven-point rating scale for a selection of 3 spaces (arab, neug, and menil). Subject responses are clustered into gradients by color, with responses that fall on the left side of the scale (1-3) in cyan and responses that fall on the right (5-7) shown in magenta. White is used for neutral ratings (4) and the dotted line shows where the median responses fall for each rating pair. The most frequent responses (summed by color) are shown as a percentage of the total number of responses. There is a substantial effect of sky type in some, but not all spaces – specifically those that see the most obvious variation in daylight composition due to sunlight penetration. The space with strongest subject consensus toward the cyan end of the rating scale (low contrast, uniform, unvaried, diffuse, simple, calming, subdued) was menil, while the magenta side of the rating scale (high contrast, non-uniform, varied, direct, complex, exciting, stimulating) was dominated by arab. While all rating scales were found to be significantly correlated, subject responses for ratings of excitement and stimulation were the most highly correlated ($\rho_s = 0.75$, Spearman’s correlation).

4.2 Effects of Experiment
The significance of experimental factors was evaluated using a 3-way Anova to test the effects of subject group, space, and sky type on each rating scale. While the ANOVA revealed a significant effect of both space and sky factors for all rating scales ($p<0.01$), the residuals were not normally distributed. A post-hoc analysis was conducted using Kruskal-Wallis, a non-parametric test, to study pair-wise comparisons between each group between the factors under consideration within each rating. This test was run for both sky type and space group on each of the semantic scales. This test revealed the effect of sky was significant on subject responses to all rating scales ($p<0.01$), except unvaried-varied.

A pair-wise comparison between sky 1 and sky 3 showed a significant effect ($p<0.01$) on ratings of contrast, uniformity, direct, complexity, excitement, and stimulation. Ratings of excitement and stimulation also showed a significant effect ($p<0.01$) between sky 1 and sky 2, which suggest that these ratings were more sensitive to the range of sky types presented in this experiment.

To test the effect of space, we grouped the examples into high, medium, and low based on the percentage of subject responses for all 7 rating pairs magenta cluster 5-7. In this test, there was a significant effect of space between all groups in the factor ($p<0.001$) for all rating pairs.
4.3 Subject Ratings vs. Quantitative Measures

To relate median subject responses for each rating pair as a function of the contrast metrics introduced in Section 2.1, a Spearman’s correlation analysis was conducted. Although a range of center and surround radii were considered for the metrics that rely on Gaussian components (DOG and RSC), only the results for \( r_c = 1 \) to \( r_s = 2 \) are listed here. No radii combinations tested in this study were found to have particularly significant correlation to subject responses.

Table 2 shows that RAMM5 (the 5th resolution level in RAMMG - 64 x 93 pixels) achieved the strongest statistical dependence to median ratings of diffuse-direct (\( \rho_s = 0.77 \)), calming-exciting (\( \rho_s = 0.78 \)), and subdued-stimulating (\( \rho_s = 0.77 \)), while RAMMG had the strongest dependence with ratings for low contrast – high contrast (\( \rho_s = 0.74 \)). Using Spearman’s correlation to pre-select contrast metrics as possible predictors of visual interest, we selected RAMM5, hereafter referred to as ‘Modified Spatial Contrast.’

The authors then applied an ordered logit model to fit the Modified Spatial Contrast (RAMM5) to subjective ratings for diffuse - direct, calming - exciting, subdued - stimulating using ordered logistic regression. The deviance of these fits was 8.78, 9.36, and 9.21, respectively. Figure 3 shows the application to a proportional odds model to predict subject ratings of calming – exciting.

When we group ratings, such as we did in the cyan and magenta gradient plots in Figure 2, we can say that a Modified Spatial Contrast of 13 (or more) triggers responses of excitement (ratings of 5, 6, or 7) for 63% of subjects, whereas a Modified Spatial Contrast of 5 (or less) produces responses of calming (ratings of 1, 2, or 3) in 59% of subjects. This probabilistic model provides the first ever objective predictor for visual interest in daylit architecture.

Contrary to those metrics which address task-plane illuminance, autonomy from electric energy sources, and discomfort glare, Modified Spatial Contrast allows designers to compute the probability of achieving specific perceptual responses to daylight across the day and year.

Table 2: Spearman’s correlation coefficients between median subject responses for each rating pair and contrast measure.

<table>
<thead>
<tr>
<th></th>
<th>Michelson</th>
<th>RMS</th>
<th>SC</th>
<th>RAMM5</th>
<th>RAMMG</th>
<th>DOG ( r_c=1 ), ( r_s=2 )</th>
<th>RSC ( r_c=1 ), ( r_s=2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>contrast</td>
<td>0.10</td>
<td>0.62</td>
<td>0.52</td>
<td>0.72*</td>
<td>0.74*</td>
<td>0.30</td>
<td>0.17</td>
</tr>
<tr>
<td>uniformity</td>
<td>0.06</td>
<td>0.55</td>
<td>0.44</td>
<td>0.67</td>
<td>0.66</td>
<td>0.32</td>
<td>0.19</td>
</tr>
<tr>
<td>variation</td>
<td>0.08</td>
<td>0.42</td>
<td>0.40</td>
<td>0.58</td>
<td>0.55</td>
<td>0.30</td>
<td>0.19</td>
</tr>
<tr>
<td>direct</td>
<td>0.17</td>
<td>0.59</td>
<td>0.63</td>
<td>0.77*</td>
<td>0.75*</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>complex</td>
<td>0.14</td>
<td>0.53</td>
<td>0.48</td>
<td>0.65</td>
<td>0.62</td>
<td>0.36</td>
<td>0.14</td>
</tr>
<tr>
<td>exciting</td>
<td>0.06</td>
<td>0.70*</td>
<td>0.70*</td>
<td>0.78*</td>
<td>0.74*</td>
<td>0.38</td>
<td>0.26</td>
</tr>
<tr>
<td>stimulating</td>
<td>0.16</td>
<td>0.61</td>
<td>0.60</td>
<td>0.77*</td>
<td>0.75*</td>
<td>0.31</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*Rating pair and contrast measurements with \( \rho \geq 0.70 \) (\( p < 0.0001 \)) were considered most significant.

Figure 3 Ordered logistic regression through RAMM5 and ratings of calming – exciting.

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Figure 4 shows the application of modified spatial contrast (RAMM5) to a selection of three spaces: *arab*, *neug*, and *menil*. This measure was applied to 56 renderings for each space, representing a symmetrical distribution of hourly and daily instances and plotted temporally to show an annual prediction of excitement. Values in magenta show point-in-time predictions of excitement while cyan shows predications of calming.

5 CONCLUSION & OUTLOOK

In conclusion, the experiment presented in this paper resulted in the following findings: 1) both space and sky condition have a significant effect on subject ratings of contrast, direction, complexity, excitement, and stimulation and 2) local neighborhood contrast measures such as RAMMG and specific levels within than metric (RAMM5, i.e. Modified Spatial Contrast) were found to be good predictors of contrast-based visual effects, especially ratings of diffuse – direct, calming – exciting and subdued – stimulating. Using a cumulative logistic model, this paper introduces a novel probabilistic model for predicting subject responses to excitement in simulated daylight renderings using an objective contrast measure.

While a single point-in-time quantitative analysis may be less useful to designers who can evaluate this performance qualitatively, modified spatial contrast is useful in its ability to predict dynamic effects which may be unanticipated. By predicting how visually engaging a space may be (and how this changes over time), this research offers a new dimension in daylight performance assessment. Rather than be satisfied with the knowledge that a space achieves enough or too much daylight, this model evaluates human arousal to daylight composition.

To further validate this approach, the authors will conduct a series of upcoming experiments with an expanded set of architectural spaces and view parameters. To limit potential error due to screen size, brightness, and tone-mapping, these forthcoming experiments will be conducted under controlled laboratory conditions using screen technologies with an extended view and luminance range. Future experimental parameters will include the assessment of daylight composition using immersive viewing techniques achieved through a virtual reality headset. This virtual method is currently being tested as a surrogate for extracting qualitative lighting assessments in live space and initial findings suggest a positive result. While a single view is convenient for the application of digital image measurements, architecture is rarely composed of a single space or view position and requires more immersive evaluation techniques.

ACKNOWLEDGMENTS

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APPENDIX A

A.1 Global Measures

*Michelson* = \( \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}} \)

where \( P_{\text{max}} \) and \( P_{\text{min}} \) represent the highest and lowest pixel intensity.

*RMS* = \( \sqrt{\frac{1}{WH} \sum_{i=1}^{W} \sum_{j=1}^{H} (p_{i,j} - \bar{p})^2} \)

where \( p_{i,j} \) are the pixels intensities at position \((i, j)\) in an image of size \( W \) by \( H \) and \( \bar{p} \) is the average pixel intensity.

A.2 Local Measures

*DOG* calculates local differences between two bi-dimensional Gaussian filters with a center component \( R_c(x, y) \) and a surround component \( R_s(x, y) \):
$$DOG(x, y) = \frac{R_g(x, y) - R_s(x, y)}{R_c(x, y) + R_s(x, y)}$$

Center and surround components $R_c(x, y)$ and $R_s(x, y)$ can be found in [18]. The authors have chosen to compute the average $DOG(x, y)$ across all pixels in a given image with width $W$ and height $H$:

$$\overline{DOG} = \frac{1}{W \times H} \sum_{i=1}^{W} \sum_{j=1}^{H} DOG(x_i, y_j)$$

RSC combines the pyramid subsampling method used in RAMMG (eq.3) with the DOG measure:

$$RSC = \frac{1}{N} \sum_{l=1}^{N} \overline{DOG}_l,$$

where $N$ is the number of levels and $\overline{DOG}_l$ is the mean contrast in level $l$ [19].

REFERENCES

The benefits of real-time rendering and game engines are evident in the AEC industry. Research exists when immersive and interactive virtual environments containing textural and material qualities of a space are created. However, most of these efforts lack the daylighting realism and fidelity of ray-tracing renderings. Previous research efforts focused on simplified experiential walkthroughs of architectural design, almost completely disregarding performance-based analysis and evaluation, and lacked formally disparate design options. The proposed method targets the exploration of virtual spaces in real time when spatial daylight distribution is pre-simulated using a validated rendering engine. This method will materialize through a prototype enabling a realistic as well as a false-color representation of daylight performance analysis to be experienced in real-time. Furthermore, the prototype will permit to experiment with different design options at distinct times throughout the year. The resulting final interface is a novel approach in presenting and experiencing the qualitative walkthrough process along with daylighting performance-based analysis of an environment. This interface allows the simultaneous evaluation of form and performance of different design options.

BIM is an intelligent and comprehensive database for geometric and non-geometric information, which facilitates the creation and management of AECO data throughout the lifecycle of a building from design to post-occupancy. In contrast with computer aided design (CAD) systems that only store the geometric definition of an object, a BIM model links the object’s three-dimensional representation with a real-time database of parametric properties [6]. Parametric BIM models are usually presented, and therefore perceived, as static finalized models. Additionally, the advantage of having a parametric model, which may generate multiple design options is usually neglected [9]. Recent advancement and broader accessibility of high-end game engines, has the potential to change the way in which we present and evaluate architectural design. The integration of game engines and parametric BIM models is a beneficial trend [1, 24]; however, it has not comprehensively addressed the complexity of design evaluation. This research, Parametric Design Review user interface prototype 2.5 (PDR-2.5), builds on a previous study, user interface prototype 2.0 (PDR-2.0) [1], of a
dynamic design review interface for parametric and performance-based models. PDR-2.0 was developed using Unity game engine. A game engine is an authoring platform that contains an integrated collection of modules to create interactive virtual environments, for example, modules that handle input, output (e.g., rendering and sound), and generic physics/dynamics for the game environment [12]. PDR-2.5, developed using Unity, acquires the ability to visualize multiple design options accompanied with their respective daylight performance using perspectival and orthographic spatial representations. By utilizing multiple existing methods, such as daylight simulation and texture baking, we arrived at a prototype, which facilitates qualitative and quantitative evaluation of parametric, BIM-based, and performance-driven models.

2 PROTOTYPING

The objective of PDR-2.5 is to design a novel user interface that facilitates the comprehension and exploration of qualitative and quantitative aspects of multi-option, performance-based parametric-BIM models. The previous prototype, PDR-2.0, is a user interface for presenting parametric models where geometric and non-geometric data are transferred directly from Revit—a BIM authoring tool—to Unity—a game engine. The result is an integrated environment of geometric, parametric, and performance-based representations. The prototype assists in acquiring comprehensive understanding of a design project by juxtaposing multiple viewports: a main viewport and a series of support viewports, which dynamically update based on the user’s spatial location. By default, PDR-2.0 utilizes Unity 5 Enlighten engine to simulate global illumination (GI) for the walkthrough viewport. However, in the support viewports it relies on Autodesk360 Rendering as a Service (RaaS) to visualize multiple daylighting simulation renderings within the interface. Additionally, the prototype allows for a real-time false-color rendering walkthrough mode where the pixel values are mapped to a color gradient.

PDR-2.5 is an attempt to address the limitations of the previous study. PDR-2.0 lacks formal design options, allowing the exploration of only a single architectural model. It utilizes a non-validated GI real-time rendering solution and an approximate real-time false-color rendering, both facilitated by the Enlighten GI solution in Unity 5. It uses RaaS as a daylighting simulation engine, which is yet to be fully validated. Finally, it utilizes a single material per Revit object. For example, a window object may only have one material, thus glass and mullions will be assigned a glass material. PDR-2.5 overcomes these limitations by engaging multiple formally different design options, and through the use of a validated daylighting simulation engine, for material textures, and false-color rendering as well as daylighting distribution analysis by utilizing Autodesk 3ds Max 2016 [18, 22].

Note for the purpose of this paper and due to time constraints, the architectural model and the user interface were simplified. PDR-2.5 contains three viewports only as opposed to the seven viewports in PDR-2.0. Moreover, for the ease of demonstration, a less complex scenario of an office space was employed instead of a full building. In the near future the two prototypes will merge for a more comprehensive experience of architectural design projects.

3 EXPERIMENTS

The experiments of PDR-2.5 are carried in three steps. The first step is the modeling of the different design options in Revit where geometric definitions are created and material properties are assigned. The second step utilizes 3ds Max to conduct daylighting simulations. The third and final step is set in the Unity game engine, where geometric and non-geometric data are brought together for an interactive performance-based design evaluation interface.

3.1 Revit Design Options

Three design options were generated in Revit to use in the prototype. These options are of a south-facing office space with different formal properties. Material properties, room width, ceiling height, and window sill height are constant amongst the design options: 20 ft room width, 10 ft floor to ceiling height, and 3 ft window sill height. Figure 1 shows

![Figure 1. Plans and sections of design option A, B, and C.](image-url)
the three design options in plan and section while Table 1 shows the specifications of the three design options. College Station, Texas weather files were used for location specific and climate-based daylight simulation.

<table>
<thead>
<tr>
<th>Design option</th>
<th>Room Depth</th>
<th>Window Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design option A</td>
<td>20 ft</td>
<td>3x4 ft</td>
</tr>
<tr>
<td>Design option B</td>
<td>30 ft</td>
<td>4x6 ft</td>
</tr>
<tr>
<td>Design option C</td>
<td>40 ft</td>
<td>4x6 ft</td>
</tr>
</tbody>
</table>

Table 1. Specifications of design options A, B, and C.

3.2 Revit to 3ds Max
To transfer the BIM models to Unity, they are first brought into 3ds Max. Linking Revit files (RVT) directly to 3ds Max documents gives more reliable results, solves interoperability problems, and eliminates errors associated with importing and exporting. The daylighting system and materials’ physical properties seamlessly transfer to 3ds Max given that they are specified in the RVT. Additionally, when the RVT is updated, the 3ds Max counterpart may be updated as well. Thus, by re-linking the RVT, any changes to the geometry or material properties may automatically be updated in the 3ds Max scene. This relinking process of updated RVT does not necessarily change the additional settings specified by the user in 3ds Max, which made it easier to update the design options without losing 3ds Max settings. Entities in the linked RVT were combined based on Revit material assignment. The advantage of this setting is the significant reduction of the number of texture baking operations in the following sections.

3.3 3ds Max Simulation
Daylight analysis in 3ds Max are based on the mental ray® rendering engine [19, 10] and Exposure technology [18]. Exposure includes a shader of the Perez Sky Model necessary for daylighting analysis. For global illumination simulation, Exposure uses the mental ray raytracer. Two methods of daylighting simulations were conducted in 3ds Max: a numerical quantitative feedback method via light meters, and a visual qualitative feedback method via rendering simulation. For each design option, we conducted the two simulation methods on four different timeframes: 12:00 PM Summer Solstice, 12:00PM Winter Solstice, and per LEED 8.1, 9:00AM and 3:00PM on September 21 (Fall Equinox). More specific settings and analysis workflows for 3ds Max can be found in the Autodesk white papers [19, 10].

Light meter simulation
A daylight simulation is a computer-based calculation of the amount of light available, in this case inside the building at a specific location under different sky conditions. Virtual sensors, i.e. light meters, are used in a grid throughout the space giving an output of illuminance and luminance values [17]. For these simulations, we used the same settings reported by Reinhart [18]. For the three design options, the light meter grid was set at 30 inches from the floor, a sample work plane height, with an offset of 1 ft from each wall. A distance of 1 ft was maintained between light meters. After conducting the light meters calculation, CSV files of simulation results were exported from 3ds Max.

Ray-tracing rendering
The procedure of ray-tracing is to trace a bundle of light rays inter-reflection effects in the scene [3]. There are two methods of ray-tracing: forward ray-tracing and backward ray-tracing. For the former, also known as Radiosity or photon mapping, the rays are view independent, and therefore computationally expensive [5]. For the latter, also known as final gathering, rays are fired from the camera thus only calculating necessary information for the scene including for example, direct and indirect lighting, textures, and shadows [18]. Mental ray may use both methods to conduct daylight analysis [18].

Daylight simulations require global illumination to compute different light attributes. Effects such as shadows, environmental lighting, and indirect illumination are computationally expensive and cannot be computed in real-time [20]. The common solution is to pre-compute these effects and store them in a texture map, a process known as texture baking [21]. Creating a UV map for the objects is a prerequisite to texture baking. A UV map is an unwrapped two-dimensional representation of three-dimensional objects (Figure 2). This two-dimensional representation allows for better texture transference from 3ds Max to Unity. Having entities combined based on Revit material assignment, in the previous step, reduced the number of UV maps from 32 to 11 UV maps per design option.
precision of data in the texture map we saved the textures as High Dynamic Range Imaging (HDRI) files. The texture maps were baked at a resolution of 1024x1024 pixels. The office space and furniture were rendered and baked once per timeframe per design option. This resulted in a total of 12 sets of texture maps. Nevertheless, due to the fact that exported FBX® files from 3ds Max have encrypted textural properties, we had to rely on a commercial plug-in, Autodesk Material Converter (AMC), to convert Autodesk materials into standard materials and to transfer this material assignment and UV maps from 3ds Max to Unity.

3.4 Processing Texture Maps
To process the baked HDRI texture maps we used wxFalsecolor, a software tool that comes with DIVA for Rhino installation. First we needed to generate Low Dynamic Range (LDR) maps, i.e. adjust the HDR texture maps to LDR based on “human sensitivity”. To do so, we simply load the texture map in wxFalsecolor and save it as a PNG or JPEG file.

Additionally, false-color representations of the texture maps were also generated from the baked HDRI files. Only few alterations were made to the default false-color menu: for consistency and design option comparisons, we maintained the base of the scale legend at zero, and a maximum of 355 candela per square meter (cd/m²). Figure 3 demonstrates the explained data flow from Revit to Unity.

3.5 Gaming
Unity gaming engine was used to create an interface within which we may qualitatively and quantitatively evaluate a multi-option architectural design project. The proposed interface is divided into two categories: a main first person viewport, and two support viewports that show the plan and section of the design project. Additional functionalities, such as design option selection, simulation timeframe, and light meter visibility, are added via drop-down menus, toggle check boxes, and keyboard shortcuts (Figure 4). The location of the user is always highlighted in the support viewports, thus allowing the user to be constantly aware of his/her location in the virtual environment.

Geometric definitions from 3ds Max and simulation results, i.e. texture maps and light meter readings, were brought into Unity in order to situate the model, texture it, define

Figure 3. Data flow from Revit to Unity

Figure 4. Parametric Design Review prototype 2.5 (PDR-2.5) showing illuminance distribution sensor grid readings (lux).
collision properties, and attach different Unity scripts to allow for interactivity. Custom scripts were created to allow for better and automated data visualization. For example, a custom class was created to process light meter data and the way in which that data is visualized. The class allows for quick adjustment of light meters’ physical representation, for example the color gradient, in the environment as well as the reading units, lux or foot-candles.

Global illumination and light settings were disabled in Unity to allow for texture representations that are consistent with 3ds Max results. Therefore, the baked LDR texture maps were applied to the objects as emission maps, i.e. self-illuminated maps.

4 DISCUSSION

4.1 PDR-2.5 Functionality

Using PDR-2.5, allows to visualize and inspect the multiple varying design options and their corresponding daylight performances. As we switch between design options the light meter readings and their representation will automatically update to visualize the appropriate set of data for the selected design option. Additionally, by selecting different simulation times, the texture maps as well as the light meters will automatically update to reflect the qualitative and quantitative results of the simulation. The user will be able to inspect the design option with or without visualizing the light meters. Moreover, the user is also able to visualize the space using accurate false-color representation. False-color images or luminance maps represent an alternate option to visualize the pixel data for HDR images in their RGB native format. They facilitate the visualization of light intensity distribution in the space portrayed by the variation in colors following a gradient scale allied to the luminance measured in candela per square meter (cd/m²) [8] (Figure 5).

4.2 Revit and 3ds Max Daylighting Engines

BIM’s rich semantics help simulate specific spaces of the model. Spaces such as closets, bathrooms, utility rooms, and rooms that are not considered as regularly occupied per LEED criteria can be easily excluded from a particular simulation. For example, in PDR-2.0, the bathroom on the ground floor was excluded from the daylighting simulation. This was done by giving each room a parameter that classifies it as regularly occupied or not, thus qualifying specific rooms for the daylighting simulation. A custom function then filters the spaces and only allows for the simulation of the qualified ones. This process is not possible in 3ds Max where only geometric and material properties affect the daylighting simulation. Therefore, different light meter objects need to be generated per space for a more time efficient simulation workflow. In contrast with Figure 5 which shows the luminance map, Figure 6 is a RaaS generated illuminance distribution map created for the previous prototype, PDR-2.0, note that the bathroom in this case is excluded from the simulation, thus rendered in blue.

Figure 5. Parametric Design Review prototype 2.5 (PDR-2.5) showing luminance maps (false-color) (cd/m²).

Figure 6. Illuminance distribution map from Revit (lux).
5 CONCLUSION, LIMITATION, AND FUTURE WORK

Real time rendering facilitated by game engines enabled us to generate a novel method to explore virtual spaces and their performances. In this study, as a proof of concept, the chosen performance was the daylight availability. A validated rendering engine in 3ds Max was used to pre-simulate quantitative and qualitative data to generate the daylight analysis. Both data were represented in the virtual environment, quantitatively via light meter readings, and qualitatively by means of texture mapping. The significance and main contribution of this research is reflected in the ability to visualize a myriad of design options at specifically selected times throughout the year. This juxtaposition of both quantitative and qualitative analyses allows for simultaneous evaluations of form and performance, which we expect will greatly enhance the design review process of parametric, BIM-based, performance-driven models.

The limitations of this research stem from two factors. On one hand, the design space is rather large for even a simple parametric model. A thoroughly conceived parametric framework may generate thousands, or even millions, of design options. Additionally, performance-based design relies heavily on computer simulations. Daylighting and energy simulations for example are process intensive, which may take hours to generate results. Design reviews and presentations usually have a limited time-frame, which necessitates pre-simulation of performance analysis. Therefore, the inclusion of performance pre-simulation of all possible scenarios is currently not feasible or possibly not even desirable. Thus the designer is required to select and pre-simulate specific design options to be presented in the design review.

On the other hand, the process presented in this paper is time consuming where multiple steps are required to arrive at the final interface. Nevertheless, as technology progresses, pre-simulation and processing time of data may be significantly reduced. Additionally, automation of many aspects in the system is possible, which will greatly reduce the number of steps and setup requirements.

Additional functionalities could be developed for future work. For example, in addition to work-plane light sensor readings, we can provide the ability to pixel sample the illuminance or luminance values in the virtual environment during the design review. For instance, as one inspects the virtual environment, it will be possible to query and compare illuminance values measured on the floor, walls, ceiling, and furniture. Conventional pixel sampling methods rely on tedious placement and rendering of multiple cameras in the virtual environment. The suggested real-time illuminance and illuminance pixel sampling method will allow to render a set of maps for an entire project. The results can be used in a design review to interrogate the model from all possible points of view.

PDR-2.5 utilized a simple scenario of an office space for the demonstration of the interface. In this case we have only altered the depth parameter of the space and the window width and height. Future work will entail engaging more sophisticated building geometric changes between the different design options.

Additionally, while 3ds Max light meter simulation provides direct, indirect, and total illuminance, in PDR-2.5 we only reported the total illuminance values. In the future we will give the user the option to alternate between direct, indirect, and total values independently.

Daylight analysis is complex and not limited to work-plane illuminance distribution. Reinhart [16] and Leslie [11] proposed dashboards that contain multiple categories and metrics for comprehensive daylight evaluation. For future studies, an appropriate metric dashboard will be included for a thorough daylight analysis interface.

Although daylighting was included as a performance-based design criterion, any other criteria may substitute daylighting or live with it side-by-side. The proposed tool does not dictate any specific performance-based analysis to evaluate a design option. It is merely a method that facilitates a new way of comprehending design projects. Therefore, more performance metrics, such as thermal performance and energy performance, can be added into the system for each design option.

Lastly, a user study is proposed to measure the effectiveness and perceived usefulness of presenting multiple design options and their associated performances in a design review assisted by an interactive walkthrough. If the effectiveness of the tool is verified, future iterations of PDR-2.5 may transform and enhance the way in which we present parametric models for design review.

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REFERENCES


Session 3: Urban Networks & Analysis

Straightness of Rectilinear vs. Radio-Concentric Networks: Modeling, Simulation, and Comparison
Didier Josselin, Vincent Labatut, Dieter Mitsche
Université d’Avignon; Université de Nice.

Spectral Modelling for Spatial Network Analysis
Pirouz Nourian, Samaneh Rezvani, Sevil Sariyildiz, Frank van der Hoeven
Delft University of Technology; 123dv Architectuur & Consult.

Urban Body Network Configurations Through Attributes of Network Elements
Eirini Androutsopoulou
National Technical University of Athens.
Straightness of rectilinear vs. radio-concentric networks: modeling, simulation and comparison

Didier Josselin\textsuperscript{1,2}, Vincent Labatut\textsuperscript{2} and Dieter Mitsche\textsuperscript{3}

\textsuperscript{1}UMR ESPACE 7300, CNRS
University d’Avignon, France
didier.josselin@univ-avignon.fr
\textsuperscript{2}LIA – EA 4128
University d’Avignon, France
vincent.labatut@univ-avignon.fr
\textsuperscript{3}Lab. de Mathématiques Dieudonné
Université de Nice, France
dmitsche@unice.fr

ABSTRACT
This paper proposes a comparison between rectilinear and radio-concentric networks. Indeed, those networks are often observed in urban areas, in several cities all over the world. One of the interesting properties of such networks is described by the \textit{straightness} measure from graph theory, which assesses how much moving from one node to another along the network links departs from the network-independent straightforward path. We study this property in both rectilinear and radio-concentric networks, first by analyzing mathematically routes from the center to peripheral locations in a theoretical framework with perfect topology, then using simulations for multiple origin-destination paths. We show that in most of the cases, radio-concentric networks have a better straightness than rectilinear ones. How may this property be used in the future for urban networks?

1 INTRODUCTION
We propose to study and to compare the \textit{straightness} of two very common networks: rectilinear and radio-concentric networks. This measure, also called directness, is related to another index called efficiency [24], and is the reciprocal of the tortuosity (a.k.a. circuity) [14] – see section 2.1 for a formal definition. In a general meaning, a high straightness reflects the capacity of a network to enable the shortest routes. It is somehow an accessibility assessment: the higher the straightness, the shorter the distance (or moving time) on the network, due to reduced detours.

First, we show a few pictures of old and current networks observed in the real-world, to highlight their peculiar structures [17]. Hippodamian or rectilinear (also called Manhattan) networks are made of rectangular polygons, while radio-concentric networks show a center location and a series of radial and circular links.

Second, we model theoretical rectilinear and radio-concentric networks. We introduce the mathematical formula of the straightness for center-to-periphery routes, and we demonstrate that in most of the cases, even with a low number of rays, radio-concentric networks provide straighter paths.

Third, we empirically process the straightness of all routes (any node to any node) using Dijkstra’s shortest path algorithm [6]. The results confirm that for any type of routes, radio-concentric structure has higher straightness.

1.1 Some Rectilinear Networks

Rectilinear networks are very common all over the world. They are also called Hippodamian maps due to the Greek architect Hippodamos. These networks are characterized by road sections crossing at right angles. Built according to land registry and road construction efficiency in a process of urban sprawl, they look like pure theoretical shapes: a grid of squares of identical surface and side length. Figure 1 shows an example of an old hippodamian urban structure in the antique Egyptian city of Kahun (pyramid of Sesostris).

![Figure 1. The antique Egyptian city of Kahun (pyramid of Sesostris); Wikipedia.](image)

More recent rectilinear networks are illustrated by the American cities of Chicago in 1848 (Figure 2), New-York with Manhattan (Figure 3), Sacramento (Figure 4) and also the Asian city of Hô Chi Minh in Vietnam (Figure 5).

1.2 Radio-concentric Networks and Shapes

The second type of network we study is also very common. It is very different in its shape, although it presents basic polygonal entities of various sizes, due to the radial structure. In these networks, the center is somehow a fuzzy location, that often refers to the old part of the town. From this supposed center, radial roads are drawn, crossing a series of perpendicular ring roads, depending on the surface of the city.

These shapes were already visible in old maps such as medieval Avignon (cf. Figure 6), especially in its \textit{intrauros} part, which is surrounded by battlements. In more recent urbanization, many urban areas reveal concentric shapes. Figures 7, 8, 9, 10, 11 and 12 are good examples of how much geometrical these shapes are. Indeed, as with rectilinear networks, there exist many degrees of spatial regularity in radio-concentric networks, from very symmetric structures like amphitheaters (Figures 11 and 12, representing the European Parliament and the antique theater of Orange, respectively)
or circular cities (Figure 10, which depicts a series of connected perfectly circular villages constituting SunCity), to more asymmetric urban shapes (Figure 7, showing the one-side radio-concentric shape of Amsterdam) or graphs with a more relaxed or degraded geometry (Figures 8 and 9, presenting Paris and Sfax, respectively).

1.3 Geographical Models of Rectilinear or Radio-concentric Shapes
Networks are often studied in geography because they depict the visible human mark of population life in their territories. Beyond monographs which describe particular places, there exist a few typologies of urban networks and schemes generally explored and measured via topological structure or functional dimensions of the cities [8, 9]. Concerning the types of urban networks and graphs, Blanchard and Volchenkov [3] presented a simple-faced classification of different types of route schemes, including rectilinear networks (e.g. Manhattan), organic towns (e.g. city of Bielefeld, North Rhine-Westphalia in Germany), shapes of corals (e.g. Amsterdam or Venice). In his book, Marshall elaborates different taxonomies of street patterns [18]. However, it is also possible to design very theoretical networks in order to study their properties, other things being equal [22]. Nevertheless, there is no consensual classification of the urban networks. Looking at the literature, it is interesting to notice that the publications about network design are actually shared by different disciplines involved in the field: (spatial) econometrics of transportation [11], mathematical optimization [4], information and communication technologies [7] or social networks [16]. These disciplines can be advantageously complemented by the domain of graph theory [2, 19, 1].

On the one hand, the main contribution of the Manhattan networks in the domain of spatial modeling and measuring is the rectilinear distance calculation, which is related to the mathematical $L_1$-norm [10], compared to the Euclidian distance based on the $L_2$-norm [13]. On the other hand, the radio-concentric framework generated several outstanding models. In 1924, E. Burgess proposed the concentric zone model to explain urban social structures [20], followed by Hoyt in 1939, who defined the sector model based on the urban development along centrifugal networks [12]. In parallel, W. Christaller [5] and A. Lösch [15] designed the central places theory to understand how cities are organized in territory, according to the distribution of goods and services to the population. These models deal with access to facilities and are
based on network design and costs. In 1974, Perreur and Thisse defined the circum-radial distance based on such structures [21]. Tobler’s law [23] and the Newton gravity model also both indicate an inverse relation between the strength of a force $F_{ij}$ and the distance $d_{ij}$ separating two points $i$ and $j$ in geographical space, giving to the center(s) a particular status in networks. All these spatial theories participate in defining and emphasizing radio-concentric models and shapes; however, they neither refute nor contradict rectilinear webs that can also own centers in different ways.

2 STRAIGHTNESS IN THEORETICAL RECTILINEAR AND RADIO-CONCENTRIC NETWORKS FOR CENTER-TO-PERIPHERY ROUTES

In this section, we focus on the straightness of center-to-periphery routes, for both rectilinear and radio-concentric theoretical networks. The results are purely analytic, i.e., no simulation is involved. The networks are theoretical and perfectly regular, with pure geometric shapes. The proposed methods are specifically designed for these types of networks.

We call radius an edge starting at the center of a radio-concentric network. An edge connecting two radii is called a side. Unlike the rectilinear network, the radio-concentric network is controlled by a parameter $\theta$: the angle formed by two consecutive radii. The constraint on $\theta$ is that there must exist an integer $k$ such that $k = 2\pi/\theta$. We suppose that $k > 2$, because with $k = 1$ the sides are not defined, and with $k = 2$, both radii are mangled. We call angular sector the part of the unit circle between two consecutive radii. A half-sector is the part of the unit circle between a radius and a neighboring bisector (cf. Figure 14).

2.1 Definition of the Straightness

For a pair of nodes, the Straightness is the ratio of the spatial distance $d_S$ as the crow flies, to the geodesic distance $d_G$ obtained by following the shortest path on the network:

$$S = \frac{d_S}{d_G}$$

(1)

This measures ranges from 0 to 1, a high value indicating that the graph-based shortest path is nearly straight, and contains few detours.

Coming from graph theory, this property is interesting in network assessment, because it measures a part (in a certain meaning) of the “accessibility” capacity of a network. It is a kind of relative efficiency to reach a point in a network. In our case, edges have neither impedance, nor direction. We do not consider any possible traffic jams in the flow propagation. In our assumption, speed is the same all over the graph and so time is proportional to distance.

Let the center of the network be the origin of a Cartesian coordinate system. In the rest of the document, we characterize a center-to-periphery move by an angle $\alpha$, formed by the $x$ axis and the segment going from the network center to the targeted peripheral node. The angle vertex is the network center, as represented in Figures 13 and 14. For the rectilinear network, we consequently note the straightness $S(\alpha)$ for the route of angle $\alpha$. For the rectilinear network, due to the presence of the parameter $\theta$ (the angle between two consecutive radii), we denote the straightness by $S_\theta(\alpha)$.

2.2 Simplifying Properties of the Considered Networks

Rotation

Both networks have certain rotation-related properties, which allow some simplifications. As mentioned before, in a radio-concentric network, two consecutive radial sections of the network are separated by an angle $\theta$. In a rectilinear network (see Figure 13), a cell is a square. The angle between two consecutive edges originating from the network center is therefore $\theta = \pi/2$. So, we can distinguish $k = 4$ angular sectors, corresponding to the quadrants of our Cartesian coordinate system.

![Figure 13](image)

Figure 13. A perfect rectilinear network, with $\theta = \pi/2$ and $\alpha$ in $[0, \pi/4]$.

Both types of networks can be broken down to $k$ angular sectors, which are all similar modulo a rotation centered at the network center. So, without loss of generality, we can restrict our analysis to the first angular sector, i.e., to the interval $\alpha \in [0; \theta]$.

![Figure 14](image)

Figure 14. A perfect radio-concentric network, with $\theta$ separating two radial sections, and $\alpha$ in $[0, \pi/2]$.

Homothety

An additional simplification comes from the homothetic nature of both studied networks. Indeed, in these networks, a center-to-periphery route can go either through the edges originating from the network, or through those intersecting with these edges, as represented in Figures 15 and 16. Let us consider a move from $p_1$ to $p_4$. In both cases, $h$ is parallel to $H$, so we can deduce that:

$$\frac{l}{l} = \frac{d}{d} = \frac{h}{h}$$

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Then we obtain:
\[ l \cdot D = L \cdot d \quad ; \quad d \cdot H = D \cdot h \quad ; \quad l \cdot H = L \cdot h \]

We can set:
\[ l \cdot D + l \cdot H = L \cdot d + L \cdot h \]

That is to say \( S \) is the same whether the destination point is located on the closest or the farthest edge to the network center, for both types of networks:
\[ S = \frac{l}{d+h} = \frac{L}{D+H} \quad (2) \]

Consequently, \textit{without any loss of generality}, we can therefore restrict our analysis to the first square for the rectilinear network and to the first triangle for the radio-concentric network.

\[\text{Figure 15. Geometry of a rectilinear network.}\]
\[\text{Figure 16. Geometry of a radio-concentric network.}\]

\textbf{Symmetry}

The last simplification comes from a symmetry property present in both networks, as illustrated by Figure 17 for radio-concentric networks. Observe that when \( \alpha \) is smaller than \( \theta/2 \), the shortest paths go through the first radius \( (p_1,p_3) \), whereas as soon as \( \alpha \) exceeds this threshold, they go through the second one \( (p_1,p'_3) \). Also note that the line corresponding to this angle \( \theta/2 \) is the bisector of the angle formed by both radii.

Let us now consider the shortest path to \( p_4 \), which corresponds to an angle \( \alpha \leq \theta/2 \). We wish to calculate the shortest path to some other point \( p'_4 \), corresponding to an angle \( \alpha' > \theta/2 \), and such that the travelled distance is the same as for \( p_4 \). We know that \( [p_1;p_2] \) and \( [p_1;p'_3] \) have the same length, so the distance to travel on the side is the same for both routes, i.e. \( H = H' \). Moreover, the angles formed by each radius and the side are equal by construction: it is \( \beta \). Let us now consider the triangles \( (p_1,p_3,p_4) \) and \( (p_1,p'_3,p'_4) \). We have two pairs of equal consecutive sides and the angles they form are equal; they are both \( \beta \). So, both triangles are congruent, and we have: \( p_3,p_1,p_4 = p'_3,p_1,p'_4 \). By definition, \( p_3,p_1,p_4 = \alpha \) and \( p'_3,p_1,p'_4 = \theta - \alpha' \), so we get \( \alpha = \theta - \alpha' \). For the same reason (congruence), \( L = L' \), meaning that the distances \( \text{as the crow flies} \) are identical for \( p_4 \) and \( p'_4 \).

Since both distances (on and off the network) are the same for \( p_4 \) and \( p'_4 \), their straightness are also equal. In other words:
\[ S_\theta(\alpha) = S_\theta(\theta - \alpha) \]

We can conclude that, without any loss of generality, we can focus our study on the first half of the first angular sector, i.e. the interval \( \alpha \in [0;\theta/2] \). The same proof can be applied to the rectilinear network, which displays the same type of symmetry. Consequently, the same simplification holds.

\textbf{2.3 Analytic Expression of the Straightness}

In the previous section, we showed that, due to certain properties of rotation, homothety and symmetry, we can restrict our analysis of the straightness to only the interval \( \alpha \in [0;\theta/2] \) for both networks. For the rectilinear network, note that \( \theta = \pi/2 \). So, in this specific case, we consider the interval \([0,\pi/4]\). Let us now give the expression of the straightness for each type of network.

For the rectilinear network, we have from Figure 15:
\[ \sin \alpha = \frac{h}{l} \quad ; \quad \cos \alpha = \frac{d}{l} \]

Then, from (2), we obtain:
\[ S(\alpha) = \frac{1}{d+h} = \frac{1}{\cos \alpha + \sin \alpha} \quad (3) \]

For the radio-concentric network, let us observe Figure 17. Note that \( p_2 \) is the projection of \( p_4 \) onto the first radius. We obtain two rectangular triangles containing \( p_2: (p_1;p_2;p_4) \)
and \((p_4; p_2; p_3)\). This allows us to write the following equations:

\[
\cos \alpha = \frac{D}{L}; \quad \cos \beta = \frac{d}{H}
\]

\[
\sin \alpha = \frac{h}{L}; \quad \sin \beta = \frac{h}{H}
\]

\[
\tan \alpha = \frac{h}{D}; \quad \tan \beta = \frac{h}{d}
\]

By removing \(h\) we get

\[
L \cdot \sin \alpha = D \cdot \tan \alpha = H \cdot \sin \beta = d \cdot \tan \beta,
\]

and hence we obtain:

\[
D = \frac{L \cdot \sin \alpha}{\tan \alpha}; \quad d = \frac{L \cdot \sin \alpha}{\tan \beta}; \quad H = \frac{L \cdot \sin \alpha}{\sin \beta}
\]

We substitute these values into (1), then simplify and obtain:

\[
S_0(\alpha) = \frac{L}{D + d + H} = \frac{1}{\cos \alpha + \frac{\sin \alpha}{\tan \alpha \frac{\pi}{2}} + \frac{\sin \alpha}{\sin \frac{\pi}{2}}}
\]

(4)

Note that these formulas are valid only for the interval \(\alpha \in [0; \theta/2]\). The other values can be deduced by symmetry and/or rotation, as explained earlier.

### 2.4 Comparison of Networks

With the analytic expression of the straightness for both types of networks, we can now compare their performance for center-to-periphery routes. Figure 18 represents the straightness obtained for the different network types and parameter values. The \(x\)- and \(y\)-axis represent the angle \(\alpha\) and the straightness \(S\) calculated using the different previous formula, respectively. The optimal straightness value is represented by the black dotted horizontal line \(f(\alpha) = 1\). The closer the graphical representation of a network is to this line, the better the network is in terms of straightness.

For the radio-concentric network, we consider several values of the parameter \(\theta\), corresponding to \(k = 3, 4, 8, 16\), represented in purple, blue, green, and cyan, respectively. The rectilinear network is represented in red. The \(x\)-axis ranges only from \(\alpha = 0\) to \(\pi/4\), which is enough, regarding the simplifications we previously described: we know all the plotted lines have a periodic behavior, which directly depends on \(\theta\).

For all lines, we have \(S(0) = 1\), which corresponds to a straightforward move on the first radius (or horizontal edge, for the rectilinear network). Then, the straightness decreases when \(\alpha\) gets larger, since the destination point gets farther from this radius, and therefore from an optimal route. This corresponds to the lower route, represented in red in Figure 17. The decrease stops when \(\alpha\) reaches \(\theta/2\) (i.e. the bisector): the straightness then starts increasing again, until it reaches 1. This is due to the fact that the shortest path is now the upper route, represented in blue in Figure 17. The maximal value is reached when \(\alpha = \theta\), i.e. when the destination point lays on a radius, allowing for an optimal route. The same ripple pattern is then repeated again, and appears \(k\) times.

As mentioned before, the periodicity directly depends on \(\theta\): the smaller the angle, the larger the number of radii, which means the number of ripples increases while their size decreases. In other words, and unsurprisingly, the straightness of a radio-concentric network increases when its number of radii increases. More interesting is the fact that most of the time, 8 (a very small number) radii are sufficient to make radio-concentric networks better than rectilinear ones.

### 2.5 Boundary Condition

Let us now consider a radio-concentric network with infinitely small \(\theta\). From the definition of \(k\), we know this would result in an infinitely large number of radii:

\[
\lim_{\theta \to 0} k = \lim_{\theta \to 0} \frac{2\pi}{\theta} = +\infty
\]

The radii of such a network would cover the whole surface of a disk. Since we focus our study on the first angular half-sector, \(\alpha\) is itself bounded from above by \(\theta/2\). So, if \(\theta\) tends towards 0, \(\alpha\) does too. From (4), we consequently get:

\[
\lim_{\theta \to 0} S_0(\alpha) = \lim_{\theta \to 0} \frac{1}{\cos \alpha + \frac{\sin \alpha}{\tan \frac{\pi}{2}} + \frac{\sin \alpha}{\sin \frac{\pi}{2}}}
\]

(5)

We have:

\[
\lim_{\theta \to 0} \cos \alpha = \lim_{\alpha \to 0} \cos \alpha = 1 \quad \text{and} \quad \lim_{\theta \to 0} \tan \frac{\pi - \theta}{2} = +\infty
\]

\[
\lim_{\theta \to 0} \sin \alpha = \lim_{\alpha \to 0} \sin \alpha = 0 \quad \text{and} \quad \lim_{\theta \to 0} \frac{\pi - \theta}{2} = 1
\]

We finally obtain the boundary for the straightness of a radio-concentric network with an infinite number of radii:

\[
\lim_{\theta \to 0} S_0(\alpha) = 1
\]
This result is obvious and consistent with the case where the complete route goes along a radius. Indeed, with an infinite number of radii, we can always find a radius to move directly from the center to the destination. Figure 18 confirms this result: increasing the number of radii reduces the period and the amplitude of the ripples, eventually leading to the optimal horizontal straight line of the equation $S = 1$.

Between the two extreme cases of 3 radii and an infinite number of radii, we should remind the reader that 8 radii are enough for the radio-concentric network to become better than the rectilinear one in terms of straightness of center-to-periphery routes. Let us see now how it goes for multidirectional moves.

3 SIMULATION OF THE AVERAGE STRAIGHTNESS FOR ALL ROUTES

Studying analytically the straightness for all possible moves (other than center-to-periphery) would be too time-consuming, so we switched to simulation. We used the statistical software R to simulate the motions on both rectilinear and radio-concentric networks. The shortest paths are processed using Dijkstra’s algorithm [6], for all pairs of nodes (see Figures 19 and 20).

These results are very interesting and confirm our theoretical findings, as well as our observations regarding the good straightness of radio-concentric networks, thrifty in number of radii, compared to rectilinear networks. Figure 21 shows that, even when increasing the granularity of the grid forming a rectilinear network, the average straightness is constant, at a value lower than 0.8. This is consistent with our remark regarding the homothety property of this network.

Figure 21. Average straightness $S$ (and standard deviation) for a rectilinear network, as a function of its size (expressed in number of squares by side).

Regarding the radio-concentric network, Figure 22 shows that the average straightness overtakes the rectilinear threshold (0.8) when the number of radii is about 8 or 10. It is interesting to notice that the number of sides does not affect the straightness much. This was expected for center-to-periphery routes, as for the rectilinear network. However, the routes considered here are more general, going from anywhere to anywhere, and moreover, the radio-concentric network is not a tessellation like the rectilinear one, so it is surprising to make this observation: further inquiry will be necessary to provide some explanations.

Figure 22. Average straightness $S$ (and standard deviation) for a radio-concentric network, as a function of its number of radii, and for different number of sides (see colors).

4 CONCLUSION
In this paper, we first presented a few urban networks based on rectilinear versus radio-concentric structures. Then, in a theoretical framework, we showed the superiority of the radio-concentric network compared to the rectilinear network, in terms of straightness. It was first demonstrated analytically in the particular case of center-periphery motions and then simulated on paths with multiple origins and destinations, using the statistical software R. To our knowledge, these results are new and original. They show that, straightness-wise, whatever the density of rectilinear networks, those cannot efficiently compete with radio-concentric networks, because their straightness is bounded by construction, at least within a theoretical framework.

However, this exploratory study does not take into account several factors that must be now studied to complete these first results. It will be interesting to find exactly over which number of radii a radio-concentric network has a better straightness than a rectilinear one. Knowing this threshold, we shall then be able to calculate the total length of both networks to fill an equivalent average straightness on similar surfaces to drain. What will be the most thrifty network in terms of length of “cables”? On another aspect, these calculations and simulations consider very theoretical networks. Geographers, architects and town planners may be interested in understanding the real straightness of urban, rectilinear versus radio-concentric networks, in real conditions (population mobility, congestion). This is also one of the further researches developed in the Urbi&Orbi project.

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REFERENCES

Spectral Modelling for Spatial Network Analysis

Pirouz Nourian¹, Samaneh Rezvani², Sevil Sariyildiz³, Frank van der Hoeven³

¹TU Delft, A+BE Delft, the Netherlands
²123dv architectuur & consult Rotterdam, the Netherlands
³TU Delft, Design Informatics, Urban Design Delft, the Netherlands
{I.S.Sariyidliz, F.D.vanderHoeven}@tudelft.nl

ABSTRACT

Spatial Networks represent the connectivity structure between units of space as a weighted graph whose links are weighted as to the strength of connections. In case of urban spatial networks, the units of space correspond closely to streets and in architectural spatial networks the units correspond to rooms, convex spaces or star-convex spaces. Once represented as a graph, a spatial network can be analysed using graph theory and spectral graph theory. We present four steps of modelling a spectrum for an urban spatial network; present an implementation of a state-of-the-art spectral graph-drawing algorithm and showcase a Spatial Eigenvector Centrality index, which is based on a novel definition of spatial networks based on Fuzzy Closeness indicators computed using Easiest Path distances.

Author Keywords

Spatial Network Analysis; Spectral Graph Theory; Spatial Eigenvector Centrality; Spectral Graph Drawing; Dominant Eigenvectors; Generalized Power Iteration

ACM Classification Keywords

I.6.1 SIMULATION AND MODELING (Model Development); G2 Discrete Mathematics as in G2.2 Graph Theory (Graph Algorithms, Network Problems)

See: http://www.acm.org/about/class/1998/ for more information and the full list of ACM classifiers and descriptors.

1 INTRODUCTION

In the same way Social Networks affect people’s social status, actions and choices, Spatial Networks have been found to affect people’s spatial actions, such as mobility and accessibility. Social Network Analysis, originated in the areas of Sociometry and Psychometry, is a relatively mature field of study, with seminal publications, which can be traced back to 1950’s and 1960’s (e.g. [1], [2]). Graph Theory has been applied to study the structure of social network, remarkably in absence of concretely manifested social networks such as those popular nowadays like Facebook or LinkedIn. The field of Spatial Network Analysis in comparison is somewhat younger and arguably less well-structured, mainly due to the discrepancies of three lineages of work in modelling spatial networks, namely Geography, Transport Planning, and Spatial Analysis. In geographical and transport-related analyses, using a Junction-to-Junction graph model is pervasive, mainly due to the ease of metric distance measurements; however, in the field of spatial analysis (as in Space Syntax [3] and similar approaches such as [4], [5] and [6] there is another approach to model spatial networks as adjacency representations of type Street-to-Street. This latter approach is fitter to human perception of space in that it corresponds to our intuition: its nodes are meaningful spaces such as streets or rooms; and its links can represent the difficulty of navigation from one space to another in wayfinding. Once a graph is constructed as an abstract representation of the spatial connectivity structure, it can be analysed using Graph Theory and Spectral Graph Theory.

Spectral Graph Theory (see e.g. [7]) studies the structural properties of graphs and networks (weighted directed graphs) by inspecting the eigenvectors and eigenvalues of some typical matrices associated with graphs, namely, Adjacency Matrix, Laplacian Matrix, Markovian Matrix (a.k.a. Transition Probability Matrix or Random Walk Matrix). We first show an intuitive application of Spectral Graph Theory in drawing large spatial graphs, by embedding their nodes in a low-dimensional Euclidean Space using eigenvectors of Laplacian and Random Walk matrices, implementing and extending the Power Iteration Method after [8]. Then, following our interpretation of a spatial network as an n-dimensional Hilbert space of random vectors $x \in \mathbb{R}^n$ where n is the number of nodes (spaces) in the network; we extend the notion of a Spatial Network to a graph that describes how close (similar) are the nodes (spaces) to one another.

We process the set of navigable spaces in these steps:

- Geographical Modelling
- Geometrical Modelling
- Topological Modelling
- Graphical Modelling
- Spectral Modelling

In this paper, we address the last two steps and give brief references of our earlier works in the previous steps. Two avoid common confusions between graphs and their drawings, we refer to graphs as comprised of nodes and links; and we reserve the terms vertices and edges for referring to topological constructs such as graph drawings. In the domain of geometry, we shall speak of points and lines analogously. The steps mentioned above transform a concrete set of geographical places gradually to a very abstract set of eigenvectors and eigenvalues.
This abstraction is done by: 1) reducing a real geographical place to a set of geometrical shapes (polylines and lines); 2) representing the topological relations among these shapes as in a Topological Skeleton (e.g. Straight Skeleton [9]), while abstracting topological Incidence Matrices and extracting Primal (Vertex-to-Vertex) and Dual (Edge-to-Edge) Adjacency Matrices as Graphs; 4) computing distances using graph-theoretical geodesics; and 5) studying the spectra (i.e. their Eigen pairs) of graph matrices such as Laplacian Matrix, and Random Walk Matrices (Transition Probability Matrices of Markov Chains) using iterative methods. Novelties reported in this paper are namely the Probability Matrices of Markov Chains using iterative Laplacian Matrix, and Random Walk Matrices (Transition distances using graph-theoretical geodesics; and 5) studying Edge) Adjacency Matrices as Graphs; 4) computing extracting Primal (Vertex-to-Vertex) and Dual (Edge-to-Edge) Adjacency Matrices as Graphs now, Vertex-to-Vertex and Edge-to-Edge, which can be shown that:

\[ G(V, E): v \in V \text{ and } e \in E \]  

Connectivity information of this graph can be captured in Incidence Matrices, whose rows correspond to vertex indices, and whose columns correspond to edge indices. We denote this matrix as \( A_{VE} \) and its transposed version as \( A_{EV} \), i.e. \( A_{VE} = A_{EV}^T \).

\[ A_{VE} = \begin{bmatrix} a_{ij}^{ve} \end{bmatrix}_{|V| \times |E|} = \begin{cases} 1 & \text{if } V_i \sim E_j \\ 0 & \text{otherwise} \end{cases} \]  

\[ A_{EV} = \begin{bmatrix} a_{ij}^{ev} \end{bmatrix}_{|E| \times |V|} = \begin{cases} 1 & \text{if } E_i \sim V_j \\ 0 & \text{otherwise} \end{cases} \]

5 GRAPHICAL MODELLING

Following [4], we form two types of graphs from the topological incidence matrices and represent them by their Adjacency Matrices. We can think of two type of adjacency matrices now, Vertex-to-Vertex and Edge-to-Edge, which we denote respectively as \( A_{VV} \) and \( A_{EE} \).

\[ A_{VV} = \begin{bmatrix} a_{ij}^{vv} \end{bmatrix}_{|V| \times |V|} = \begin{cases} 1, & \text{if } i \neq j \text{ and } V_i \sim V_j \\ \text{Deg}(v), & \text{if } i = j \end{cases} \]  

\[ A_{EE} = \begin{bmatrix} a_{ij}^{ee} \end{bmatrix}_{|E| \times |E|} = \begin{cases} 1, & \text{if } i \neq j \text{ and } E_i \sim E_j \\ \text{Deg}(e), & \text{if } i = j \end{cases} \]

It can be shown that:

\[ A_{VV} = A_{VE} A_{EV} \]  

\[ A_{EE} = A_{EV} A_{VE} \]

In the above equations \( \text{Deg}(v) \) denotes the number of vertices immediately (through a single intermediary edge) adjacent to a vertex \( v \) and \( \text{Deg}(e) \) denotes the number of edges immediately (through a single intermediary vertex) adjacent to an edge \( e \). We denote \( A_p \) as the adjacency matrix corresponding to the primal graph \( \Gamma_p(N, L) \) and \( A_d \) as the adjacency matrix corresponding to the dual graph \( \Gamma_d(N, L) \); in addition, we consider diagonal matrices \( D_p \) and \( D_d \), whose diagonal entries are respectively equal to degrees of vertices and edges in \( G \).

\[ A_{VV} = A_p + D_p | D_p : := \text{row sums of } A_{VE} \]  

\[ A_{EE} = A_d + D_d | D_d : := \text{row sums of } A_{EV} \]
It is of course quite straightforward to obtain $A_p$ and $A_d$ from $A_{WV}$ and $A_{EE}$ computationally. So far, we showed that based on the same topological model two graphical models could be constructed. We choose our dual graph $A_d$ as the basis for representation of the spatial network for walking (and cycling). However, this graph is yet not a network (i.e. it only captures topological information) because it is not weighted yet. If we assign costs/impedances to each link in this graph, then we can find optimal paths in this graph. This is interesting to note that this graph, as long as not weighted is flat, and straightforward as possible. These paths are found by searching the network space whose links are inversely made a dual graph representation that finds the Easiest Paths for walking or cycling [15]. These paths are as short, flat, and straightforward as possible. These paths are found by searching the network space whose links are inversely biased by attributing costs to traversal in terms of minutes of travel time. We show an exemplary graph as such on a hypothetical space network shown in Figure 2. Spaces are represented as lines (at right), modelled as a dual graph and then weighted asymmetrically by impedances of going from each street to another considering elevation angle (the slope lowering walking speed), azimuth angle (the steering angle complicating navigation) and the path lengths from/to the black dots as midpoints of the spatial nodes. The matrix plot in black and white shows the adjacency matrix that is symmetric, suggesting the underlying graph is undirected. However, once the impedances are assigned, the network graph model becomes directed; because its adjacency matrix is asymmetric, i.e. it is a directed [dual] graph models.

![Figure 2](image1.png)

**Figure 2.** A hypothetical street space network, impedances of the links are asymmetric due to the differences between downhill and uphill traversals.

In order to model the cognitive difficulty of navigation $\zeta^A$ we formulate cognitive impedance as a function of the azimuth angle between to streets that ranges between a maximum confusion time $\tau$ and 0.

$$\zeta^A := \begin{cases} 
    h(\theta), & \text{if } \text{Deg}(n_{\text{junction}}) > 2 \\
    0, & \text{otherwise}
\end{cases}$$

The total impedance of traversing a link $\zeta_{i,j}$ is then formulated as below:

$$\zeta_{i,j} = \begin{cases} 
    (\zeta^W_{i,j}) + (\zeta^A_{i,j}), & \text{if walking} \\
    (\zeta^C_{i,j}) + (\zeta^A_{i,j}), & \text{if cycling}
\end{cases}$$

![Figure 3](image2.png)

**Figure 3.** a) A Shortest Path without considering the terrain and difficulty of navigation on an example network from "Tarlabasi", Istanbul, data set provided by Ahu Sokmenoglu; b) Easiest Path geodesic found considering the terrain and $\tau=0$ for angular confusion (thereby no cognitive impedance); c) Easiest Path geodesic computed not considering the terrain and $\tau=15$ seconds; d) Easiest Path geodesic computed considering the terrain and $\tau=15$ seconds. The parameter $\tau$ (tau), introduced in equation (10) determines the maximum time wasted for making a navigation choice at a junction.

Walking time and cycling time when traversing $i$th street to $j$th street are denoted as $\zeta^W_{i,j}$ and $\zeta^C_{i,j}$, respectively. It is notable that these values are parametric and can be adjusted to represent motor assisted bikes. The easiest path is then the path $\pi$ that minimizes the following sum over all possible paths.

$$\min_{\pi} \sum_{(i,j) \in L} \zeta_{i,j} = \{(i,j) \mid (i,j) \in L \cap \pi\}$$

### 5.1 Revisiting Network Distance

Any notion of distance is based on a corresponding geodesic or optimal path of some minimum cost or distance; this is because otherwise the notion of distance will be subject to different interpretations. While many studies take it for granted that shortest path is the basis of network distance, we argue that network distance should be defined for each mode of transportation; hence, we redefine network distances for pedestrians or cyclists as travel times experienced through Easiest Paths.
5.2 Geodesic Centrality Models

Using the Easiest Path (EP) algorithm, we can compute a class of 'directed geodesic centrality’ indices, namely (generalized) Betweenness Centrality [16] and Closeness centrality [2]. We call them geodesic centrality measures because they are directly computed using geodesic paths or geodesic distances. We compute EP Betweenness as an indicator of how many times a certain street space happens to be part of a geodesic (Easiest Path), provided that the destination of the path is not further than a threshold radius of search (inspired by Local Integration Centrality of Space Syntax). EP Closeness Centrality is then computed as the following: for each node we compute the average distances of all nodes reachable within a search radius and then Fuzzify (as in Fuzzy Logics [17]) that distance to assign a closeness index.

Figure 4. Easiest Paths Betweenness Centrality, \( \tau = 15' \). Directed Graph, Search Radius is 10 Minutes Walking

Figure 5. Easiest Paths Closeness Centrality, \( \tau = 15' \). Directed Graph, Search Radius is 5 Minutes Walking, revealing a polycentric structure in the neighbourhood

6 SPECTRAL MODELLING AND SIMULATION

Spectral analyses begin with inspecting a few eigenvectors of a graph matrix. One of the most intuitive evidences of the usefulness of spectral methods in studying networks is its application in drawing the undirected graph associated with the network. The point is that although eigenvectors seems to be very abstract, they turn out to be capable of reconstructing a concrete topological embedding that is often a ‘good’ graph drawing. Other applications of spectral methods can be found in forming a measure of centrality called Eigenvector Centrality that also has an intuitive interpretation in spite of its sophisticated name. Eigenvector Centrality (based on [1], [18], and [19]) assumes that the centrality of a node is determined by the centrality of the nodes that are immediately linked to it. A variant of this centrality index is used in the Google PageRank algorithm for ranking webpages as to their importance [20]. We hereby show the application of dominant eigenvectors of some matrices associated with graphs in spatial analysis. In doing so, we focus on some subtleties and issues in using eigenvectors in analysing (potentially large) spatial networks. To have a smooth transition to the topic we begin by the intuitive topic of Spectral Graph Drawing.

6.1 Spectral Graph Drawing

A graph is an abstract construct that captures the relations between a set of elements (nodes) as in their pair-wise relations. We usually have a tangible idea of a graph, as a spatial network because of the history of graph theory that was remarkably started by Leonhard Euler in studying a spatial network (the famous 7 bridges of Konigsberg, the current city of Kaliningrad). However, note that this form of a spatial network representation is only one way to capture connectivity of spaces, which is in our terminology a Junction-to-Junction adjacency representation. The point is that a graph per se needs not to have a geometric or topological representation to exist. Once abstracted, it will be simply a matrix of adjacencies without any direct reference to geometric space. If we later decide to draw a graph, we can do it in a number of different ways, such as assigning a set of geometric points to the set of nodes and drawing geometric lines so as to represent links between the nodes. This will always be by definition an arbitrary choice, for a single graph can have infinitely many correct drawings as such. This way of representing a graph is called topological embedding. In the context of graph drawing one usually speaks of goodness of a drawing in terms of such things as good distinction between vertices (representing nodes), i.e. to avoid crossings between edges (representing links). While there are many methods for making ‘good’ graph drawings, there is one method that is scientifically very interesting as it has a unique topological solution using only a matrix associated with the graph. Historically, the first matrix used for this purpose was the Laplacian Matrix \( L = D - A \) [21], in which \( D \) is a diagonal matrix whose diagonal entries equal node degrees (row sums of the adjacency matrix in case of undirected graphs).
The Laplacian matrix can be used to obtain a good drawing. Assuming the average vertex to be centered at vertices equal to a constant. The variance of the vertices, the edges of the embedding. The following is not a proof, potential energy stored in imaginary springs representing of the Laplacian corresponds to the minimizers of the first eigenvectors associated with the smallest eigenvalues associated with the largest eigenvalues. Note that using the Matrix for Spectral Embedding, specifically those works also use the first few eigenvectors of the Adjacency Matrix for Spectral Embedding, specifically those associated with the largest eigenvalues. Note that using the first eigenvectors associated with the smallest eigenvalues of the Laplacian corresponds to the minimizers of the potential energy stored in imaginary springs representing the edges of the embedding. The following is not a proof, but a mathematical explanation of how the eigenvectors of the Laplacian matrix can be used to obtain a good drawing.

Figure 6. spectral drawing of a graph representing spatial connectivity of a hypothetical configuration of rooms (left), using Laplacian Matrix (middle) and using the Lazy Random Walk Matrix (right)

We know that the potential energy stored in a spring is proportionate to its squared length. Assuming a position vector \( x(i) \in \mathbb{R}^k \) for the \( i^{th} \) node of a graph (i.e. a vertex in \( \mathbb{R}^k \)), while \( k \) is typically 2 or 3, then we are interested in minimizing the sum of squared spring lengths:

\[
\min_{(i,j) \in \mathcal{E}} \sum_{(i,j) \in \mathcal{E}} (x(i) - x(j))^2
\]

(13)

Which can be shown to be the same as the ‘quadratic form’ associated with the Laplacian Matrix \( L \), meaning:

\[
x^T L x = \sum_{(i,j) \in \mathcal{E}} (x(i) - x(j))^2
\]

(14)

This minimization problem has a degenerate trivial solution of \( x = 0 \), which is not interesting at all. To avoid this, we can impose a constraint, which keeps the variance of the vertices equal to a constant. The variance of the vertices, assuming the average vertex to be centered at \( \bar{x} = 0 \) can be written as below:

\[
x^T x = \sum_{i=1}^{n} (x(i))^2
\]

(15)

These two equations together mean that we can minimize the following:

\[
\min_{x \neq 0} \frac{x^T L x}{x^T x}
\]

(16)

This quotient is widely known as the Rayleigh Quotient, whose minimizers are indeed eigenvectors associated with its minimum values that are the lowest eigenvalue, while of course eigenvectors are linearly independent, i.e. \( \langle v_i, v_j \rangle = 0 \) for \( i, j \in [1, n] \):

\[
\lambda_i = \min_{x \neq 0} \frac{x^T L x}{x^T x}
\]

(17)

\[
v_i = \{ x | R_L(x) = \lambda_i \} = \arg \min_{x \neq 0} \frac{x^T L x}{x^T x}
\]

(18)

6.2 Finding the Dominant Eigenvectors

The Laplacian matrix is related with the negated Adjacency Matrix, so its eigenvectors are reversely ordered; this is why in Spectral Graph Drawing, some scholars use the top eigenvectors of the adjacency matrix, although not with very nice results [8]. What is interesting about top eigenvectors (i.e. those associated with the largest eigenvalues) is that they can be found quickly for large graphs using iterative methods such as Power Iteration Algorithm. This is the same algorithm used for finding the eigenvector representing Google PageRank. Note that the alternative to iterative methods is finding the Eigenvalue Decomposition (EVD) that is a prohibitively complex computational process for large matrices. While the solution to finding the top one eigenvector is widely known and applied, as in finding Google Page Rank, for finding the first few dominant eigenvectors there is no direct hint to a straightforward intuitive method in the literature. We here give a simple algorithm extracted and generalized from [8] for this purpose:

**Algorithm 1.** Find k Top Eigenvectors via Power Iteration after [8]

**Inputs:** Matrix[n × n] M, int k, int MaxIter//for Hermitian Matrices

**Outputs:** Vector[] EVecs, double[] EVals //arrays of results

**vector[n][k] u=new vector[n][k]/[k]//Evecs
**double[k] lambda=new double[k]/[k]//Eval

for (int i = 0; i < k; i++)

  double CoDir=0; int counter=0;
  vector \( \tilde{u} = \) Vector.Random(n); \( \tilde{u} \_ normalize(2); //p-norm
  do{
    o u[i] = \( \tilde{u} \);
    o for (int j = 0; j < i; j++)
      • u[i] = u[i] - (\( \tilde{u} \_ normalize(2) \_ orthogonalise \) • u[j] / u[j] \\
        • u[i].Normalize(2);
    o }
  o \( \tilde{u} = M \_ u[i]; \tilde{u} \_ normalize(2);
  o CoDir = \( \langle \tilde{u}, u[i] \rangle / \text{counter++;}
  • while(CoDir<1 - ε) ε (counter<MaxIter))
  • u[i] = \( \tilde{u} \);
  • }

for (int i = 0; i < k; i++) [lambda[i]= \( \langle u[i], M \_ u[i] \rangle ];

EVecs= \( u \); EVals= lambda;
Using the first ‘top degree-eigenvectors’ (generalized by Yehuda Koren [8]) of the matrix \( M = \frac{1}{2} (I + D^{-1}A) \), a.k.a. the Lazy Random Walk Matrix we can obtain a Spectral Drawing, which is more interesting than the one done by Laplacian for it is more intuitive and scalable because it uses top eigenvectors and so those eigenvectors can be computed by a generalized power iteration method.

The reason this algorithm converges can be understood by thinking of a random vector as being defined in terms of a linear combination of eigenvectors. This can be done because eigenvectors are mutually perpendicular to one another and thus for an ‘orthogonal basis’. That is: 

\[
x = \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \ldots + \alpha_n \mathbf{v}_n \quad (19)
\]

If we multiply both sides by a matrix \( \mathbf{A} \), we get:

\[
\mathbf{A}x = \alpha_1 \mathbf{A} \mathbf{v}_1 + \alpha_2 \mathbf{A} \mathbf{v}_2 + \ldots + \alpha_n \mathbf{A} \mathbf{v}_n \quad (20)
\]

By virtue of the fact that vectors \( \mathbf{v}_i \) are eigenvectors with corresponding eigenvalues as \( \lambda_i \) we can replace all \( \mathbf{A} \mathbf{v}_i \) terms by \( \lambda_i \mathbf{v}_i \) terms:

\[
\mathbf{A}x = \alpha_1 \lambda_1 \mathbf{v}_1 + \alpha_2 \lambda_2 \mathbf{v}_2 + \ldots + \alpha_n \lambda_n \mathbf{v}_n \quad (21)
\]

Therefore:

\[
\mathbf{A}^2x = \alpha_1 \lambda_1^2 \mathbf{v}_1 + \alpha_2 \lambda_2^2 \mathbf{v}_2 + \ldots + \alpha_n \lambda_n^2 \mathbf{v}_n \quad (22)
\]

Therefore:

\[
\mathbf{A}^kx = \alpha_1 \lambda_1^k \mathbf{v}_1 + \alpha_2 \lambda_2^k \mathbf{v}_2 + \ldots + \alpha_n \lambda_n^k \mathbf{v}_n \quad (23)
\]

This means by multiplying a random vector many times by the matrix in question, the product gradually converges to (is determined by) the direction of the dominant eigenvector; because other terms are attenuated by their lesser eigenvalues.

6.3 Fuzzy Closeness and Closeness Graph

We hereby explain the basis of our Fuzzy approach to forming such a Closeness Matrix. We define closeness as a Fuzzy linguistic variable that can be interpreted in view of a factor saying what is absolutely far for the perceiver of closeness. If one is not willing to walk more than 5 minutes, then every destination below 5-minute walk will be somehow close to them but destinations farther than a 5 minutes’ walk will be absolutely far. Representing the truth level in the statement referring to closeness of a destination, we can formulate it as value between 0 and 1. In Crisp Logic, statements are either true (1) or false (0), but in Fuzzy Logics [17], we speak of the whole range [0,1] as for correctness of statements. We define Fuzzy Closeness as follows, where \( x \) represents temporal (travel-time) distance; \( \mu \) represents an adjustment coefficient; and \( F \) denotes the temporal How-Far threshold:

\[
C(x) = \frac{1}{1 + e^{\mu(x-F)}} \quad (24)
\]

We intend to obtain a sigmoid function to show the concept of closeness as it is perceived for a person.

Figure 8. Fuzzy Closeness as a function of temporal distance

To ensure that the Fuzzy Closeness \( C(x) \) will have a value smaller than \( \varepsilon \) at the threshold distance \( F \) we can set \( \mu \) to the following:

\[
\mu \geq \frac{2}{F} \ln \left( \frac{1}{\varepsilon} - 1 \right) \quad (25)
\]

It is then straightforward to translate each temporal distance value in a distance matrix (whose entries are Easiest Path distances) to a Fuzzy Closeness value and form a Closeness Matrix. This matrix will be the representative of a graph that can be seen as a literal translation of the famous expression, a.k.a. the First Law of Geography, by Waldo Tobler: “Everything is related to everything else, but near things are more related than distant things” [22].

6.4 Spatial Eigenvector Centrality

On our undirected adjacency matrix, we can find eigenvector centrality rankings. Eigenvector centrality is a natural generalization of the intuitive notion of degree centrality, which is usually the first thing that comes to mind when speaking of centrality. If we say a more important node (say a person in a social network or a street space) is the one with more links (a person with many connections or a street where many other streets meet) then we are speaking of degree centrality. However, if we differentiate between connections (neighbours), we can redefine the centrality (importance [18], status [1], or accessibility [19]) relative to the centrality of the neighbours themselves in a recursive manner. This is of course an intuitive notion like “people are known by their friends” or “an important person is a person who is connected to important people”. Formally:

\[
\text{Figure 7. Left: 3D Spectral Graph Drawing of the example spatial network using the eigenvectors of the Laplacian Matrix; Right: 3D Spectral Graph Drawing of the example spatial network using the eigenvectors of the Lazy Random Walk Matrix, after Kroen [8]}
\]
\[ c^e(i) \propto \sum_{j=1}^{n} c^e(j) \quad (26) \]
\[ c^e(i) = \eta \sum_{j=1}^{n} c^e(j) = \eta \sum_{j=1}^{n} a_{ij} c^e(j) \quad (27) \]

\( c^e \) is a vector holding eigenvector centrality values, we can rewrite the same equation in matrix form:

\[ c^e = \eta A c^e \quad (28) \]

This would be more interesting if we reformulate as below where \( \lambda = 1/\eta \):

\[ A c^e = \lambda c^e \quad (29) \]

This centrality can be computed in two different ways on a spatial network:

- Firstly, by literally using the adjacency matrix of the network; and
- Secondly, by computing it on a ‘Fuzzy Closeness’ Matrix

We propose the second approach viewing a graph as a construct that captures similarity (proximity in the temporal-spatial sense) between nodes.

**Figure 9.** Eigenvector Centrality of the adjacency matrix

**Figure 10.** Eigenvector Centrality index of the Closeness matrix, when distances above “10 minutes cycling” are considered ‘far’

**Figure 11.** Eigenvector Centrality index of the Closeness matrix, when distances above “15 minutes cycling” are considered ‘far’

**Figure 12.** Eigenvector Centrality index of the Closeness matrix, when distances above “25 minutes cycling” are considered ‘far’

7 CONCLUSION

In this paper we introduced a number of novel models, methods and algorithms for Spectral Modelling in Spatial Network Analysis. We have generalized the concept of spatial network from the ‘topological connectivity’ (in Adjacency matrices) to the ‘perceived closeness’ (in Fuzzy Closeness matrices). This new definition of the Spatial Network comes closer to a Social Network, where places are all related to one another but near places are more related. Our fuzzy closeness approach, the Easiest Path algorithm, and its underlying graph representation are novel constructs that make spatial analysis more intuitive, understandable, and more easily interpretable; and at the same time connect it to the field of spectral graph theory. The main advantage of spectral analysis in modelling and simulation of large datasets is the fact that it reduces the dimensionality of the data to a few important factors and directions, using which we can transform our \( n \)-dimensional dataset to a low-dimensional Euclidean space, within which similarities based on distance would be representatives of similarities in the original space. The success of spectral graph drawing in producing ‘nice’ drawings using only abstract topological information is remarkable and illuminative. Similarly, the fact that we are able to reconstruct closeness-like distributions using eigenvectors on our generalized fuzzy graph definition proves a point about relevance of spectral methods in Spatial Network Analysis.
8 IMPLEMENTATION
The methods reported in this paper are all implemented in the new version of a freeware toolkit for Urban Configuration Analysis by the first authors. The toolkit will be available for download here. We have used MathNet library for Linear Algebraic data structures and algorithms.

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* This is a newer version of our previous work [15], in which we have considered underlying graphs as directed graphs and obtained different results.
† Since we are dealing with undirected graphs in Spectral Drawing, these eigenvalues correspond to symmetric (Hermitian, Self-Adjoint) matrices and are therefore real-valued.
Urban body network configurations through attributes of network elements

E. Androutsopoulou

School of Architecture, National Technical University of Athens, Athens, Greece
Corresponding author: E-mail: iandroutsopoulou@gmail.com

Abstract
The methodology presented here is grounded on the analysis and relational relocation of mixed attributes of the urban body, deriving both from the reconstruction of the urban body as a network configuration as well as from research-driven properties which in this case reflect geometry, traffic and accessibility. Cluster analysis is applied in an attempt to restructure those attributes of the urban body which emerge from the position of each element (node) in relation to other elements of the network and not from the Cartesian topology. The methodology proposed here is a way of mapping the multiplicity of elements' structure, in terms of crowds of elements and sets of attributes' values which redefines identity as a shifting threshold of similarity which forms families of things of different qualities, which however keep a certain amount of similarity within the immaterial and evolving boundary of identity. What is more, being able to represent material and non-material elements as nodes (Hillier, 2007), counter-bodies of mixed proprieties emerge, including physical presence and their attributes. In contrast to the hierarchical constructions, network constructions allow for multiple connections between elements (Alexander, 1965), therefore being closer to the complexity of the associative forces found in the structure of the urban body.

Author Keywords
Data; Mutation; urban body; cluster analysis; network; data manipulation.

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING

1 INTRODUCTION
Following the research towards urban cohesion where supra-local nodes inscribed on the Attic peninsula in Greece (Figure 4) were evaluated as being well-connected nodes or as being the nodes though which other groups of nodes interconnect and where we finally described a proposed set of actions that would result in the self-adaptation of the urban body in a way that would re-evaluate its processes towards a structure of a coherent whole (Androutsopoulou, 2014), we focus here on data manipulation techniques and specifically on the definition of the shifting urban identity based on nodes' attributes. This is made possible through the application of similarity functions between objects (nodes) and their attributes, those which reflect the network structure, as well as their research-driven properties which in this case reflect geometry, traffic and accessibility.

Through the application of community detection (Figure 5) (Blondel et al., 2008, Rosvall et al., 2009) and centrality algorithms (betweenness centrality, degree centrality, closeness centrality) (Newman, 2010), the autopoietic attributes of the network's nodes are revealed and a real-time self-adaptation of the urban body is produced, on the basis of the alteration of the nodes' attributes and the identity of the nodes themselves (Figures 1,2,3). In order to reveal further relationships between network and urban body structures, supra-local nodes are regarded as multidimensional objects and the attributes emerging from the network configuration (autopoietic attributes), as well as attributes reflecting geometry, traffic and accessibility appear as a set of values (dimensions), allowing for a clustering methodology of objects and their attributes. Through the application of certain distance (Pearson correlation coefficient) and linkage functions (average group linkage function) (Hastie, Tibshirani, Friedman, 2003), each node/attribute is relocated to an hierarchical tree, where the position of each element reflects its relational similarity, following a gradual procedure of selection of two sets of elements and based on the strength and the direction of their relation.

The application of similarity and linkage functions on the attributes of the urban body network configurations allows for the detection of relations between nodes and their attributes, as well as for the reflection on whether clustered attributes reflect urban identity through mixed properties of things (autopoietic and research-driven properties).
Figures 1, 2, 3.
Autopoietic properties are assigned at the nodes of the network. The nodes’ colors correspond to a certain type of property assigned on them. The network configuration is readapted as counter-bodies (communities) of the network are progressively introduced.

Figures 4, 5

**Figure 4.** The network configuration describing supra-local nodes and their connections. **Figure 5.** Community detection based on modularity class (Blondel et al., 2008). Colouring of communities reflects the differences in communities compared to mapequasion method (Rosvall et al., 2009).
2 ATTRIBUTES REFLECTING NETWORK STRUCTURE (AUTOPOIETIC PROPERTIES)
Supra-local nodes are treated as objects whose attributes' values derive from the network structure and therefore reflect the autopoietic dynamics of the network (Maturana, 2002). The application of the distance and linkage functions results in a data tree where nodes, as well as their attributes, are visualized in a color mosaic which captures the proximity of data values to each attribute's lowest and highest extreme values (Figure 6).

Through mapping of the gradual procedure of nodes' union into clusters and being able to trace the distance function results at each step, the visualization of the proximity of nodes in terms of similarity is made possible, as well as the schematic plan of these relations at the resulting hierarchical tree, where the length of the branches reflects the similarity value between objects.

The interrelation of attributes resulting from the structure of the network configurations allows for the estimation of possible divergence or convergence of other attributes in relation to one known attribute. In the case where we find, for example, that a node's value has a proximity to a lowest/highest value of an attribute, in what concerns its relational position at the network and defined by the application of algorithms which measure certain qualities of the network structure, other qualities could be estimated beforehand through association. It is therefore possible, through the application of similarity/linkage functions and through the production of scattergrams showing convergent/divergent relations between attributes, to shape the structure of network attributes' association (Figures 7,8).

Figure 6. Cluster analysis visualized as a color mosaic and dendrogram of supra-local nodes.

The methodology adopted is considered as a schematic representation of the structure of network attributes' association and a resulting dimension decrease when dealing with the inquiry of distinctive characteristics which aids in the interpretation of clusters' function. Using similarity function and being able to further explore interrelations between things through values which result from given network structures, it is possible to acquire an overall understanding of the network attributes' association (Figures 7,8), as well as to retrieve a cognitive structure which provides the frame of interrelations of the properties of things.

This approach suggests the transition from a clear perception of an object/urban site to the ambiguity of multiple properties of things, presented as a set of data values and rendered in the form of scattergrams, color mosaics and dendograms. Among the possibilities originating from this approach is the witness through visualization and understanding of the concurrent alterations taking place in a given network construction among all node's characteristics with the shift of one property, a kind of structural coupling between body and environment (Maturana, 2002).
Based on the results of the applied similarity/linkage functions in what concerns the nodes' grouping of the supra-local nodes for 3 (minimum similarity: 0.758-0.653) and 16 resulting clusters (minimum similarity: 0.994) (Figure 9) and comparing them to the community detection results (Blondel et al., 2008, Rosvall et al., 2009) (Figure 5), the nodes' integration to clusters is further explored, looking at the issue this time from the angle of analogy and identity of objects with certain properties and not focusing merely on the network's structure.

The resulting clusters, comprised of sets of nodes, when applied at the network visualization, appear as sparse entities whose location on the network map doesn't seem to originate at all from topological network proximity, presenting a strong difference in results and, of course, in methodology from Blondel and Rosvall methods. The implementation of similarity results in the network structure shows that proximities of things this time resides in homogeneity and heterogeneity and not in topological proximity.

The transition from the physical space to the network structure means the retention of proximity through network's connections only, exempting any other analogy or dependency from the objects' Cartesian's coordinates at the physical space. This second transition, from network structure to treating network characteristics as object's properties and conducting comparative studies, produces clusters whose configurations do not keep a straight link or analogy to the network's proximity of objects, in spite of the attributes' emergence from those qualities of proximity between things.

While focusing on higher values of minimum similarity and therefore producing a higher number of clusters, things that belong to each cluster get more similar to each other and the reasons why one cluster is comprised from certain nodes and not others become clearer (Figure 9). However, even in the case of the production of three clusters, where the value of minimum similarity is rather high, the ability to track and comprehend similarity is less viable but remains reachable. (Figure 10).

In the case where the minimum similarity is defined to contain a range of values between 0.758 and 0.653, the concentration of values referring to each of the three clusters, for pairs of attributes reflecting network structure is rather distinct, even suggesting an evident qualitative dissociation, as is shown for the pairs of betweenness centrality - closeness centrality, eigenvector centrality - betweenness centrality, eccentricity - closeness centrality (Figure 10).

Being therefore able to track the concentration of values for each cluster and detect the interrelation of attributes reflecting network structure, identity is being traced and redefined, in this case as a set of distinctive characteristics for each cluster which show a certain amount of distinction for each group of elements and as a relocation of elements in a map of associations deriving from network structure.
Figure 9. The application of the similarity/linkage functions results on the network's visualization, for 16 (minimum similarity: 0.994) and 3 clusters (minimum similarity: 0.758-0.653) respectively.

Figure 10. Scattergrams of pairs of attributes reflecting network structure (autopoietic properties) for each one of the three clusters produced when the minimum similarity is set within a range of values from 0.758 to 0.653.
3 ATTRIBUTES REFLECTING GEOMETRY, TRAFFIC AND ACCESSIBILITY

The research presented here aims at offering a way of dealing with the multiplicity of elements in what concerns their properties' inclusiveness, as well as a methodology of approaching the association of attributes, towards an attitude of embracing the ambiguity of things. In order to extend the range of attributes we are dealing with, properties of nodes which reflect quantitative and qualitative characteristics are examined.

Geometric and qualitative characteristics of the urban body are examined here alone, without including the attributes which reflect network construction and include the geometric characteristics of the total area, the built-up area and the free area of the urban sites, the number of floors and qualitative attributes such as the degree of accessibility of pedestrians and cyclists to the sites and from metro/isap stations, as well as the visitors' traffic observed at each node.

The associations between properties of things, the way elements cluster in accordance with the degree of similarity/dissimilarity and the constant variation of the accepted difference, constitute a continuously evolving field of identity definition. Identity is defined at this step from the geometric and qualitative characteristics of the urban sites, which are examined as things with multiple qualities. In a way we deal here with the urban body as an entity which occupies space, resides in areas of close proximity or relative remoteness to metro/isap stations, is geometrically defined from soft or harder boundaries which allow easy access to the pedestrians and cyclists or not and is constituted by urban nodes of greater or smaller streams of visitors' traffic. The integration of objects into the same family or the exhibit of a certain amount of segregation depends on the degree of focus (minimum similarity/cutting the tree), the threshold which defines the penetration into more detailed ways of organizing elements, acting accordingly to the amount of wished similarity by convergence or the accepted amount of difference, creating thus greater assemblages of things while accepting a greater amount of heterogeneity between elements (Figures 11, 12).

The urban identity is explored here in terms of an overall consideration of a crowd of things and a set of values, which are comprised of quantitative and qualitative characteristics, constituting an understanding of identity which is continuously sculptured, following a process of capturing similarity between samples. These samples react in certain ways to questions posed which can be specific or rather vague, can be answered positively, negatively, or with a certain exact value or could be answered only within a range of possible value variations. However, what really matters at the end of this process is the definition of focus into similarity within an extended field of possible configurations.

Figure 11. Similarity /Difference resulting from 8 attributes: The difference in colors (presented here in b&w) reflects the different clusters (min.sim.: 0.835), while the white columns dividing the clusters reflect the inner structure and possible subdivisions in the clusters (min.sim.: 0.996).

Fig. 12. Similarity /Difference resulting from 4 attributes reflecting geometry only: The difference in colors (presented here in b&w) reflects the different clusters (min.sim.: 0.835), while the white columns dividing the clusters reflect the inner structure and possible subdivisions in the clusters (min.sim.: 0.996).
4 CONCLUSIONS
Rather than proposing a discussion on overall equality, the research presented here is a discourse on revealing difference through properties of equal number and on exploring the evolving nature of a property of things called identity. It is claimed here that identity is comprised of things of different qualities, which however keep a certain amount of similarity within the immaterial and evolving boundary of identity. The set of things withheld into this cognitive envelope of identity depends on our flexibility in what concerns the range of the threshold which determines identity's sensitivity on difference. In fact, identity in this case seems to be a family of things with certain characteristics, urban elements which join together to breed a broader aspect of the notion of identity, in terms of homogeneity and heterogeneity. Urban quality in this sense, could be a sum of distinctive quantitative and qualitative characteristics of the urban sites.

The methodology proposed here is a way of mapping the multiplicity of elements' structure, in terms of crowds of elements and sets of attributes' values which redefines proximity as similarity and remoteness as difference. This allows for the relocation of the ambiguity of information, shown in a way which enables us to arrive at an understanding of information in the grounds of similarity, to look into the aspect of multiplicity of things, to draw upon a potential exploration of proximity in terms of homogeneity and to capture an ever-evolving field of difference and therefore identity, with an altered degree of focus into the accepted divergence of things.

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Session 4: Agent Based Modeling

A Computational Framework to Simulate Human Spatial Behavior in Built Environments
Davide Shaumann, Michal Gath Morad, Einat Zinger, Nirit Putievsky Pilosof, Hadas Sopher, Michal Brodeschi, Kartikeya Date, Yehuda E. Kalay
Technion - Israel Institute of Technology; UC Berkeley.

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A Multi-Agent System for Design: Geometric Complexity in Support of Building Performance
Evangelos Pantazis, David Gerber, Alan Wang
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A computational framework to simulate human spatial behavior in built environments

Davide Schaumann\textsuperscript{1}, Michal Gath Morad\textsuperscript{1}, Einat Zinger\textsuperscript{1}, Nirit Putievsky Pilosof\textsuperscript{1}, Hadas Sopher\textsuperscript{1}, Michal Brodeschi\textsuperscript{1}, Kartikeya Date\textsuperscript{2}, Yehuda E. Kalay\textsuperscript{1}

\textsuperscript{1} Technion – Israel Institute of Technology, Haifa, Israel
\{deiv, michalm, einatm, niritpp, hadassfr, brodesch\}@campus.technion.ac.il, kalay@tx.technion.ac.il
\textsuperscript{2} UC Berkeley kartikeya@berkeley.edu

ABSTRACT
The research addresses current lack of computational tools at architects’ disposal to predict to what extent a built environment will support the activities of its future inhabitants.

Despite recent efforts of agent-based models to represent the dynamic reaction of synthetic characters to the surrounding spatial and social environment, current approaches do not allow simulating larger narratives that describe how people use space over time in larger and complex buildings, such as hospitals.

In this research, human spatial behavior is modeled through Events – computational entities that direct one or more agents to perform specific activities in specific spaces to achieve goals related to the building function (e.g. hospital, airport, or museum). Events allow describing human behavior patterns at different levels of complexity, accounting for social, cultural, spatial and environmental factors.

The paper describes the Event-based system architecture, and presents the simulation of a medicine distribution procedure in an abstracted representation of an existing hospital setting.

Author Keywords
Human behavior simulation; multi-agent system; event-based model; building occupancy prediction.

ACM Classification Keywords
I.2.11. DISTRIBUTED ARTIFICIAL INTELLIGENCE: Intelligent agents, Multiagent systems; I.6.5 MODEL DEVELOPMENT; J.5 ARTS AND HUMANITIES: Architecture; J.6 COMPUTER AIDED ENGINEERING: Computer-aided design (CAD)

1 INTRODUCTION
The buildings designed by architects are settings for human activities. A good design can foster interactions among users, boost productivity, and maximize satisfaction, while a poor design can hinder users’ performance, reduce satisfaction, and even undermine people’s safety. Assessing whether a design will be considered good or poor before its realization is one of the main challenges for architectural design.

Different from most other design practices, where products can be tested before mass production, architectural artifacts are too big, complex and costly to be prototyped and tested before their construction. It is therefore imperative for architects and clients to predict and evaluate a building’s performance during the design process itself. While current prediction methods involve calculations related to structural aspects, light, energy and wind, less reliable methods allow assessing human behavior aspects, such as how well a building will support human activities.

Simulations would provide an adequate prediction method, if proven feasible. They allow iterative testing of what-if scenarios to fine-tune the building design against a wide set of requirements related to different building use scenarios, matched to the expectations of different stakeholders.

To simulate human behavior, however, geometrical built environment representations generated with Computer Aided Design (CAD) and Building Information Modeling (BIM) tools need to be paired with representations of the people that will inhabit such environments, and the activities they will perform.

The proposed research aims to do that. A computational framework to dynamically simulate human behavior patterns in built environments is presented. The framework relies on an Event-based model \cite{18, 16} that allows coordinating multiple agents’ behavior to achieve larger goals as determined by the organization that occupies the built environment.

Agents’ behavior is driven both by scheduled Events that need to be performed, as well as by unscheduled Events that originate from agents’ situated interactions with their physical and social environments.

Hospitals have been chosen as test bed for the system development and use. Designing hospitals is a complicated task because of the wide range of users and the variety of functions that are carried out in the same location. Yet, given the general aim of hospitals to heal patients, hospitals can be considered as highly specialized “machines” that...
implement state-of-the-art medical technologies and procedures to "fix" ailing patients. This formalization is advantageous for the purposes of our research, because it provides a comprehensive and agreed-upon set of behavior patterns on which to build the model.

The paper describes the computational framework to model and simulate human spatial behavior by means of Events, and presents the simulation of a medicine distribution procedure in an existing hospital setting.

## 2. RELEVANT STUDIES

Understanding the relationship between the built environment and its human inhabitants has fascinated many researchers in fields such as psychology, sociology, ergonomics, philosophy, and cognitive science, among others. Doing so before the environment has been built, however, is one of the most difficult building performances to predict and evaluate.

### 2.1 Predicting and evaluating human behavior in built environments

Architects mostly extrapolate from past experiences to predict and assess human behavior in future projects. Post Occupancy Evaluation (POE), for instance, leverages accumulated experience gleaned from prior case studies. Such knowledge, although easily implemented in the form of norms and regulations, ignores the context-dependent, dynamic and stochastic nature of human activities. It can only provide a static representation of average human behavior [26]. A gap, therefore, exists between what architects expect and how users actually behave once the building is built.

Pre-occupancy direct-experience behavior observations, such as full-scale mock-ups and virtual environments, attempt to provide up-to-date, real-life experience of environments that do not yet physically exist. While they are common in most other engineering disciplines, constructing realistic experimental settings is expensive. Furthermore, such types of experiments rely on the experience of a limited number of users, whose response may not be representative for the actual future users.

Empowering the representational means typically used by architects to evaluate a building before it is realized (e.g. drawings and models, physical or digital) would provide an adequate solution. Nevertheless, current CAD (Computer-Aided Design) and BIM (Building Information Model) systems only provide a static building representation, ignoring the dynamic aspects of building occupancy.

Generalized representations of users’ activities in relation to spaces have been proposed by Eastman & Siabiris [7], Ekholm [8], and Wurzer [24].

Mathematically-inclined methods that analyze the impact of the built environment on users’ perceptual and cognitive abilities, have been developed by Hillier & Hanson [10], and Hölscher [11], and can be used to test the proposed design solution against certain functionalities, such as way-finding capabilities and visual connectivity.

Simulation methods have been proposed to generate a dynamic, time-based representation of building in-use. Agent-based models, in particular, have proved to be particularly useful for this task. Different from other simulation paradigms such as system-based and process-based approaches (also known as discrete event models), agents’ behavior is triggered by their local condition (both spatial and social) rather than global information, and affects and is affected by the behavior of other agents in a reactive fashion [23]. Each agent pursues its individual goal (e.g., exit the building, in case of a fire egress simulation), while reacting to the environment they perceive, as well as the actions and behaviors of other agents. Complex behaviors emerge from the unfolding of low-level behaviors and the interactions among the agents [4].

Most agent-based models have focused on simulating specific circumstances, such as pedestrian movement [3], or fire egress situations [15, 6]. Steinfeld [19] and later Yan & Kalay [21] developed a general method for human behavior simulation by means of Virtual Users—anthropomorphic goal-oriented agents that mimic human behavior in virtual settings to evaluate existing and not-yet existing built environments from a user point of view.

Similar synthetic characters have been used by other researchers to test micro-scale aspects of human interactions with their immediate surrounding, such as for testing ergonomic aspects of vehicles, work areas, machine tools, and assembly lines [1], and simulating crowd behaviors [14, 20]. Kalay’s approach, instead, aimed at investigating the macro-scale impact of physical and social aspects of a built environment on the behavior of multiple agents to support the architectural design process.

Despite the advantages of using agent-based models over process-based simulations for simulating agents’ response to their physical and social environments, the assumption that complex behaviors can be modeled by increasing individual agents’ complexity provides both conceptual and computational limitations, especially to reproduce collaborative, goal-oriented activities in complex settings.

### 2.2 Modeling and simulating Event-based narratives

Expanding on existing work on agent-based models, Simeone et al. [18] and Schaumann et al. [16] proposed a different method to simulate behavior patterns in complex settings, such as hospital environments.

The proposed model relies on the notion of Events, computational entities that coordinate single or multiple agents’ behavior by meaningfully combining information concerning actors (who?), the activity to perform (what?) and the spaces in which to perform it (where?).

While in everyday language an event can be defined as something that occurs in a certain place, during a specific
interval of time, in this work the nature of Events is essentially computational. Our aim is to abstract essential features of the performing of events in the physical world, and to reproduce them in a computational environment.

If in the physical world events can be considered as mundane, temporal, goal-oriented routine activities commensurate with social and cultural contexts [25], in a virtual world Events become computational entities that can coordinate temporal, goal-oriented routine activities performed by virtual actors.

The main novelty of the approach is that, different from agent-based models, the decision-making abilities are placed in Events, instead of the agents themselves. Accordingly, Events have the ability to describe what happens if some conditions are verified, as well as what should happen if some pre-conditions are not satisfied. For instance, an Event could describe how a nurse and a doctor approach a patient’s bed to perform a clinical procedure, as well as what should happen if one of them is delayed or called away to attend another duty: it could instruct the remaining actor to wait, or abort the entire event, since the conditions required for the Event to occur are not satisfied.

To reduce Events’ computational efforts in managing the performing of a behavior pattern, each of the Event’s constituent parts, namely the actors, spaces and activities, is equipped with dynamic calculation capabilities to support the Events’ conditional decision-making abilities and performing procedures. For instance, Space entities calculate at each timeframe environmental properties, including the number of people within their boundaries. Actor entities, instead, automatically update their status in relation to environmental conditions, and they update information about their knowledge of the surrounding environment. The Event entity relies on such information to trigger and perform context-dependent activities.

3 SYSTEM ARCHITECTURE
To generate a dynamic representation of building occupancy, four different types of information are required: a designed space, a list of actors that populate the space, a list of activities that the actors perform, and a list of Events that meaningfully combine actors, spaces and activities. Events are organized into larger compositions, called narratives, which combine Events to generate a coherent representation of the building use process.

Each type of information is encoded in a separate database, and is connected to a simulation engine that calculates the step-by-step advancement of the narrative in relation to space and actors’ profiles, as well as dynamic social and environmental conditions. The simulation output consists in a dynamic visualization of the building use process, and/or in a log describing relevant data generated during the simulation.
Each zone is able to autonomously update its dynamic attributes. For instance, it is able to detect the presence of actors and activities, and update accordingly its semantics, and its environmental parameters. Furthermore, zones can communicate information to actors and Events, to mediate actors’ perception and ease Events’ computational efforts.

3.2 Actors
Actors are anthropomorphic goal-oriented virtual users that inhabit a virtual setting. Each actor is associated with a specific role in the organization that occupies the building. Like spaces, a hierarchical taxonomy defines different actor types (e.g. a medical staff member, a nurse, or a head nurse).

Actors have physical properties, attributes whose values remain static during the simulation process (e.g. type, age, gender, experience) or vary dynamically according to the activities performed (e.g. tiredness, stress), group affiliations and social connections [6], and knowledge about the surrounding world [23]. Actors’ attributes are shown in Table 2.

Actors impact space via their presence and activities. At the same time, actors interpret space in a way that resembles perceptual abilities. Environmental perception, however, rather than being encoded in the actors themselves, is mediated through zones’ calculation abilities. For example, the information about the number of actors present in a room will be stored in the “room” entity, rather than in the actors present. This approach ignores sight lines and gaze direction, as is done in other research projects at a much higher computational cost. We consider this approach an acceptable trade-off for the purposes of our simulation.

Even though environmental factors are calculated at the zone level, each actor holds an individual threshold of tolerance for such environmental parameters, which may affect the development of the narrative. For instance, if the noise level in a zone is higher than the actor’s threshold, the activity performing may fail. As a consequence the Event directing the agents’ behavior might devise a different plan to achieve the goal. If no such plan can be found, the entire Event can be aborted or postponed.

Actors’ knowledge is stored in the form of a database of facts known or believed to be true. For instance, an actor knows that a nurse can be usually found at a nurse station. Different actor types have different knowledge related to their role in the organization. Preferences are encoded in the form of rules that will affect actors’ decision-making. Events, in particular occasions, may in fact consult the actors’ preferences to determine the next goal to pursue, or to decide which strategy to use to pursue the goal. While preferences remain static, actors’ knowledge is updated during the simulation.
Actors can move in space to reach targets assigned by Event entities. Actors' movement depends on spatial conditions (e.g., obstacles, or semantics of the zone to traverse), social conditions (presence and activities of other actors in the surrounding space) and their own knowledge and preferences.

### 3.3 Activities

*Activities* are fundamental actions that agents perform to achieve a goal [13]. They describe the interactions between actors and their surrounding environments at each moment in time. Such activities affect both the actors and the surrounding environment.

Every actor is associated to a list of activities, based on his/her role in the organization. Events trigger a specific activity for each actor, which together achieve a larger goal.

The temporal aspect of activities, such as their duration, is determined by spatially contingent situations, or is predetermined by an Event entity. For instance, the duration of the activity “move to a target” depends on the building layout, as well as on the actors’ properties (e.g., age, tiredness, etc.), and the environmental context.

Parametric activity formalizations allow reusing the same activity multiple times in different contexts, by changing only some parameters (e.g. the target in a “move to” activity). Such activity representation resembles previous studies on Parametric Action representation [2]. Interactions among multiple agents, intended to perform collaborative activities, are also coordinated by Event entities.

### 3.4 Events

Events are responsible for planning and coordinating the behavior of one or more agents to achieve a goal. To plan, events rely on data calculated by actors, activities and spaces. Every event is composed of a set of *pre-conditions*, *performing procedures*, and *post-conditions*. Pre-conditions specify the requirements for an event to be triggered. They might relate to the activity, space, or actors involved in the Event, or to time. After verifying the compliance with the preconditions, a set of performing procedures guides the Event execution. Such procedures involve one or more actors performing an activity in a certain space. Upon termination, Events can update the status of some of all the entities involved in its execution (such as actors, spaces, equipment) by means of post-condition instructions. In case the pre-conditions of an Event are not met, the Event seeks an alternative plan to achieve the same goal, which can be stored within its performing procedure. If such plan cannot be found, the Event is aborted.

Events are structured hierarchically, such that lower-level Events address more detailed tasks, whose sequence is determined by their parent Event. Larger Events compositions are called *narratives*. They provide a logical plot structure that unfolds during the simulation according to Event preconditions, as well as to stochastic processes.

Events can be defined as *planned* or *unplanned*. *Planned* events are triggered at specific times (e.g. the procedure for doctors’ rounds in a hospital ward). *Unplanned* events occur due to the situatedness of the agents in a physical and social context (e.g. a doctor on a round meeting a colleague in the hallway).

Figure 3 describes a typical planned event performed in a hospital environment, namely the Medicine Distribution procedure. The first task of the parent Event (1) is to assign each of the nurses on duty in the ward a list of patients to take care of. A sequence of sub-Events (1.1, 1.2, 1.3, 1.4) instructs a nurse to move to a central medicine room (1.1), prepare for all patients the required medicines (1.2), put the medicines on a cart (1.3), and distribute the medicines to all the patients (1.4). Event 1.4 also requires a sequence of tasks to be performed (1.4.1, 1.4.2, 1.4.3), which direct a nurse toward each patient to subministrate the medicine. If a patient is in his/her bed, Event 1.4.3 will instruct the nurse to subministrate the medicine to the patient. If the patient is not in the bed, the subministration process will be postponed (Event 1.4.3.2).

Complexity in the narrative development emerges from the interaction of several events that occur in the same setting, at the same time. For example, a patient can be away of his/her bed, because another Event has called him/her away (e.g., take an X-ray). In this case, the nurse responsible for distributing the medicine to the patient may be instructed by the Medicine Distribution Event to go to the next patient on the list, and return to the absent patient after a specific period of time.

An Event Manager is responsible to resolve conflicts among Events that compete for the same actor, or for the same space. For instance, if a planned event is directing a nurse to distribute medicines, but an unplanned Event (such as a visitor striking up a conversation with a nurse in the corridor) can also be performed, the Event Manager will evaluate the nurse personal traits and status (e.g. politeness, tiredness, or stress) and will determine if he/she can be interrupted, and for how long.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Role</th>
<th>Age</th>
<th>Gender</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurse_1</td>
<td>Medical</td>
<td>Staff</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
</tr>
</tbody>
</table>

Table 2. Actor attributes
3.5 Simulation Process
To generate a time-based representation of a building use process, a simulation engine combines and “activates” the information provided by the different input modules, namely the actors, spaces, activities and Event-based narrative. The engine updates, at specific time frames, the status of the world and all the entities involved. The simulation output can be observed in the form of real time visualization, or as a data log that might account for longer simulation time spans. It allows testing and evaluating the impact of the environment on the agents’ behavior patterns against the expectations of the design.

Design stakeholders, such as architects, hospital administrators and staff will be able to perform multi-criteria evaluations in accordance with established goals by analyzing data from the simulation output (such as travel time, distance, circulation paths, activity durations, interferences, and space utilization), or by observing the simulation itself while looking for expected and unexpected patterns of behavior under different scenarios (for example, weekdays, weekends, and emergencies).

4 CASE STUDY
To elucidate the capabilities of the proposed method, the paper presents the simulation of a medicine distribution scenario in the abstracted representation of the Internal Medicine Unit in the Sammy Ofer Heart Building, at the Tel Aviv Sourasky Medical Center. The medicine distribution procedure is abstracted in the form of an Event (as showed in Figure 3), and performed concurrently with another Event that directs visitors who enter the ward to visit hospitalized family members (a rather common process).

While each of the two Events is planned, the interaction between them causes unplanned Events to emerge, such as when nurses and visitors randomly meet in the corridor. Such social interactions may be desirable in many cases, but are disruptive to the nurses’ medicine distribution task, as they can lead to mistakes and errors [26, 22, 17].

Data about the medicine distribution procedures has been gathered in existing hospitals by means of direct-experience observations and interviews to the medical and administrative staff. The ward was modeled, as were actors, activities and events, as described in the previous sections. Both scheduled and unscheduled events were simulated.

In the simulated narrative, four nurses are responsible for distributing medicines to 31 patients. An Event Manager resolves conflicts arising when at a particular point in time nurses can be interrupted to talk with a visitor. Depending on the stress level of the nurse and on his/her politeness, the Event manager will decide whether or not to interrupt the nurse, and if so, for how long.

Figure 4 shows a snapshot taken while the simulation is running. The colored lines describe the nurses’ circulation paths, while the dotted red lines highlight situations in which visitors interacted with nurses. Several different parameters have been measured, such as the nurses’ walking distances, the number of interactions with visitors, the patients’ waiting times before they receive their medicines, etc.

Table 3, 4, and 5 show information about the Events’ performances after the simulation’s completion. They show how one Event impacts on the other, and what are the consequences of Events’ interactions on the use of space.

Such information can be related to one or many simulation runs, and can include statistical analyses.

This simulation was facilitated by a host of computational tools: Autodesk Revit was used to model the space and equipment; Unity 3D was used as the simulation engine. Spatial semantics, agents’ profiles, activities, and Events were scripted in Unity using C# as a scripting language.
The case study presented here demonstrates the feasibility of the proposed computational framework to systematically consider questions related to human behavior in built environments in a way that current tools for representing architectural design issues do not. This case study considers only three types of events (two planned, and one unplanned), but the Event Manager and Event hierarchy mechanisms make it possible to increase the complexity of the simulation in terms of numbers of events, actors, activities and spaces.

Simulating events in built environments facilitates different types of evaluation. First, it is possible to systematically evaluate chosen metrics and study how they interact in a given design. Second, the spatial-temporal presentation of the simulation enables architects to observe not only how planned events cause and interact with unplanned events in different designs, but also re-evaluate their conceptions of spaces in their design process.

The case study presented here shows that two rather common behaviors affect each other, because they share the same space at the same time. It may partially explain errors in medicine distribution, which are known to have detrimental effects on patients’ wellbeing (as well as in terms of the legal and financial consequences for the hospital).

The simulation shows not only that interferences occur, but also where and when they might occur. This can lead to spatial as well as procedural decisions, such as widening the corridor next to the nurses’ station, which will reduce congestion, or changing visiting hours such that they will not interfere with the nurses scheduled tasks.

Such decisions will be made by the appropriate stakeholders. The intent of the simulation is to help them identify possible causes of problems, and visualize, or analyze, the impact of design changes.

### 5 DISCUSSION

The scope of the proposed simulation framework could be further extended to:

- Hospitals
- Schools
- Airports
- Museums

The Event-based simulation model is a work in progress. Subsequent steps of the work will involve field validation and further efforts towards generalization. The aim of the project, in fact, is to be able to model and simulate human spatial behavior in different types of settings, such as hospitals, schools, airports, museums, etc.

### 6 FUTURE WORK

The Event-based simulation model is a work in progress. Subsequent steps of the work will involve field validation and further efforts towards generalization. The aim of the project, in fact, is to be able to model and simulate human spatial behavior in different types of settings, such as hospitals, schools, airports, museums, etc.

The scope of the proposed simulation framework could be further extended to:
• Test the impact of smart technologies (e.g. smart buildings or wearable devices) on human spatial behavior.
• Enhancing Building Information Modeling (BIM) standards to account for human behavior aspects.
• Simulating human spatial behavior at the urban scale, coupling the proposed framework with other existing simulation methods.

ACKNOWLEDGMENTS
This research is supported by a European Research Council grant (FP-7 ADG 340753). We are also grateful to the nurses, doctors and hospital manager of the Tel Aviv Sourasky Medical Center for their availability, and to the following research group members for their work on the simulation: Prof. SW. Hong, A. Nicola, and M. Kislev.

REFERENCES
Crowd Modeling in the Sun Life Building

Michael Van Schyndel¹, Omar Hesham¹, Gabriel Wainer¹, Brandon Malleck²

¹Dept. of Systems and Computer Engineering
Carleton University, Ottawa, ON, Canada
{MichaelVanSchyndel,OmarHesham}@mail.carleton.ca
gwainer@sce.carleton.ca

²Bentall Kennedy
Ottawa, ON, Canada
BMalleck@bentalkennedy.com

Abstract
Pedestrian movements are a critical component that must be taken into account when one is interested in planning and designing urban areas, buildings and large public spaces. Pedestrian and crowd modelling and simulation has become popular in order to provide information that can be incorporated into the design. This paper presents and discusses an advanced pedestrian model built using the Cellular Discrete Even Specification (Cell-DEVS) formalism. The new model allows the designer to provide an accurate representation of pedestrian behavior. The models presented here were applied to a real world scenario in the city of Ottawa, Canada. The case study focused on the effects of the construction of a new Light Rail Transit (LRT) System, and its influence on the flow of pedestrians into the Sun Life Financial building, located close to one of the main LRT stations. Further illustrated is how the pedestrian model was initialized and verified using data collected from the scene, resulting in accurate pedestrian behaviour. Finally, it’s shown how these results were used to provide insights into possible problems and how to avoid them.

Author Keywords
Pedestrian dynamics; Crowds; Bi-directional flow; Discrete Event Simulation; DEVS; Cell-DEVS; Application.

ACM Classification Keywords
I.6.3 [Simulation and Modeling]: Applications; I.6.5; I.2.11 [Artificial Intelligence]: Distributed Artificial Intelligence.

1 INTRODUCTION
In the context of architectural and urban design, crowd simulation is often used as a demonstrative tool, providing an optimistic vision for the type of real-world utility of a given space. These virtual crowds could be used to guide the direction of development during the early design phases of a project, and are often considered to be an integral digital asset for any marketing effort down the line.

Beyond illustrative uses, crowd simulation is finding increased importance as part of the analytical tool chain that studies a given structure’s safety and capacity concerns [1]. Typical uses include the simulation of emergency evacuation procedures, identifying traffic bottlenecks, and shaping pedestrian flow by manipulating access point allocations and doorway designs.

Modeling and Simulation (M&S) can also be useful in other aspects of Building Information Modeling (BIM). Throughout a building’s lifetime it will undergo many changes and renovations. These remodels can be to update the architecture or in response to a change in the environment. For large buildings, they can be a costly and lengthy undertaking. Therefore, it is very important that all aspects be taken into consideration during the designing phase. M&S can be used to help determine where problems might occur before construction has even begun, and it aids in shaping the new designs, potentially saving the developers both time and money.

Here, it’ll be shown how M&S was used to help during the design phase of the remodel of the Sun Life Financial Building in Ottawa, ON, Canada, by simulating the effects of increased pedestrian traffic through the building and determining possible points that could cause problems in the future, so they could be addressed during the remodel of the building. The simulation is built on Cell-DEVS [10], a formalism based on the Discrete Event System Specification formalism (DEVS). Cell-DEVS combines an event-driven response with continuous timing. DEVS provides good means for coupling model components, hierarchical, modular construction [10]. Cell-DEVS combines the Cellular Automata (CA) theory with DEVS, dividing the model space is broken up into discrete cells, each with their state machine. Cell-DEVS has many benefits, chiefly, that cell state changes can be executed asynchronously. Additionally, unused cells can remain dormant until woken up by an external event or state change, reducing execution times by eliminating unnecessary burdens.

This research aimed to study the effect of the new Light Rail Transit (LRT) System on the Sun Life Financial building in Ottawa, Canada. There are fears that the increase in foot traffic through the building may negatively impact the daily routines. With construction under way, now is the time to make any changes to mitigate any future problems the LRT may cause. The paper shows how the model was designed and initialized using data collected from the scene, making it capable of modelling pedestrian behavior accurately to the specific conditions of the application environment. Finally, these results were used to provide insights into possible problems and measures that could be taken to avoid them.
2 RELATED WORK
The Modeling and Simulation (M&S) of human behaviour is a complex endeavor [2]; and crowds are no exception. To this end, previous efforts have tackled the problem through varying levels of abstraction, depending on the application at hand. This section outlines those abstraction categories and their typical use cases. For a more detailed treatment, the reader is referred to the critical assessments in [1] and [3].

2.1 Modeling Pedestrian Flow
Pedestrian modeling can be divided into the following general categories, in order of increasing granularity: flow-based, entity-based, and agent-based methods.

Flow-based methods represent a macroscopic view of pedestrian dynamics. There are methods that treat the crowd as a continuum that behaves similarly to fluid flow [4], which is achieved by incorporating decision-making elements within existing fluid dynamics equations. Others tackle it from an operational research point view, using network optimization to solve a graph-based reduction of the crowd’s environment [5]. This can be applied, for instance, to the modeling of building evacuation scenarios in which rooms are mapped to nodes on a graph whose edges represent the capacity-limited paths connecting them. The graph is solved for the shortest path to identify optimal exit routes. Computing the graph’s maximum flow would identify potential bottlenecks around those nodes. These methods are computationally inexpensive making them suitable for large-scale projects that involve high crowd densities [6]. This level of abstraction is most appropriate when seeking a general sense of a crowd’s orientation, density distribution, and collective rate of locomotion, without much concern for the specific actions of its individuals.

By contrast, entity-based methods simulate individual entities, which collectively result in the emergence of crowd dynamics. Each entity uses a global class of behaviors that dictate its interactions with the elements in its surrounding local neighbourhood. Typically, this results in highly homogenous entities and parallelization-friendly implementations of microscopic interactions [1]. Cellular Automata (CA) has become a popular entity-based method [7, 8]. In CA, a space is discretized into a uniform lattice of non-overlapping cells (i.e., entities), typically based on any tileable shape with a consistent pattern (i.e., a square grid). A global clock periodically triggers a simultaneous update of all entities, where the next state of each cell is determined by the state of all cells in its neighbourhood.

Agent-based abstractions view each pedestrian as an autonomous entity that encodes spatial interaction laws and has the capacity for goal-oriented decision-making. With this level of detail, minute variations to each pedestrian’s goals, personality, kinematic properties, and the type of actions taken to reach such goals (e.g. leave work early vs. leave after rush hour, take elevator vs. take stairs, etc.) can produce near authentic representations of the real-life processes that lead to the emergent behaviour of crowds. However, this level of detail comes with a significant computational cost, making the use of agents prohibitive towards iterative development and composability with other models [9].

For the scope and practical considerations of this project, a cellular entity-based approach was chosen, as it delivered an adequate granularity with a computational efficiency suitable for repeated trials and rapid iteration.

2.2 Cell-DEVS Modeling of Pedestrian Flow
The Cellular Discrete Event System Specification (Cell-DEVS) [10] is a spatial modeling technique based on DEVS (Discrete Event System Specification) [10], which, much like CA, tessellates a space into a grid of cells. Each cell is an atomic model that connects with other cells in its local neighbourhood, effectively defining a coupled model for each entity and its environment. The modeler is able to define global properties of this coupling, and they are able to define the classes of behaviour that each cell could encode.

For this project, the pedestrian flow is modeled using Cell-DEVS, because it afforded several advantages compared to discrete-time CA, namely: event-dependent time stepping, asynchronous execution among entities, composability with DEVS and event-based architectural systems (e.g. [11]); and the ability to submit the model to formal verification, validation, and static analysis techniques [12].

Cell-DEVS was used for discrete-event pedestrian behaviour modelling in [13], where the authors showed how to integrate Building Information Modeling (BIM) to generate floor plans and exit flow maps for a multistory Cell-DEVS. The pedestrian entities shared a unified goal of exiting the building in the shortest path and time possible. Later developments included the ability to simulate bi-directional flow [9] using corrective sub steps to avoid oncoming traffic, and configurations for scalable execution on the RISE middleware [14], a cloud-based distributed simulation platform.

The proposed method improves upon the bi-directional flow models described in [9] by defining additional classes of goal-oriented pedestrians. This provides a mechanism for the necessary distinction between the building employees and the LRT passengers. Model complexity increases, as each class differs in their interactions with the environment, and in particular with an elevator system. Additionally, a run-time flow field remapping method was developed to automatically adjust the shortest path calculation based on the currently available destinations cells, enabling the integration of an explicitly dynamic elevator system.

3 THE SUN LIFE FINANCIAL BUILDING
The Sun Life Financial Building (SLF) located at 99 Bank Street, Ottawa, Canada (as seen in figure 1) provided a unique chance to demonstrate the proposed methodology.
The SLF consists of two building separated by a mezzanine (as seen in figure 2). The City of Ottawa is in the process of expanding their light rail transit system to extend into the downtown core. Once the LRT is operational, it will be used to transport commuters to the downtown core. One of the LRT terminals will be located adjacent to the SLF building, and commuters will exit near the building’s mezzanine.

Figure 2. Building plan for 50 O’Connor and 99 Bank

With the new LRT terminal will come a large increase in the pedestrian traffic through both buildings and the mezzanine. The impact of an increased number of pedestrians through the building at 50 O’Connor will have very little impact on it as there are wide hallways and the elevators banks are located off the main hallways. The building at 99 Bank however, has one very narrow hallway that is rarely used, as seen in figure 3. To compound the problem further, along this narrow hallway are the 10 elevators that service the building. These elevators are used by the hundreds of employees that work at 99 Bank as well as patrons of the Rideau Club located at the penthouse suites.

The purpose of this research was to examine the impact an increased number of pedestrians through 99 Bank will have on the daily operations. More importantly, that during the cold months or the days that have adverse weather conditions, commuters using the LRT will choose to cut through the SLF instead of walking around the building outside, resulting in a drastic increase in traffic through the building. This already happens at a smaller scale, but during peak hour (8-9 am), as many 2686 commuters arriving from the LRT may benefit by passing through the building.

Figure 3. 99 Bank Street Elevator hallway

A model was generated to simulate the pedestrian traffic in the hallway in question to determine what impacts the increased number of pedestrians may cause and possible solutions to rectify the problems.

4 MODEL DEFINITION

The goal of this model is to portray the physical and sociological behaviors of the pedestrians as they move through the building accurately. These behaviors are created from a set of rules, which can be organized into three categories: mapping, movement and elevators. For each type of pedestrian, these rules will vary to reflect their specific goals. There are three types of pedestrians modeled. The first are the people using the elevators, who enter from either the lobby or the mezzanine and head to an elevator. The second are people passing through the building, heading from the lobby to the mezzanine. The final type is the people who pass from the mezzanine to the lobby. In the following sections discuss the different rules which were implemented in the CD++ toolkit [15]. The reader can find the simulator in http://cell-devs.sce.carleton.ca, and obtain the models from http://www.sce.carleton.ca/faculty/wainer/wbgraf.
4.1 Mapping
The mapping rules focus on building a shortest path diagram from any cell to a desired destination. To do so, we store a direction vector in each cell, which is used during the movement phase to determine which move(s) will get the person closer to their goal.

The mapping process begins in the cell adjacent to the exit. The model computes how many cells away it is from the exit iteratively. A cell’s value is determined by taking the value of an adjacent cell that has a value, as seen in figure 4. The process continues until all cells have a value.

![Figure 4 Mapping](image)

The direction vectors are created by a simple rule. If the adjacent cell value is less than the current value than it is a valid direction (furthermore, additional rules can be easily created to add more complexity).

Several maps needed to be created for the different types of pedestrians (as each of them had a different destination). This was an easy fix as Cell-DEVS allows each cell to contain several state variables. This method was used in [15], in which the map was created at the very beginning of the simulation (and once created, cannot change). However, when the destinations location is dynamic, as in the case of elevators, the map needs to be updated regularly. The re-mapping process starts when a destination (elevator) becomes unavailable. A ping is propagated throughout the map, erasing all values. This ping that is created is akin to the bell that sounds when an elevator arrives. It notifies the people of a new destination and they react by recalculating the closest destinations.

4.2 Movement
The rules dictating the movement of pedestrians during the simulation were based on a variation of the method presented in [15], called the handshake method. This method reduces the neighborhood to simply the eight surrounding cells, as seen in figure 5. This is an important aspect because the cell’s state is determined by the cells that are located in its neighborhood, and, in order to define complex rules, the neighborhood can become quite large. This can cause the rules to become too complex or result inefficient.

The handshake method implemented in this model consists of 3 phases as seen in figure 6. The first phase is when an agent in occupied cell announces its intended destination (which is determined by the mapping; priority is given to movements in the four cardinal directions).

| (-1,1) | (-1,0) | (-1,1) |
| (0,-1) | (0,0)  | (0,1)  |
| (1,-1) | (1,0)  | (1,1)  |

![Figure 5 Neighbourhood Definition](image)

In phase II, the unoccupied cells check their neighborhood for any cells indicating they want to enter. There are three possible outcomes: there is a person that wants to enter that location, there are more than one people desiring to enter that cell, or there is no one wanting to enter the cell. If only one person wants to enter the cell, its state is updated to create a link between the source and the destination cells. If more than one person is attempting to enter the cell, one is chosen and a link created. If no one wants to enter the cell, it remains available. Once a pair is linked, they will remain so until the end of the final phase. If a link is not created, an occupied cell will repeat phase I until either one of two things happen, 1) a link is eventually created, or 2) there are no empty cells available (the person must remain there).

Once phase I and II are complete, phase III makes occupied cells that are linked become empty. Empty cells that where linked will receive the person and occupied cells that were unable to form a link will remain occupied.

This method is beneficial for several reasons. First, by linking the source and destination cells it ensures that no errors will occur. In other methods, it is difficult to deal with collisions when two occupied cells try to enter the same cell, which sometimes results in errors. Another benefit is, as previously mentioned, a smaller neighborhood. This is because only the destination cell must lie in the neighborhood, whereas with other methods would require being able to “see” further to avoid collisions.

4.3 Elevator
The elevator model introduces new complexities compared to the cases when the destinations (doorways) remain static. An elevator however, is a dynamic destination, its cell state...
is constantly changing between open and closed. The rules governing the elevators behavior are straightforward.

1) Upon opening a door, a ping is generated to update the map, as previously discussed.
2) The elevator will remain open until a person enters said elevator
3) Once a passenger has boarded the elevator, it will remain open until one of two things has occurred
   a. The elevators maximum capacity has been reached
   b. The time since the first person has entered has exceeded a set time
4) The elevator will remain closed for a period of time, the length of which is normally distributed about a mean wait time that is chosen

5 EXPERIMENTAL SETUP
Before simulating the impact of the LRT, it was important to re-create the current activity in the SLF, later referred to as baseline data. The collection of actual data from the building was critical to generating accurate models specific to the conditions at the scene.

5.1 Baseline Data Collected
The data used to develop the model was collected by examining security camera footage from the month of January. There were several reasons for this. First, a winter month was desired, as it would see the largest number of days in which it would be preferable to remain indoors for the longest time possible. For average Canadian winters, this would fall between December and March. December was not used, as around the holiday season traffic patterns would be too sporadic. To narrow the parameters further, data was collected between the hours of 8 am to 9 am as this represented the highest volume of traffic through the building from both employees and people passing through. Additionally, the projected data was provided for the peak hour of 8-9 AM. Table 1 shows the average breakdown of the three types of pedestrians during this one-hour period.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Employees</th>
<th>Lobby</th>
<th>Mezzanine</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 – 8:10</td>
<td>45</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>8:10 – 8:20</td>
<td>65</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>8:20 – 8:30</td>
<td>70</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>8:30 – 8:40</td>
<td>75</td>
<td>38</td>
<td>29</td>
</tr>
<tr>
<td>8:40 – 8:50</td>
<td>77</td>
<td>38</td>
<td>27</td>
</tr>
<tr>
<td>8:50 – 9:00</td>
<td>66</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>398</td>
<td>194</td>
<td>149</td>
</tr>
</tbody>
</table>

Table 1. Data Collected

With employees referring to people who used the elevators, lobby referring to pedestrians that are passing through that entered from the lobby and mezzanine referring to the pedestrians that are passing through who originated from the mezzanine. Only the number of employees seemed to have any real pattern, which was a peak between 8:30 and 8:50 after which traffic for the elevator slowed.

Other observations that where important to take into consideration are as follows:

- Elevator round trips ranged from 0:45 to 4:30 with a mean of 2:00
- Elevator wait times ranged from 0:00 to 0:45 with a mean of 0:10
- Elevator occupancy ranged from 1 to 8 with a median of 2
- Elevator queues (more than 2 people) occurred between 3 and 5 times per 10 minute interval

5.2 Baseline Simulation
The first step to setting up the model parameters was to determine a cell size. For the purpose of this model, a cell’s dimensions were defined as 0.75 meters by 0.75 meters. There were several reasons for choosing these dimensions. First, the width of the elevator doors works out to be about 2 cells wide. Secondly, the dimensions represent the area a pedestrian can occupy without becoming uncomfortable. As this is an office building and not a busy sidewalk or a subway, a reasonable amount of space is expected. Finally, this cell size is widely used in crowd simulations using CA.

Furthermore, each frame in the simulation represents 0.5 seconds or a rate of 2 frames/second. As a pedestrian has a maximum speed of 1 cell per frame, this means that the average velocity of the pedestrians is 1.5 m/s [16]. Figure 7 shows the comparison between the floor plan and the cell space used in the model as well as the cell states.

![Figure 7](image-url)

Table 2 outlines the results of a baseline trial. Once a baseline had been achieved that was able to recreate the real world scenario it was possible to modify the parameters to test the hypothesis. It was desired to examine the impact that an increased number of pedestrians passing through the SLF building would have. As previously stated the LRT would bring approximately 6400 additional commuters during the peak hour, every day. As many as 2686 of whom
might benefit by passing through the building at 99 Bank St. While it would be reasonable to assume that people would be favorable to cut through the building it would be unreasonable to assume all the people exiting at the mezzanine would do so.

<table>
<thead>
<tr>
<th>Observations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Employees</td>
<td>66</td>
</tr>
<tr>
<td>Lobby</td>
<td>34</td>
</tr>
<tr>
<td>Mezzanine</td>
<td>24</td>
</tr>
<tr>
<td>Number of Queues Formed</td>
<td>3</td>
</tr>
<tr>
<td>Queue Lengths</td>
<td>Min = 2 Max = 8</td>
</tr>
<tr>
<td>Elevator Wait Times</td>
<td>0:00 to 0:55</td>
</tr>
<tr>
<td>Elevator Occupancy</td>
<td>Min = 1 Max = 8</td>
</tr>
</tbody>
</table>

Table 2. Observed Baseline Data

The simulations run would produce results for 10-minute periods. Therefore, the maximum number of additional people passing through would be 447. To best see the impact increasing the traffic would have, the simulation was started with 5% or approximately 22 additional people passing through over the 10 minute period, followed by 25% and 35% or, 111 and 156 people respectively. Since the number of employees should remain within the same range as the baseline, the elevator parameters would remain the same.

6 SIMULATION RESULTS

This section shows the simulations results for different sets of parameters. Videos of the results can be found on the following link www.youtube.com/user/ARSLab. Furthermore, the model and simulation log files are available at http://vs1.sce.carleton.ca:8080/cdpp/sim/workspaces/test/lopez/BK.

To determine the effects of the increased traffic, the number of queues formed and their lengths are examined. The maximum wait time for an elevator and the number of collisions (in this case, it’s considered a collision when a person in the simulation becomes stuck) are also studied. In most cases a person is able to avoid any obstacle, however when traffic is particularly heavy a person may not be able to move around the obstacle and become stuck for a period. Such incidences were rare when testing the baseline model, and were rarely observed from the security footage. However, such incidence became more frequent during tests with increased traffic.

6.1 Low increase of possible commuters scenario

The first test case was to increase the number of pedestrians entering from the mezzanine by approximately 5% of the total possible commuters arriving via the LRT. As previously stated, this indicates that it’s expected to see an additional 22 people enter the hallway from the mezzanine over a 10 minute frame. As the creating of people is random, the numbers for the employees and people entering from the lobby will vary but will remain within the ranges found in table 1.

The simulation results showed 56 employees entering the hallway, 34 people passing through from the lobby and 56 passing through from the mezzanine. The number of people passing through from the mezzanine has increased by approximately 7% of the 2686 commuters that would arrive via the LRT. The simulations resulted showed eight queues form while waiting for an elevator with a maximum length of six. The maximum wait time for an elevator was approximately 52 seconds. Finally, there were four instances of minor collisions and four major collisions.

6.2 Medium increase of possible commuters

The second simulation tests were built to try to demonstrate the impact of increasing the number of people entering from the mezzanine by 25% of the LRT commuters. This corresponds to an increase of approximately 111 people over a 10-minute period.

The results of the simulation show that over a 10 minute period 74 employees used the elevators, 36 people entered the hallway from the lobby and exited into the mezzanine and 132 people passed through via the mezzanine. This represents an increase of approximately 102 people, which is close to 25% of the LRT commuters. The results show that over a 10-minute period six queues formed with the longest containing seven people. The longest wait for an elevator was 33s. During the simulation period, there were 22 minor collisions and 4 major collisions.

6.3 High increase of possible commuters

The last simulation tests study the effects of increasing the number of people entering from the mezzanine by approximately 35% or 156 people over a 10-minute period.

The simulation results shows that over a 10-minute period 70 employees used the elevators, 26 people passed through from the lobby and 184 passed through originating from the mezzanine. This corresponds to an increase of approximately 152 people or close to the 35% desired. There were 10 queues formed during this period with the largest having five. The longest wait for an elevator lasted 34s. During the simulation there were 24 minor collisions as well as four major collisions.

7 VISUALIZING

One of the barriers to widespread adoption of M&S formalisms in real-world applications is the difficulty of reproducing the results in a consistent manner across platforms and work environments. This problem is particularly accentuated when dealing with clients and domain experts. The simulation modeler is left with little choice but to use annotated
images or video to illustrate and share the results. Video is a non-interactive medium that limits exploration, feedback, and collaboration on new ideas with third parties, since a new video had to be created for every iteration of the discussion. To address these concerns, a new visualization platform built on web technologies (HTML, CSS, and JavaScript) was developed in parallel to, and based on what’ve was learned from, the crowd simulation project. To visualize the results, an internally developed Cell-DEVS visualization engine written entirely using web technologies (HTML, CSS, and JavaScript) was used. This provided us with a high degree of platform independence, which was important in such a collaborative and application-oriented simulation project, involving simulation developers and domain experts alike. The platform is designed with a data core optimized for DEVS and can be interfaced with using a flexible set of programming APIs.

For instance, it’s possible to visualize the simulation directly on a webpage using the hardware-accelerated Web Graphics Library (WebGL), encode the results into a compressed video file, or export the scene to an Alembic 3D file. Since the visualization is computed on the client side, multiple visualization clients can query a single simulation source, such as the distributed DEVS simulation service RISE [14].

The key motivation here is allowing users to share and modify the visualization parameters (e.g. color-coding, sprite-coding, statistical graphs, etc.) without requiring expert knowledge of the underlying simulation model or having to install specialized software on their devices. The engine operates on any HTML5-capable web browser or mobile platform.

![Figure 8. Rendered Model of Hallway](image)

Rendering the Cell-DEVS grid data directly on the page using WebGL was sufficient for the early development phases of the project, which demanded the rapid iteration and prototyping of pedestrian dynamics. Later efforts aimed at contextualizing the pedestrian simulation results within their target environment required us to export the kinematic information of the pedestrian entities into an Alembic 3D file.

![Figure 9. Rendered Visualization of Simulation Results](image)

This was then imported into a 3D content creation package, such as Autodesk Maya, to be used as destination guides for color-coded and pre-animated 3D sprites, which represented the different pedestrian classes in the scene. The pedestrians are integrated into a representative 3D model of the environment, and links are formed between the dynamic elements to their respective events (e.g. elevator availability triggers door control). Figure 9 was created from the model’s simulation results using the aforementioned visualization tools.

8 DISCUSSION

The results from the simulations provided several important insights regarding the effect an increase in foot traffic may have on the daily operations of the building at 99 Bank St.

The hypothesis was that the increased traffic would cause delays and serious congestion in the elevator hallway. The results showed an increased number of queues formed. However the length of the queues where significantly shorter and the maximum wait times remained unchanged.

Another fear was that long queues would create significant barriers that, with an increase in foot traffic, would cause chokepoints. As previously mentioned the results showed more frequent but shorter queues. In the simulation, the people were able to remain along the walls and leave the middle of the hallway free.

Finally, even though there was no detrimental effects to how quickly employees entered the elevators, there was a significant increase in the number of collisions, especially with a 35% increase. While observing the simulation results it became apparent that the hallway began to resemble a
busy sidewalk than an office hallway, something employees working there may not appreciate.

The benefits of M&S became apparent when running the tests for several reasons. Not only was it possible to test the presented hypothesis but also possible to observe things not previously thought of. For example, while the east side of the hallway, as seen in figure 9, is wide open the west side contains three glass doors. During the simulation, there were several occasions with bottlenecks. As the doors would not operate as efficiently as they did in the model, this would likely be a significant problem that would need addressing. Overall, it proved beneficial for the building planners and architects to be able to visualize the impact the LRT would have on their building.

9 CONCLUSION
The goal of this project was to determine what impact, if any, an increased number of pedestrians would have on the daily operation of the Sun Life Financial Building. Through the work presented here, it was possible to determine the theoretical impact of such a scenario as well as discover other unforeseen consequences. It was also shown how M&S could be integrated into the design process.

To improve the quality of the results generated by the model there are several areas that can be improved upon. One benefit to DEV5 is the ability to link many smaller models together to represent a larger more complex system. For example, a DEV5 model could be created to simulate an elevator, where the inputs would be number of people and the output would be how long it was free. Linking this model to the current model would improve the overall quality. Similarly, other DEV5 models could be created to increase the functionality of the model. Having models for sliding doors, revolving doors, escalators, horizontal escalators, would help improve the functionality of the Cell-DEV5 toolkit for use in building simulations.

Lastly, in order to accommodate more freeform and non-axis-aligned structures, one is motivated to consider a Lagrangian approach to computing the relevant physical quantities - i.e. position, orientation, and vision assessment being computed at the vector location of each entity as it moves continuously through space- instead of the current Eulerian fixed grid approach.

ACKNOWLEDGMENTS
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REFERENCES
A Multi-Agent System for Design: Geometric Complexity in support of Building Performance

Evangelos Pantazis¹, David Gerber¹², Alan Wang²

¹ University of Southern California, Viterbi School of Engineering
Los Angeles, USA
dgerber@usc.edu, epantazi@usc.edu
² University of Southern California, School of Architecture
Los Angeles, USA
dgerber@usc.edu, alanwang@usc.edu

ABSTRACT
This paper presents the continuing development of research into the applicability, customization and evaluation of a multi-agent systems approach for architectural design. The research describes the system architecture of a bespoke generative and multi-objective optimization design system and computational workflow. Through the use of the system a large solution space of façade designs are generated and ranked in an automated fashion for their improvement in their affect on lighting distribution, intensity, and efficiency. The paper presents the evolution from framework to implemented methodology, the initial in depth experimental design, experimental results, and provides discussion of the analysis of design process and design product improvements. The paper then presents a set of next steps for incorporation of further parameters of relevance to our interest in defending complex geometry for improving building performance. The research culminates with an argument in which we attempt to articulate the benefits of highly intricate geometry as not only a feasible but as well potentially more optimal approach within contemporary architectural discourse and production.

Author Keywords
Multi-Agent Systems; parametric design; generative design; multi-objective optimization; building performance; design complexity

ACM Classification Keywords
• Computing methodologies~Multi-agent systems • Computing methodologies~Simulation evaluation

1 INTRODUCTION
The work is premised on an interest in the potential multi-fold capability of emergent systems for generating intricacy and complex geometry. It is further premised on the simple hypothesis that automated systems in design will afford greater intricacy and geometric variation. Such automated systems, if modeled and simulated to optimize across a complexly coupled set of objectives will produce design outcomes that in fact out perform those designed by conventional or even purely parametric means.

The work is motivated in part by the theoretical argument that given a post-fordist epoch, geometric intricacy and complexity are no longer limitations of the industrial revolution. While this is true in theory, there are many limitations of the architecture, engineering, and construction (AEC) value chain that inhibit this coming to fruition in the immediate term. For example, there still remains a need to empirically prove that novel formalisms are not simply geometry-centered but in fact can be shown as superior in their effects upon building performance. Therefore, another motivation of the work is to engender designers with the necessary simulation tools and arguments to delve further into tectonic systems that not only enhance the possibilities for new formalisms but do so with an ability to also provide for environmental stewardship incorporative of the open-ended set of complexly coupled design objectives. Our research objectives are manifold including; 1) a desire to bring to architecture the state of the art in non-linear and emergent design systems; 2) to lead to architecturally intricate and geometrically complex designs, which perform better across multiple objectives; and 3), to prove the benefits of a Multi-Agent Systems (MAS) approach for aiding architects to ’design in’ complexity with greater certainty in terms of the performance criteria discussed subsequently. The general objective of the research is to improve design decision-making by incorporating agent based modeling (ABM) techniques, which operate beyond swarm intelligence algorithms. Another objective is to develop a design methodology that effectively addresses the ill defined and synthetic nature of the design problems by means of artificial intelligence techniques.

The work is partially instigated by analogous research that focuses on bottom up processes such as termite mounds, flocks, swarms, and other biological systems that dynamically create intricate and highly efficient built form. Existing research within the sciences is investigated in order to find and adapt more sophisticated agent based models [28] for design purposes while research within architecture and design computing [14, 24]is critically surveyed as being for the most part aesthetic and material in nature. The research builds a MAS for design that explores the emergent design process through automation and
generative design. The work specifically explores the search and optimization across multiple objectives through the customization and implementation of a MAS.

Our hypothesis states that if a designer declares a set of objectives, and gives an initial geometric rule set, the MAS will improve the base case of the multi-objective problem and will do so more rapidly and more extensively in design option terms, i.e. number of possible well performing solutions. In this regard we believe the work is beginning to expand the geometric palette for design decision making not just in the limited aesthetic realm, which is important to us, but in conjunction with the performative and optimization realms too. In the paper we present an evolved framework, a developed system, and experimental simulations that begin to couple analytical results with the generative parameters of design outcomes. At this point the focus is on addressing the successes and limitations of the system, the modeling approach, the simulation of the process and presentation of initial results. In section 2 the precedents for the work and our initial forays are summarized. In section 3 the development of the current system in brief and the design of the experiment are described. In sections 4 and 5 we present the results, which include a sub-set of generated geometries and corresponding analyses, and discuss these results along with our next steps.

2 BACKGROUND AND REVIEW

With increased access to computational design tools and the consequent rapid evolution of algorithmic design methods [17, 27], associative parametric modeling [5, 13], and multi-disciplinary design optimization [6], architectural designers have been provided with a new set of design exploration possibilities. As a result the discipline has seen an emergence of digital design tools with customizable components. In architectural and urban design discourse there exists a burgeoning interest in emergence, agent based modeling (ABM), and non-linear systems as means to improve the design process through formal generation but little empirical production of higher performing design outcomes through the resultant intrinsic geometric intricacy. The critical position of the work acknowledges the progress made by design practitioners and researchers in the development of ABM techniques for architecture but it also highlights a critical gap. Most of the precedent work has been successful in the generation of design intricacy but has not coupled it to design performance. Yet the predominant use of ABM or MAS outside of design has been for the purposes of optimization and negotiating across complex multi-objective problems [3, 15, 26]. Our current approaches in design have yet to fully embrace the capabilities for agent or multi-agent based methods to optimize for enabling of highly differentiated buildings and building systems. Additionally, research suggests that simulations have played a significant role in design practice for gaining insight and evaluating different performance criteria including for factors such as risk, cost, energy efficiency, structural efficiency, lighting, and social utility [1, 4, 29]. Although, there has been a significant interest in integrated workflows which utilize simulation to inform design [2, 22], there still remains a set of open problems to be solved including the incorporation of; user feedback in the early design phase, robotic construction constraints as design parameters, and the combining of multiple design performance analysis as design drivers. We highlight the need for a new design methodology that can address design complexity not by reducing it and segmenting it into disparate domains but rather by integrating knowledge, objectives, models, and techniques from different disciplines early in the design process. Therefore, the research builds upon work within, but also outside the domain of architecture and design computing and has been in large part influenced by unique collaborations with computer science, civil engineering, and social scientists. Our research precedents specifically include work on emergent systems [11, 14] and multi-disciplinary design optimization [12] as well as our own previous work, which evolved from associative parametric modeling and genetic algorithms for multi-objective design optimization [6] to that of MAS based simulation.

In the context of the literature the work uniquely brings together generative design, building performance and human building interaction via an automated digital workflow. This is achieved through multi-disciplinary collaboration and has lead to the development of the research methodology described in the next section and has provided for a number of key innovations in the work, including data capturing techniques of human subjects, data visualization of design alternatives, and the development of agent libraries that include generative, analytical, and behavioral advances. Presented here is the application and evaluation of the design methodology based on initial results. The suggested approach shifts from purely linear and deterministic design methods to that of incorporating the non-linear and bottom up approaches for exploring design generation in relation to design performance and optimization [10]. It is important to note that in our research we utilize MAS and the concept of emergence for enabling “design exploration” as the primary conceptual motivation, acknowledging the importance of the synthetic and human nature of design while reinforcing design through computational benefits of MAS driven optimizations [8, 19]. In surveying the literature, a conclusion is drawn that suggests a MAS approach for design purposes offers a potential productive paradigm shift for exploring self-organization of building components by establishing hierarchies locally within the constituent systems. Such an approach can offer efficiencies in the design exploration, the automation and generation of design alternatives, the human design decision-making, and elevation of performance into the design and or sub-system.
RESEARCH METHODOLOGY

The general hypothesis of our research states that a design outcome of a non-deterministic emergent process, will generate higher performing results given; a) a proper abstraction of the problem is achieved (figure 2); b) a successful coupling of the design parameters to the functional requirements is established in the MAS, and c) given enough simulation time and computational power is provided. The specific hypothesis of the research experiment described in detail states that for the façade of a standardized commercial office building, a bottom up design approach which incorporates lighting performance analysis coupled with user preferences for daylight and artificial lighting levels, will provide a larger set of design alternatives that perform better than the conventional ones; where better implies less electrical load coupled with higher occupant satisfaction. Our proposed system consists of a series of negotiating subsystems, each focusing on singular design objectives, which are then combined, see figure 3.

The validation of the experiment is measured against a normative benchmark condition, that of a bris-soleil system and then is cross-compared against a starting design scheme and final set of design alternatives. Parameters that are agent driven in the research include, a) design parameters of the façade panels, b) lighting (lux) performance criteria as they relate to established standards and user preferences, as well as, c) number of equivalent or higher performing design solutions. Finally, as one of the core research motivations, to enable design freedom and intricacy and hence complex geometry, we also attempt to quantify the complexity of the geometry as an important metric.

Our research methodology has been to formulate a MAS workflow and to develop a set of bespoke tools and algorithms that enable the system to operate on a series of design scenarios with an increasing number of objectives. The work takes an empirical approach towards a majority of the motivations and objective of the research. However, since design outcomes are subjective and driven by a designer’s interest in particular geometric pattern, we also discuss the work in terms of qualitative outcomes in the discussion section. The research is first an extension of the projects that began to move beyond the deterministic work of our MDO and Beagle system [6]. In the initial experiments over the last two years, the team used the existing MDO system as an agent, to explore the solution space for highest ranking solutions through breeding of optimality across three competing but highly coupled objectives [16]. In the second iteration of the work a new system was prototyped to design explore a form found structural shell. The shell is coupled through the MAS with a derived perforation pattern as a means to minimize material and assembly cost while enhancing lighting distribution under the canopy [18]. A third iteration of the work focused on the formulation of a MAS framework, which integrates feedback from real world human behavior and user preferences with environmental analysis as well as the initial development of the agent classes [7]. The current phase and extension of the research presented here includes the revised framework and experiments described in figure 1. It is important to note that the tool in itself is not the goal of the research however the tool is built in order to pursue answers to the affordances of automation, generative design, and MAS based performance optimization and ultimately design decision-making.
In this regard, the methodology first establishes a set of questions; 1) does such a system enable a designer to increase his or her palette of design alternatives; 2) does our MAS improve upon the rate and count of feasible designs that address a complexly coupled set of design and performance objectives; and 3) does the MAS improve the empirical objectives more rapidly when benchmarked to a normal use case. In order to facilitate these outcomes as measurable, the number of simulations is measured as a function of time, the ranking of the design alternatives are plotted as a function of a pareto frontier, and then compared to illustrate the improvement of performance criteria. The research method steps include the development of an experimental case study that initially deals with a simplified design problem that of the design of non-structural fenestration system. In future steps this is extended with more design requirements including structural criteria and alternative spatial contexts. The second step has been to develop a set of programming modules, or functional components, and to link them to existing associative parametric, visual programming, and analytical engines, shown in figure 3. A third step in the development of the research has been the incorporation of human subjects preferences, which have been measured within an immersive virtual environment (IVE). A fourth step has been to develop a geometric design scheme, with a specific number of design parameters, which is of adequate complexity and relevance to the discussion of design novelty in conjunction with building performance. A fifth step has been to model the problem as a mathematically bounded solution space and to run the simulation of 4950 phenotypical offspring in the system. In order to observe the relationship between the environmental analysis results and the generative parameters the final stage of the method includes the plotting and graphing of the results and the search for the governing correlation function for the generated fenestration geometries.

3.1 The Design of the Experiment

This experiment focuses on the highly normative curtain wall condition of the pervasive commercial office building. The designers’ problem is to design explore and find a set of optimal configurations, defined as the best performing fenestration patterns that improve upon the Useful Daylight Illuminance (UDI), Continuous Daylight Autonomy (CDA), and Day Light Factor Autonomy (DLA); all lighting factors measuring the user preferences (UPA) from the IVE experiments. [9] The design problem assumes a regular office plan and a regular distribution of furniture. It furthermore assumes a fixed number of openings for view where the generative pattern is not allowed to grow and hence block light; tested with two and three openings similar to our benchmark case. The context, basic requirements and rules of the fenestration systems for the design problem are illustrated in figure 2.
agent may have the ability to adapt and change its’ behavior based on its own evolution and interaction history, therefore individual adaptation requires agents to have memory in order to keep track of their actions, usually in the form of a dynamic agent attribute; and, 4) agents have resource attributes that indicate their current stock of one or more resources (energy, material, information).

The prototype of our system is built on top of a number of technologies which include open source software platforms and tools as well as commercial software that offer open application programming interfaces (API). The core classes of the system are developed in Java using the Eclipse Platform that serves as the common integrated development environment (IDE) providing open APIs to facilitate our integration with other interfaces [21]. Our MAS utilizes libraries and classes from Processing, a java based programming language with its’ own IDE that has been developed with the aim to assist designers [20]. For the geometric manipulation of the building components, the IGE library is implemented, developed to offer automatic data management of NURBS geometry and agents [25]. A java applet and a graphical user interface (GUI) have been developed to generate geometrical configurations for importing into the Rhinoceros 3D design environment for further analysis. The designs are environmentally analyzed and evaluated through Grasshopper, a visual scripting editor within Rhinoceros and Python based, environmental simulation plugins, Honeybee and Ladybug, as well as OpenStudio, EnergyPlus, Radiance, and Daysim. The obtained data is saved as text files which, are used to model and form the parameter bounds of an environmental set of agents. A ‘federated’ system architecture is used to relate multiple software environments with Python in order to handle the calls of the different platforms with eXtensible Markup Language (XML) used to manage the data passing among the agents. XML provides flexible and adaptable information identification since it is a meta-language (i.e. a language for describing other languages), which allows for designing a customized markup language for almost any type of document [23]. Lastly, another component for enabling the data collection of human subjects is developed on the Unity game engine where we simulate the office space in a virtual environment using a Head-Mounted Display (HMD). The equipment includes an Oculus DK2 HMD, an Xbox-360 controller, and a positional tracker that tracks the participant’s head and neck movements while navigating the space. Figure 1 (box no. 5) illustrates all of the components of our MAS for design system and the corresponding relationships within our environment.

4 RESULTS AND ANALYSIS

The experimental design has 5 possible variables resulting in a design alternative factorial of 8. For this phase of the research we focused on isolating the position of the opening and to observe their relationship to the angulation of the façade panels. This is done in order to deduce a mathematical relationship between the analysis results and

Figure 3: MAS for design workflow diagram, which illustrates the steps, reasoning, feedback loops, components and relationship of the developed system.

3.2 MAS Model and Simulation System

The systems as shown in figure 3 describes the set of model inputs, the initialization step, subsequent steps and feedback loops, and the final outputs of the system for empirical and subjective analysis and design decision-making, i.e. choice.

The proposed MAS is comprised of agents that correspond to the defined design sub-domains. The four main populations are: 1) a generative design agent that contains the design intention and geometric properties; 2) a knowledge-based agent that contains a particular expertise’s (i.e. the CDA, UDI, DLA and UPA agent populations) all expressed as a set of rules; 3) a coordination agent that ensures each agent is aware of other agent’s state; and 4) an evaluation agent that produces design adaptations while trying to ensure overall agreement with the other populations. The notion of an “agent” central to computer science literature has no single universally accepted definition, hence we provide a general description of the term “agent” based on [28]. For our definition an “agent” I is denoted as a software-based computer system that shares the following properties: 1) agents live in an environment and respond to it while interacting with other agents; an agent is situated in the sense that its behavior is based on the current state of its interactions with both the rest of the agents as well as with the environment; 2) an agent may have explicit goals that drive its’ behavior and is directly related to specific performance criteria; the goals are not necessarily targeted to maximize but have goals; 3) an
specific design parameters as well as for being able to initiate sensitivity analysis. It remains an open question how to prioritize or factor which of the variables within the geometric system will have the greatest impact on the result performatively. The research has a search space of approximately 32,768 solutions given the 8 factorial of all possible parameter combinations. For this stage of the research we limited our investigation to focus on window opening position in relation to panel leaf angulation and therefore the initial search space was limited to the 950 possible window opening combinations. In order to develop a heuristic the research isolates one variable of design interest (i.e. generative angle) shown in figure 2 and then by implementing a hill climbing algorithm, we change the opening position at each run and analyze its’ potential for creating a diversity of solutions that perform above set thresholds, in this case for values >250 lux. As described above the work at this stage is measured for its generative capabilities (i.e. number of design solutions), the geometric diversity of these solutions measured as a delta of configuration difference, and in terms of improvement of the measurable lighting objectives UDI, CDA, DLA constrained by UPA. The graphing and plotting of these results is developed through the use of Python libraries and our Java IDE and was performed in an automated fashion post the simulation runs.

In figure 4, the plotted results of 950 generated geometries and their corresponding CDA, indicate that certain angulations (PI/2 & PI/12) resulted in larger number of higher performing design alternatives. However so far the results do not allow us to deduce a specific mathematic relationship between the angulation and the obtained analysis. In figure 5 we combine the two types of environmental analysis (UDI and CDA) and we highlight the highest ranking geometries in terms of both analyses by plotting the pareto frontier. The system was run on multiple machines and hence a variety of system configurations and therefore the speed of the generation is not measured, but each design and analysis iteration was generated within a 3 to 5 minute cycle. The data source set was accumulated over the period of a three-weeks on four different systems. The different runs were then amalgamated in order to analyze the search space in full.

5 DISCUSSION AND FUTURE WORK
What the work has produced at this stage is a proof of concept that a MAS for design can satisfy both the objective of generating geometric intricacy and complexity while simultaneously producing higher performing solutions. While this level of our objective is being met there remains a series of further objectives and proofs that are being worked on. The future work includes the following set of experiments in progress and the following set of extensions and integrations. In order to satisfy our design context goals the MAS for design is being used not only on a generic office tower context but also on a contemporary freeform office tower in order to be able to benchmark our approach against an existing building. Moreover, it will be use on a set of form found shells for reasons of wanting to increase the performance criteria complexity and relevance by incorporating of another set of structural constraints and objectives. Another extension of the work is to further add the complexity of tectonic and fabrication constraints in the simulation and optimization system. These extensions are envisaged by adding to the set of specialist agents similar to the UDI, CDA, DLA, and UPA agents. Lastly as a final step, we aim to validate our methodology by physically constructing one of the best ranking geometries in order to be able to cross-compare values obtained in simulation space with values obtained in physical space. In order to validate our approach in terms of user preferences another set of experiments with human subjects will be held, where the geometries that best match the user lighting preferences will be passed into the IVE in order to be re-evaluated by the users. What we hope to achieve is further evidence that the modeling and simulation and use of parallel computing will further enable the construction of highly complex geometry again with empirically driven performance criteria. The work situates itself at the intersection of the general discussion of the non-linear systems research and that of the multi-agent based design model, agent based optimization in computer science, and finally projects itself into automated robotic fabrication as a last step.

6 CONCLUSION
It is important to reflect upon the diverse motivations of the work: 1) that of taking an interest in the development of MAS for design that goes beyond the superficial argumentation of geometry for geometry sake; 2) that of taking interest in proving that highly intricate geometry can be developed to outperform the norm or common fordist paradigm; and 3), that multi-objective optimization and therefore more expansive performance can be achieved through the development of a MAS. Underlying the motivations is to provide theory and tools that empowers the human design endeavor in his or her design decision making. The work has clearly shown an increase in the rate of generation and optimality of a large solution space. Yet the work is still based on a highly specific tree like fenestration and would need to be proven and tested to
accommodate “any” possible geometric rule set. A further limitation is that while our core argument is for justifying post-fordist geometry our current use case is a veneer of the fordist icon, that of the vertical commercial office tower. This is addressed in our next iteration of the work and was prefaced in previous iteration of the work on form found shells and reciprocal frames. Another critical limitation of the work is that we are still in development of the negotiation and mathematics that control the core set of agent negotiations. The implementation and viability of the system to use a Markov Decision Process (MDP) is underway. The designer/ user interface is also underway where the designer is able to interface through a custom Java applet graphical user interface (GUI). In summation, the work has made significant progress in being able to not only generate geometries that perform beyond that of the simple geometric objective and the overly simple swarm. It is furthermore important to note that this work has begun to harness the capabilities of parallel computing and automation for the enabling of design decision-making.

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Figure 5: A sub set of the generated solution space and the initial pareto frontier plot of the performance characteristics.
REFERENCES


Session 5: Data Driven Design

Form-Based Code (FBC) Modelling for Urban Design of High-Dense Cities
Yingyi Zhang, Marc Aurel Schnabel
Victoria University of Wellington.

A Method for Data-Driven Insights on the Nexus of Green Infrastructure, Water System, and the Urban Environment
Yannis Orfanos, Sang Cho, Spiro Pollalis
Harvard Graduate School of Design.

An Approach Towards Developing Methods to Analyze and Visualize Energy Flow of HVAC System
Aly Abdelalim, Zixiao Shi, William O’Brien
Carleton University.
Form-based Code (FBC) Modelling for Urban Design of High-dense Cities

Yingyi Zhang and Marc Aurel Schnabel
Victoria University of Wellington
Wellington, New Zealand
{yingyi.zhang, marcaurel.schnabel}@vuw.ac.nz

ABSTRACT
This research explores Form-Based Code (FBC) modelling and its impact on urban design of high-dense cities. Our paper consists of three parts. First, we discuss the context and components of FBC methodology. Although originating from zoning, FBC is totally a new approach in urban planning and design, which mainly lays emphasis on “form” instead of “land-use”. Second, we present the process of creating FBC models. There are five elements in FBC implementation, Regulating Plan, Public Standards, Building Standards, Administration and Definitions. Modelling FBC has three phases, documenting, visioning and assembling. Last, we end with a pilot study in Hong Kong. There is no real practice of FBC in high-dense cities, however, we argue the potential and challenges of FBC application in high-dense cities through the hypothesis of FBC model making in the case of Hong Kong.

Author Keywords
Form-based Code; modelling; urban design; high-dense; Hong Kong.

ACM Classification Keywords
I.6.5 MODEL DEVELOPMENT (modelling methodologies).

1 INTRODUCTION: FBC, “A NEW APPROACH”
Rigid segregation zoning was a predominant way of creating urban planning in America in past century. It regulated the structural framework and space typologies in both urban and rural areas. Zoning generally became a practical tool assisting governments and planners to avoid ‘inappropriate’ building-scale and urban construction. Following after the zoning theory, form-based codes developed into an innovative design reform basing on Smart Growth, New Urbanism and Transect. Form-based Code, FBC for short, is a land development regulation that fosters predictable built results and a high-quality public realm by using physical form (rather than separation of uses) as the organizing principle for the code [3].

Compared with zoning, FBC advocates to take land use, pedestrian space, streetscape and neighbourhoods into code-making parameter system. In conventional zoning, land use is primary consideration; while in FBC, physical form and character are primary considerations [4]. In 2008, Parolek et al raised the relationship and differences between zoning and FBC (Table 1). The main purpose of FBC creating is to suggest unique ways to preserve or shape urban form, especially in public realm, for each specific planning site. Form-based code works as a regulation adopted into city, town, or county law, which offers a powerful alternative to conventional zoning regulation [3]. To some extent, FBC can be regarded as a valid approach to resist the urban assimilation under the unrestrained globalization.

<table>
<thead>
<tr>
<th>Conventional zoning</th>
<th>Form-based Codes (FBCs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use is primary consideration.</td>
<td>Physical form and character are primary, with secondary consideration to use.</td>
</tr>
<tr>
<td>Segregated land-use planning principles.</td>
<td>Mixed use, walkable, compact development oriented principles.</td>
</tr>
<tr>
<td>Districts</td>
<td>Neighbourhoods/streets.</td>
</tr>
<tr>
<td>Organized around land use zone.</td>
<td>Used spatial organizing principles to reinforce urban hierarchy.</td>
</tr>
<tr>
<td>Reactive to individual development proposals.</td>
<td>Proactive community visioning.</td>
</tr>
<tr>
<td>Proscriptive, regulating by numeric parameters E.g. Plot ratio, setbacks, parking ratios.</td>
<td>Prescriptive, describe the requirement.</td>
</tr>
<tr>
<td>Regulate to create buildings Focus on sites, right-of-way.</td>
<td>Regulate to create places Attention on street and streetscape.</td>
</tr>
<tr>
<td>Uniformity in neighbourhoods.</td>
<td>Diversity in neighbourhoods.</td>
</tr>
</tbody>
</table>

Table 1. Comparison of conventional zoning and FBCs [8].

The core of FBC modelling is the so called “Smart Code”, which addresses all scales of planning, from the region to the community to the block and building [9]. In form-based coding procedure, transect code always represents form.
code. Because transects show actual development requirements such as building location, set back lines, or allowable building heights [6]. Basing on transect investigation and environment analysis, Smart Code was developed in the 20th century. A transect of natural landform is intended to express a sequence of environment (Figure 1), analogously, humans also need a system that (re-)create portions in their habitat conditions (Figure 2). In this way, the basic of Smart Code is developed. The rural-to-urban transect is composed of six zones (T1-T6), and these zones are various in different physical and social characters. After FBC makers’ analysis of site contexts, Smart Code modelling is manipulated, aiming to control urban spaces, patterns and frameworks, as well as simulate future urban forms and developments.

2 ELEMENTS AND PROCESSES OF FBC

The original intention of FBC is to be used in the redevelopment of design scenarios. Some scholars also equal “form-based” to “design-based” [12]. Through a series of applications and implementations by architectural praxis, urban designers and planners in the USA, FBC began to be seen as a place-making plan methodology, such as renewal in neighbourhoods, regulating urban constructions, creating road networks and shaping high quality public realm. The Seaside Urban Code in Florida (1986) [10] is one of the most typical projects using “code” concept in urban planning in the early stage of urban coding practice. It’s a courtesy of Duany Plater-Zyberk & Company (DPZ). The seaside code included setbacks, lots lines, yards, porches and balconies, and parking. From then on, form-basing takes up the vital coding principle in the whole planning and design process. FBC has been used in the down town mixed use master plan in Benicia, 23rd Street corridor design in Richmond, Hercules waterfront TOD master plan and Loma Rica ranch specific plan and other hundreds of projects. In general, making FBC needs five main elements and three phases.

2.1 Five Main Elements in FBC

Layouts in FBC are expressed by words, diagrams, models and other visuals in multi-scale and transect-based regulation. FBC is established mainly by five elements. They are Regulating Plan, Public Standards, Building standards, Administration and Definitions. Besides, there are some additional optional elements, such as Block Standards, Landscaping Standards, Signage Standards, Environment Resource Standards and Annotation.

Regulating Plan

Following the transect classification, regulating plan delimits the geographic areas and designates the locations where various building form standards should be applied. Regulating plan is vital in the whole FBC making process.

The regulating Plan has three goals. First is Administration. Interfaces of the regulating plan assign different developing standards, meanwhile provide an appropriate commencement for people to recognize and use FBC tests and imageries. Second is Direct Regulation. Regulating plan has the responsibility to present practical developing demands, like special architecture design or atypical façade. Third is Planning. Making regulations for development or redevelopment contribute towards the master plan vision. It is an inevitable portion of urban design research. These regulations describe the characteristics and forms of regions, which is important to ensure the urban growth matches the goals outlined in communities. Regulating plan becomes the cornerstone of public realm construction in FBC.

Public Standards

The quality of urban space is largely influenced by public streets, parks, squares, sidewalks and other public spaces. Public standards are the core elements of FBCs. There are two portions in public standards, thoroughfare and civic spaces. Thoroughfare controls the standards of circulation space interface. Road facilities, including road green belts and transport functional squares, contribute 20%-40% in gross urban constructed land. So thoroughfare design is a key element in FBC. Most of FBC making procedures tend to create road standard system to approve qualified urban road network.

Besides, the intersections between physical place-making and social activities are also important to public standards. Civic spaces act as a role of this kind of “intersection”. Civic spaces contain parks, squares, markets and playgrounds. They enhance to the characteristics of civic realm visually and emotionally. Public standards contribute
to the framework for civic communication and social activities, which is meaningful for community health both economically, culturally and environmentally.

Building Standards
Building standards mainly describe the physical form of buildings and building environments, like features, configurations and functions of buildings which define and regulate public spaces. Typical building standards specifically contain building’s position and form, function, car parking, land-use and frontage type, as well as building typologies and styles. Through FBC regulating, most buildings of communities have corresponding guides for design and construction. Building standards are benefit to reconcile the complicated relationships between public and private spaces.

In FBC methodology, the forms of buildings are the most important basis for classification rather than building function. Form takes priority over all other urban design contents. In conventional zoning era, the pursuit of density and plot ratio makes developers to fill buildings simply into regions to meet the required value of number. Blindness filling urban space gives into economic demands at the cost of form context and urban fabric. On the contrary, building standards regulate a series of building types to create lively, humanly, form-based urban space.

Administration
Public and private institutions are necessary to collaborate and implement a community FBC plan together, especially in administrative procedures of examining and authorizing. As a new design and plan method, FBC formulate form standard, not just advising, to fulfill the development requirements in different communities. It needs a clearly defined application and examination mechanism. David Walters considered the inability of design standards to take hold bears witness to the fact that guidance was not enough. As in America, the detailed rules, or codes, that govern urban development is supposed to be changed. Unfortunately, good design needs to be mandated, not simply encouraged [12]. After making the regulating plan, FBC has to contain some compulsory measures, under the legal force and local policies, to guarantee the cogent implementation in community development.

Definitions
Definitions work as appendices of a FBC version. They help to ensure the technical terms are used precisely in practice.

Besides the main five elements, there are some other relevant aspects also important. They are not so dispensable in FBC model making, however, they are part of enhancing the success of implementation. For example, architectural standards regulate the façade of buildings, windows and doors, details and materials; landscaping standards describe the plant materials on private property as they impact public spaces; signage standards set the signage sizes and placement.

2.2 FBC Making Process
The process of creating FBC is a key point in controlling practice and implementation. It is fundamentally differ from traditional zoning methodology. FBC processes contribute to the public participant no matter in urban design scenarios or community policies development. The processes can be divided into three phases, documenting, visioning and assembling (Figure 3).

Figure 3. FBC creating processes [8].

Documenting
Before creating FBCs, designers need to identify the unique characteristics of a community from existing form. This phase is documenting. Data collected during documenting phase is analysed to support the creation of FBC. In a sub-areas scale, designers may begin with the neighbourhoods, districts and corridors. Neighbourhoods are always unified in character and have clearly centre, edge and style tendency. These help designers know more about the composition of the target community. Districts are considered as specified functional areas where human’s public activates happened, such as industrial districts, commercial districts and residential districts. Corridors contain roads, railways, highways, even rivers. They are always acting as boundaries in one neighbourhood unit or between different neighbourhoods.

By gathering the physical environment data, designers can create an existing conditions map to summary physical form and patterns. In a smaller scale, designers need to collect more details in the existing conditions map. Basic elements are varieties depended on different communities, like buildings (types, functions, placements and forms), public spaces (parks, gardens and plazas), architecture and landscaping. Once the documenting is completed, designers value these collected forms and determine which are most representative of typical conditions. The basic forms are the measurements for practical FBC system.
Vision
In the second phase, the vision of target community should be defined in details by FBC. The main coding purpose is to predict outcomes of the built environment, “vision” is required for setting a clear goal for the desired outcomes. There are two ways to understand a community’s vision. One is through gathering background plans or comprehensive maps. Communities may already made their vision clear in them. The other is through public participation – talking to residents and community council to come up with a specific vision for their future. After knowing the community vision, designers proceed to create the FBC system with the reliable foundation.

Vision phase contains three steps. First is illustrative plan and imagery. Illustrative plan shows the imagery distributions in future, including neighbourhood, districts and corridors. The models of public space, buildings and road lines also can be included in it, which depend on the required scope and research depth. Designers are supposed to put some unique or characteristic elements into vision sheet by valuing these data. Second is coding. Once the vision sheet is placed in, transect, micro-scale matrixes and administration review process constitute the regulation plans. Last but not least, administrative review help to define the follow-up procedures and make community know more about future environment. In this phase, designers adjust or refine the program and coding grammar continuously to fulfil the urban development goals.

Assembling
Different from 2D outcomes of conventional zoning, FBC is more conciseness and understandable. In the last phase, designers translate FBC layouts into visual 3D models to offer interfaces for public participations, which is user-friendly and interactive to space users of a community. Nowadays, developing Parametric models to support FBC expression gains increasing attentions. Digital tools, like BIM, GIS and CityEngine, provide smart platform for both designers and space users. Because of the flexibility of the FBC digital models, designers can renew or alter programs, layouts and typologies based on the public comments. The final formatting layouts usually contains content, acknowledge, regulating plan, building standards, street standards, public space model, administration, definitions and other appendixes.

3 A STUDY OF HONG KONG
FBC theory is still developing. There is nearly no attempts in high-dense urban areas. Yet, high-dense cities are in much greater need of efficient, interactive and smart approaches to analyse, predict and guide urban development. Subsequently, the FBC methodology has great potentials of making a contribution in high-dense built environments.

For our research, we choose Hong Kong as a study case. Hong Kong has been built in a very short time [12], “high-dense” is one of the most typical form characteristics of the fast developing processes. Some researchers propose it is a social problem that high-dense cities lead to high crime rate, traffic problems and the lower quality of living environment. For most high-dense cities, the limitation of topographic condition makes high-dense form become an inevitable choice. The gross area of Hong Kong is more than one thousand km², the average population density is about six thousand or more per kilometres. Because of the natural environment condition, Hong Kong only has about 15% gross area can be constructed [2]. As mentioned above, FBC modelling provides the possibility to rethink the urban form and planning in a rational way that allows for more flexibility and adjustment “on the go” that is more suitable for dynamic and rapidly developing cities. Can we employ FBC as a pilot tool to controlling and (re)coding high-dense cities’ development?

Applying the FBC methodology into the intrinsic urban planning mechanism of Hong Kong is not just a simple replacement. Government and planners have to engage in a variety of demonstrations, discussions, and even improper attempts. We argue the opportunities of making FBC in Hong Kong and present specific ways to guide implementation. Before making FBCs, a rural-to-urban transect has to be prepared, which describes basic information of neighbourhood features and architecture diversity. Hong Kong does not have a common pattern that can be summarized in a single district. Figure 4 shows a rough territorial-wide transect from rural to central area.

Figure 4. Territorial-wide Transect of Hong Kong [4].

The development situation in the core of Hong Kong Island differs from the suburbs, irregular small scale figure ground of Sai Ying Pun region and regular big scale figure ground of Sham Shui Po are totally different (Figure 5). It is a challenge to generalize the six transect zones as Parolek et al mentioned in Form-based Code: A Guide for Planners, Urban Designers, Municipalities, and Developers.
Minimizing the research scope to specific streets, designers are able to create more accurate transect figures than in region scale. The FBCs work well for community development if the six transect zones is coincident with existing physical forms accurately. There are some attempts of making FBC standards basing on existing streets and buildings in Wanchai and Shatin showed in Figure 6. They are the only attempt of FBC in Hong Kong, which designed by Kan at the Hong Kong University in 2012 [4].

In Alvin’s research, complicated streetscape was simplified into a few types. There is no practical assessments for the design hypothesis. Coding in high-dense cites like Hong Kong needs more consideration about people’s impressions and experiences of a specific street space and the behaviours to environment. As a super city with especial historical background and developing time, Hong Kong is unable to avoid urban expansion with its growing population, followed by the construction of new towns and renewal of old centres of city. Urban coding based form is appropriate to be used into new town’s urban plan procedure, which not mentioned by Alvin, for FBC modelling is a rational way to regulate communities’ growth and control development of this metropolis. Through the classification of urban form, the street space has the opportunity to be simplified as regular cubes. That’s benefit to control developing tendency and predict maximum capacity of the population. Although in the last decade, population growth in Hong Kong began to slow down, the requirements of urban facilities, high quality public space, and the use of mountain areas, parks and wetlands have never receded in neighbourhood’s wish list.

Compared with the loose form towns and cities, sustainable, connective and pedestrian friendly urban forms are more important standards for concentrated cities. Sustainability is defined as meets the needs of the present without compromising the ability of future generations to meet their own needs [12]. FBC helps to set standards of urban forms which meet the sustainable community visions, and in this way, avoids aimless construction and unsustainable development. In the next research step, coding in a specific street region in new town of Hong Kong by using form and making a criteria system for the implementation of FBC in Hong Kong are necessary. Besides, connectivity and pedestrian friendly are both elements in transportation. Road system is skeleton and transportation is blood of a crowded city. High-dense city will not operate organically without well-organized road system. In Hong Kong, FBC is also expected to improve road standards, not only for motor vehicles and public transportations, but especially for bike riders and pedestrians.

**Figure 5.** High-dense neighbourhoods in Hong Kong. Row by row from top, left: Tsuen King, Tai Koo, Sham Shui Po and Chi Kiang Street; Right: North Point, Sai Ying Pun, Tai Po and Fuk Loi [5].

**Figure 6.** Graphical Presentations of Streets of Wanchai and Shatin, Hong Kong [4].
4 CONCLUSION
FBC is an alternative approach and new angle to create design standards, evaluate community development and regulate urban extension through existing forms. Different from conventional zoning mechanism, which is simply place emphasis on land-use, FBC aims to collect data about physical form and characters with secondary consideration to use. Also, FBC modelling provides intuitive platform to designers and publics by using text, imagery and 3D scenarios instead of 2D zoning layouts.

FBC’s consistent basing form towards to (re-)create diversity urban spaces. Under the force of globalization, urban contexts and form characteristics, especially in Asian cities, are becoming crucial applications of FBC in order to generate sustainable and liveable city areas. FBC modelling has the potentials to (re-)create well-founded, executable urban space. To some extent, that’s an effective way to keep features of historical segments of a city.

As a new methodology, the implementation of FBC is still at the early stage of development. There is no mature practice in high-dense cities until now. Different designers and investigators have different understandings of transects and building forms. How to compromise the divergences and optimize FBC standards need a more comprehensive FBC modelling mechanism. That will be challenging in future study.

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A Method for Data-Driven Insights on the Nexus of Green Infrastructure, Water System, and the Urban Environment

Yannis Orfanos¹, Sang Cho², Spiro Pollalis³
¹,²,³ Harvard Graduate School of Design, Cambridge, MA, USA
{orfanos, scho2, pollalis}@gsd.harvard.edu

ABSTRACT
The paper concerns the development of a computational framework focusing on quantitative relationships between green infrastructure, the urban water system, and the urban environment. Specifically, we present a methodology that designates the quantitative impact of green infrastructure interventions on the water system’s performance and the city’s impervious surface coverage. The computational method is derived from identifying green infrastructure opportunity areas in the city through geospatial and urban parametric analysis which considers site constraints and best management guidelines.

The architecture of the water infrastructure system is decoded so that water supply, stormwater, and wastewater flows are linked computationally. The outputs estimate the water system’s performance in relation to different green infrastructure planning alternatives. The output metrics focus on average annual estimations, while the objective is to achieve the level of abstraction that provides informative meaningful results and educates on the basis of macro decision making. Data-driven insights are then enabled through the lens of infrastructure-based sustainable city planning.

Author Keywords
Green infrastructure; geospatial analysis; data analysis; water system; visualization.

1 INTRODUCTION
U.S. coastal cities are particularly vulnerable to future anticipated effects of climate change (e.g. heavy rainfall, storm surge, and sea level rise) over a long period of time. In recent years municipalities have been adopting green infrastructure as a cost-effective approach to reducing stormwater runoff and flooding. Green infrastructure such as green roofs, street planters, permeable pavement, and rain barrels can perform as natural filters by retaining and absorbing stormwater runoff. The reduction and delaying of stormwater runoff can provide environmental, public health, and economic benefits by preventing groundwater contamination and reducing the cost of water treatment, in addition to other well-documented benefits.

Specifically, we developed a method to examine how a data-driven approach can enhance our program’s infrastructure-based approach to sustainable urban planning [1]. Our method uses a computational process that quantifies the impact of green infrastructure planning alternatives. Our investigation didn’t aim for a modeling tool that performs hydrological simulations that certified professionals use. Rather, our objective was to generate estimates to provide non-experts an understanding of the relationships between green infrastructure, the water system, and the urban environment. Specifically, we focus on the early stages of the urban design and planning process where an overview of the systemic impact of green infrastructure is needed. Quick meaningful results can influence the decision making of urban designers and planners, but also of critical stakeholders such as mayors, city managers, and the community.

In this paper, we first present the precedents of similar data-driven approaches to urban water management and green infrastructure. Then we present our methodology using the city of Chelsea (Massachusetts) as a case study. First we describe the steps that integrate green infrastructure opportunities by framing the related geospatial information and provide evidence-based constraints, assumptions, and priorities for green infrastructure interventions. We then refer to the process that decodes the urban water system’s performance through data analysis. By integrating all the above, our computational method quantifies the impact of green infrastructure opportunities on the city’s impervious surface area, stormwater management, and the overall water system’s annual performance. Next, the results from the application in Chelsea are discussed. In conclusion, we mention the potential of our approach.

2 RELATED WORK
One of the existing tools that uses an integrated approach is EPA’s National Stormwater Calculator, which estimates the annual amount of runoff from a specific site area in the United States accounting for local soil conditions, land cover, and historic rainfall records [2]. Users can add green infrastructure practices to the Calculator to influence the results, but this is limited to replacing a percentage of the site’s impervious cover with green infrastructure without considering planning information. Other tools such as the NYC Green Infrastructure Co-Benefits Calculator, the National Green Values Calculator [3,4], or more specific tools such as the Rainwater Harvesting Runoff Reduction Calculator [5] are similar independent calculators, not
linked to a spatial model, and therefore they don’t give real-time information during the planning process. In contrast, Envision Tomorrow, an ArcGIS extension tool, through the Green Infrastructure App allows users to conduct planning scenario analysis [6]. On the same logic, the recently launched Green Stormwater Infrastructure, an extension of Autodesk’s Infraworks [7], provides simulations of green infrastructure based on parametric input from the spatial model.

At the same time, despite the growth in the availability of effective tools, we observed that there is a great margin for improvement in how municipalities in the U.S. engage with data-driven insights on performance. The work of New York’s Department of Environmental Protection on post-construction monitoring of green infrastructure at the neighborhood level is one of the examples that show an interest in incorporating performance-based decision making [8]. Our review of related work revealed that there are tools that connect green infrastructure and urban environment through computation, but these tools do not incorporate a systemic approach that integrates the impact on the overall performance of a city’s water infrastructure system.

3 METHODOLOGY
Our methodology concerns the development of a computational framework for the quantitative relationships between green infrastructure, the urban water system, and the urban environment. The included metrics (inputs and outputs) are selected so that they describe better the operation of the system on a macro level. The inputs include historical performance data of the water system, spatial information from the urban environment, and data from identified green infrastructure opportunities. The outputs regard the estimation of water system performance data in relation to different green infrastructure alternatives. The objective is for the outputs to achieve a level of abstraction that provides informative meaningful quantitative results on the basis of water system annual performance for high-level city planning decision making.

3.1 Integrated Computational Method
The authors set up the script in Grasshopper, the graphical algorithm editor for the 3D modeling tool Rhinoceros, used ArcGIS for the geospatial analysis, and used the statistical software Stata for exploratory data analysis. The script consists of two linked parts, the deployment of green infrastructure opportunities and the urban water system’s flow performance. As a result, different green infrastructure scenarios (within the given green infrastructure opportunities ranges) give different outputs regarding the water system’s performance and the urban environment’s permeability. Output metrics such as urban runoff, stormwater inflow, wastewater flow, drainage, distributed water, and fraction of impervious surfaces enable data-driven insights through the lens of infrastructure-based sustainable city planning.

3.2 Green Infrastructure Opportunities
Green infrastructure opportunity areas (e.g. land ownership, soil infiltration capacity, right of ways) and site constraints (e.g. rooftop slope, topography, hydrologic soil groups) were the result of GIS analysis and gray literature overview of best management practices (BMP) [9,10,11,12,13,14,15] and recommendations for the city of Chelsea along with similar communities. We selected four green infrastructure types (green roof, street planter, permeable pavement, and water harvesting) that can be implemented in an existing urban environment (e.g. sidewalks, parking lots, building rooftops, and residential parcels) in Chelsea.
Green Roof Opportunity Areas and Site Constraints

The green roof opportunity areas are located in buildings with flat roofs, with minimum rooftop area of 1,000 sq.ft (93 sqm). The opportunity areas are primarily sorted by building use and ownership (urban public institutional, industrial, commercial, and residential), and secondarily sorted from the largest to the smallest rooftop area. Institutional publicly owned buildings with flat roofs (i.e. city and town owned) were assigned as primary opportunity areas to promote green infrastructure educational awareness, and for feasibility of utilizing already acquired land [9]. We selected flat rooftops (excluding pitched roofs) in the order of industrial, commercial, and residential (e.g. condo, apartment 4 story, apartment 8 story, and public housing) as secondary opportunity areas.

The buildings selected must have the structural capacity to withstand regional snow loading [10]. Therefore, we made assumptions that the roofs of the buildings have the structural capacity to withstand the weight of lighter green roof types along with snow loading. Although the selected BMP literature for this study does not account for building age (e.g. buildings built 1980 or after) as a green roof opportunity area or site constraint, we assigned this as a site constraint criterion to account for potential structural capacity requirements at the screening level.

Residential buildings with flat roofs (e.g. condo, apartment 4 story, apartment 8 story, and public housing) were retrieved from the Assessors’ dataset. Land use data intersecting buildings (e.g. industrial, commercial, urban public, and institutional) with flat roofs were selected. Buildings, built 1980 and after, were extracted from the Assessors’ dataset.

The stormwater runoff estimates used a mean green roof coverage of 75% for each rooftop area, while the remaining 25% is considered to be impervious surface. The sub-catchment area is defined by 100% of the green roof area (75% of the roof top area). For this sub-catchment area the local runoff is calculated based on the annual runoff volume reduction rate of 0.45 [11].

Street Planter Opportunity Areas and Site Constraints

We defined specific sidewalk width based on assumptions for potential green infrastructure opportunity areas. Site constraints were identified according to road classification, hydrologic soil group, and slope percentage. We assigned sidewalk widths of 10 feet or wider as opportunity areas which can meet ADA requirements (i.e. five feet width for wheelchair access) with space left for implementing street planters of various sizes.

Sidewalks were selected along road classifications 4 and 5 (i.e. major road and minor road) excluding highways to maximize sidewalk use for street planter implementation. Areas characterized by hydrologic soil groups (A, B), known for high infiltration capacity and retention, were selected as potential areas for street planting areas [9]. Sidewalks and roads with slope less than 5% were assigned as a site constraint. Although required depth to seasonal high water table (e.g. 2 feet or more) is an initial constraint, this criterion does not impact soil hydrologic infiltration with raised planters [12].

Road classifications 4 and 5 (major road and minor road) were separately extracted from the Massachusetts Department of Transportation (MassDOT) road layer classification. Sidewalk width of 10 feet or greater was intersected by the road classification. Roads with slope less than 5% were analyzed with 3-meter contours. Hydrologic soil groups (A, B) were extracted from SSURGO datasets from MassGIS.

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Table 2. GIS layers for street planters.

We assume that 30% of the sidewalk’s entire length is covered with street planters, leaving always 5 ft for circulation. The sub-catchment area is defined as 2 times the street planter area. For this sub-catchment area the local runoff is calculated based on an annual runoff volume reduction rate of 0.40 [12].

Permeable Pavement Opportunity Areas and Site Constraints

We selected permeable pavement opportunity areas by locating parking lot parcels. Site constraints were determined by slope of less than 5% [13]. Parking lot parcels were retrieved from the Assessors’ dataset. Parking lot parcels with slope less than 5% were analyzed with 3-meter contours.

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Table 3. GIS layers for permeable pavement.

The sub-catchment area is equal to 100% of the permeable pavement area. For this sub-catchment area the local runoff is calculated based on the annual runoff volume reduction rate of 0.45 [13].

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Table 1. GIS layers for green roofs.

We assume that 30% of the sidewalk’s entire length is covered with street planters, leaving always 5 ft for circulation. The sub-catchment area is defined as 2 times the street planter area. For this sub-catchment area the local runoff is calculated based on an annual runoff volume reduction rate of 0.40 [12].
Water Harvesting Opportunity Areas and Site Constraints

The opportunity areas for residential rain barrels were assigned to residential parcels with non-flat rooftops. Storage is sized for the rooftop surface area and the rainfall depth to be captured. We assume household rain barrels of 50–100 gallons, as were recommended for city of Chelsea households, or cisterns or underground tanks when needed [14].

We extracted residential parcel data from the Assessors’ dataset and excluded flat roofs (e.g. condo, apartment 4 story, apartment 8 story, and public housing).

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Table 4. GIS layers for rainwater harvesting.

The sub-catchment area is defined by 100% of the buildings’ footprint. For this sub-catchment area the runoff (local) is calculated based on the annual runoff volume reduction rate of 0.90 [15]. We assume the reuse (outdoor and non-potable indoor use) of all captured rainwater by the installation of multiple barrels to increase storage.

3.3 Water System

The water system flow diagram (see Figure 3) maps the main critical constituent components and their interactions. It is based on the methodology to decode infrastructure systems as developed by our research group for the (omitted) research project [16]. Specifically, the water infrastructure system is decoded on four system levels (water consumption, supply, treatment, networks) that include the respective components. The level of detail of the system flow diagram is based on the strategies for sustainable water system planning and the set of planning guidelines that correspond to each system level [1]. The system flow diagram was developed through a series of mapping iterations across twelve water system case studies in US cities as part of another (omitted) research project [17]. The mapping logic was calibrated after receiving feedback from water department representatives [18]. In the case of Chelsea, the water system is considered a system of the subsystems of water supply, wastewater, and stormwater.

Historical Data

Next the system flow diagram was used as a roadmap for quantitative analysis. Historical performance data were collected from the Massachusetts Water Resources Authority (MWRA) which provides water supply and wastewater services to the city of Chelsea. Average monthly data (MGD) over the calendar years 2010–2014 were gathered for water consumption [19], wastewater flow, stormwater inflow, dry day inflow, sanitary flow [20], and rainfall [21]; no respective data were available for runoff and drained stormwater in Chelsea. Since Chelsea has a combined sewage infrastructure, a key challenge was to quantify the stormwater inflow in the wastewater collection system. Stormwater inflow depends on several factors such as rainfall patterns (volume, intensity, and duration of rainfall events) [22] or the location of catch basins, which implies the use of complex hydrological simulations similar to the computational engines that tools such as Storm Water Management Model (SWMM) use [23].

However, for the scope of estimating the average annual performance inflow we followed a macro approach to designate the relation between rainfall, runoff, and stormwater inflow. The part of rainfall that becomes runoff depends on the impervious surfaces, while a part of runoff becomes stormwater inflow which depends on the combined sewage ratio and its distribution in the city.
Exploratory data analysis of the collected data showed that water consumption has the lowest variability, followed by dry day inflow and stormwater inflow, while rainfall has the highest variability. The correlation coefficient for rainfall and stormwater inflow is 0.913, which indicates a very strong linear relationship, in contrast to the correlation between rainfall and dry day inflow which is 0.317.

The difference from the subtraction of runoff from rainfall is considered the sum of infiltration and evaporation. When new green infrastructure opportunities are accounted for, the calculation method is modified in order to better capture the contribution of green infrastructure in reducing runoff. The simple method was still used for the area of Chelsea (global), but now it excluded the sub-catchment areas of the added green infrastructure. The runoff for the green infrastructure sub-catchment areas is calculated on the local level by the percentage of annual reduction as defined earlier in the paper. The total urban runoff is the sum of the global and local results.

As mentioned, there is a very strong linear relationship between the stormwater inflow to the wastewater collection system and the rainfall. Since the simple runoff coefficient method was used, the runoff and rainfall have also a linear relationship. A least squares regression analysis showed the following relation: (average) inflow = 0.2(rainfall). Subsequently: (average) inflow = 0.35(runoff), with coefficient of determination: $R^2 = 0.8342$. The remaining amount of runoff (runoff – stormwater inflow) is considered as inflow to the drainage system. Based on observations on terrain slope analysis and feedback by city officials [18], we concluded that Chelsea doesn’t receive a considerable amount of stormwater from the neighboring communities.

## Computation Method for the Water System

Our framework estimates the water system’s average annual performance measured in million gallons per day (MGD) based on monthly average historical data from years 2010–2014. According to the findings from the analysis method, total water use, sanitary flow, and dry day inflow are integrated as constant input parameters. Due to nonavailability of monthly data on unaccounted water, it is considered to be a constant 12% of the purchased distributed water for every month [18].

Chelsea has a combined sewage system (70% combined, 30% separate) [24], therefore a part of urban runoff goes to the wastewater collection and the rest to the drainage system. After reviewing modeling methods that related rainfall to runoff, we identified three basic methods, the rational, the curve number, and the nonlinear reservoir method. Based on literature and after receiving feedback from field experts, we decided to use the rational runoff coefficient method, since our purpose was the indicative estimation of average annual performance for the sake of building a framework than a simulation model.

The urban stormwater runoff was then calculated based on the following relations: $R = P \times Pj \times Rv$, where: $R =$ annual runoff (inches), $P =$ annual rainfall (inches), $Pj =$ fraction of annual rainfall events that produce runoff (0.9), $Rv =$ runoff coefficient. $Rv$ is calculated from $Rv = 0.05 + 0.9Ia$, where $Ia =$ impervious fraction [25]. The impervious cover that is used concerns the area within the administration boundaries of Chelsea. The annual rainfall and runoff are converted from inches to gallons by the assumption that one inch of rain falling on 1 acre of ground is equal to about 27,154 gallons [26].

The simple method was still used for the area of Chelsea (global), but now it excluded the sub-catchment areas of the added green infrastructure. The runoff for the green infrastructure sub-catchment areas is calculated on the local level by the percentage of annual reduction as defined earlier in the paper. The total urban runoff is the sum of the global and local results.

As mentioned, there is a very strong linear relationship between the stormwater inflow to the wastewater collection system and the rainfall. Since the simple runoff coefficient method was used, the runoff and rainfall have also a linear relationship. A least squares regression analysis showed the following relation: (average) inflow = 0.2(rainfall). Subsequently: (average) inflow = 0.35(runoff), with coefficient of determination: $R^2 = 0.8342$. The remaining amount of runoff (runoff – stormwater inflow) is considered as inflow to the drainage system. Based on observations on terrain slope analysis and feedback by city officials [18], we concluded that Chelsea doesn’t receive a considerable amount of stormwater from the neighboring communities.
case of water harvesting solutions, the footprint of the buildings is still accounted as impervious surface.

4 RESULTS AND DISCUSSION

4.1 Results from Application in Chelsea

The application gave us the opportunity to harness the results on the quantitative impact in two ways: first per each green infrastructure solution and second per their combinations. The main criteria for evaluating the output metrics are the percentages of reduction and their relation to sustainable planning strategies for the city of Chelsea. For each green infrastructure solution the opportunities were incrementally allocated according to a qualitatively oriented opportunity range (see Figure 6).

Results for Each Green Infrastructure

For green roofs, 93 opportunities were identified with a mean footprint of 2,290 sqm, of which 21.5% were considered institutional buildings, 30% industrial, 41% commercial, and 7.5% residential. The green roof sizes have a standard deviation (StDev) of 2,723 sqm, which shows a significant overall variability, while the commercial buildings have the highest variability, institutional and industrial average, and residential the lowest. The median impact on the city’s impervious surfaces is 2.52% reduction and the maximum is 4.86%. The median runoff reduction is 0.83% and the maximum is 1.6% (49,100 GD). The maximum respective average annual savings in wastewater flow to the treatment plant is 17,400 GD and for drainage outflow 32,300 GD.

For street planters, 223 streets of opportunity were identified with a mean length of 86 meters, of which 21% were in good soil, and 79% in bad soil as raised planters. The maximum impact on the city’s impervious surfaces is only 0.4%. The maximum runoff reduction is low (~0.4%). For permeable pavement, 71 lots were identified with a mean footprint of 1,720 sqm, of which 90% were considered small-scale pavement and 10% large-scale. The overall variability of the areas is low. The maximum impact on the city’s impervious surfaces is 2.85% and the maximum runoff reduction is 1.6%.

For water harvesting, 3,504 buildings were identified with a mean footprint of 150 sqm, of which 3% were considered institutional buildings and the remaining 97% residential or of other uses. In this case, the impervious cover is not affected (0% change), but the city’s need to purchase water from MWRA has a median reduction of 4% (0.14 MGD) and maximum 12.6% (0.44 MGD). The median runoff reduction is 3.4% (0.1 MGD) and the maximum is 10.8% (0.33 MGD). The maximum respective average annual savings in wastewater flow to the treatment plant is 0.11 MGD and for drainage outflow 0.21 MGD.

Results for Green Infrastructure Combinations

The computational method also enables the examination of numerous scenarios that combine green infrastructure solutions. We ran two indicative sets of scenarios: numerically based and strategy-based. The numerically based scenarios consider equal inputs from each range of green infrastructure opportunities. We tested the scenarios of combined 0% (no intervention), 25%, 50%, 75%, 100% from each green infrastructure.

The 50% green infrastructure scenario results in a reduction of the city’s impervious surfaces by 2.93%, runoff reduction is 4.6% (0.14 MGD), and the average annual savings in wastewater flow to the treatment plant is relatively low, while the city’s need to purchase water from MWRA is reduced by 4%. By comparison, the 100% green infrastructure scenario reduces the city’s impervious surfaces by 8.1%, the runoff by 14.4% (0.44 MGD), wastewater flow saving is 0.15 MGD and for drainage 0.29 MGD, while the water demand from MWRA is reduced by 12.6% (0.44 MGD).

For strategy-based scenarios, green infrastructure solutions are deployed based on specific strategies. For instance, one scenario includes green roofs in institutional and industrial buildings, street planters in areas with good soil, small-scale porous pavement, and water harvesting in institutional buildings. For this scenario, the impact on the city’s impervious surfaces would be 3%, the runoff reduction would be 1.75%, with low annual savings in wastewater flow and drainage. The water demand from MWRA would be reduced by only 0.7%. Similarly, the computational framework allows the generation of multiple combinations.

4.2 Discussion

All four green infrastructure solutions contribute to the reduction of stormwater runoff. The output values indicate
the consequent reduction in wastewater treatment needs and the reduction of drainage (gray infrastructure). The water quality of adjacent water bodies is accordingly improved and flooding is reduced. In terms of quantitative impact on runoff, water harvesting solutions bring the most significant reductions followed by both permeable pavement and green roofs, while street planters have the least contribution. Regarding the fraction of impervious surfaces, green roofs reduce it the most, followed by porous pavement and street planters, while water harvesting reduces significantly the water import needs for the city of Chelsea by increasing the available local water supply (see Figure 7).

![Figure 7. Accumulative impervious cover and runoff reduction across opportunity range](image)

For decision making, the quantitative results are accompanied by additional qualitative performative criteria. Green roofs, permeable pavement, and street planters can improve air quality, reduce atmospheric CO2, and reduce urban heat island effect and noise pollution. Green roofs and street planters improve aesthetics, improve habitat, and reduce energy use, while permeable pavement reduces salt use [28]. The results from combinations of different green infrastructure solutions can be interpreted by performance- and strategy-based criteria. Thus, before working with experts, city stakeholders can gain insights and explore different scenarios of combinations.

Our research seeks to address the gap between technical green infrastructure barriers such as deficiency of data and performance outcomes for non-expert decision makers. Furthermore, many municipalities have limited GIS and historical performance datasets, making it a challenge to screen green infrastructure BMP opportunity areas even with adequate resources and when technological knowledge is readily available. By compiling and documenting the necessary up-to-date datasets, the runoff performance output can gain much-needed accuracy with the geospatial data we used. Therefore, the goal of our research was less focused on finding the exact runoff estimate than to test a computational framework for decision making that can become more accurate in the near future based on better available information. Technologies such as the internet of things can help municipalities collect the right data about missing related metrics in the future.

5 CONCLUSION

The study presented in this paper examined a computational method that quantifies the relations between green infrastructure, the urban water system, and the urban environment on an average annual basis with the scope to provide a framework for data-driven insights. The framework can be enhanced by integrating more advanced computational models (e.g. nonlinear runoff method) and by using more accurate geospatial information and historical performance data when they become available from the municipalities. However, we see our computational method as having a value as an educational tool for non-expert awareness that reveals basic but meaningful quantifiable synergies. One of our next steps is to develop the educational dimension of the method through a web interactive platform that enables community stakeholders with information regarding the nexus of green infrastructure, the water system, and the city.

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18. Meetings with City officials, incl. the Planning & Development Department of the City of Chelsea.


An Approach towards Developing Methods to Analyze and Visualize Energy Flow of HVAC System

Aly Abdelalim, Zixiao Shi, William O’Brien

Human Building Interaction Lab, Carleton University, 1125 Colonel by Dr., Ottawa, ON K1S 5B6
{AlyAbdelalim, zixiaoshi}@email.carleton.ca, liam.obrien@carleton.ca

ABSTRACT
In the field of building operations, it is essential that building operators understand the dynamics of energy use, control strategies, and occupant comfort in buildings. Nowadays, modern commercial buildings’ resource consumption is metered at various levels of spatial and temporal resolution to track and reduce energy use and the associated cost and greenhouse gas emissions. This leads to many data sources at the building level. As a result, lots of data are available but not necessarily in a readily comprehensible form. Furthermore, the current data availability and visualization tools have some limitations in identifying system inefficiencies and possible solutions. This paper proposes a method to estimate and visualize energy flows through different components of heating, ventilation, and air-conditioning (HVAC) system using Sankey diagrams to make data more accessible and to identify inefficiencies. The proposed method is then applied to an 8,000 m² multi-zone Canadian university building.

Author Keywords
Energy flows in HVAC; HVAC loads; Sankey diagrams.

1. INTRODUCTION
Energy demand in commercial and institutional facilities across Canada grew by over 35 percent between 1990 and 2004 [1]. In Canada, approximately 56 and five percent of the total energy allocated for residential and commercial energy-use are used for space heating and cooling, respectively [1]. Nowadays, modern commercial buildings utilize energy management and control systems (EMCS) for monitoring and optimizing building systems during operation. Frequently, buildings’ resource consumption is metered at various levels of spatial and temporal resolution to track and reduce energy use and the corresponding cost and greenhouse gas (GHG) emissions. This leads to many data sources at the building level. An example of energy dashboard implemented at Carleton University is shown in Figure 1. As stated by [2] and [3], the identification of system inefficiencies through monitoring could lead to an energy savings of between 15 and 40 percent. The improvements in the monitoring and supervision capabilities of EMCS have served to make operational problems more visible and quantifiable to the industry [4].

As indicated by building energy regulations [5], building energy rating systems and certification schemes [6] and [7], and the standardization of inspection, operation and maintenance (O&M) plans of HVAC systems, energy efficiency of heating, ventilation and air conditioning (HVAC) systems has become a priority objective for energy policies [8,9,10].

Figure 1. The existing building dashboard interface implemented at Carleton University

Nowadays, many researchers have been focusing on analyzing and evaluating HVAC systems energy-use. Perez-Lombard et al. [11] proposed a wide-scope analysis of HVAC systems by tracing the energy flow from energy sources to final services and by the examination of the intermediate devices. The aim of the study was to provide guidelines for easier energy analysis in the HVAC field. Another study by Sakulipatsin et al. [12] presented a method for exergy analysis of buildings and HVAC systems, according to an energy demand from the building side to the energy supply side. Fan et al. [13] evaluated the operation performance of HVAC system based on exergy analysis using simulation model. Another study by Salsbury et al. [4] used simulation predictions as performance targets with which to compare monitored system outputs for performance validation and energy analysis. Mendes et al. [14] presented a generic educational user-friendly environment using mathematical models for simulating HVAC systems and integrating it to a whole building hygro-thermal model.

On the other hand, new diagnostic software tools are becoming available to facilitate the detection and diagnosis of energy and other performance problems for HVAC systems.
systems in commercial buildings [15]. Gayeski et al. [16] described the current metrics and visualization techniques available at different scales ranging from enterprise to project scale. Austin [17] claimed that Trend Analysis is a powerful tool for HVAC troubleshooting. Moreover, Meyers et al. [18] presented data visualization techniques of HVAC and lighting systems, which can help building operators to achieve substantial improvements in energy management.

On the visualization side, the current data availability and visualization tools have some limitations in identifying system inefficiencies and possible solutions. One of the visualization tools that is useful in energy management and performance improvement is Sankey diagrams. A study by [19] proposed several methods to analyze and visualize building-level water, natural gas, and electricity consumption and the upstream environmental impacts using Sankey diagrams and other graphical techniques. Perez-Lombard et al. [11] graphically represented the energy flows in a typical constant air volume systems installed in office buildings in Spain using Sankey diagrams. Another study by [20] used Sankey diagrams to compare and contrast the performance of a domestic legacy gas ducted heating system with a contemporary, well-installed split-system heat pump heating system.

This paper proposes a method to analyze and visualize energy flow through different components of a typical air handling unit (AHU) and HVAC loops of commercial buildings using Sankey diagrams. A major contribution of the paper is to convert sparse sensor data into estimated energy flows for each major AHU and HVAC plant component. The objective of this paper is to make operational problems more visible and quantifiable in order to identify opportunities for energy savings and to facilitate the decision-making by building operators, campus planners, and other stakeholders. The proposed method is then applied to a case study: Canal Building at Carleton University campus in Ottawa, Canada using historical data obtained from EMCS.

2. METHODOLOGY

The main objective of this study is to develop a method to obtain, process, analyze, and visualize energy flow of a typical AHU and HVAC loops configurations of a commercial building as shown in Figure 2. The methodology focuses on developing energy balances for AHU components (i.e. heat recovery wheels (HRW), fans, economizers, air filters, and cooling and heating coils) and HVAC loops (i.e. air loop, chilled water loop, refrigerant loop, condensing water loop, and heat rejection loop). Moreover, the study analyzes the feedback loops utilizing spatial and temporal analysis.

The following sections aim to illustrate energy balances for typical HVAC equipment (i.e. boilers, cooling towers, chillers, pumps, and air handling unit (AHU) sub-systems). The following energy balance equations of each component are written in terms of final energy, making use of the following symbols: thermal load $Q$, positive for heating and negative for cooling, $m$ is the mass flow rate of fluids, $C_p$ is the specific heat capacity, and $T$ and $h$ are the temperature and enthalpy of fluid in and out of the system, respectively. All units are in SI. The equations rely on a set of assumptions. For instance, no internal energy change (i.e. steady-state). Moreover, heat lost from air handling unit (AHU) to the surrounding and frictional losses through the AHU is ignored in the current study.

Contrary to simulation-based studies, energy flows are often not readily available as readings from EMCS. Instead, modern buildings sense fluid flow rates, temperature, humidity, and electrical power. Thus, a contribution of this paper is to convert sparse measurements into a comprehensive set of energy flows.

2.1 Central Heating Plant (CHP)

As many communities and campuses have centralized heating plants in order to reduce equipment size and cost, improve efficiency, and centralize operations. The steam delivered from the central heating plant (CHP) passes through a heat exchanger that uses the thermal energy to provide heat to the hot water-glycol loop as shown in Figure 2. The energy balance across the heat exchanger yields as shown in Equation (1).

$$Q = m_{steam} \times (h_{Steam,return} - h_{steam,supply}) = m_{HW} \times C_p(T_{HW,avg} \times (T_{HW,return} - T_{HW,return}))$$ (1)

2.2 Cooling Towers

Heat from the condenser is carried by condensing water (CDW) to the cooling tower to be cooled and returned to the condenser. This loop is called condensing water loop. Equation (2) shows calculation for the amount of heat extracted from the refrigerant.

$$Q_{CDW} = m_{CDW} \times [C_{p,in}(T_{in}) - T_{out} \times C_{p,out}(T_{out})]$$ (2)

2.3 Chillers

The refrigerant (water-propylene glycol) for the case study building extracts heat from the water in the evaporator and transfers it to the condensing water by means of a vapour compression cycle. The energy balance across the chiller is shown in Equation (3) [21].

$$Q_H + Q_L + W = 0$$ (3)

Where, $Q_H$ is the amount of energy transferred from the condenser to the condensed water loop. $Q_L$ is the amount of energy gained from the evaporator and calculated as shown in Equation (4). $W$ is the amount of power consumption by chiller, this value can be obtained from EMCS.
\[ Q_L = \dot{m}_{CHW} \times \left( h_{in} - h_{out} \right) = \dot{m}_{CHW} \times C_p \times (T_{in} - T_{out}) \]  

where, the subscript \( CHW \) refers to the chilled water.

### 2.4 Pumps

The pumps are used to increase the pressure and temperature of the return fluids in the chilled water, refrigerant, condensing water, and steam loops. The energy balance through the pump is expressed in Equation (5).

\[ P_{el} = \dot{m}_{reference} \times \left( \frac{\Delta P}{\rho_{reference}} \right) + \sum F \]  

\( P_{el} \) is the electric energy consumption, \( \Delta P \) is the differential pressure, \( \rho \) is the density of fluid, and \( \sum F \) is the friction losses through the pump. The subscript \( \text{reference} \) refers to the type of fluid passing through the pumps (i.e. steam, chilled water, condensate water, or refrigerant). Furthermore, by considering the whole piping/pump system as a single pump, and their total mechanical loss as head loss. Then, the high difference between the lowest point and highest point of the fluid loop can be used to calculate the efficiency of the pump as shown in Equation (6).

\[ \eta = \frac{\dot{m}_{reference} \times g \times \text{head}}{P_{el}} \]  

Where, \( g \) is the gravity constant (9.81 m/s²).

### 2.5 Air Handling Unit (AHU)

The air handling unit is used to condition and distribute air to building zones as part of an HVAC system. In the context of Canal Building, the air handler contains fans, heating and cooling coils, filters, humidifier, economiser, heat recovery wheel (HRW), and dampers [22]. The energy balance for the AHU is expressed in Equation (7) [23].

\[ Q = \dot{m}_{return} \times h_{return} + \dot{m}_{fresh} \times h_{fresh} + Q_{recovery} + Q_{in} = \dot{m}_{supply} \times h_{supply} + \dot{m}_{exhaust} \times h_{exhaust} + L \]  

The term \( Q_{in} \) refers to heat added or extracted from the system, thus it can be positive for heating and negative for cooling. On the other hand, \( Q_{recovery} \) refers to the recovered heat by the heat recovery wheel and \( L \) is the losses in the system (e.g. frictional losses through AHU ducts). Moreover, the recirculated air is controlled by a modulation damper. The following discussion focuses on the amount of heat added or extracted and recovered in the AHU.

**Heat Exchangers**

Heat exchanging devices (such as heating and cooling coils) linking thermal loops (water coils, evaporators and condensers) do not use energy but destroy exergy (second-law of thermodynamics) [11].

For the cooling coils, the water-propylene glycol absorbs heat from the air stream passing through the cooling coils and returns to the chiller evaporator to be cooled. This loop is called chilled water loop which is driven by pumps. The energy balance through the cooling coil is shown in Equation (8). The enthalpy is used in this equation to account for sensible and latent heat.

\[ Q = \dot{m}_{CHW} \times \left( h_{in} - h_{out} \right) = \dot{m}_{air} \times \left( h_{in} - h_{out} \right) \]  

The energy balance across the heating coil can be expressed as shown in Equation (9). Heat is transferred from the hot
gylcol water to the air stream running through the exchanger.

\[ \dot{m}_H W \times C_p(T_{H W, \text{avg}}) \times (T_{H W, \text{return}} - T_{H W, \text{supply}}) = \dot{m}_a i r \times C_p(T_{a i r, \text{avg}}) \times (T_{a i r, \text{leaving heating coil}} - T_{a i r, \text{entering heating coil}}) \]  \hfill (9)

The hot water return from the heating coil runs through another heat exchanger by means of water pumps. Furthermore, the performance of the heat exchanger should be considered in the analysis. Increasing transfer area of exchanging devices reduces temperature differences, and thus increases exchanging effectiveness [11]. The effectiveness of heat exchanger is calculated as shown in Equation (10).

\[ \text{Effectiveness} = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}} \]  \hfill (10)

Actual and maximum possible heat transfer for a heat exchanger are shown in Equations (11) and (12), respectively. Cold and hot fluids refers to the colder and hotter fluids entering and leaving the heat exchanger, respectively. For instance, the steam entering the heat exchanger is the hot fluid as it losses heat to other fluid (in this case the hot glycol water).

\[ \dot{m}_{c o l d \ fluid} \times C_p(T_{c o l d \ fluid, \ \text{avg}}) \times (T_{c o l d \ fluid, \text{out}} - T_{c o l d \ fluid, \text{in}}) \]  \hfill (11)

\[ \dot{m} \times C_p(T)^{\text{minimum}} \times (T_{\text{hot fluid,in}} - T_{c o l d \ fluid, \text{in}}) \]  \hfill (12)

Heat Recovery Wheel (HRW)

An enthalpy wheel allows both sensible and latent energy to be recovered from the exhaust air stream. Equations (13)(13) and (14) show sensible heat recovery and latent heat energy recovery by energy wheel, respectively.

\[ Q_{\text{recovery}} = \dot{m}_r \text{turn} \times (1 - \% \text{OA}) \times C_p(T_{a i r, \text{avg}}) \times (T_{a i r, \text{exhaust}} - T_{a i r, \text{return}}) \]  \hfill (13)

\[ Q_{\text{recovery}} = \dot{m}_r \text{turn} \times (1 - \% \text{OA}) \times (h_{a i r, \text{exhaust}} - h_{a i r, \text{return}}) \]  \hfill (14)

Where, \( h_{d a} \) and \( h_{e} \) are the specific enthalpy for dry air and specific enthalpy for saturated water vapor, respectively. \( W \) is the humidity ratio and \( T \) is the temperature in Celsius. The enthalpy (h) including moisture is shown in Equation (15) [21].

\[ h_{\text{moist}} = h_{d a} + W \times h_{e} \approx T + W(2501 + 1.805T) \]  \hfill (15)

Fans

In this study, a variable volume fan is discussed. The aim is to calculate the efficiency of the fan and to determine the state of air exiting the fan. The rate of electrical energy consumption by fan's motor is shown in Equation (16).

\[ P_e l = \frac{W_{\text{fan}}}{\eta_{\text{fan}}} \]  \hfill (16)

\( W_{\text{fan}} \) is the rate of energy transfer by work from fan to air as shown in Equation (17). The electrical energy consumption can be obtained from EMCS. While, \( \eta_{\text{fan}} \) is the efficiency of fan’s motor.

\[ W_{\text{fan}} = \dot{m} \times \frac{\Delta P}{\rho} \]  \hfill (17)

On the other hand, the frictional losses can be determined as shown in Equation (18).

\[ P_e l = \dot{m} \times \left( \frac{\Delta P}{\rho} \right) + \Sigma F \]  \hfill (18)

Where, \( P_e l \) is the electric energy consumption, \( \Delta P \) is the differential pressure, \( \rho \) is the density of air, and \( \Sigma F \) is the friction losses. Moreover, the state of air leaving the fan is expressed in Equation (19).

\[ h_{\text{out}} - h_{\text{in}} = \frac{P_e l \times [\eta_{\text{fan}} + \beta_{\text{motor}} \times (1 - \eta_{\text{fan}})]}{\dot{m}} \]  \hfill (19)

Where, \( \beta_{\text{motor}} \) is the fraction of heat loss from motor that is transferred to the air stream in the AHU as shown in Equations (20) and (21).

\[ \beta_{\text{motor}} = \frac{\dot{Q}_{\text{motor-to-air}}}{\dot{Q}_{\text{motor}}} \]  \hfill (20)

\[ \dot{Q}_{\text{motor}} = P_e l \cdot W_{\text{fan}} \]  \hfill (21)

\( \dot{Q}_{\text{motor}} \) is the rate of heat addition from fan to air due to friction. On the other hand, \( \dot{Q}_{\text{motor-to-air}} \) depends on the fan location in the air stream. Thus, the amount of heat gain can be obtained by Equation (22).

\[ \dot{Q}_{\text{motor-to-air}} = f \times \frac{\text{power rated}}{\eta_{\text{fan}}} \]  \hfill (22)

The factor \( f \) can be determined based on the location of fan in the air stream [24].

Filters

Air filters are used in air handlers to remove the dust from both the ventilation air and the recirculated air. The energy consumption of the air filters typically accounts for approximately 10 to 70 percent, of the total fan energy consumption for typical air handling units [25]. This study focuses on evaluating air filter based on their resistance to air flow. The differential pressure can be obtained from EMCS. Thus, the frictional pressure can be calculated as shown in Equation (23).
\[ \sum F = \dot{m} \times \left( \frac{AP}{P_{\text{air}}} \right) \]  \hspace{1cm} (23)

**Outdoor Air Fraction**

The percentage or fraction of outside air can be estimated by using carbon dioxide (CO₂) concentration of supply, return, and outdoor as shown in Equation (24) [26].

\[ OA\% = \frac{\text{CO}_2\text{ supply, air} - \text{CO}_2\text{ return, air}}{\text{CO}_2\text{ outdoor, air} - \text{CO}_2\text{ return, air}} \]  \hspace{1cm} (24)

Due to errors that could be encountered in CO₂ measurement, as in the case of Canal Building, an alternate approach is to estimate outdoor air fraction using temperatures, as in Equation (25).

\[ OA\% = \frac{m_{\text{RA}} \times \eta \times (h_{\text{RA}} - h_{\text{EA}}) + m_{\text{MA}} \times \left[ (1 - \eta) \times (h_{\text{RA}} - h_{\text{EA}}) \right] \cdot (h_{\text{MA}})}{m_{\text{MA}} \times \left[ (1 - \eta) \times (h_{\text{RA}} - h_{\text{EA}}) \right] \cdot (h_{\text{OA}})} \]  \hspace{1cm} (25)

where, \( m_{\text{RA}} \) and \( m_{\text{MA}} \) are mass flow rates of return air and mixed air, respectively. \( \eta \) is the efficiency of the HRW. While, \( h_{\text{RA}}, h_{\text{EA}}, \) and \( h_{\text{MA}} \) are the enthalpy of return air, exhaust air and mixed air, respectively.

**Humidifiers**

The humidification processes is the transfer (addition) of water vapor to air. This process is usually accomplished by introducing water vapor or by spraying fine droplets of water that evaporate into the circulating air stream [27]. The humidification load is computed by Equation (26).

\[ \text{Humidification load} = \dot{m}_{\text{air}} \times (h_{\text{out}} - h_{\text{in}}) = \dot{m}_{\text{steam}} \times (h_{\text{out}} - h_{\text{in}}) \]  \hspace{1cm} (26)

Moreover, the mass flow rate of steam \( \dot{m}_{\text{steam}} \) is obtained from the amount of moisture (W) added to the air stream as shown in Equation (27).

\[ \dot{m}_{\text{steam}} = \dot{m}_{\text{air}} \times (W_{\text{out}} - W_{\text{in}}) \]  \hspace{1cm} (27)

3. **CASE STUDY**

The Canal Building (CB) is a seven-story mixed-use academic building with total floor area about 8,000 m² as shown in Figure 3.

The building began its operation in 2011, including a large variety of functional space such as private offices, open-plan offices, lecture rooms, computer labs, design labs, research labs, conference rooms and other facility rooms. There are four air-handling units (AHU). Two small AHU are designated for the mechanical rooms, while the rest of the building is conditioned by two separate air-handling units. This paper will be focusing on one of the AHUs installed. The heating system uses campus steam generated at a central plant. The cooling system uses a 60% water-40% propylene glycol loop. This building is equipped with two chillers (ElectricEIRChiller Centrifugal Carrier 19XR 1407kW/ 6.04COP/ VSD), which supply cooling to CB and one of the adjacent buildings. Both chillers operate in parallel. Thus, the first step is to identify the chiller consumption assigned to the building.

This was done by obtaining data for water-propylene glycol flow rate for Canal building as shown in Equation (28). The air distribution system is single-duct variable air volume (VAV) with reheat and radiant panels to reduce cold surfaces.

**Chiller consumption for a specific building** = \( \frac{\text{Chillers total consumption} \times \left( \frac{\text{Flow rate for a specific building}}{\text{Total flow rate for all buildings sharing the same chillers}} \right)}{\text{Chillers total consumption}} \)  \hspace{1cm} (28)

4. **SANKEY DIAGRAMS**

Sankey diagrams are a useful graphical tool for mapping energy and mass flows including losses for a system. Sankey diagrams are comprised of arrows of varying widths, where the width indicates relative magnitude of flow and the direction indicates the connection between sources and sinks for each flow. Sankey diagrams allow resource flows to be visualized within complex systems with interacting subsystems. This study applies Sankey diagrams on HVAC sub-systems to visualize energy flows through each component and stage in the system.

Sankey diagrams were rendered in a browser using Scalable Vector Graphics (SVG). The layout was derived from D3’s Sankey layout code developed by Google Developers that provided more flexibility in organizing nodes, colors, and font sizes [28]. In order to create nodes with the connection links, a set of rows containing data for source, target, and magnitude for each flow was created using comma-separated values (CSV) format.

Sankey diagrams should be read based on the direction of the flow (i.e. from left to right). All energy inputs come from the left side, while energy outputs leave rightward. For instance, during winter, heat is added to the building. While during summer, heat is extracted from the building.
Figure 4. Sankey diagram showing AHU energy flow during two winter weeks

Figure 5. Sankey diagram showing AHU energy flow during two summer weeks
Hourly system operation and energy data for HVAC subsystems have been collected from EMCS. On the other side, the steam consumption was recorded from meters installed in the building. Raw data were reported on a server operated by the Facilities Management and Planning (FMP).

The obtained data were used in the equations mentioned in the methodology section in order to create Sankey diagrams. Some modest errors were associated with some of the sensors such as missing or incorrect data points. Thus, for short time-periods (< 6 hours), it is recommended to use simple interpolation to generate missing values. While for long time-periods, the data was excluded from the analysis.

5. RESULTS AND DISCUSSION

The aim of this study is to analyze and visualize energy flow through different components in the air handling unit and their impact on primary energy use. The study focused on hourly data for two weeks in winter (1st to 15th of February, 2015) and summer (1st to 15th of July, 2015). Figure 4 and Figure 5 show the energy flow and feedback loops for the AHU in the winter and summer periods, respectively. Due to limited data for relative humidity for the state of air entering and leaving the HRW, the latent energy term is excluded from the study.

During winter, it was noticed that the supply fan energy is unexpectedly high and the heat introduced from the motor is similar in magnitude to the heating of the airstream from the heating coil and humidifier. Approximately 28 percent and eight percent of the heat is added by the heating coil and steam humidifier, respectively. While, heat added from the recirculated air and the HRW are 24 percent and nine percent, respectively. This is due to the high internal gains from equipment, lighting, occupants, and heat added by VAV-reheat coils and radiant panels installed in some of the perimeter zones. However, it was observed that the HRW is infrequently used.

During summer period, the latent energy was neglected. It was observed that the HRW did not contribute significantly to recovering energy as it was rarely turned on. As mentioned above, due to the high internal gains and heat gains from building envelope, only a small amount of the recovered energy was recorded from the recirculated air. Furthermore, while the coefficient of performance (COP) of the chiller is approximately three, the 1.65 units of electricity were required for every unit of heat removal from the building. The building also relies on free cooling (i.e., cooler outdoor air instead of mechanical cooling) when the outdoor temperature is below 22°C.

Moreover, the supply fan consumes a large amount of energy, this appears to be due to high frictional losses recorded through the air filter installed before the heating and cooling coils and also the pressure losses through the ducts.

6. CONCLUSION

The aim of the proposed method was to analyze and visualize energy flow by different components of an air handling unit in multi-zone Canadian university building. The aim of this proposed method was to make use of real-time and historical data obtained from EMCS to facilitate the decision making by building operators to manage the operation of building system level. This was achieved by converting sparse sensor data into estimated energy flows for major components of AHU and HVAC plant.

The implication of this work is that it would help in making operational problems more visible and quantifiable in order to identify opportunities for energy savings.

More sensors will be installed in the near future to obtain more information regarding the state of air at different locations in the AHU.

Future planned work includes a survey that will be applied to building operators to test the proposed visualization effectiveness. More analysis on the secondary air handling unit (i.e. VAV-box in this case) will be involved in the future.

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REFERENCES


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Self-Reported Positioning within Spatial Configurations: Combining Big Data and Space Syntax Analysis for Urban Mobility Research

Ricardo Andrade\textsuperscript{1} and Angelos Chronis\textsuperscript{2}

\textsuperscript{1}Universidad Gabriela Mistral
Santiago, Chile
randrade.arq@gmail.com

\textsuperscript{2}University College London
London, United Kingdom
angelos.chronis.09@ucl.ac.uk

ABSTRACT
Space syntax is one of the most established methodologies in urban mobility research. One of the current challenges with this methodology is the integration of geolocation data into urban studies. Digital interfaces that combine spatial data and urban analysis remain absent in current space syntax-based software. The proposed methodology is based on the combination of Facebook check-ins – as a measure of urban mobility – and normalised angular choice values – as a predictor of pedestrian flow – in the same interface in order to examine how these two approaches converge or contradict each other. Early findings suggest that this method confirms the space syntax-related idea that states that urban functions tend to be located in streets with good accessibility and that the lack of correlation between the two measures implies that other factors are influencing pedestrian behaviour in cities. This research highlights the potential of the combination of Big Data and space syntax techniques to reveal new insights on urban analysis.

Author Keywords
Big Data; Visualisation; New Tools and Methods; Computer Applications.

ACM Classification Keywords
H.2.8 DATABASE APPLICATIONS (Spatial Databases and GIS).

1 INTRODUCTION
Urban mobility has become one of the most important research subjects in contemporary urbanism. The relevance of the ability of people to move around an urban area has increased in recent decades. Currently, 54% of the world population lives in cities, and this percentage is expected to increase to 66% by 2050 [27]. Issues regarding sustainability, efficiency and congestion in urban areas are some of the main challenges for decision makers, urban planners and economists. Space syntax, which was established at The Bartlett, University College London, is one of the core research fields developing theories and analytic techniques to inform urban studies, decision making and urban planning [23, 24]. Its approach to urban analysis is based on the understanding of human movement as the main action that generates social interaction in cities, and the way such an action is influenced by the geometric structure of the urban grid.

In spite of space syntax’s well-established reputation in the field of urban studies, criticism has been raised regarding the lack of integration between its analytical toolkit and location-based data [20]. It has been pointed out that the widespread use of mobile devices and other ubiquitous and pervasive systems has an important effect on urban life. In other words, these new technologies are changing the way people interact socially in urban spaces [21], thus turning urban mobility into a more complex and adaptive phenomenon. Moreover, this explosion of spatial ‘Big Data’ has changed the field of urban analytics due to the possibility of exploring new patterns of urban mobility working with these datasets [2]. The current lack of full integration of space syntax-oriented software with Big Data databases such as government datasets, GPS logs, Twitter activity and social network geotagged data is a challenge that must be addressed in order to complement current space syntax methodologies focused on urban mobility research. Hybrid methods combining space syntax’s cognitive and geometrical approach to city spaces with spatial data’s mathematical and physical models of urban analytics can help generate a multidisciplinary understanding of urban complexities.

This report examines how the introduction of Facebook data into space syntax methodologies can inform knowledge of urban dynamics and land use by combining two measures of urban mobility in the same interface: space syntax normalised angular choice values – as a predictor of pedestrian flow – and Facebook Place check-ins – as a measure of social activity and place popularity. The aim is to analyse whether location sharing by mobile-device users in spaces with high concentrated social activity is related to spatial conditions of the urban grid. We propose that this approach confirms space syntax theories regarding the location of catering and trade activity in spaces with good accessibility although a street’s spatial condition is not the sole factor influencing users to share their location in an urban space. We first examine the theoretical background of space syntax theories and methodologies as well as social navigation through social media data. Then, we
describe our methodology, which includes the development of a prototype and the analysis of 15 areas in London, UK. Finally, we discuss our findings, their implications and the contributions of our study.

2 BACKGROUND
The research presented in this paper takes the combination of space syntax analysis and social media data as a starting point for designing a digital interface suitable for urban mobility studies. We propose that interfaces that allow the analysis of location-based data on a spatial representation of urban spaces can contribute to the understanding of the dynamics and complexities of cities. To accomplish this aim, we provide a brief introduction to space syntax and ‘social navigation’, which inform the main structure of our methodology.

2.1 Space Syntax
Space syntax is one of the most well-known research fields that study the way people move through the built environment. It is a set of theories and analytical techniques that examine the relationship between space and society [14]. According to space syntax, spatial configuration—the analysis of the relation between spaces—can detect the social factors involved in the generation of spatial patterns and the implications these structures confer to the social life of inhabitants [15]. Space syntax methods apply graph-based techniques on axial maps—a simple representation of streets using a minimal set of straight lines—and segment maps—a more accurate spatial structure generated by the fragmentation of axial lines at their intersections—to identify streets that attract higher levels of pedestrian flow than others. A range of colours, from deep blue to red, identifies levels from low pedestrian flow to high urban movement (Figure 1).

Figure 1. Normalised angular choice analysis in Bank Junction, City of London, UK.

Levels of accessibility are measured by two values: ‘integration’ (closeness) and ‘choice’ (betweenness). The main difference between these concepts is the way in which urban movement is conceived: whilst integration refers to the idea of ‘to-movement’, or how accessible a street is as a destination, choice is based on the idea of ‘through-movement’, or the extent to which a space can be a part of the shortest route to a destination [15]. Further developments have complemented the topological approach of early studies by focusing on the influence of spatial cognition on pedestrian movement. Based on the application of J. J. Gibson’s ‘natural vision’ theory [8] in isovist graphs, space syntax highlights the importance of visual affordances in guiding an agent through space and emphasises the role of visual straight lines in agent movement [26].

Research on spatial cognition has demonstrated that human beings tend to walk linearly along routes that minimise angular deviation and use spaces with wide visual fields to gather spatial information [3]. These findings confirm people’s tendency to navigate mainly with a geometrical model of angles, followed by a topological model of turns and finally, a model of metric distance [15]. Thereby, segment analysis calculates angular deviations in the urban grid according to the metric radius implemented in a study; this is up to 800m for analysing pedestrian flow, with larger radii for vehicular movement [1].

Another important addition to the field was the introduction of new measures for segment analysis: normalised angular integration (NAIN) and normalised angular choice (NACH) [16]. This development was necessary to address issues encountered when comparing cities or urban areas at different scales. Another implication is the way in which the calculation of NACH values combines both the ‘to-movement’ and ‘through-movement’ concepts, making this measure a more accurate indicator of urban movement. Therefore, roads with high NACH values indicate spaces with high levels of urban flow and the degree of interruption of the global structure of an urban network; on the other hand, mean values imply lower movement and a continuous system related to the local structure [1].

The London Pedestrian Routemap [22] summarises the key findings of space syntax research regarding pedestrian behaviour in cities such as London: 1) people tend to follow constant patterns; 2) people prefer to walk along main streets; 3) people select safer routes; and 4) people tend to choose simpler and more accessible streets. However, Ratti [20] raised criticism regarding the lack of location data provided by mobile devices in space syntax studies. It has been argued that by ignoring the significant resources available from GPS logs, social media databases and other geo-tracking technologies, space syntax methodologies are lacking as they fail to consider an important factor that is changing the social behaviour of pedestrians.

2.2 Social Navigation
The concept of ‘social navigation’ refers to people’s tendency to navigate towards ‘footprints’ that other people have left in physical and virtual spaces [5]. Through this behaviour, people can obtain a sense of location and
orientation in space. Social media platforms have integrated social navigation functionality that include recommender and voting systems based on information generated by users with similar preferences. These algorithms contribute to the publicity of well-evaluated places and, in this way, urban sites and local businesses acquire higher chances to be selected as potential destinations for inhabitants or tourists.

Current research on pervasive computing has raised the idea that global experiences can influence personal choices since ‘digital footprints’ left in the built environment can turn into recommendations that help people select routes and destinations [9]. These digital footprints can be passive or active; the former is generated without users’ awareness, and the latter is voluntarily created and shared by users [19]. Many social media platforms have incorporated location-sharing features that allow users to create new geotagged data. This allows researchers to study the interests and tastes of different groups of people in regard to places and urban spaces. Girardin has emphasised the importance of active digital footprints for urban mobility studies since there is a certain kind of ‘richness’ in the ‘intentional weight’ attached by people to their shared contents [10]. Therefore, the notion of subjectivity is brought to the relationship amongst people, places and spaces [4].

The ‘check-in’, or the ‘self-reported positioning’ feature, is a social media functionality that allows users to leave a digital footprint in a place. Recent research using check-in data as a measure of human mobility and social activity has taken advantage of the fact that users share their locations by means of this feature [12, 31]. Furthermore, it has been demonstrated that check-ins offer a reliable measure of place popularity since the most popular places tend to be selected as potential destinations for a number of reasons, namely, that catering and entertainment categories tend to have concentrated check-ins in specific parts of a city and that the urban context can influence people’s choices [12].

The research presented in this paper proposes the combination of space syntax NACH values (a spatial feature) as a predictor of movement in a street and Facebook check-in data as a measure of human mobility and social activity in a particular place in order to develop a methodology that integrates Big Data resources into space syntax techniques.

3 METHOD
Based on the theoretical framework introduced above, the methodology developed in this paper combines two strategies for the design of a digital interface suitable for urban flow research. First, space syntax segment analysis as the spatial representation of the urban grid was computed using NACH values. These measures, as indicators of accessibility and route availability, were added to each place profile retrieved from the Facebook database. Second, this spatial representation was combined with the visualisation of Facebook Places on the segment map according to the geolocation and number of check-ins. High self-reported positioning activity in a place was considered a digital footprint in the urban space, or an indicator of places with rich social activity.

The methodology development comprised three steps: developing a prototype of a digital interface that combines space syntax analysis and Facebook data (3.1); testing the application for 15 areas of London (3.2); and analysing urban mobility by comparing and combining these two strategies (3.3).

3.1 Prototype
The prototype was designed with Java-based Processing [7]. The development steps are outlined below:

Facebook API
Facebook’s Application Programming Interface (Facebook API) for open source development and crowdsourcing was used for the identification of places for location-sharing [6]. The Facebook database was chosen since earlier attempts to use the Foursquare database revealed a limited number of places comparatively. This database can be represented as a social graph, where nodes correspond to Users, Pages, Groups, Places and other objects and edges correspond to relations between nodes. The data requested by the API search engine was incorporated into the prototype, where the query is a place category, the type is a place, the centre is the point coordinates of the central location and the metric distance is the radius of the area to be analysed.

Place Visualisation
A requested Facebook Place profile contains an ID, name, category and geolocation consisting of WGS84 (World Geodetic System 1984) latitude and longitude coordinates. Further requests using the ID number provides additional cumulative data such as the number of “likes” and “check-ins” for a place. This data was retrieved on a JavaScript Object Notation (JSON) format that the prototype parsed and stored for visualisation tasks. The interface made use of the Unfolding Maps library [17, 18] to visualise a map of London as the background. This Processing library uses the same WGS84 coordinate system. Next, places were drawn on the map as circles whose radii correspond to mapped values of the number of “check-ins”.

Space Syntax Analysis
The prototype combined Facebook geolocation-based data with the spatial value of the urban space by incorporating NACH values as predictors of flow movement into the place profiles. The angular segment analysis was calculated with depthmapX [28], a software program currently in development at The Bartlett, University College London. It was visualised in the digital interface using an imported CSV file. Since this software works with the UK Grid Reference (OSGB 36), the data was translated to WGS84 coordinates.
Since this research is focused on pedestrians, the segment map was calculated with local radius $R=800m$. This radius is equivalent to a 10-minute walk, which is suitable for pedestrian flow analysis [1]. Normalisation was computed with the formula

$$NACH = \log(CH+1)/\log(TD+3)$$

where $NACH$ is normalised angular choice, $CH$ is angular choice value and $TD$ is total depth [16]. Colours simulating the space syntax manner of representation were used in the application’s visual interface. These range from red for more accessible streets to deep blue for less accessible streets.

**Nearest Street Search**

To add the spatial feature to each place profile, a perpendicular distance algorithm was implemented to find the nearest street to each location. The perpendicular distance was calculated with the formula

$$d = \frac{|ax_0 + by_0 + c|}{\sqrt{a^2 + b^2}}$$

where $d$ is the distance between a given point $(x_0, y_0)$ and a given line $ax + by + c = 0$ in a two-dimensional space [30]. The prototype calculated the distance between each location and each street in the system, then sorted the stored values to find the street where the place is located, and finally extracted the $NACH$ value of the street to add it to the place features.

**Place Graph**

To determine which places are the most visited and popular in an area, the application produced a list of the 20 places with the most check-ins on their Facebook profiles. A place graph was then visualised with the aim of assessing how the selected places are located in the urban structure. To build this graph, each place was connected to the five places on the list nearest to it. This new layer was visualised in the segment analysis, increasing the visibility of the spatial influence of this set of places in the area.

**Charts**

Finally, a scatter plot was used to show each place in terms of its mapped location in the NACH R800 scale of the area and to evaluate the potential correlation between number of check-ins and pedestrian accessibility of the street on which a place is located. In addition, two bar charts were included in the interface. The first chart displayed the number of places by category, with the aim of comparing land use in the studied area. The second chart included the same information but restricted the list to the 20 most-visited places to determine which place category can be considered the main attractor of social activity in the area.

The interface with all the aforementioned functionalities received the following inputs: the WGS84 coordinates of the centre of the area, the radius of the query and the user’s Facebook access token. The categories could be changed by the user of the interface as well (Figure 2).

**Figure 2.** The prototype interface.

### 3.2 Experiment

The application was tested with 15 London areas. To include high levels of social activity, areas surrounding the busiest tube stations were selected for this task [25]. The areas selected based on this criterion are: Oxford Circus (OC), King’s Cross St. Pancras (KC), Waterloo Station (WS), Victoria Station (VS), London Bridge (LB), Liverpool Street (LS), Stratford Station (SS), Bank & Monument (BM), Canary Wharf (CW), Paddington Station (PS), Leicester Square (LSQ), Piccadilly Circus (PC), Euston Station (ES), Green Park (GP) and Tottenham Court Road (TCR).

All of these areas have high social activity in terms of trade and catering services inside the buildings and in the surroundings. Some areas are important transport interchanges on a regional and national scale because they are railway stations as well (WS, VS, LS, LB, ES, PS, KC and SS). Others are located near some of London’s main tourist attractions, including Trafalgar Square (LS and PC), Bank Junction in the City of London (BM), Oxford Street (OC and TCR), Buckingham Palace (GP) and Canary Wharf business district (CW). Four place categories were retrieved in each area: three catering/entertainment categories – Restaurants, Pubs and Cafes – and a retail category. These categories were defined by the urban functions that depend on human movement, following previous space syntax research [13]. Facebook Place data was retrieved on 8th October 2015.

### 3.3 Study

Assessment of the approach was conducted by answering the following questions:

- **Spatial accessibility:** Do the results validate space syntax theory regarding the fact that catering and trade locations tend to be located in highly accessible streets? Validation was achieved by sorting NACH values into eight ranges to determine in which range places are concentrated.
Check-ins/NACH correlation: *Is there any correlation between the number of check-ins of a place and the spatial quality of the street where a place is located?* Linear regression was analysed in a scatter plot, where the x-variable was a set range of NACH R800 values and the y-variable was the number of Facebook check-ins.

Place categories: *What categories can be considered urban attractors according to the number of check-ins?*

Place categories were analysed to determine whether this approach is useful in terms of finding the most popular categories and places that play the role of flow attractors.

**4 RESULTS**

The approach presented in this paper was validated by answering the aforementioned questions: whether this combination of urban mobility data validates space syntax theory in regard to urban location of catering and trade; whether there is a correlation between number of check-ins and the spatial condition of a street according to NACH values; and the extent to which the interface is useful for analysing land use according to the most popular and visited categories and places within the studied areas.

**4.1 Spatial Accessibility**

A set of all the places retrieved from the London areas analysed in this study (S1) was sorted according to eight ranges of NACH R800 values: R1 (0-0.2), R2 (0.2-0.4), R3 (0.4-0.6), R4 (0.6-0.8), R5 (0.8-1.0), R6 (1.0-1.2), R7 (1.2-1.4) and R8 (1.4-1.6). Most of the places are located on streets with medium to high accessibility; 89% of places are located on streets with accessibility between R5 and R7, 28.1% are located on streets with accessibility in R6 and 44.5% are located on streets with accessibility in R7 (Figure 3). For the whole set, the average NACH R800 value is 1.1.

Figure 3. Number of places and percentage for each NACH range in S1.

Regarding the set of places comprising the 20 most-visited and popular places in each analysed area (S2), the graph shows that the trend is maintained, with 88% of places situated between R5 and R7. The highest concentration of places was shared by R6 (33%) and R7 (36.6%) (Figure 4). In this case, the average NACH R800 value was also 1.1. Since most of these well-visited places—according to the high number of check-ins—are located on streets with good accessibility, this raises the question of whether there is a relationship between users’ location-sharing activity and the spatial quality of streets.

Figure 4. Number of places and percentages for each NACH range in S2.

**4.2 Check-ins/NACH Correlation**

S1 and S2 were mapped onto scatter plots, where the x-variable was the NACH R800 value and the y-variable was the number of check-ins. Although the mapping showed a concentration of places between 0.8 and 1.4 (Figure 5), no linear correlation was observed between these variables in either set. The scatter plot revealed the existence of popular places located on streets with lower accessibility—0.0 to 0.8—corresponding to 8% for S2 (Figure 6). The next stage was to analyse the main place categories from the Facebook database.

Figure 5. NACH R800 values for each place in S1.
4.3 Place Categories

The analysis of place categories revealed that the areas with the most services are Leicester Square Station (849) and Piccadilly Circus Station (823), which are located near Trafalgar Square; and Tottenham Court Road Station (752) and Oxford Circus Station (691), which are both on Oxford Street, one of the main roads in London. The area with the lowest amount of retrieved places is Euston Station (226), which is located next to the residential area of Regent’s Park (Figure 7).

Table 1. Place categories in both sets.

<table>
<thead>
<tr>
<th>Category</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restaurants</td>
<td>10%</td>
<td>42%</td>
</tr>
<tr>
<td>Pubs</td>
<td>46%</td>
<td>45%</td>
</tr>
<tr>
<td>Cafes</td>
<td>20%</td>
<td>6%</td>
</tr>
<tr>
<td>Stores</td>
<td>24%</td>
<td>7%</td>
</tr>
</tbody>
</table>

5 DISCUSSION

This paper suggests that the incorporation of social media location-sharing data into space syntax analysis can contribute to the development of space syntax urban mobility research by combining Facebook check-ins and NACH values in the same interface. The findings from our assessment support the idea that catering and trade tend to be located on streets with high accessibility since most of these places (72.6%) are concentrated in streets with NACH values between 1.0 and 1.4. Place graphs also confirm that the most visited and popular places are located in streets within the same range in most cases. However, six places in S2—five bars and one restaurant—fall in R1, representing 2% of the whole set. Although this is a marginal percentage, it indicates that some popular places may be located in streets with low levels of accessibility and that these local attractors can be good places for location-sharing activity. Additionally, the absence of a direct correlation between number of check-ins and NACH values suggests that the syntactic measure of a street, or its spatial quality of being a receptor of human flow, is not the only feature that influences self-reported positioning in a social network.

Land-use analysis shows that the largest concentrations of places are located near two of the busiest areas of Central London: Oxford Street and the surroundings of Trafalgar Square. Both areas are well-known tourist and local attraction and thus exhibit high levels of social activity and interaction. On the other hand, the Euston Station area, next to Regent’s Park Estate, has the least services since it is located in a residential/commercial hybrid area. Land-use analysis also shows that the Pubs category has the highest number of retrieved places amongst the analysed London areas whilst the Restaurants category has the lowest number. However, analysis of place categories in S2 reveals that restaurants tend to be picked as places of location-sharing by Facebook users, nearly reaching the level of pubs. Thus, this approach supports the observation made by Hasan et al. [12] that catering and entertainment activities tend to concentrate check-ins in specific areas of the city. Another finding is that people tend to not often share their locations in stores and cafes. This suggests that whilst a store may not be a place where people gather in a socially interactive mood, a cafe may be a space that can harbour rich social activity but not enough to encourage customers to share their location with friends on a social network.
It should be noted that one of the main questions in the Big Data field is how to interpret large resources of numerical data in order to use them in research and practice. This issue raises questions regarding the limitations of check-ins as a measure of urban mobility. First, this data is associated with a limited population group. According to a survey carried out amongst a population of 2,252 American adults in 2013, although Facebook was the most preferred location-sharing service, only 12% of users share locations on it [32]. Second, some findings have discussed the motivations behind sharing one’s location on a social network. In particular, privacy and surveillance concerns and ethical considerations regarding the manipulation of user-generated data [19] can drive users to avoid generating digital content. Other contextual factors such as type of audience, kind of place and potential benefits of reporting locations have been considered as determinants for self-reported positioning activity [11]. In addition, certain features on user profiles can influence the generation of this data, such as cultural background, nationality, level of familiarity with a place, technical expertise and users’ sense of orientation [10]. Moreover, psychological aspects, such as a user’s level of self-disclosure and extraversion [29], that influence location-sharing actions must be taken into account. Thereby, other circumstances such as a place’s condition and importance and emotional traits of users can be added to potential factors for location-sharing and destination choice.

Another important limitation of this approach is the presence of ‘fake data’ and ‘ghost places’ in social media databases. The former are generated due to the tendency of some users to share locations and geotagged media content whilst they are actually far from these places. The latter are produced when places that are out of business still have a Facebook Place page included in the database. Moreover, some users create places with incorrect coordinates. A potential solution to address these issues is the implementation of filtering algorithms to separate reliable data from fake data. An effective procedure for this was described by Wu et al. [31].

Finally, since emotional and psychological implications may be involved in location-sharing and urban mobility, qualitative methods such as field observations, interviews, questionnaires and other empirical data can inform quantitative data mining. As Girardin discussed [10], quantitative data can reveal emerging and divergent behaviour that can be used to generate additional inquiries in regard to urban dynamics. Observation techniques and other qualitative assessments are a core part of space syntax analytical techniques and can complement Big Data analytics in efforts to ‘make sense of data’. In other words, we point out how the urban phenomenon can be perceived as both a global and a personal experience. Thereby, mixed methods have the potential to give meaning to large resources of numerical data.

6 CONCLUSION

This paper demonstrates that the introduction of social media data in space syntax methodologies has the potential to inform and enhance urban studies based on cognitive and geometric approaches to urban mobility. Early findings have indicated the potential of this approach for finding patterns of emergence in urban dynamics and of convergence and divergence between data-oriented spatial analysis and socially-oriented spatial analysis. This research, which takes into account the limitations of check-in data, supports the idea that eating/entertainment and trade activities are mostly located in well-connected parts of the urban grid but also implies the feasibility of adding social media data to space syntax analysis in order to raise new questions for space syntax research.

Our main contribution to the space syntax and urban mobility fields is how the combination of syntactic measures –NACH values as predictors of urban flow in streets– and social media data –check-ins as indicators of urban mobility and popularity– show that different aspects, including spatial and psychological aspects, are influencing how people select their routes and destinations in urban areas. It can be concluded that digital interfaces that combine these two spatial models can be useful for studying urban mobility and land use in cities. This approach emphasises the potential of connecting space syntax methods to large resources of location-based data and, in this way, evaluating theory under a new light.

Future work should focus on development of the prototype including: 1) the possibility of selecting other segment maps to work in different urban scales; 2) the introduction of the Like voting system, which can help analyse how some people’s choices are guided by recommender systems; 3) the integration of geotagged media content such as messages, photos and videos; and 4) the option to adapt the prototype to other social media platforms such as Twitter, Instagram, Flickr and others.

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REFERENCES


ARch4maps: a mobile augmented reality tool to enrich paper maps

Filipe Gaspar¹,², Steven Gomes¹, Ricardo Resende¹, Sara Eloy¹, Miguel Sales Dias¹,², Mariana Lopes² and Nuno Faria²

¹Instituto Universitário de Lisboa (ISCTE-IUL), ISTAR-IUL
Lisbon, Portugal, Portugal
stevenrmgomes@gmail.com, {jrpre, sara.eloy, jmd}@iscte.pt

²Microsoft Language Development Center
Lisbon, Portugal
{t-filipg, t-marig, Miguel.Dias}@microsoft.com

ABSTRACT
This paper describes an augmented reality app running on a Windows tablet that recognizes image features on a city paper map and overlays, in real-time, digital content related to the relevant buildings of the city. The system register in 3D the location of those buildings in the map, enriching the user experience with several multimedia information per building: image, text and 3D models which can be explored in detail in an included BIM viewer. Displayed buildings can be queried and filtered by associated meta-data such as decade, author, conservation, etc. The main target users of this system are tourists or users interested in architecture or history. Our usability evaluation study conducted with several users shown that our app increase the scope of applicability of a paper map.

Author Keywords
Augmented Reality; Paper maps; Mobile; Architecture; Tourism.

1 INTRODUCTION
Maps assist navigation to a pre-chosen place, as an exploration aid or to represent geographical information to support decision-making. From the onset of their use, maps convey several layers of graphical information (roads, cities, urban landscapes, orography, etc.), and are enhanced with non-spatial information through annotations, symbols defined in legends and, in some cases, even companion books. In the last decades, geo-referenced geographical information systems (GIS) have been driving the generation of maps, and have been enriched with meta-information which can be hidden or displayed, searched and correlated. Google maps, Bing maps and some other cloud based platforms are now ubiquitous on laptops and mobile devices and are extensively consumed via apps and browsers. Nevertheless, paper maps present advantages over digital versions. They allow a natural “zoom” as the user can focus in one particular area, which is especially useful in the field, thus many users are used to manipulating this traditional media (paper). Naturally, the information on paper maps contain is limited by existing space, book-maps can contain much more information, such as critical texts, fact sheets, photographs, historical and cultural features and technical drawings. They are, however, cumbersome to use and, in general, paper maps and books cannot be updated, just replaced.

This paper describes an augmented reality (AR) solution, referred to as ARch4maps, running on a Microsoft Windows tablet, that provides a hybrid paper-digital response to the problem. Using a computer vision technique developed in-house, we recognize, in real-time, features on a paper map and overlay geo-referenced digital content, such as 3D models representing the location of points of interest (POI). Using touch-based interaction on the tablet surface, a user can explore several modalities of multimedia information in each POI: images, text and detailed 3D models layered according their BIM classification (structural, architectural, infrastructural, interior design, etc). ARch4maps is able to display or hide each component, and explore the building in AR through different perspectives (by walking around the map with the tablet, or manipulating the map directly), cross-sections, plans or sections. Search and building selection by pre-defined criteria is also possible. In the implemented use case, buildings that won the Valmor award, a century old architecture award in the city of Lisbon have been integrated in our system. It is possible to search such buildings, by decade, author, conservation, possibility of visit, etc. We have carried a usability and satisfaction evaluation study of ARch4maps, with a panel of students of the Architecture master degree at ISCTE-IUL, interested in architecture history that concluded on the validity of our approach.

2 STATE OF THE ART
There are several guides and maps dedicated to architectural heritage, which is a very common tourist niche. In what regards paper guides for the city of Lisbon, we have the following. The Valmor and Lisbon Council prizes map (1902-2002) was used in this case study (Figure 1). With a dimension of 60x100 cm, on the front side it shows a map of the city with the buildings location identified by a number, letter and color code and, on the right side the basic information of the 115 works highlighted in the map: name of the building, prize, year, architect, location, nearest public transport and in some cases, images). On the flip-side of the map we have more information on the awards and building
descriptions and images, organized by decades. *Lisbon Architectural Guide* [2] is a 374 pages guide book presenting detailed information on relevant Lisbon buildings from 1948 to 2013. The large amount of information convey book-guides to be, less appropriate to use as an exploration aid within a reasonable period of time. *Argumentum Architecture Maps* [1] has a synthesized fashion map per each Portuguese district, similar to the Valmor, and the content is dedicated to the architecture audience. It provides building’s location, functions, history and architects.

Mobile apps may contain a practically limited amount of information in several formats, even without permanent web access, but are limited in their readability by the screen size. The *Architectural Guide Portugal* [6] iPhone/iPad app displays works from main Portuguese architects: Álvaro Siza Vieira, Souto Moura, Gonçalo Byrne, among others. Works are indicated using the users location and allows saving favorite works, search by area, author, and function. It is connected to TomTom and Google Maps. It also has an accompanying website and paper books.

### 2.1 Augmented Reality

Augmented Reality is a multi-disciplinary area of fusion between computer vision and 3D computer graphics that allows the 3D registration of computer-generated data in real world, usually overlay on real objects. This is achieved by performing instantaneous virtual camera pose (position and orientation) calibration, i.e., by computing, in real-time (for interactive apps), the virtual camera parameters that match the position and orientation of the observer or sensor (physical camera) in the real scene. Vision-based methods estimate the real camera pose relative to visually distinctive features present in greyscale, color or even map images [9]. In general, AR technologies provide the means for “intuitive information presentation, which enhances the perceiver’s situational awareness and cognitive perception of the real world” [4]. Several guides employ nowadays AR to help users locate remarkable buildings, both with the architecture and mainstream tourist users in mind. Wikitude is a framework that has been employed by a large number of mobile AR applications since it has several tracking technologies available such as GPS, WiFi, inertial sensors and image-based recognition [14]. Rewind Cities Lisbon is a mobile app that alerts the user which can then watch multimedia content overlaid on the city image captured by the camera in pre-determined places in Lisbon [5]. Archeoguide is an Augmented Reality-based Cultural Heritage On-site Guide that displays a 3D course in Mount Olympus with reconstructed images of the buildings [7]. In this paper, we build upon an existing AR app, referred to as ARch [11]. This app shows and manipulates 3D models of buildings in AR using a tablet with a built-in camera. The major novelty brought by Arch, is that it includes operations usually available in 3D CAD software for Architecture, Engineering and Construction, such as BIM model viewing and real-time cross-sections.

### 3 THE ARCH4MAPS APP

This paper describes an AR application running on a tablet that allows a user to superimpose location of buildings on a map, displaying additional information like digital 3D models, the building technical drawings such as their plans, sections and elevations, historical and cultural information. To this end, this app was designed to be informative, interactive and simple to use. The target audiences for this application are mainly tourists, architects and users interested in architecture. Two possible scenarios are: 1) two tourists seated in the cafe look into a paper map and want to know more information on interesting buildings nearby; 2) an architect/researcher wants to gather information from a paper map about awarded buildings in a specific decade or from a specific architect.

Figure 2 depicts the user experience common to both scenarios, in three steps. From these scenarios, we were able to derive the following user requirements for our app:

1) Identify the base map, or parts of it, as a visual marker to aid our AR engine in performing virtual camera pose calibration, in real-time;
2) Overlay the locations of the buildings on the correct position on the map;
3) Filter buildings’ on the map by several criteria: type of award, date of the award, architect name, building identification, possibility of visitation, conservation status; adulteration status;
4) Display available information about a building, chosen by the user when touching on a registered virtual point painted on the tablet screen. The information that can be displayed is descriptive text; plans, pictures, photographs or drawings.

![Figure 1. Valmor & Lisbon Council Awards 1902-2002 map](image1)

![Figure 2. Arch4maps’s user experience. a) Map identification; b) Click on building’s point; c) Overlay the 3D model on the map.](image2)
5) Benefit from the already available ARch features (BIM viewer, interactive cutting planes, etc.), which experience relies on touch interaction. Texture Tracking

3.2 Texture Tracking

We perform virtual camera calibration, to achieve AR, by means of a texture tracking technique which uses the physical map captured by the camera of the device, as a visual marker. Given that map images are usually rich in topology (lines and geometric elements) but poor in high contrast regions, we have selected Scale Invariant Feature transform (SIFT) [10] to detect, describe and match these regions and compute the virtual camera pose in the first video frame. SIFT uses a multi-resolution pyramid of greyscale images to highlight distinctive high contrast regions in several frequency ranges. These features are very appealing for AR, since they are invariant to rotation and translation changes, are tolerant to lighting changes, but are computation demanding. To achieve real-time AR we track SIFT features between contiguous video frames using Natural Ubiquitous Texture Tracking system (NUTTS) [3] which proven to be effective with planar natural scenes and recover lost features from previous frames using optical-flow, texture back-projection and image reconstruction. Once SIFT features are tracked, the 3D virtual models are registered in the real world, on top of the map, using the virtual camera pose estimated. Our method only need a few sparsely located known SIFT features (from a pool of hundreds usually available) which means that the map can be partially occluded thus allowing the user to pan and zoom in without losing tracking.

3.3 Functionalities and Interface

ARch4maps was developed and evaluated on a Microsoft Surface Pro 2 tablet with the following specs: Windows 8.1 Pro 64-bit; Intel Core i5-4200U Dual Core; 4 GB RAM; Intel HD Graphics 4400; SSD disk of 64 GB. The use of a tablet was the solution given the requirement to display several multimedia information including detailed building’s 3D models. The app interface was designed to allow the user to experience AR quickly and easily through natural right hand gestures (click, swipe and zoom) in the main part of the screen (right), while the left hand holds the device and clicks on the menu located on the left hand side of the screen (Figure 3). A short demo video of the application is available at http://istar.iscte-iul.pt/index.php/ProjectsAR. After the app is started on the tablet the camera is pointed to the map. The texture tracking module computes the virtual camera pose in each video frame, and the 3D locations of the buildings in the database are registered and shown on the screen, overlaid on their actual position in the physical map.

Search menu: displayed at left hand side and fulfilling the requirements defined in section 3.1, buildings can be searched and filtered by its name, architect, awards, accessibility status (entirely or partially) and conservation state (demolished, poorly preserved, acceptable or well preserved). For each search criteria, the user can select several options from a drop-down list. In the right hand side of the screen, buildings within the search criteria are represented by virtual sphere registered in building location in paper map’s coordinate system and scale (Figure 4, middle). The user can also perform compound filters. For example, one can look for buildings from the 1910-1920 decade in an acceptable state of conservation and that can be visited. Boolean logic is applicable to the filters, i.e., conditions can be operated with conjunction and disjunction. Multimedia menu: As the user selects a building on the screen by clicking on its corresponding virtual sphere, the building’s 3D model is registered in the center of the paper map via AR and a variety of multimedia content becomes available (Figure 3):

- Description, which displays a descriptive text;
- Drawings and Pictures, where the user browses through plans, sections, elevations, renders of the buildings or other associated imagery such as historical photos.

Other ARch features, namely, the 3D BIM visualizer engine where the user can explore in depth the building 3D model, perform interactive cutting planes, etc. ARch allows user to view the virtual building from all angles including moving the tablet around the map or by rotating the map itself. It is also possible to show, enhance or hide different components of the building (defined as a BIM model), such as its structure, walls and pavements, furniture or infrastructure. Finally, it is possible to observe the interior of the buildings through vertical and horizontal cutting planes, as shown in Figure 3.

4 USABILITY AND SATISFACTION TESTS

The app was submitted to usability and satisfaction evaluation study, with eleven participants, 91% of which aged between 21 and 35. The academic formation of the participants varied between practicing architects (4), students (4) and the remainder (3) had varied occupations. Most (10 out of 11) of the subjects travel and visit buildings regularly but their interest in such visits is “some” (7) to

Figure 3. ARch4Maps main features. a) Active filters on the left hand side and filtered building locations over the map on the right. b) Building’s photo navigation browser. c) 3D model of a building overlaid on the map. d) Vertical cross-section cut of a 3D model.
“high” (4). The relationship with IT was good for the majority (9) and three of the users have had prior experiences with augmented reality. After testing the app the subjects answered four questions with the answers being on a scale of one (No/Poor/Not likely) to five (Yes/Excellent/Certainly). Q1) The application makes the maps more informative? Q2) The application facilitates understanding of the information contained in the map? Q3) The application displays the buildings clearly through the 3D model? Q4) Would you use the application in the future? Analysis of the answers, displayed in Figure 4, shows 73% of the users reported that the app delivers much more information than the paper map, but only a smaller proportion reported that understanding of the conveyed information was extremely facilitated. A majority found that map utilization is improved a lot or significantly. Two in three users reported they would certainly or most likely use the application. Given that in some of the tests participants were subject to small system failures (tracking errors of the map), we think these numbers may improve when our tracking technique will be more robust to handle physical maps.

5 CONCLUSIONS

This work focused primarily on the definition of an app that allows users to take advantage of cities’ physical maps to increase the information provided via AR, enabling the visualization of buildings in an interactive and dynamic way. ARch4maps provides to the user the possibility to search and filter throughout several layers of multimedia information such as descriptive texts, pictures, technical drawings as well as real time interactive 3D models. Our customer satisfaction and usability evaluation on a map of Valmor and Lisbon Council awards through AR shown that most participants easily handled the application and were satisfied with its performance. This way, ARch4maps proved to be very capable in increasing the amount and type of information of the maps, while having the possibility of launching and manipulating buildings’ 3D models of buildings, which was very appreciated and considered to work well and transmit the reality of the building to the general public, which is not used to read plans and cross sections. We can thus conclude that ARch4maps has the potential to enrich both specialist and the general public with an interest in architecture and built heritage.

6 FUTURE WORK

Besides the fixing of minor flaws found in ARch4maps the informal comments obtained from participants in the user study allows us to prioritize some further work: 1) Addition of more multimedia content such as videos and biographical information about the architects and awards; 2) Integration of an geo-referenced sub-system such as Bing maps to allow the user to find the buildings and organize visiting routes; 3) Add a social and feedback component to the app (e.g. Facebook) allowing users to rate and comment the building; 4) Allow users to submit building’s related multimedia.

Finally, we are interested in augment outdoor map supports, usually placed in strategic point in cities, such as the popular maps made of ceramic tiles which are quite popular in Portugal.

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A Combining Approach of Visibility Analysis to Participate in the Urban Design

Ziyu TONG¹, Chao CHENG² and Bingqing KUAI³

¹Nanjing University
Nanjing, China
tzy@nju.edu.cn

²Institute of Architecture Design & Planning CO., LTD, Nanjing University
Nanjing, China
742015349@qq.com

³Nanjing University
Nanjing, China
616340679@qq.com

ABSTRACT
Visibility is an essential factor in urban design, especially within the scenic area. Viewshed analysis, a Geographic Information System (GIS) based method, is commonly used to evaluate the urban design. However, it's hard to be directly applied to aid the urban design in advance. The paper presents a approach to take an active part in the urban design with visibility analysis. A set of GIS-based spatial analyses are integrated to calculate the optimized height of buildings. The generated result could be used as the reference to guide the plan and design. It is significant to improve the rationality of the urban design. The paper introduced the case study of Lake Taihu Bay, China. The entire design process showed that the visibility analysis is an effective method in the project with complex terrain.

Author Keywords
Visibility Analysis; Urban Design; Viewshed Analysis; GIS.

ACM Classification Keywords
I.6.5 MODELING DEVELOPMENT

1 BACKGROUND
Visibility is an essential factor in urban design. Especially within the scenic area, the volume of the buildings will dramatically influence or even damage the natural landscape. Visual perception is an important means for controlling landscapes in urban design [1]. It has become a general technical method to evaluate the damage of the volume of buildings through visibility analysis [2, 3].

Geographic Information System (GIS) and spatial analysis technology have great advantages for the organization, management and analysis of the spatial data of urban scale. Viewshed analysis based on GIS technology is also a typical spatial analysis method, and has been widely applied to analyze and evaluate urban landscapes [4-7]. However, at present, the means of visibility analysis is mainly applied to evaluate design achievements, and it is hard to directly guide or be applied to design. Based on the practical experiences of urban design, this paper combines visibility analysis into urban design, and provides basis and judgment for urban design through the analysis, in order to raise the rationality of the design.

2 METHOD

2.1 Division of a Region According to Visual Sensitivity
In order to take active participation in design, we need clearer instructions at early stage, such as the classification of design areas. This paper brings forward the concept of visual sensitivity, and divides the areas through it. Visual sensitivity indicates the different influences on the visual perception of landscapes in scenic areas. In areas of high visual sensitivity, we shall try to maintain natural landform and topographic feature, and reduce artificial construction. In areas of low visual sensitivity, we may improve the development and construction, and raise the use efficiency of the limited land resources.

Visual sensitivity is mainly calculated by applying GIS-based viewshed analysis technology. By setting up important observation points in a scenic area and within a certain scope surrounding, a set of viewshed maps are calculated. Superposing the viewshed maps of all observation points, we can obtain the observation frequentness of any cell in the area through cumulative calculation [4]. The areas with a higher numerical value will have higher visual sensitivity.

2.2 Control of Building Height
Building height is an important factor affecting visual perception, and reasonable building height could achieve the balance of real estate development and landscape protection. In practical operation, simple and rigidly uniform index are usually adopted in the development of buildings in scenic areas, for example, all buildings don't exceed 6 floors or 24 meters. Such crude design technique cannot guarantee the reservation of landscapes, and will possibly induce the wastage of land resources. In the earlier research, we have obtained ultimate value of building height by constructing sight surface, and thus completed the control on building height [8]. Sight surface is the plane formed between observer’s route and target, and the height difference between the sight surface and natural terrain becomes the maximum value of building height (Figure 1).
Once building height exceeds this value, sightline will be blocked, and the visual landscapes will be damaged.

Figure 1. Using sight surface to calculate the building height [8]

In this research, we have further developed the rationality of sight surface construction. With the division of the region according to visual sensitivity, we may determine the observer’s route and the observed target more reasonably. Firstly, we picked up one area of high visual sensitivity, and extracted its boundary. Secondly, we carried out viewshed analysis with the boundary as observation route, and thus obtained corresponding viewshed area. According to the mutuality of sightlines, the areas are available to be observed from the boundary of high sensitive areas can also see these visually sensitive areas easily. Then we superposed the viewshed analysis result with the main roads in these areas, and obtained the observation grade of the roads. The road segments with high grade could be regarded as the preferred observation routes to this visual sensitivity area. Following the same procedure, each of high sensitive area could get a corresponding observation route.

By taking the observation route obtained through calculation and the boundary of the areas of high visual sensitivity as input conditions, we may construct sight surface in GIS. And by subtracting the landform, we obtain the corresponding building height control value. Through further classification, the building height control area could be reclassified, and be provided as the reasonable index applied in urban design.

3 CASE STUDY
In the urban design of Lake Taihu Bay in Changzhou, China, a practical project, we came across plentiful problems in terms of visibility control. In order to solve these problems, we applied combining visibility analysis method to effectively protect the natural landscapes.

3.1 Location
Changzhou-Taihu Bay is located at the northeast corner of Lake Taihu, one of China’s five largest fresh lakes, in the Eastern China (Figure 2). A series of mountain ranges is outspread along the banks of the Lake, and forms six bays naturally. The mountains and water set each other off, and form very beautiful natural scenes. An around-lake avenue passes through the mountains and water, becomes the main traffic artery of this region. The designed region covers a total area of 4km², and the shoreline along the lake is around 7.8km (Figure 3). In surrounding areas, the height difference between the vertex of mountains and the water surface is 177.5m. In the design, how to protect the natural landscapes in the precondition of real estate development and construction becomes an important judgment criterion for the completion of design. This also brings great difficulty for the design. In case of designing aimlessly, then conducting verification through visibility analysis, making further adjustment, and conducting re-verification..., we will achieve extremely low efficiency, and encounter many difficulties in operation.

Figure 2. Site of Changzhou-Taihu Bay

Figure 3. Satellite image of Changzhou-Taihu Bay (From Google Earth)

3.2 Determination of Visually Sensitive Area
The whole design area is relatively big, and involves relatively complicated scenic spots and observation routes, so the division of visually sensitive areas is beneficial for design.

In this case, we firstly divided observation points into long-distance view and short-distance view based on the clarity of observation.

Long-distance indicates 5km from the scope, which based on the visual recognition and visible distance during the
hazy weather. We take three observation points along the circle with a radius of 5km and the core of involved scope as center. The point on the south lake bank indicates the view along the road. The two points on the lake surface indicate the view from the cruise (Figure 4).

Figure 4. Long-distance view points and viewshed analysis result

Short-distance view mainly indicates the around-lake road sightline analysis. Because the landscape is perceived different by car drivers and by pedestrians [5], the short-distance view is divided into bicycle, automobile, and tourist. According to the three different behavior features, we selected different calculation methods and sightline direction settings. For bicycle sightline analysis, we set up the speed to be 15km/h, and obtained one observation point every 10s. Along the around-lake road, we set up one observation point at every 40m for viewshed analysis (Figure 5a). For automobile sightline analysis, we set up the speed to be 30km/h, and obtained one observation point every 10s. Along the around-lake road, we set up one observation point at every 85m for viewshed analysis. In addition, automobiles drive quickly, and drivers’ sightline scope is restricted, so horizontal visual angle restriction shall be added according to the driving direction of automobiles for the viewshed analysis. In the present case, taking driving direction as central line, we analyzed total 120-degree horizontal visual angle. Considering different driving directions, we carried out viewshed analysis as per the back and forth directions for every visual point (Figure 5b). For tourist sightline, we selected four most important scenic areas within the scope, and carried out viewshed analysis by taking the central point of the four scenic areas as visual points (Figure 5c).

Figure 5. Short-distance view points and viewshed analysis results. The darker area means higher visual sensitivity.

By superposing the results of far-distance view analysis and three short-distance views analysis, we obtained visual sensitivity analysis diagram. Wherein, areas of higher numerical value have more opportunities to be observed, and have higher visual sensitivity; the areas of smaller numerical value have fewer opportunities to be observed, and have lower visual sensitivity (Figure 6a). By picking up the areas of highest sensitivity, we can define the zones unsuitable for construction (Figure 6b).

Figure 6. Analysis of the visual sensitivity

3.3 Determination of Regional Control of Building Height

Based on the division of visibly sensitive areas, we extracted the boundary of corresponding visually sensitive areas, divided it into segments according to its winding condition, and obtained a series of visual target segments. Then, we carried out viewshed analysis on each visual target segment once again, superposed them with the road along the lake, and obtained corresponding observation route sections (Figure 7).

Figure 7. The visual target segments and their corresponding observation route sections

By connecting the observation route sections and visual target segments, the sight surface was constructed. And by superposing the surface with the terrain, we got the building height control area of each target segments. By superposing the results of analysis on building height control of all target segments, we took the minimum value as the building height control value of the area.

With Xiangshu Bay in the design scope as an example, the figure 8 shows the whole analysis process and results. The maximum height permissible of the buildings in the area is
21m. Meanwhile, some areas are prohibited for any building construction.

The research is based on the views shed analysis to construct the combining visibility analysis method. However, GIS-based views shed analysis itself still has great limitations, including the negligence of the range of visibility, and the vertical dimension of terrain. Raising the accuracy of views shed analysis could further improve the rationality of urban design.

It is important to stand out that this study is still a work in progress and, therefore, the results and conclusions here presented are still preliminary. The analysis on the factors affecting visual effect is not comprehensive enough, and the research on the control indexes and methods of building density is not completed yet. All these will be further developed in subsequential research.

4 CONCLUSIONS
Visibility analysis has decisive functions for controlling landscapes in urban design, especially in the scenic areas. The case of Taihu Bay urban design project shows that, compared to design assessment, the combining approach of visibility analysis presents more clearly defined conditions for design, effectively raises the efficiency of design, and makes the maintenance of landscape resources more definite and more purposive. The application of combining visibility analysis method is an active design strategy.

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Automated prediction of preference level by artificial neural network for simple geometry

Josef Musil
Czech Technical University
Prague, Czech Republic
jmusil@fosterandpartners.com

Samuel Wilkinson
swilkinson@fosterandpartners.com

ABSTRACT
This paper provides an overview and analysis of research-in-progress and thought-provoking work on user preference simulation-based design tool. This tool automates prediction of aesthetic preference levels for a simple abstract geometry. An artificial neural network is trained on a random sample of interactively user-evaluated geometries and creates a user preference profile. This profile is then used to automatically generate a new geometry that would theoretically be preferred by all users with different profiles. This saves time and avoids user fatigue compared to interactive genetic evolution. The tool is implemented as an online tool running in a web-browser. In this paper we will present the relationship between the artificial neural network and the genetic algorithm that are used for interactive creation of a preference user profile to stimulate further research in the area of preference level prediction and automation.

Author Keywords
Preference levels; machine learning; generative design; prediction; design decision tool; artificial neural network; genetic algorithm.

ACM Classification Keywords
I.2.5. Programming Languages and Software: Expert system tools and techniques

INTRODUCTION
Implementing user aesthetic preferences into an automated optimisation process of current architectural design is highly desirable. User preference selection is usually the last step of a process that optimises architectural design for multiple criteria.

High numbers of design variants are generated rapidly and need to be further evaluated. Having user preference a part of the automatic process reduces the number of models needed to be further evaluated and also allows for algorithmic implementation of multiple different user preferences. ‘Preference’ is here understood as the most probable choice between multiple variations of a design based on aesthetic appeal. Although quantifying or even rationalising a person’s aesthetic preferences can be complex, it is possible to identify trends with pattern recognition algorithms such as machine learning.

Finding intersection between multiple trends in different profiles predicts a geometry that is preferred by all the corresponding users. As architectural design involves evaluation from multiple users, this tool can also facilitate finding the compromise solution among multiple opinions.

BACKGROUND
Two main existing methods are studied on preference integration. The first approach is an interactive evolution [2, 1] that uses human intervention in a genetic algorithm (GA), as the fitness function is not known. The main drawback is that the number of evaluations received from one user is limited by user fatigue and that human evaluation is slow. The second approach is fitting user preferences using a regression function [7].

There is a recent interest in algorithmic understanding of the relationship between content and artistic style. This has been shown on training an artificial neural network on selected paintings in a novel way [3, 10, 4]. Other works show generating user preferred geometries based on interactive genetic algorithm [5, 8, 9]. However, more research is needed to focus on increasingly complex architectural geometry and the requirements of such a design guide tool in practice.

Here fitting user preference of simple geometries is seen as a regression problem with real-valued evaluation. Artificial neural networks (ANN) are trained to predict different user preferences and a GA generates a new geometry while using these ANNs as a fitness function and maximizes the sum of their predictions. This tool is prototyped as an online tool (http://josefmusil.altervista.org/aestimator/index.html) running in a web-browser and allowing for online collaboration.

Artificial neural network
ANNs are a matrix of interconnected ‘neurons’ configured into input, hidden, and output layers. The input layer consists of parameters defining the problem (here the geometry) and the output is a real-valued parameter to be learnt (here the preference level). The weights of the hidden layer neurons

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can be adjusted from their initial random value until the output values correspond accurately with the input parameters. As such, ANNs can be used for approximating or predicting unknown functions of theoretically arbitrary complexity, regardless of the underlying system.

**Interactive genetic algorithm**

Genetic algorithms (GAs) are stochastic search heuristics or optimisation algorithms which use successive ‘populations’ of candidate solutions which encode the input design parameters as the individual ‘phenotype DNA’. By an iterative process of inheritance, mutation, selection, and crossover, the population converges towards an optimal solution.

An interactive GA uses human input in the fitness evaluation stage and belongs to a more general category of Interactive Evolutionary Computation (IEC). The main application of these techniques include domains where it is hard or impossible to design a computational fitness function, for example, evolving images, or artistic designs and forms to fit a user’s aesthetic preferences.

IEC or aesthetic selection is a general term for methods of evolutionary computation that use human evaluation. The number of evaluations that IEC can receive from one human user is limited by user fatigue. In addition, human evaluations are slow and expensive as compared to fitness function computation. Hence, one-user IEC methods should be designed to converge using a small number of evaluations, which necessarily implies very small populations.

**WEB-BASED TOOL**

Here user fatigue is overcome by using the interactive human evaluation to teach ANN by a smaller number of samples and use this trained ANN then to automatically evaluate a large number of design options generated by a GA.

Firstly random geometries are generated and multiple users have to evaluate them with a real number between 1.0 (most preferred), and -1.0 (least preferred). These values are stored and used for supervised learning of ANNs. Actual geometry is generated by a marching cubes algorithm [6] with fixed strength and radius. The default number of blobs is 7 and each has an x and y parameter within an interval of 0 and 1. The whole geometry has thus 14 parameters by default. When evaluated, these parameters are stored and used as an input vector for the ANN and the stored evaluation is the desired output of ANN after regression. Each ANN has two hidden layers with 14 neurons in each layer. Hidden neurons have a sigmoid activation function and stochastic gradient descent method is used for teaching.

In the second step a GA generates a new geometry that all users would, hypothetically, evaluate as most preferred. It thus combines multiple user preferences and can be integrated with optimisation for other criteria. Also it overcomes the constraint of interactive evolution where users would have to evaluate excessive number of variants. The GA uses a population of 20 genomes, each genome represents 14 x and y parameters in a series x0, y0, x1, y1... The fitness function is a sum of all ANNs predictions which the GA tries to maximize.

**Interactive user interface**

The upper half of the tool running in a web-browser shows a 3-dimensional scene with the generated geometry. This scene is interactive and allows users to rotate, pan and zoom this geometry. That helps the user to better understand it and evaluate it. The left graph in the bottom half of the web-page shows data collected from both users during the evaluation process and outputs from both ANNs for this training data. The right graph shows the fitness value of the best genome across all generations produced by genetic algorithm.

The program is controlled by a graphic user interface in the top right corner (Figure 6). Users can change the number of control points used for the marching cubes algorithm. This changes the number of neurons in the ANN correspondingly and is twice the number of control points (as each point has two parameters x and y coordinate). Parameter timeEvalStep changes the time given for evaluation in seconds and when new geometry is generated and shown. Each user then has a slider with values between -1 and 1 to evaluate that geometry. Additional buttons are used to start and end the training for each of the two ANNs. Learning rate can be set at the beginning of this process. The last buttons start running the GA and has an option to either show all the interim geometries or only the best one to speed up the process.
Usage example
A simple design example is described to demonstrate the functionality of this design decision design tool. A generation of a hypothetical non-functional form is shown. Two users train the ANNs by interactive evaluation of marching cubes geometry based on 7 control points. Figure 2 shows initial setup of ANNs. The bottom left image shows ANN trained for User 1 and the right ANN shows preferences of User 2. The actual geometry shows the first evaluated image from User 1.

Thirty five percent of evaluation was used for validation of ANNs. Figure 3 shows the result after running GA with predicted maximised positive evaluation of both users. In Figure 4 you can see how well the ANN approximates the input data of both users. This graph shows details of fitting of the training data. Figure 5 shows how the GA gradually maximizes the predicted evaluation for both users, which in this case is a value of 2 (as a sum of two users evaluating both up to 1).

DISCUSSION
It is expected that generic preferences from different users can be stored and reused on multiple projects. User preferences are stored as weights and thresholds of ANNs and thus loading these values will rebuild this profile. On the other hand if a new project would benefit from predicting preferences on different features, a new profile can be generated from scratch.

The aim of this tool is integration of user preferences earlier on in the design process and pursues this by automating it. The methods are two-fold: interactive evolution and regression functions. Preferences are described by an unknown function that is unique for each user. While the tool finds one best solution to demonstrate its functionality, further research is suggested to be done on multiple outputs. In this case the
tool gives a whole range of best solutions and further live input is expected. This gives an option at the very final stage of the design process to break a fully automated system and introduce a direct user input.

The results show that the ANN has a good approximation of user evaluation. With careful selection of training data that samples well the whole design space of all input parameters, the ANN can correctly predict design variations. Integrated into automated design process optimising for multiple other criteria, this approach can speed up the way of getting towards preferred forms in a more fluent process.

Potential impact of this work goes even further. Eventually having a user preferences profile and putting this in relation to other persons characteristics could trigger an interesting question of how to predict these individual preferences based on those characteristics only.

**Known system limitations**

High dimensional space explored randomly does not give ideal design space exploration and leaves certain parts, especially boundary conditions unexplored. More sophisticated semi-random search and progressive search based on previous answers will be explored in further research.

The use of control points and the marching cubes algorithm results in very simplistic geometry, which perhaps means it is difficult to have a preference for individuals. To allow this tool to be used on a real world project, the framework established here needs to be extended to geometric complexity more realistic in practice. This would naturally lend itself to parametric or procedural models where users would have the ability to define all design features and have a direct integration with their preferred modeling software.

**ACKNOWLEDGMENTS**

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**REFERENCES**


ABSTRACT
The design and construction of a building is inherently complex and a myriad of decisions must be made during the design and planning process. No single stakeholder (architect, client, building physicist) has complete knowledge and visibility of the consequences of each decision and each stakeholder group is driven by different objectives.

Those aspiring to construct low-energy buildings, and Passivhaus in particular, are subject to numerous constraints, relating to building performance, site restrictions and planning policy (amongst others) and seemingly innocuous small changes to the design can divert decision-makers from their aims.

Multi-criteria decision making provides a method of attempting to satisfy numerous, often conflicting objectives, in order to reach the ‘optimum’ solution, and therefore provides a means to combine these varied goals. Existing research in the sphere of building performance simulation often focuses on its application to quantitative criteria.

This paper proposes incorporating stakeholder preference modelling in multi-criteria decision making by first analysing stakeholder goals, to gain a greater understanding of their motivation and decision paths, within the context of Passivhaus construction in the UK.

Author Keywords
MCDM; Decision Support; Passivhaus

1 INTRODUCTION
Under the terms of the Climate Change Act 2008, the UK has a legal obligation to reduce CO₂ emissions by 80% by 2050 [7]. Improved building performance is crucial to achieving this target, given that the construction and operation of buildings is responsible for half of the UK’s CO₂ emissions [20]. This sits within the wider European context of 40% of emissions originating in the construction sector [5]. In response to this issue, the Energy Performance of Buildings Directive requires all EU member states to ensure that all new buildings achieve “nearly-zero energy” status by 2020, with a deadline of 2018 for publicly-owned buildings [4].

As the de facto standard for energy efficient building, Passivhaus offers a potential solution, since standards are independently set by the Passivhaus Institute and hence not subject to international differences in building standards or the vagaries of changing government policy [10]. It has clearly-defined constraints for successful certification, covering targets for peak heating/cooling load, annual heating demand, primary energy consumption and frequency of overheating [10]. Buildings constructed to the Passivhaus standard are of particular focus in this study.

The tools and methods offered by Multi-Criteria Decision Making (MCDM) have a clear application in this context. Building design is a complex process, involving multiple stakeholder groups, all of whom make key decisions which impact on the building performance. The design and construction of buildings is subject to multiple objectives, ranging from energy efficiency and indoor air quality requirements, through to more subjective aspects, such as architectural aesthetics. Often the pursuit of one criterion can be to the detriment of another, for instance, designing to minimise heating demand may compromise aesthetics, particularly when retrofitting heritage properties [19]. Hence, there are trade-offs between competing criteria.

2 METHODOLOGY
A literature review of stakeholder decision-making in the design process was conducted and used to inform the development of a stakeholder goals matrix. This research is in the very early stages and will ultimately form part of wider consultations, by using a case study to examine the preferences of stakeholder groups relating to a specific building design.

3 LITERATURE REVIEW
Two elements are reviewed in relation to stakeholder preference modelling and its role in MCDM: the use of subjective measures in MCDM and the role of different stakeholders in the design process.

3.1 Applying MCDM to Subjective Measures in BPS
Much work has been done on the application of MCDM methods to the quantitative aspects of building performance [9, 10, 17, 22]. However, little research has been completed on how subjective aspects, such as aesthetics, can be incorporated alongside technical measures in MCDM [8].
Furthermore, BPS is often used to verify compliance to regulations [12], rather than to inform decision making. Hence, the purpose of BPS is not to offer design ‘solutions’, but to aid understanding by providing users with outcomes of potential design choices. It is hypothesised that, users need a more developed, easy-to-use, tool to aid multi-variate decision-making in a timely manner, with clearly-defined levels of accuracy. The wide-ranging criteria for performance and ubiquitous issue of uncertainty both serve to add to the complexity [3].

3.2 Design Process and Stakeholders
In the UK, the Royal Institute of British Architecture (RIBA) defines the design lifecycle using their Plan of Work. Although it is designed with the UK in mind, it is indicative of the construction process in other countries. Within this structure, there is scope for flexibility; pre-application discussions with planners may take place during stages 0 and 1 and a planning application may be submitted as part of stages 2, 3 or 4. Similarly, finance may be sought at any point during these stages. The key stakeholders at each stage are illustrated in Table 1.

<table>
<thead>
<tr>
<th>RIBA Design Stage</th>
<th>0 Strategic Definition</th>
<th>1 Preparation and Brief</th>
<th>2 Concept Design</th>
<th>3 Developed Design</th>
<th>4 Technical Design</th>
<th>5 Construction</th>
<th>6 Handover and Close Out</th>
<th>7 In Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stakeholders</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Planner</td>
<td>Client Occupant</td>
</tr>
<tr>
<td></td>
<td>Planner</td>
<td>Engineer</td>
<td>Builder</td>
<td>Engineer</td>
<td>Builder</td>
<td>Builder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Financer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Design Stage Stakeholders (derived from RIBA 2013)

Architect: Clearly, the role of architects is apparent at every stage in the design process, hence, they have a key role in ensuring effective continuity of communication [18].

Client: A client may be a social housing provider, such as a housing association, a private individual or a property developer, each of whom will have differing priorities and levels of experience. Understandably, inexperienced clients can find the design life-cycle a source of concern, due to the lack of familiarity, as well as socio-technical reasons. Architects might be well-advised to use visual approaches to aid comprehension and help fill the void in client understanding [14].

Building Physicist: In the context of Passivhaus, the specialist role of the building physicist focuses on ensuring that the design satisfies energy efficiency criteria. Amongst other aspects, the building physicist is concerned with the magnitude of passive solar gains, which have an impact on the heating demand. Hence, building density will be a concern, given the potential for over-shadowing from neighbouring properties [23].

Planner: Planning decisions in England are governed by the National Planning Policy Framework, which covers a wide range of criteria, including aesthetic and heritage concerns. Specialist technical knowledge is not part of their remit; that lies in the domain of building regulations [2]. In a survey of the adoption of the CASBEE sustainable building standard in Japan, it was found that the majority of local authorities employed no accredited professionals [21]. Hence, they were unable to make an independent assessment and were influenced by elected officials, rather than industry professionals. This situation may cause a “vicious circle”, whereby an absence of knowledge in the local authority, leads to a lack of public awareness and without wider knowledge of low-energy building, demand will stagnate [21].

Builder: Knowledge shortages have been identified as a barrier to builders delivering improved standards in the construction of low-energy building [6]. Achieving the airtightness target is essential to Passivhaus accreditation, therefore, attention to detail in the implementation of a design is vital [10].

3.3 Research Questions
If the UK is to reduce CO2 emissions by retrofitting homes, then a more holistic approach is needed, which takes into account the link between CO2 emissions reduction and the importance of incorporating aesthetic and heritage aspects [19]. Furthermore, despite its potential to tune building performance, BPS is rarely used as a decision support tool, due to usability issues [12].

The research so far raises some pertinent questions:

- To what extent are the goals of client synonymous with those of the owner or occupant? Whilst a property developer will bear in mind the purchasers’ needs, they do not necessarily share their priorities; similarly, the objectives of a buy-to-let investor do not necessarily align with those of a tenant or those of an owner-occupier.
- To what extent does a client’s choice of architect dictate success in Passivhaus construction?
To what extent does the decision-making process differ in Passivhaus compared to conventional construction? Can the Passivhaus paradigm be considered as a microcosm of the construction industry in general?

4 RESULTS & DISCUSSION
Following the initial literature review, a number of themes emerged, which resulted in the development of a stakeholder goals matrix, a subset of which is illustrated in Table 2.

<table>
<thead>
<tr>
<th>Capital Cost</th>
<th>Client</th>
<th>Planning</th>
<th>Physicist</th>
<th>Architect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetics</td>
<td>[12]</td>
<td>[1, 19]</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>Building Density</td>
<td>[1]</td>
<td>[23]</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>[15]</td>
<td>[13]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>[6, 15]</td>
<td>[12]</td>
<td>[16]</td>
<td></td>
</tr>
<tr>
<td>IAQ &amp; Thermal Comfort</td>
<td>[13]</td>
<td>[10]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Building Design Stakeholder Goals

There is a semantic difference between a goal, as opposed to an incentive, a driver or a benefit; some benefits of Passivhaus are only fully appreciated upon occupancy, such as improved thermal comfort and indoor air quality [10]. Conversely, capital cost might be perceived as a constraint or indeed a barrier, rather than a goal, particularly in the context of Passivhaus.

4.1 Sectoral Differences
It must be noted that, the priorities differ somewhat between the different sectors (self-build, social housing and commercial developer) and according to whether the project is a new build or a retrofit. Whilst some goals are universal (for instance clients’ desire to minimise capital cost) others vary between sectors. For instance, housing associations are motivated by minimising the cost of maintaining a property; whereas builders viewed the increased cost of building low-energy homes as a disincentive [13, 16]. In the UK, there are mixed findings on house-buyers’ attitudes to energy efficiency, with the Office of Fair Trading (OFT) report of 2008 stating that 19% of people chose a new build home based on their perception of better energy efficiency, compared to existing buildings, whereas, Heffernan et al note that the criteria of price, size and location dominate the decision process for home-owners [6, 15].

4.2 Roles & Influence
In some instances, there is overlap between the stakeholder groups, for instance the role of the “hybrid practitioner”, who has knowledge spanning the domains of architecture and building physics [12]. In most cases, the owner is not a direct stakeholder in the design process; whereas, in the self-build sector, the client will also be the owner and occupant, and in some instances the financer [15]. Some stakeholders have a more central role than others, hence their influence will be more significant; a failure to communicate crucial information to the relevant stakeholder in a timely manner causes poor decision-making; hence an architect’s role in co-ordinating project data is central to project success [14].

4.3 Interaction Between Qualitative and Quantitative Variables
Incorporating energy efficiency measures can impact the spatial quality of a building. Focussing on a non-technical benefit provides a different stimulus for motivating a decision-maker; for instance, changes to the percentage of glazing on a building façade impacts the spatial quality and the view, as well as the energy performance. Furthermore, perception, rather than reality often guides decisions, an aspect which is illustrated by building density, where proximity to other buildings, building height and street width impact perception [1].

5 FUTURE WORK
This research aims to address the research gaps highlighted in the literature review by incorporating stakeholders’ preferences and including all stakeholder groups.

- Sensitivity Analysis
- Uncertainty Analysis
- Filter & Progress with most significant parameters
- Derive Visual Display of Results
- Incorporate Stakeholders’ Preferences
- Apply MCDM Methods

Figure 1: MCDM Prototyping Approach

Both qualitative and quantitative measures will be included in an MCDM model and, eventually, this model will be used to analyse the extent to which a decision support tool
might be used to inform better decision making, in the context of Passivhaus.

The future of this research will incorporate MCDM in the prototyping process as outlined in Figure 1.

The next step will be further refinement of the stakeholder goals matrix to group goals under unifying themes, for instance: property developers’ motivations might be largely governed by “financial expediency”, which covers capital cost and building densities.

To conclude, subjective aspects are key factors in decision-making in the building design process. Whilst it is difficult to put a value upon them, their impact on building performance can be significant.

Hence, there is a need to incorporate qualitative preferences in MCDM to reflect stakeholders’ opinions, if UK construction is to achieve its share of carbon emissions reduction targets [8].

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Objective Driven Design Tool in Support of Early Phase Architectural Design

Bruno Lee¹, Tze Chun Lam¹, Hua Ge¹ and Michael Jemtrud²

¹Concordia University
Montreal, Canada
bruno.lee@concordia.ca

²McGill University
Montreal, Canada
michael.jemtrud@mcgill.ca

ABSTRACT
Building energy performance simulation tools are commonly deployed as post-design evaluation tools. The one-to-one relationship between the inputs and performance results discourages users of simulation tools from exploring the impact of their architectural design decisions on building energy performance. During early design phase, effectively comparing design alternatives supports better decision making than precisely evaluating building performance. This paper presents a design tool that enhances the building design process by offering an on-demand visual performance comparison to support design decision making. The proposed design tool is a pre-simulated performance database driven visual design tool that is based on visual basic programming platform. The design tool offers a user friendly interface with reduced number of inputs such that the designers can have a holistic understanding of the performance impact due to different design options.

Author Keywords
Simulation and Design theories; Big Data; Building Performance Simulation; Graphical User Interfaces.

ACM Classification Keywords
D.2.2 DESIGN TOOLS AND TECHNIQUES;
H.2.8 DATABASE APPLICATIONS

1 INTRODUCTION
Green building rating systems such as LEED [5] and BREEAM [2] do promote the use of computational whole building energy simulation to evaluate energy performance of buildings. However, in a conventional building design workflow, energy performance of buildings is commonly specified according to the recommendation of design guidelines [1, 3] for many of the design options (e.g. energy saving potential of installing insulation at a certain thermal resistance value). Following recommendation based on individual design options works reasonably well for office buildings based on the assumption that there are universally accepted “best” design option (e.g. higher thermal resistance) regardless of the operation.

For office buildings, where operational variations are mainly occupant behavior driven, the impact of design options is not at all comparable to that for other building types, such as industrial halls, where operational variations are mainly process load and occupancy schedule driven. In such cases, under greater and discrete operational variations, the “best” design option for a particular operational scenario may not work well for another scenario. Moreover, to achieve a high energy performance requirement, the designers often have to evaluate a number of design options. However, choosing an appropriate combination of design options is not as simple as summing up the effect of a few design options, which individual option supposedly offers performance improvement. Lack of a systematic way to explore combinations of design options will lead to at best, missed opportunities for performance improvement; or at worst, design pitfalls fall short of performance. It is important to the building designers to have a holistic view of the performance of the design options. Performance based design is one of the design paradigms that achieves the design goal with a comprehensive evaluation of the quantifiable performance of interest.

Computational whole building energy simulation tools facilitate the execution of a performance based design. However, designers often have to carry out multiple design iterations until a satisfactory performance is achieved. Moreover, performing building simulations requires lots of input data, which in most cases, are not readily available at the early design phase. This lack of information discourages designers to explore design alternatives, not to mention, perform multiple design iterations. At the early design phase, such a detailed analysis is at all not contributing since the resulting evaluation, though detailed, is based on input data, which more often than not, made up by assumptions with great uncertainty.

In fact, current simulation tool offerings serve mainly as post-design evaluation tools rather as design aids. That is, a simulation tool helps evaluate the performance of a design, but does not facilitate the exploration of different design options. On the other hand, a true performance based design approach shall offer building designers, at the early design phase (with limited knowledge of specifics and details of the building), a means to:

- unbiasedly, exploring different design options.
- effectively, identify design options / design option combinations that satisfy the performance requirement.
The proposed objective driven design tool fully supports a performance based design approach that starts with a performance requirement and ends with building design solutions. This is the opposite of the aforementioned current simulation practice where design is made before the performance is evaluated. The proposed design tool enhances the building design process by offering an on-demand visual performance comparison to support design decision making through exploring the many design possibilities and their corresponding performances in a convenient way. The proposed tool is demonstrated by a case study of industrial halls for their rather extreme and distinct operation characteristic.

2 THE CASE STUDY
Industrial halls studied in this paper can be characterized as single-storey, large floor area, rectangular structures, which are commonly built in suburban industrial settings in Europe and North America. The interest of this paper is the operational energy design (e.g. heating, cooling, lighting) and not the activities (e.g. manufacturing processes) of the buildings. Industrial halls, which are of simple geometry and construction methods, are best suited to demonstrate the proposed design tool, since design parameters related to the energy performance of industrial halls are much less than those of office buildings.

There could be many possible design parameters. However, as discussed, one of the barriers to performance based design is the availability (with uncertainty) or unavailability (lack of information) of too many inputs at the early design phase. Sensitivity analysis is an effective means to significantly reduce the number of inputs without affecting the energy performance results. Through sensitivity analysis with Partial Rank Correlation Coefficient (PRCC), six most influential design parameters have been identified and listed in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design Range</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation (Thermal resistance, Roof)</td>
<td>1.5 – 4.5 m²K/W</td>
<td>7</td>
</tr>
<tr>
<td>Insulation (Thermal resistance, Wall)</td>
<td>1.5 – 4.5 m²K/W</td>
<td>7</td>
</tr>
<tr>
<td>Construction Types (Roof)</td>
<td>Steel or Concrete</td>
<td>2</td>
</tr>
<tr>
<td>Construction Types (Wall)</td>
<td>Steel or Concrete</td>
<td>2</td>
</tr>
<tr>
<td>Skylights (as % of roof area)</td>
<td>0 – 15 %</td>
<td>4</td>
</tr>
<tr>
<td>Transpired solar collector (as % of south wall)</td>
<td>0 – 100 %</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1. List of influential design parameters with their design ranges and resolutions.

They are the insulation values of the roof and walls, construction types (steel or concrete) of the roof and walls, skylight coverage and transpired solar collector coverage. In fact, the PRCC is -0.350 for the least influential design parameter being studied in this paper (construction type of walls) whereas the PRCC is 0.007 for the most influential one not been studied (surface reflectance of walls). Table 1 presents the studied design parameters with their respective ranges and resolutions of the investigation.

Steel sheets are assumed to have no thickness and no thermal resistance. Concrete is assumed to have a thickness of 0.2 m with a density of 2400 kg/m³, a thermal conductivity of 2.1 W/m-K, and a thermal capacity of 1 kJ/kg-K. For newly built industrial halls, steel and concrete constructions can be considered as quite airtight with infiltration mainly coming as a result of opening doors, which is more of an operation issue. A constant infiltration rate of 0.2 ACH is assumed [22].

3 CONVENTIONAL DESIGN PRACTICE
Under conventional design practice, design trend of a particular design parameter is quite commonly observed. Figure 1 presents a design trend that illustrates the interdependency of heating, cooling and lighting energy consumption due to daylighting. As the skylight coverage increases beyond 15% of the roof area, increase in energy consumption due to heating and cooling more or less cancel out the reduction in lighting energy consumption.

For an investigation of large number of design parameters, such as that presented in Table 1, a design trend shows how the performance changes with respect to different values of the design parameters.

4 PROPOSED DESIGN TOOL
With current simulation tool offerings, the aforementioned design trend is the typical results of an energy investigation. The building designers are left with no choice but to select
the design options that seemingly yield the desired performance level as indicated by the design trend. The role of the building designers is limited and designers are only involved in the final selection process.

Moreover, the single objective investigation of energy discussed so far might lead to yet another type of bias since the design solution fulfilling one objective, most probably, is the worst case in another objective. In a multi-criteria design decision making, the design solutions always exhibit a trade-off. It is up to the building designers to select the solutions according to their preference. The concept is illustrated in Figure 2. In his recent paper, the first author presents a design space exploration approach that facilitates the decision making process by enabling the building designers to identify the building designs according to the desired performance levels for the studied criteria, namely, minimizing energy and carbon emissions, and maximizing cash flow [4]. The data visualization aid developed in that paper forms the basis for the proposed design tool.

Workflow of the current simulation practice:

![Workflow of the current simulation practice](image)

Workflow of the proposed design tool:

![Workflow of the proposed design tool](image)

**Figure 2.** Conceptual workflow of the proposed design tool as contrasted to the workflow of the current simulation practice.

In fact, the generation of the aforementioned design trend already involves comprehensive coverage of the design space and extensive simulation work. It is only the mindset of the current simulation practice and the unavailability of an appropriate visualization tool that preclude the execution of a true performance based design. Based on the availability of a large set of energy performance data for the many design solutions, this paper proposes a dynamic design tool that interacts with the building designers according to their performance needs. This design tool is based on Microsoft visual basic programming platform. It is meant to facilitate the design process. The tool offers a user-friendly interface such that the designers could take full control of an interactive design process.

### 4.1 Development of the Design Tool

The proposed design space exploration approach offers a comprehensive database of energy performance. Based on previous definitions of performance indicators; carbon emissions and cash flow are both derived performance indicators and are evaluated through post processing of energy performance data. At their assigned ranges of values and resolutions, the six design parameters presented in Table 1 result in 4,704 different combinations following a full factorial design space exploration. Some combinations perform poorly in both energy and carbon emissions, while some combinations yield negative cash flow. There are 192 Pareto solutions (trade-off solutions that cannot be improved in one design objective without worsening another design objective). In fact, there are quite many design option combinations that yield very similar performance in all three performance aspects. Out of those, there are similarly configured combinations and there are also quite drastically different combinations. The latter combinations are of particular values to the designers since they allow the designers to opt for alternative designs and yet to maintain the same desired performance.

### 4.2 Demonstration of the Design Tool

The proposed design tool of this paper presents a way to explore all combinations, with very similar performance, freely without being constrained by the tool. Figure 3 presents the user interface of the design tool. Based on the users’ preference on level of performance in each of the performance aspects, namely, energy, carbon emissions, and cash flow, the users can select the level of performance with the respective slide bar.

The resulting radar chart presents all the six design parameters at each of the corners with smaller values at the center to larger values on the outermost ring. The design solutions (different combinations of design options) that fulfill the users selected levels of performance are bounded by the largest possible values (blue line) and smallest possible values (red line) of all six design parameters.

To demonstrate, an example is made for a typical steel building in, with both roof and wall having a thermal resistance value of 3.5 m²K/W and with no TSC or skylights installed. Such a steel building design yields zero cash flow and has an energy consumption of 51 kWh/m²-yr, and a carbon emissions of 19 kg CO₂/m²-yr. The evaluation process described here is exactly the current practice to carry out a simulation based on a design (in this case, a typical steel building with well-defined specification).

The question is, if the predicted performance level is exactly what the designers want, is there any other design solution that will yield very similar performance? Figure 3 demonstrates how the design tool works. By positioning the slide bars to the corresponding performance levels, the design solutions bounded by the largest and smallest values of each design parameter are presented on the radar chart. For this particular example, design solutions are those with a roof insulation value between 2.0–4.5 m²K/W, a TSC coverage between 0%–100%, together with values of the other four design parameters. All these design solutions fulfill the desired performance requirement.
Figure 3. User interface of the proposed design tool.

5 RESULTS AND DISCUSSIONS
As demonstrated in Figure 3, the proposed design tool offers designers the flexibility, and more importantly, the control to select the design solution of choice. Within the bounded area, the designers indeed have the flexibility in finding alternative design solutions that could achieve the same desired performance. With the design tool, the designers can explore the whole space in a holistic manner.

Figure 4 represents an environmentally conscious design with a very low energy consumption of 37 kWh/m²-yr, and carbon emissions of 15 kg CO₂/m²-yr, but a negative cash flow of -0.75 euro/m²-yr. Such environmentally conscious design can be achieved through a variety of design option combinations. A steel roof deck is required, but it can be on either steel or concrete walls. Wall insulation can be flexible, but roof has to be highly insulated. 15% coverage of skylights is required, while more than 50% coverage of TSC is recommended. There are some flexibilities in wall construction, but no flexibility in roof construction. With the design tool, the designers are able to make informed decision by knowing where the flexibility is.

This example illustrated that through the exploration process of the design space, the designers gain better understanding on how their design decisions impact the performance. In fact, with the flexibility and ease of use of the interface, the designers are encourage to explore the whole objective space freely.

6 CONCLUSION
This paper identifies the issues in current design practice by demonstrating with notable example, the pitfalls in following single objective design trend recommendation, and ignoring the interdependency of design parameters.

Based on issues in current design practice and the fact that there is a lack of information at the early design phase, an objective driven (performance data driven) design tool is proposed. The design tool is built upon a pre-simulated performance database, which reference [4] provided an extensive explanation on the approach. The proposed design tool enable users to:

- explore the design space without bias
- identify design solutions based on desired performance
- consider alternative solutions with similar level of performance

The design tool offers a true performance based design workflow. Its applicability to the design of industrial halls is demonstrated. Future work shall investigate its applicability to other building types.

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ABSTRACT
This study conveys novel ideas of an open platform for urban design by showcasing a student architectural design competition. We set up an experiment that opens the whole process of the competition on the web not just for archiving submissions but for facilitating interactions between participants by sharing their interim results. The site consists of fifteen plots and a participant can choose one of those plots. Participants were asked to submit their design proposals with 3D models on the web-based urban simulation platform in three phases. Most interestingly, they were asked to assign a context set, a list of other participants’ projects to which they referred as their prospective neighborhood. This paper reports the strategy of this experimental open competition and the process of developing the open platform. Focused on the interim interaction between participants on the context reference network, we speculate social impacts of the constructive conversation among urban design actors. At the end, we discuss about lessons of collaborative creativity in urban design where diverse decision drivers simultaneously cultivate civic environment.

Author Keywords
Context Reference Network, Urban Design, Open Competition, Open Source, Collaborative Creativity

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g., HCI): User Interfaces. J.5 Computer applications: Arts and Humanities

1 INTRODUCTION
Design competition is a popular format for provoking new ideas and actively engaging people from diverse domains. It promotes public awareness of the matter and demonstrates a vast range of the possible solutions for the target problem. At the same time, it offers opportunities for young professionals to propose fresh ideas and to implicate those into the given condition. In order to magnify such benefits, recently, world-class architecture competitions have attempted to open all the entries and a part of decision process on the web publicly during the competition period [2, 3]. In result, they could establish public dialogues and reputations in an innovative way, since contents went viral over SNS. Even though the new paradigm of open competition is emerging [2,6,8], the authoritative role of jury dominates review process, and the participatory channel for an applicant is quite limited besides passive public voting.

This study conveys novel ideas of an open platform for design competition by showcasing an experimental project related to Junglim Architecture Awards. In 2015, we set up an experiment that opens the whole process of the competition on the web not just for archiving submissions but for facilitating interactions between participants by sharing their interim results. It also embraces the notion of participatory urban planning, which are deeply related to contemporary architectural practice [1,7].

This paper presents prototype development of the open platform and describes strategies of evaluation and expected impacts that will frame out new standards of collaboration.

2 THE DESIGN COMPETITION
The Junglim Architecture Award is one of the best renowned student competitions in South Korea. The topic in 2015 was ‘Porous City’, which encouraged to examine a low-rise and high-density development as well as a mixed-use approach.

2.1 Key Challenges
Site Paradox: Motivation for Sharing
The site is located in Kaesong, a historic city of North Korea. Due to political situation, it is almost impossible to visit the site in person. More seriously, the site information is extremely limited. Ironically, we only can reach there virtually through global crowd-source GIS platform. We anticipated that such a condition would boost participants’ motivation for sharing, since it may be beneficial if the whole community can share collective information.

Compete vs. Collaborate
The site is divided into 15 different plots (Figure 1). Participants should assign one of 15 plots, and each plot could be occupied by up to 20 teams. In other words, participants competed with others who were in a same plot as well as in neighborhood. In the competitive situation, it is difficult to determine a proper level of collaboration [4,6]. Nevertheless, we encouraged participants to autonomously share ideas and opinions, which would affect
own design process and attitude responding to the surrounding context.

Figure 1 The site: plot numbers and its adjacency network

Procedural Reviews
The most significant challenge is how to intervene procedural results. Participants were asked to submit their work-in-progress concepts by phases, and all other participants, jurors, and even general public could browse and give comments on them.

2.2 Basic Logistics
Throughout the competition, participants made online submissions three times and jurors monitored online activities and scored design proposal to select semi-finalists. Over 200 entries were registered, and 166 entries participated for the phase of online submission and it ended up 119 entries at the final phase. After the online period, 10 semi-finalists gave in-depth public presentation and discussion with more traditional materials such as posters and physical mock-ups, with all compiled materials they had been submitted online.

3 DEVELOPING AN OPEN PLATFORM
Two major issues emerged for developing an open platform; the first is technical feasibility, and the other is operational integration of the competition process. We developed an online submission system with 3D urban viewers, and set up an orientation session for participants and regular monitoring sessions for jurors in order to promote collaborative participation.

Figure 2 Timeline of the competition

3.1 Main Features of the Online Submission System

Collective 3D Urban Viewer
A 3D model is the best way to deliver architectural ideas. The embedded 3D urban viewer powered by Google Earth enables a user to navigate and explore all submitted design proposals and the context.

Project Cards with Social Dialogues
The project card list is assorted by plots and versions of the design phase. The card expands to detailed description and direct links to 3D model and participants’ comment conversations.

Context Set
Participants were asked to designate a Contest Set - a list of other participants, which they presumably considered as surrounding context of their proposals. This is the most unique feature that combines dynamic urban phenomenon as an in-situ condition of the site.

Versions
A user can track three versions of a design proposal by design phases.

Figure 3 A sketch of the online submission system interface
3.2 Education for Preparation
At the orientation session, we covered not only technical tutorial but also intensive conversation on ethics of sharing. Participants communally comprehended that the intellectual property issue could be critical in sharing premature ideas, as well as benefits of sharing.

3.3 Jury Review Process
During the online submission period, jurors tolerantly observed and regularly discussed about online activities in order to give feedbacks if necessary. Even though the ultimate evaluation focused on architectural interpretation of urban porosity, it became a critical mission for jury to determine the impact and potential of the open platform. Despite of compelling potentials, we pursued only qualitative evaluation for participant’s social impacts at this time.

4 PRELIMINARY ANALYSIS OF CONTEXT REFERENCE NETWORKS
In this preliminary study, we intended to extend capabilities of analysis on context reference networks between participants in order to introduce more intriguing evaluation criteria. We can extract meaningful data which enables reasoning the participant’s social actions in design process. For instance, from the context set data, we apply network analysis to examine the influences, and to characterize the types of interactions throughout the competition.

4.1 Plot-to-plot relationship
When we asked a context set as a prospective neighborhood or their own reference, the only restriction was that they could choose only one neighbor in one plot. A participant could select just one neighbor which is the most influential, or could take multiple neighbors. It turned out that they consider 6.9 neighbors in average as a context.

As a piecemeal approach, the interrelationalship between plots could be initially inherited from locational circumstances of the plot. Nevertheless, compared to the adjacency network from a given condition (Figure 1), dynamics of plot-to-plot context reference network was vary as shown in Figure 5 & 6. The popularity of plots was various, and thus, statistical characteristics can imply diverse social influences. For instance, participants did not tend to prefer inner blocks - plot 7, 10, 11, 12, however likely referred as their context. The least preferred plot 15 for plot choice turned out the most influential plot.
rank had been contributed sophisticated site analysis at the beginning. Majority of participants expressed their gratitude, referred to it, and continued conversations and shared their analysis. On the other flip, there were a quite amount of self-referenced entries.

4.3 Interactive Information for Assessment
We can suggest an interactive diagram that links all the complicated data together for mediating assessment endeavor, since cross referencing of complex consideration is important for evaluation. Locational surroundings, decent architectural design, and social contribution are all interwoven as if it happens in real world urban design. All the information could be linked within this network.

5 DISCUSSION
This paper reports an early stage of open competition experiment. We still remain a considerable rage of works such as in-depth analysis of context reference network, jury’s UX design supporting decision making, user study design, feedback loop development, and etc. We will utilize the framework that this study showed as an initial ground in order to continue examination of collaborative creativity supported by urban simulation.

Even though we dealt with a case specific study of open platform at this time, it intrigues more generic questions of competition and collaboration in architectural industry and urban planning domain. In the complex context of contemporary city, participatory design that engages multiple domains of knowledge in local issues becomes more and more important. The synergic framework that sustains both competition and collaboration based on social capital will support an ultimate and mutual winner for all.

As for a student centered event, the pedagogic notion of open competition is noteworthy. Open competition facilitates the situated learning opportunity. Ethics of sharing and communicative attitude are imperative quality especially for youth and young professionals who will lead future dynamics in the era of sharing.

As this preliminary study illustrated, more systematic and interactive methods to evaluate contents are technically feasible. Once we develop and deploy them into design process, we anticipate to track and rebuild the design decision and rationale more comprehensively.

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Elif Erdine
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Rethinking Conceptual Design: Computational Methods for the Simultaneous Integration of Tower Subsystems

Elif Erdine

Architectural Association (AA)
School of Architecture
London, United Kingdom
elif.erdine@aaschool.ac.uk

ABSTRACT
The paper describes the computational methodological approach of a recently completed PhD thesis. The principal argument is the demonstration that the initial phases of the long and complex chain of design development can be shortened by the designer working in the computational environment of a typical laptop. The design domain is the Tower, and emphasis is on developing a generative system of design that offers simultaneous integration and differentiation throughout the subsystems of a concept for a tall building during the conceptual design phase. In this framework, the functional parameters of the tower system are incorporated with principles of biological models. Tower subsystems are grouped as the structural system, floor system, vertical circulation system, façade system, and environmental system. The paper focuses on the principles and structure of the Processing algorithm developed according to the rules of the key methodology, multi-parameter integration. Global constraints pertaining to each subsystem and the overall system are described, followed by the structure and operational logic of each subsystem’s classes. Correlations which encompass several subsystems simultaneously are presented. Finally, evaluation of the output model is presented via progressive Finite Element Analysis (FEA) procedures in order to illustrate how each subsystem influences the structural behavior of the tower.

Author Keywords
Tower; Integration; Processing; Object-Oriented; Agent-based system; Multi-agent system.

ACM Classification Keywords
D.1.5 OBJECT-ORIENTED PROGRAMMING; I.6.5 MODEL DEVELOPMENT (e.g. Modeling methodologies); J.2 PHYSICAL SCIENCES AND ENGINEERING (e.g. Physics); J.3 LIFE AND MEDICAL SCIENCES (e.g. Biology)

1 INTRODUCTION
The research presented in this paper formulates the computational approach of a recently completed PhD thesis. It is witnessed that the high level of complexity encountered in the initial phase of tower design is not managed in its entirety by establishing connections between multiple design parameters which have the potential to control the performance of several tower subsystems, revealing that presently there is partial integration of tower subsystems during the conceptual design phase. The tower is selected as the building type for research, since from an architectural and engineering point of view, building form, vertical circulation, and building systems function very differently in a tall building than low-rise buildings. In this respect, the research focuses on the incorporation of the functional parameters of the tower system with principles of biological models in order to propose computationally generated dynamic systems for the tower typology. The principle aim is to achieve simultaneous integration of tower subsystems which can coherently adapt to their internal and external context during the initial phases of the design process. In this framework, the tower subsystems are grouped as the structural system, floor system, vertical circulation system, façade system, and environmental system.

Initially, various design parameters obtained from previous research on current tower subsystems and selected biomimetic examples are grouped into functional parameters, geometrical parameters, and topological parameters so that the focus is on convergence and integration. Design parameters are integrated with a hierarchical approach where interdependencies across multiple tower subsystems arise on a multitude of levels. The purpose of employing generative form-finding simulations is to analyze how design parameters that are conventionally regarded to serve one sub-system can converge and operate across various subsystems concurrently. This property presents the potential to incorporate multi-functionality for each tower sub-system during the design process. Moreover, the employment of form-finding simulations introduces a dynamic quality to the design process, since the iterative character of conventional design processes, whereby subsystems are usually designed independently from each other, is replaced by the simultaneous creation of all tower subsystems, hence providing feedback for each other’s formation processes and performance.
The initial phase of the research has investigated the distinct properties of each tower subsystem, focusing specifically on their performance-based capacities as a response to external and environmental conditions [1]. Furthermore, subsystem integration techniques currently in architectural practice have been examined [2]. This stage of the research has led to the conclusion that the differentiation of material organization in the tower system has been limited to one subsystem only, the load-bearing structure. As such, tower structural systems have developed with single objective optimization. Other performance-related capacities, such as circulation, facade, and environmental aspects, have developed independently of the material organization of the tower structure. Moreover, the tower structure has become devoid of responding to the spatial differentiation that takes place within, acting merely as a homogenous container. It has not responded to the changes and shifts in its programmatic diversity, which in effect influences circulation, façade-related, and environmental differentiation. This additive approach, where each subsystem is considered as a separate layer, results in the inefficient use and development of the tower material organization. It is necessary to explore and learn from existing systems which are capable of integration, multi-functionality, and co-adaptation, hence the biological paradigm has been selected to research how such notions are realized in living organisms.

Throughout the research, the aspects of multi-functionality and co-adaptation are articulated with the investigation of specific biological models in nature. The biomimetic analogies are the mechanical and organizational properties of branched constructions [3], the mechanical properties of the bamboo stem [4], and the microstructure of the porcupine quill/hedgehog spine [5]. The main motive behind selecting these natural structures is their shared property of increasing buckling resistance against environmental factors by self-organizing their material arrangement via certain geometrical rules [6]. Moreover, the quality of multi-functionality is observed through the achievement of geometrical differentiation to the same material organization across vertical and horizontal axes. The methodology formulated by design parameters lays the foundations for a new integration approach, termed as multi-parameter integration, where the focus is set on the convergence of multiple design parameters simultaneously. Biomimetic analogies formulate the principals of geometrical behavior mechanisms, which together with motion behavior mechanisms establish the geometrical parameters of the devised methodology. Geometrical behavior mechanisms are inscribed in the data structure of various agent systems, each of which is responsible for generating a tower subsystem. The output model combines key properties of the biomimetic principles with geometrical and mathematical descriptions in order to devise a differentiated tower formation where the discrete subsystems behave in an inter-dependent manner.

2 COMPUTATIONAL APPROACH

2.1 Global Setup

There are various principal rules and feedback mechanisms which operate across all the classes in the Processing algorithm [7]. First of all, it must be stated that each of the
five subsystems of the tower system is generated as one class or a cluster of classes (Figure 1). The numeric values of the starting parameters for the simulation have been selected after a series of initial experiments that take into account slenderness ratio, size of circulation system, and Net Floor Area (NFA) [8]. The vertical circulation agent system, the interior structure agent system, and the exterior structure agent system are generated in the initiation of the code as independent classes. The parameters which pertain to these agent systems in the initiation of the code are the base radii of the exterior and interior agent systems (22 meters and 16 meters), the radius for each vertical circulation agent group (3.5 meters), the overall height of the tower (300 meters), the floor height (4 meters), and the number of agents for each agent system (40). The circulation agent class then initiates the circulation node class and the floor slab agent class. The floor slab agent class in turn initiates the floor node class. As such, there is a linear flow from the circulation agent class towards the circulation node class, the floor slab agent class, and the floor slab node class. The interior structure agent class initiates the interior structure node class, while the exterior structure agent class initiates the exterior structure node class. The interior and exterior structure agent classes together initiate the outrigger agent class as well as the interstitial slab agent class. As the exterior and interior structure agent classes are activated independently from each other, the outrigger agent class and the interstitial slab agent class are formed as a result of the feedback relation between the exterior and interior structure agent classes. The interstitial slab agent class consecutively initiates the interstitial slab nodes. The exterior structure node class initiates the façade agent class, which in return initiates the façade node class.

The principal geometrical behaviours of the interior structure agent system and the exterior structure agent system follow flocking and bundling / branching algorithms. There is a feedback mechanism between the circulation agent class and the interior structure agent class, whereby if the interior structure agents flock towards the circulation agents more than a specified distance, they need to flock away. In this way, a certain distance can be kept between the vertical circulation system and the interior structure system. In a similar fashion, there is a feedback mechanism between the interior structure agent class and the exterior structure agent class such that if the exterior structure agents flock towards the interior structure agents more than a specified distance, they are prompted to flock away.

The floor agent system is generated according to flocking and bundling / branching rules. The formation of the outrigger system follows the geometrical rules of the vertical section of the bamboo stem. Correspondingly, the generation of the interstitial slab system takes place according to the geometrical rules of the bamboo stem and the porcupine quill / hedgehog spine.

Finally, the creation of the façade system takes place in response to the density levels of the exterior structure agent system as a result of bundling / branching rules acting on the exterior structure. The general outputs of the Processing code are the exterior structure, interior structure, vertical circulation elements, floor slabs, outriggers, interstitial slabs, and façade, collectively constituting the tower system. Figure 2 portrays the complete set of tower subsystems generated via the Processing algorithm, while Figure 3 depicts the generation process of tower subsystems in a more close-up perspective.

2.2 In-Depth Computational Setup

The structural system combines the principles of the formation of branching structures, geometrical rules of bamboo stem, and the microstructure of porcupine quill / hedgehog spine. Consequently, the structural system is conceived as a double-layer configuration which is inter-connected on certain levels in order to generate a dense circumferential “fibrous” geometrical organization. The exterior and interior structure agent systems are instigated directly in the main initiation of the code as two separate classes. Each agent system has common private methods which regulate flocking behaviour.
Starting from value 0, as the height of the agent reaches increments of the floor height parameter, a new node in the agent’s trail is generated. As the nodes carry on attributes and methods of particle-spring systems, it is now possible to create real-time dynamic interaction between them. At this instant, the mathematical description of minimal detours system as a function of proximity is applied to the nodes in their respective classes. If the nodes are within a maximum neighbouring distance to each other, then a force which bundles them together is created. This force is applied until the distance between the nodes reaches a minimum amount specified as a parameter. Additionally, a maximum amount of bundling force is determined as a parameter in order to limit the strength of bundling. The calculation of this force is time-based, during which the particle-spring system reaches its resting position. The parameters of the minimal detours system applied on the exterior and interior structure nodes can be varied according to the height of the nodes or other external factors, such as the position of the sun.

The vertical circulation agent system is initiated in the main initiation of the code. A tall building is generally divided into a number of lift zones corresponding to its height, where each zone is served by a certain sized group of lifts. Each lift group normally serves 15-18 floors. For buildings above 50-60 storeys, the possibility of serving all floors directly from the ground floor becomes ineffective, due to the increasing size of the lift core on the lower floors; therefore, it is reasonable to introduce sky lobbies which can be served by express lifts [9]. Accordingly, as the overall tower height for the selected experiments is 300 meters, a sky lobby is introduced on 40th floor, corresponding to 160 meters. There are a total number of 8 lift groups in the tower, 4 of which are located below the sky lobby, and 4 of which are located above the sky lobby. The lift groups can be arranged in a centralized or dispersed arrangement, and the radius for each lift group is 3.5 meters. Each lift group serves 10 floors; therefore, their heights are multiples of 40 meters.

The vertical circulation agent system moves vertically simultaneously with the exterior structure and interior structure agent systems. During this process, the circulation agent class produces its circulation nodes for every floor level. Figure 4 depicts the formation of interaction levels between the exterior structure agent system, interior structure agent system, and vertical circulation agent system. In Figure 4.A., as the flocking of the three agent systems takes place, interaction occurs only between the interior structure agent system and vertical circulation agent system. If the interior structure agents approach circulation agents more than 10 meters, a repulsion force is applied to the interior structure agents. In Figure 4.B., interaction is added in between the exterior structure agent system and interior structure agent system. If the exterior structure agents approach interior structure agents closer than 7 meters, a repulsion force is applied to exterior structure agents. The repulsion behaviours prevent the three agent systems from intersecting with each other, a condition which could potentially create problems to the structural stability of the overall system. In Figure 4.C., repulsion behaviour is differentiated according to the vertical position of the agent systems.

Figure 5 depicts in more detail how the behaviours of the exterior and interior structure agent systems alter according to the positioning of the vertical circulation agent system. In Figure 5.A., the vertical lift groups below and above the sky lobby are positioned centrally. In Figure 5.B., the vertical lift groups below and above the sky lobby are positioned in a dispersed fashion. The distance between the lift groups is 7 meters. In Figure 5.C., the vertical lift groups below the sky lobby are dispersed; the vertical lift groups above the sky lobby are centralized. This diagram demonstrates how the overall form of the tower is altered in relation to the different positioning of the vertical circulation system, since according to the feedback mechanisms in-between the vertical circulation agent system, interior structure agent system, and exterior structure agent system described above, the interior and exterior structure agents need to adjust their positions during flocking.
As the interaction levels between the exterior structure agent system, interior structure agent system, and vertical circulation agent system are established, more attention can be given to the variations of the bundling algorithm which takes place on the exterior and interior structure nodes during flocking. Figure 6 depicts design alternatives which are achieved with bundling behaviour. Figure 6.A. shows homogenous bundling along the vertical axis of the exterior and interior structure system. The minimum bundling distance is 2 meters, and the maximum bundling distance is 4 meters. In Figure 6.B., bundling of the exterior structure takes place according to the distance of the exterior structure nodes to a point located outside the tower. This point can represent the location of the Sun on a certain day throughout the year. The exterior structure nodes which are only affected by bundling are the ones closer than 1.44 meters, which is calculated as the distance between the normalized node vector and normalized point vector. In Figure 6.C., bundling of the exterior and interior structure nodes is differentiated according to height.

The outrigger system is generated simultaneously as the exterior and interior structure nodes are created, as an individual class inside the interior structure node’s class (Figure 7). The outrigger system generation is analogous to the geometrical principles of the bamboo stem section [10]. The bamboo stem is comprised of internodes and nodes. The stem itself is a hollow cylindrical shell along which the nodes correspond to the internal diaphragms, described as transversal connectors located throughout the height of the bamboo stem. The diameter of the stem changes slightly at the nodes, which also function as location for new growth.
The association of the internode heights along the vertical axis of the bamboo stem is reflected in the creation of the outrigger system. As the lateral loading condition and the weight from gravity is highest at the base of the stem, the internode heights at the base become shorter than the mid-height. As such, smaller internode heights increase moment-carrying capacity and buckling resistance. Above the mid-height of the culm, the internode heights decrease once more in proportion to the internode diameter as a reaction to increasing lateral loads. The equations which describe the correlations between the internode number, internode length, internode diameter, and wall thickness of the bamboo stem are abstracted in the Processing algorithm.

The floor system slabs is a direct outcome of the interactions between the interior structure nodes and the vertical circulation agent system. The main motive behind the generation of the floor slabs is to create all possible connections in-between the circulation agents themselves and between circulation agents and interior structure nodes in such a way that the connections create a minimal detours system and they do not cross over each other. As such, it is expected that the floor slabs, vertical circulation system, and the interior structure system complement each other in a geometrical and structural fashion, while topologically establishing associations which stay unchanged in spite of the continuous differentiation of the exterior and interior structure systems. The original position of the floor slab agents is identical to the position of the circulation nodes. When the slab agent system is instigated, slab agents begin flocking towards the perimeter of the tower structure with a defined velocity. As the major aim is to generate a minimal detours system on every floor level without creating any self-intersections, a special method which is based on the proximity between the slab agents and circulation nodes is applied. When all the interior structure nodes are connected to the slab agents through springs, the floor slab agent system completes its course (Figure 8).

The interstitial slabs are analogous to the stiffeners of porcupine quill / hedgehog spine and they generate the interstitial spaces between the exterior and interior structures. The interstitial slabs are created by linking each interior structure node to the closest exterior structure node located at the same height. In this way, it is predicted that the interior structure, interstitial slabs, and exterior structure will contribute to each other’s structural performance. Following the discussion on floor slabs, the topological relations formed by the interstitial slabs between the interior and exterior structures remain unaffected by the differentiation within the double-layer structure system. When the interstitial slab agent is within a certain distance range from the exterior structure node, a spring is formed between the interstitial slab agent and the exterior structure node, concluding the motion of the interstitial slab agents (Figure 09).

The façade system generation rules.

The façade system should allow for varying levels of transparency along the vertical axis in order to establish comfort inside the habitable areas, at the same time ensuring that it possesses structural and passive environmental performance attributes. In this respect, the objective in creating the façade system is to form lateral inter-connections within the exterior structure system so that the overall tower system can resist lateral loading and other environmental forces in a differentiated manner. Façade agents’ position corresponds to the location of the exterior structure nodes. Façade agents are connected to each other diagonally according to various proximity rules. The areas of the external envelope, where the distance between the exterior structure nodes is high due to bundling, are populated with more diagonal façade ribs. As such, the differentiation of the exterior structure system is directly reflected in the differentiation of the façade system (Figure 10).
The output model is characterized as a fibrous formation with a certain level of redundancy. The condition of redundancy is viewed as a positive feature rather than a disadvantage, since one of the key mechanisms observed in natural structures is the trait of robustness as an outcome of redundancy. In nature, redundancy is a strategy for supplying additional capacity in order to enhance performance and adaptation to environmental conditions, leading to the robustness of the organism [11]. As such, in contrast to the conventional method of engineering efficient solutions with a limited quantity of materials chosen for specific functions, it is argued that multi-parameter integration can lead to the emergence of multi-functionality, differentiation, and co-adaptation throughout the tower system due to its inherent qualities of redundancy and robustness.

3 EVALUATION PROCESS
A metric has been developed for measuring the level of integration on the overall performance of an example of design output via progressive Finite Element Analysis (FEA) conducted in McNeel Rhinoceros Grasshopper’s plugin Karamba [12] in order to calculate the changes in the structural behaviour as each subsystem is introduced to the overall tower system (Figure 11). FEA analysis has been chosen as the primary method to analyse the changes in the performance of the tower system as a result of the implementation of multi-parameter integration, since the most essential condition which the tower needs to fulfil is its structural performance. The structural analyses are conducted as beam analysis, whereby the linear elements generated via real-time generative form-finding techniques in Processing are treated as beam elements with specific material and cross-section properties. The first step of FEA analysis is conducted on the structural subsystem which comprises the exterior structure, outriggers, and interior structure. In the second step, the vertical circulation subsystem and floor slabs are added to the configuration. The interstitial slabs are added in the third step, and the façade subsystem is added in the fourth step. From the first till the fourth step, the beams of each subsystem has a constant cross-section throughout the height of the tower. In the fifth and final step, the cross-sections of various subsystems are altered according to their vertical position in the tower.

Every step of the FEA analyses is conducted with two materials, steel and carbon fibre composite [Table 01, Table 02]. In this way, the performance of the tower can be evaluated not only in relation to the amount and distribution of beams, but also in relation to the choice of material.

| Young’s Modulus | 20,000 kN/cm² |
| Shear Modulus   | 6,667 kN/cm²  |
| Specific weight | 78.5 kN/m³    |
| Yield Strength  | 22.5 kN/cm²   |

Table 1. Material properties of steel.

| Young’s Modulus | 15,000 kN/cm² |
| Shear Modulus   | 5,000 kN/cm²  |
| Specific weight | 17.65 kN/m³   |
| Yield Strength  | N/A           |

Table 2. Material properties of carbon fiber composite.

Several conclusions can be drawn from the FEA analyses in relation to the structural performance of the tower and the ways in which it can be improved. First of all, the comparisons between steel and carbon fibre composite cases illustrate that the choice of material is critical. Due to the fibrous nature of the tower system, steel proves to be too heavy to be employed throughout the entire beams of the tower. It is witnessed that the carbon fibre composite, which is considerably lighter in comparison to steel, is more appropriate for such intertwined structural composition. In this respect, it is argued that the tower beams can be made up of either steel or carbon fiber composite according their vertical location along the tower. In this case, the beams on the lower parts of the tower can be made of steel, while the beams in the upper sections can be employed as carbon fiber composite. It is also observed that introducing differentiation to the cross section of the beams along the vertical axis of the tower proves to be advantageous for structural performance. As such, the concept of differentiation, which has been explored on several levels in
this research, is incorporated into the structural behavior of the tower system.

4 CONCLUSIONS

The computational approach described in the paper achieves multi-parameter integration in the computational paradigm via real-time generative form-finding techniques, described as bottom-up processes where design output emerges from the interaction between autonomous agents and their environment in the Object-Oriented Programming environment, Processing. The designer has the freedom to make design decisions related to the primary functional requirements of the tower system through the parameters in the initial setup of the algorithm, such as plan form, location of service cores, floor height, and overall height. Motion behaviour mechanisms, geometrical behaviour mechanisms, and topological associations, all of which are defined by parameters in the agents’ data structure, govern the generation of differentiated global patterns which could not have been predicted at the outset of design explorations. Therefore, the generative nature of the chosen computational paradigm shifts the focus of design explorations away from the end result towards the process of formation. This condition redefines the role of the architect such that the architect does not get involved with creating an end product according to rules/parameters, but instead becomes the system designer whose task is to observe the outcomes of the system as it is continuously adapted on a multitude of interdependent levels.

The paper aims to illustrate that the implementation of agent-based systems as a dynamic computational tool facilitates the creation of a hierarchical systematic approach where the quality of emergence from lower-level systems towards higher level systems is possible. In the developed model, agents are defined as lower-level entities on a first order, simultaneously generating each tower subsystem. The interactions between tower subsystems in return depict each subsystem as a lower-level system on a second order, collectively working towards the generation of a higher level system, the output tower model. Therefore, the capacity to create a hierarchical computation system correlates with the intention to devise a hierarchical system for the integration of tower subsystems. The creation of a hierarchical design system entails the properties of interdependency and multi-functionality among tower subsystems as inherent qualities. Each individual subsystem has a role in achieving the structural integrity of the tower system. In this way, the distribution of loads takes place over the entire fibrous members of the tower in a seamless fashion, presenting a significant shift from conventional engineering practices which concentrate on devising efficient solutions with limited amount of materials chosen for specific tasks.

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Supporting Exploration of Design Alternatives using Multivariate Analysis Algorithms

Rusne Sileryte\(^1\), Antonio D’Aquilio\(^1\), Danilo Di Stefano\(^2\), Ding Yang\(^3\), 1 and Michela Turrin\(^3\), 1

\(^1\)Delft University of Technology
Delft, The Netherlands
{a.daquilio, r.sileryte, d.yang-2, m.turrin}@tudelft.nl

\(^2\)ESTECO SpA
AREA Science Park, Padriciano
99, Trieste 34012, Italy
distefano@esteco.com

\(^3\)State Key Lab of Subtropical Building Science, South China University of Technology
Guangzhou, China

ABSTRACT
Parametric modelling allows quick generation of a large number of design alternatives. Ultimately, it can be combined with optimization algorithms for obtaining optimal performance-driven design. However, setup of design space for optimization is a very complex task requiring designer’s a priori knowledge and experience. Therefore, this paper focuses on the process that happens before the optimization. It proposes to use multivariate analysis algorithms for exploring and understanding the relations between various design parameters, after sampling the design space. Additionally, portrayal of geometry is introduced as an extension of conventional visualization methods, which accounts for evaluation of ill-defined design criteria by using designer’s expertise. The proposed method is computationally efficient and integrated into an environment familiar to architects. It relies on multivariate analysis algorithms together with database querying capabilities and an interactive dashboard developed for geometry portrayal.

Author Keywords
Design & Optimization, Design Computation, Multi-objective Optimization, Visual Analytics, Multivariate analysis, Design Exploration, Parametric Modelling

ACM Classification Keywords
H.2.8 Database Applications; J.6 Computer Aided Design

1 INTRODUCTION
The traditional design process relies on designer’s knowledge, experience and intuition, which help to determine an optimal solution to a design problem. However, in recent years project complexity has increased while challenges of performance evaluation have decreased due to emergence of computational tools and methods. Therefore, design process is no more expected to find safe solutions by performing the correct calculations in later stages of a design, but rather explore a wide range of potential options, to come to informed decisions at every design stage. Fortunately, the advance in big data handling and analysis technologies has made design studies easier, providing more information to a designer.

However, as noted in [14], automated optimization procedures fail to take advantage of designer’s expertise, while in architectural design an important role should be given to the learning process of a designer, providing him with knowledge on the trade-offs between various disciplines (e.g. climate, structural design, etc.) and performance objectives. This problem has been partly tackled in [16] by utilizing statistical assessment of complex data for post-processing results. Furthermore, [8] has used k-means clustering and Archetypal Analysis to derive general knowledge linking architectural features to design performance. In [10] a phi-array visualization system is introduced to analyse sub-optimal solution.

This paper presents a design environment that integrates guidance-based support for exploration of the design space, combining efficiency, user-friendliness and flexibility. It uses multivariate analysis algorithms of ModeFRONTIER [9] optimization software in tandem with Grasshopper-based [3] geometry visualization dashboard. The proposed method can additionally be used to explore solutions after running an
optimisation; however, it primarily aims at supporting initial knowledge generation before defining the desired design space.

The research is conducted in TU Delft, Faculty of Architecture with the help of ESTECO on using multivariate analysis algorithms. A case study (Jiangmen Sports Center, Jiangmen, China) is provided by South China University of Technology.

2 EXPLORATION OF DESIGN ALTERNATIVES

The interactive evolutionary optimization algorithms focus on including a designer’s preferences mostly within the optimization cycle in the phases of selection and breeding [15, 11, 1] or result in visualization after running an optimization process for investigating sub-optimal results [16, 10]. In contrast, this paper focuses on supporting the design space definition before running the optimization (Figure 1).

The design space definition typically describes the following elements: set-up of a model, which usually contains the solver or the simulation for the evaluation of the chosen performance values (both defined numerically and ill defined); establishment of criteria, which must be minimized, maximized or constrained; selection of the parameters and their domains. It is a complex procedure requiring a priori knowledge and experience; however, it also has a great influence on the optimization results. On the one hand, a too limited design space can miss a large number of optimal or sub-optimal solutions; while on the other hand, a too broad design space may result into a number of redundant computations and extended optimization times. In addition, the relevance of the model set-up to the defined problem needs to be tested explicitly to ensure that the subsequent evaluation is able to lead the optimization towards a desired solution.

The proposed framework for exploration of design alternatives can be seen in Figure 1. A parametric model is developed using Grasshopper plugin for Rhino [3]. Sampling of the design space is consigned to ModeFRONTIER optimization software [9]. The software allows sampling of the design space using such algorithms as Random Sequence, Sobol, Latin Hypercube, Monte Carlo, Cross-Validation, etc. [9]. These methods eliminate subjective bias and allow a good sampling of the design space. The evaluation (or simulation) of the chosen samples can be performed in any desired software both through Grasshopper and ModeFRONTIER environments.

An important requirement for setting up the exploration environment is to have a comprehensive and versatile representation of the results. A large number of design alternatives may be formed by numerous inputs, all yielding multiple performance values. They can form a result space, which is impossible to perceive through conventional data visualization methods like scatter plots or parallelograms. Similarly, such graphs as correlation or scatter matrices are able to summarize the interrelationships, without, however, providing a visualization, which would be intuitive enough to analyse the data. Distinct from the aforementioned methods, multivariate analysis algorithms such as Self Organizing Maps (SOM) and Hierarchical Clustering are more suitable for capturing interrelated effects within a broad design space.

However, the above algorithms can only account for the numerically defined performance values, while the exploration of the design problem requires a portrayal of corresponding geometry. For instance, some certain design variables can have no influence on performance; however, they cannot be discarded from the optimization process due to their influence on aesthetics or similar design criteria.

In order to address this problem, the chosen clusters or parts of SOM are visualized in a Grasshopper-based dashboard through a series of pictures, which correspond to the generated solutions. A PostgreSQL database [13] is used as an intermediary between the two software for efficient

![Figure 1](image.png)
organization and querying functionality, as well as preserving a backup of collected data.

Use of the database also facilitates a selection of preferred design direction, which can be chosen using a Grasshopper-based dashboard and fed as a new initialized population for an optimization algorithm. Alternatively, the design space can be redefined and re-explored repeating the previous steps until a commonly acceptable design direction is chosen. The possibility to re-explore previous definitions, as well as combinations of multiple design spaces or their parts, is also enabled by employing the database.

3 MULTIVARIATE ANALYSIS ALGORITHMS IN MODEFRONTIER

ModeFRONTIER, developed by ESTECO, includes a set of multivariate analysis algorithms, some of which are described hereafter.

3.1 Self-Organizing Maps

SOM is an unsupervised neural network algorithm that projects high dimensional data onto a two-dimensional map [5]. The projection preserves the topology of the data so that similar data items will be mapped to nearby locations on the map. This is particularly useful when analysing un-correlated multidimensional data – such as dependencies between numerous design parameters and multiple objectives. Moreover, the representation of SOM is generally summarizing all the dependencies in a 2D space, which is an intuitive visualization technique.

SOM is a sheet-like neural network, with nodes arranged as a regular, usually two-dimensional grid (for an example, see Figure 7). Each node is directly associated with a weight vector. The items in the input dataset are assumed to be in vector format. If \( n \) is the dimension of the input space, then every node on the map grid holds an \( n \)-dimensional vector of weights. The basic principle is to adjust these weight vectors until the map represents “a picture” of the input data set. The objective is to achieve a configuration in which the distribution of the data is reflected and the most important metric relationships are preserved. Interest is in obtaining a correlation between the similarity of items in the dataset and the distance of their most alike representatives on the map. In other words, items that are similar in the input space should map to nearby nodes on the grid.

The algorithm proceeds iteratively. In each training step, a data sample \( x \) from the input space is selected. The learning process is competitive, meaning that a winning unit \( c \) on the map is determined when its weight vector \( m \) is most similar to the input sample \( x \).

\[
\| x - m_c \| = \min \| x - m \| \quad (1)
\]

The weight vector \( m_c \) of the Best Matching Unit (BMU) is modified to match the sample \( x \) even closer. As an extension to standard competitive learning, the nodes surrounding the BMU are adapted as well. Their weight vectors \( m \) are also “moved towards” the sample \( x \). Nodes closer to the BMU will be more strongly adjusted than nodes further away. At the beginning of the learning process, the BMU will be modified very strongly and the neighbourhood is large. Towards the end, only very slight modifications take place and the neighbourhood includes little more than the BMU itself. This corresponds to “rough ordering” at the beginning of the training phase and “fine” tuning near the end.

Since not only the winning node is tuned towards the input pattern but also the neighbouring nodes, it is probable that similar inputs in future training cycles will find their BMU weight vector at nearby nodes on the map. During the learning process, this leads to a spatial arrangement of the input patterns. The more similar two patterns are, the closer their BMUs are likely to be on the final map. It is often said, that SOM folds like an elastic net onto the “cloud” formed by the input data, as can be seen in Figure 3. SOM training ultimately results in a set of weight vectors, which resemble the input data. If one of the components of the weight vectors is reported on top of the grid, each node can be used to display the value of that component for its BMU (algorithm in Figure 2).

3.2 Hierarchical Clustering

Cluster analysis tries to identify homogeneous subgroups of samples in a dataset such that they both minimize within a group variation and maximize between group variations [4]. It can be used to gain insights into the distribution of data.

Figure 2. Algorithm of SOM sequential training

for each \( t \)-th iteration do
Pick up a sample \( x_i \) from the training data
for each \( m \)-th unit do
\( d_m \leftarrow |w_m - x_i|\)
end for
\( c = \arg \min (m) d_m \)
for each \( m \)-th unit do
\( w_m (i + 1) \leftarrow w_m (i) + \alpha (t) \times h_{cm} (r (t))\)
end for
end for

Figure 3. Different phases of SOM training. Three-dimensional input data are represented by empty dots. SOM is the elastic net, which folds to reflect the distribution of input data.
within a set, observe characteristics unique to each cluster, and help identifying clusters of interest for further analysis. Graphs like parallelograms, scatter plots and multidimensional scaling algorithms facilitate visualisation of clusters for interpretation purposes.

To perform hierarchical clustering the user must specify a linking method based on which clusters should be merged. It creates nested clusters, not mutually exclusive, where larger clusters in later stages of the agglomeration may contain smaller clusters created at the earlier stages. Different methods exist to merge pairs of clusters at each step, each of which will result in different cluster patterns:

- Single Linkage: the distance between two clusters is the distance between their closest points.
- Complete Linkage: the distance between two clusters is given by the distance between their two furthest points.
- Average Linkage: the distance between two clusters corresponds to the mean distance between all possible inter-cluster pairs.
- Centroid Linkage: the distance between two clusters is the distance between cluster centroids (mean point calculated between all cluster members over all the variables of the data set).
- Ward’s method: the distance between two clusters is computed as the increase in the sum of squares of the deviations from the centroid after merging two clusters into a single one. Ward’s method minimizes the sum of squares of any pair of clusters to be formed at a given step.

The results of a hierarchical clustering can be represented by a tree chart called dendrogram, in which the dissimilarity between two samples can be read from the height at which they join a single group. Cutting the dendrogram at a specific height will produce a clustering with a selected level of resolution (Figure 4). The cutting level of the dendrogram is a critical choice: if it is too low, a trivial clustering will be obtained of a “one to one” kind where the number of clusters is almost equal to the number of observations. If the cutting level is too high, the “true” cluster structure of a dataset can get over-smoothed.

A good rule of thumb on where to cut the dendrogram is to look at the largest gap between two successive groupings. Such large gaps stand for good clustering, mainly because adding one more cluster decreases the quality of the global clustering structure, so cutting before such steep decrease occurs is desirable [7].

4 GRASSHOPPER-BASED GEOMETRY VISUALIZATION DASHBOARD

The dashboard has been developed at TU Delft. It is mainly an extension to the previously described multivariate analysis algorithms, which serves as a tool to visualize design alternatives in tandem with the performed analysis. It aims to provide a designer with insight into the relationship between the generated geometry and corresponding performance, as well as facilitate the directing of design space towards solutions that both satisfy architectural and performance-based criteria.

The communication between multivariate analysis performed in ModeFRONTIER and the dashboard is established using PostgreSQL database as an intermediary. The database contains all evaluated design alternatives, including their input parameters, performance values and any additional intermediate information, which may be required by the designer, even if not part of the defined performance values. The solutions are later enhanced with analysis results, indicating the cluster they belong to, Pareto frontier solutions, feasibility information, etc.

4.1 Dashboard functionality

The developed proof of concept of the dashboard includes but is not limited to the following functionalities. All functions are embedded as customized Grasshopper components scripted in Python programming language. Image visualization on canvas is enabled by Embryo plugin [2].

Visualizing typical solutions of SOM

The typical representation of SOM components facilitates understanding of relationships and correlations between all different values and is rather easy to interpret. However, the particularity about dealing with architectural design is that most input values are related to geometry; therefore, each hexagon in SOM can be visualized as a geometrical solution.

Visualization / Exploration of clusters

As mentioned previously, ModeFRONTIER allows various methods of clustering using the same input data. Moreover, clustering can be performed based on various criteria, e.g. clustering based on input parameters will result in having similar designs within one cluster, while clustering based on
performance values will allow to explore a range of designs which all yield similar results. Dashboard allows querying the solutions based on a chosen cluster as well as a combination of them.

Additional functionalities
A number of functionalities have been introduced in addition to multivariate analysis.

One of them is exploring Pareto Frontier. Pareto Frontier is a set of solutions, which are not dominated by any of the performance variables. That means that for such set there are no such solutions, which would have better performance in one of the criteria without having a worse one in another. Dashboard allows choosing all the solutions that belong to the Pareto Frontier within the chosen set of solutions (e.g. all values, a single cluster, a combination of clusters, etc.)

Another powerful functionality of the dashboard is its ability to filter the results based on multiple criteria. The criteria can be set based on the additional information (e.g. chosen cluster, Pareto Frontier, feasibility, etc.) as well as based on the desired range of input parameters or performance values, or any combination of those.

4.2 Dashboard elements
Every set of solutions retrieved from the database by the previously explained functions is portrayed on Grasshopper canvas as shown in Figure 5 together with a number of additional elements.

Querying of design alternatives is performed by customized Grasshopper components based on the designer requirements, retrieving a set of ids (1), which are associated with geometry images. The images are recorded during the evaluation phase of design alternatives. Dashboard user may choose the size and type (perspective, front, back view, etc.) of images to visualize (2).

Images can be sorted based on any chosen numerical criteria, ascending or descending and labelled with a chosen type of cluster (3). The dashboard also gives an overview of the number of solutions, which belong to the chosen set, as well as a number of Pareto Frontier solutions within a set (4).

Images are visualized in sets of six (5) together with the label, which indicates the name of the cluster that the solution belongs to and whether it belongs to the Pareto Frontier.

Additionally, two panels summarize the domains of input and performance variables of a chosen set in comparison to all the other solutions, i.e. they indicate the bounds of a chosen set within the explored design space (6).
5 CASE STUDY

The swimming pool of the Jiangmen Sports Centre is used to demonstrate how the support system works. The project is located in Guangzhou (China) and will be used for sport events on a national level.

5.1 Design space

The input parameter space is composed of 18 variables, including such geometrical parameters as roof curvature, skylight number and their dimensions, construction material properties, building rotation and presence of glazing. The given bounds of parameters are rather wide, aiming to avoid too limited design space at the first exploration.

Four performance values have been set as objectives:

- Maximizing of average UDI (Useful Daylight Illuminance) value; it stands for the percentage of daytime hours with an illuminance level falling between a minimum and maximum threshold set as comfortable, according to the program requirements during the opening hours of defined design period [12].
- Minimizing of the energy need (kWh/m2) in terms of cooling and heating, meaning the energy needed to be supplied to or extracted from a space in order to keep a comfortable thermal environment according to the building program, measured over a defined period.
- Maximizing of energy production value; it is defined as the amount of electrical energy that can be produced by a roof surface if a certain percentage of it is covered with Photovoltaics.
- Minimizing the area of roof surface results in a lower amount of materials needed for the construction of the envelope, meaning less embodied energy and lower construction costs.

An ill-defined criterion is set for building aesthetics, which is decided using the expertise of a designer.

Grasshopper plugins Honeybee and Ladybug [6] together with simple mathematical functions (e.g. surface area calculator) are used as external solvers for the evaluation of performance values. Design space sampling has been performed by ModeFRONTIER using Uniform Latin Hypercube algorithm with 340 alternative designs, out of which 334 were evaluated as feasible.

5.2 Multivariate Analysis

Two types of hierarchical clustering have been applied on all feasible solutions. Both types used Ward’s approach, since it was proven to provide clusters the most similar in size. One approach has clustered solutions based on input parameters with 17 to 46 solutions in each of the twelve clusters, while another one has been applied on performance values (Figure 6) with 32 to 54 solutions in each of the eight clusters.

SOM has been trained using the four performance values of all feasible solutions. Although the SOM is trained using only the objectives as training components, ModeFRONTIER also records the variation of other parameters as separate component maps. The resulting SOM hexagonal grids for each of the input parameters and design objectives can be seen in Figure 7.

Every hexagon in a grid corresponds to a set of real or virtual solutions in a way the nearby hexagons are more similar than the distant ones. Every hexagon holds a single value for each of the parameters and objectives; therefore, it is possible to visualize every point on a grid using the proposed dashboard. It must be noted that the colours in hexagonal grids always correspond to the numerically normalised values rather than the actual range of parameters, i.e. even a Boolean value would be displayed as blue corresponding to False (or 0), red to True (or 1) and a gradient in between, which would rather display the fuzziness between the two.

Figure 6. Every cluster is represented by its own Parallel Chart, helping to discover which variables determine the cluster structure as indicated by the internal and external similarity values. These charts represent visual means for assessing the compactness and the uniqueness of clusters.
5.3 Geometry Visualization

Four types of geometry images have been recorded while running the evaluation of design alternatives: perspective, top, side and front view. All images contain text with the solution’s ID and both values of input parameters and performance.

Additional images are generated for each of the grid cells of SOM in order to visualize chosen geometries quickly.

5.4 Results

After exploring the results of multivariate analysis combined with the geometry visualization on the dashboard, a number of conclusions were drawn about the relationships between the parameters and performance values. It has also facilitated modifying the initial broad design space could also be modified in such a way that it would lead the subsequent optimization towards the preferred direction. Part of these insights is presented hereafter.

While browsing through the clusters based on specified input variables (Figure 6, top), it has been noted that cluster 1.3 which can be characterized by small skylights, no facade glazing and non-expressive roof, results in poor aesthetical performance. The same can be noted about clusters 1.7 and 1.9, which have bigger skylights. However, they display a box-like appeal not compliant with the initial concept of the building. By looking at the performance domains of these clusters, it is obvious that they are not falling into the range of the highest performance values. Therefore, such sets can be safely discarded.

Clusters based on output variables (Figure 6, bottom) suggest that the most desired behaviour can be found in clusters 2.5 and 2.6, where many designs with expressive roof curvature can be found that is also preferred by the designer. It can be noticed that only certain types of wall and roof curvature fall within these clusters, however, since they are mostly not influencing building aesthetics (with some exceptions), they can be chosen purely based on numerically expressed performance values. Clusters 2.3 and 2.4, which both have very poor performance, suggest that a combination of small skylights and glazed facade, as well as big skylights concentrated close to each other, results into poor performance and should be avoided in future designs.

SOM components chart (Figure 7) very clearly demonstrates that surface area and energy production are contradicting values, which have high correlation with overhang length and width. Since designers’ preference is to have as large overhang as possible, it is suggested that the value can simply be decided in a way that it somewhat satisfies both of the criteria, especially taking into account designer’s opinion. Even though it is expected that overhang size should influence energy need for cooling and heating and UDI, because it protects the facades from direct solar radiation, it is obvious that in this case there is almost no influence on these objectives, therefore the parameters can be kept stable for further optimization.

Furthermore, while analysing all of the available chart and the dashboard, it has been noticed that only some certain configurations of roof curvature values result in both aesthetically appealing and well-performing designs. Since these combinations of curvature values are not bounded within a single domain, varying constraints can be set to capture the preferred design direction. For example, if values “roof1” and “roof2” are similar, values “roof3” and “roof4” should be as high as possible; if there is a high difference between value “roof1” and “roof2”, then “roof3” and “roof4” should stay the same. It is also important that the difference between “roof1” and “roof2” is not bigger than the one between “roof2” and “roof4”.

All the mentioned insights have been used to adjust the initial design space before running an optimization process. Additionally, a number of important dependencies have been noted which value may exceed the specificities of a particular project.

6 DISCUSSION AND FUTURE WORK

The developed proposal is work in progress; therefore, many more tests need to be performed, including more case studies.
with varying disciplines and multiple objectives, different sampling algorithms and a number of design alternatives. The work should also be validated towards its benefits for the optimization results compared to results obtained while using only human expertise for setting up the design space.

Currently, the method is designed for the Rhino/Grasshopper environment, but may also be implemented in other environments, such as Revit/Dynamo.

Considering the multivariate analysis, the drawback of clustering is that it does not provide clear insights into the correlations. On the contrary, the drawback of SOM is the visualisation of geometries, since in case there are 100 hexagons, 100 geometries need to be visualized, overburdening the gain of insights. A good solution for these problems seems to be clustering performed on SOM. When SOM is trained based on outputs, clustering can be based on inputs that allow grouping similar geometries and exploring the relationships between them all at once.

7 CONCLUSIONS

This paper has presented an interactive environment that integrates guidance-based support for exploration of the design space. The proposed method is computationally efficient and integrated into an environment familiar to architects. It relies on algorithms available in ModeFRONTIER software together with database querying capabilities available in PostgreSQL and a developed dashboard, which uses the Grasshopper interface.

The proposed method has demonstrated that it is able to support the exploration of design space and facilitate its definition in order to lead the design towards the preferred direction. At the current stage of the method’s development, it is possible to tell which design variables can be discarded and which parameter domains need to be limited, considering both numerical and ill-defined performance values. In addition, the method provides insights about introducing varying constraints or their combinations.

Finally, a designer is provided with additional knowledge about dependencies between design variables and their combinations, which yield particular performance values.

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REFERENCES

Multivariate Interactive Visualization of Data in Generative Design

Andre Chaszar\textsuperscript{1,3}, Peter von Buelow\textsuperscript{2}, Michela Turrin\textsuperscript{3}

\textsuperscript{1}Singapore Univ. of Technology
Singapore
andre_chaszar@sutd.edu.sg

\textsuperscript{2}University of Michigan
Ann Arbor, USA
pvbuelow@umich.edu

\textsuperscript{3}Delft University of Technology
Delft, The Netherlands
M.Turrin@tudelft.nl

ABSTRACT
We describe our work on providing support for design decision making in generative design systems producing large quantities of data, motivated by the continuing challenge of making sense of large design and simulation result datasets. Our approach provides methods and tools for multivariate interactive data visualization of the generated designs and simulation results, enabling designers to focus not only on high-performing results but also examine suboptimal designs’ attributes and outcomes, thus discovering relationships giving greater insight to design performance and facilitating guidance of further design generation. We illustrate this by an example exploring building massing and envelope design (fenestration arrangement and external shading) with simulations of daylighting and heat gain. We conclude that the visualization techniques investigated can help designers better comprehend inter-relationships between variable parameters, constraints and outcomes, with consequent benefits of: finding good design outcomes; verifying that simulation results are reliable and; understanding characteristics of the fitness landscape.

Author Keywords
parametric; performance design; optimization; exploration; visualization; multi-objective; multivariate; evolutionary computing.

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B.4.4: Performance Analysis and Design Aids
H.2.8: Database Applications
I.6.3 Applications
I.6.6 Simulation Output Analysis

1 INTRODUCTION
While increasingly powerful computational resources are permitting designers to explore increasing quantities of design variations, challenges remain in making sense of the correspondingly large volume of data involved [3, 16, 17, 18, 19]. Generative design systems in particular pose such challenges. In this paper we present our research on using multivariate interactive visualization of data to support design space exploration, optimization and design decision making via generative design systems. The method employed in this research combines parametric form generation with performance analysis using simulation software guided by a multi-objective genetic algorithm to fill a database with representative solutions from the design space. This design space can subsequently be explored using SQL search and filter commands. The results can be compared through graphic images as well as data depictions: scatter plots or parallel coordinate graphs.

Optimization and design space exploration via generative algorithms and other evolutionary techniques is becoming a widely adopted approach in design, engineering and other fields. Their use offers the opportunity to identify sets of well performing design alternatives, which can be used as design solutions and also to suggest further improvements for new design solutions. However, the complexities of problem-definition and of results-interpretation pose persistent challenges to effective use of evolutionary computing for design applications. One reason is the large volume of data involved, which needs to be digested by users. Another reason is that such systems can be ‘black boxes’ which tend to obscure their inner workings and thus the important relationships among the variables involved and between these variables and the outcomes. In addition, due to the progressive generational characteristic of most evolutionary methods, it is ineffective to change the search algorithm (the fitness function) without essentially starting over. This limits the “exploratory” quality of the method. The method we used instead employs the ParaGen model: a Non-Destructive Dynamic Population Genetic Algorithm (NDDP GA) which maintains a database of all solutions and creates breeding populations dynamically, on demand, differing from e.g. [22]. In this way the search direction can be changed at any instant without restarting the process. This in turn allows a truer exploration of the design space.

In the next sections we first briefly recount relevant precedents to our work, followed by a description of our experimental apparatus and a specific design task case. We then present some results of the experiments and conclude with a summary and pointers for future work.

2 PRECEDENT WORK
Data visualization provides a body of knowledge and set of techniques which can alleviate both the large-volume and obscured-workings problems mentioned above. Ranging from Scientific Visualization through Interactive Information Visualization and Visual Analytics, much work has been done and results achieved assuming that humans’
visual pattern recognition can provide powerful insights to help unravel complex situations [1, 2, 3, 7]. In the work we present here, we have been motivated to apply some of these visualization techniques – especially those with potential for extension via interactivity – to the problems of making sense of the data from evolutionary computing.

2.1 Optimization processes as exploration tools

In traditional optimization, a single best solution (or a front of best solutions) is found for a given set of objectives applied to a specific problem. Optimization techniques have been mostly used in order to solve a specific (monodisciplinary or interdisciplinary; single-objective or multi-objective) design problem by searching for an optimum solution. In this light, the role of optimization in design is to find within the design space the configuration that best matches desired performance goals [11]. This is unquestionably one of the major potentials of optimization techniques. However, this does not support a fully informative exploration of design solutions. In fact, there is a key difference between the process of design exploration and the search for an optimum solution. [4] presents this difference by distinguishing the design process in three possible types: routine process, innovative process, and creative process. From routine to creative, the attempt to describe a solution search loses potentials of precise and predetermined definition. A routine process is close to the concept of search, a creative one to a process of exploration. A key need in design exploration is the learning process of the designer [2, 3, 5, 13, 18].

There are some precedents addressing this point, promoting optimization processes as exploration tools rather than as search for a specific optimum, e.g. [8, 18]. Some of the precedents propose solutions by focusing on the design objectives to be evolved during the process; the design variables to be set more freely; the consideration of the importance of the sub-optimal solutions. Among those focusing on the design objectives, [9] proposes a GA system which allows the co-evolution of the fitness function and design solution by representing the fitness as part of the genotype. Focusing on the exploration of different design variables, some precedents allow the user to intervene in the process by modifying, adding and/or deleting variables, redefining the range of modification for variables, and modifying their constraints. It is for example the case of the work by [11], in which simulated annealing is used to assist in the preliminary design phase for acoustic measures, in which the user can optimize over materials and geometry either separately or simultaneously. Still, in these examples, once the optimization is initiated, no relevant attention seems to be given to sub-optima. As [12] points out, sub-optimal solutions are usually discarded and in most of the precedents they do not contribute to decision making after optimization runs. They stress instead that ‘the discarded “inferior” solutions and their fitness contain useful information about underlying sensitivities of the system and can play an important role in creative decision making’, a view supported also by [14]. Based on this consideration, [12] proposes a visual method to analyze sub-optimal solutions. These are retained during optimization and represented in a fitness array visualization system called phi-array. Another precedent worth mentioning concerning a certain attention given to sub-optimal solutions is BGRID [10], a decision support system for the conceptual design of commercial office type buildings, employing GAs. It searches for viable design options in light of both structural and architectural criteria. Specifically, it is meant to support defining the layout of columns in floor plans including also lighting requirements and ventilation criteria. BGRID provides the user with a selection of optimal solutions to enhance the understanding of the underlying processes.

In contrast with the above methods, we wish to investigate more generalized visualization methods which both allow thorough examination of all data points – not only high-fitness ones – and also support this examination with interactivity. Statistical exploration tools such as X-/G-/R-Gobi [15] have such capabilities; however, we decided to work here with a more design-oriented platform, ParaGen [20, 21], described further in Section 3.

2.2 Interactive visualization of multi-variate data

The techniques existing for visualizing multi-variate data are many and various [3, 6, 7], some of which are also indicated in the section above. We have chosen to focus on ‘parallel coordinates’ and ‘scatterplots’ for our present investigation, emphasizing the potential contributions of interactivity to these graphing techniques.

To review briefly: parallel coordinates (or ‘parallel axes’) are a more than century old method which consists of plotting all independent and dependent dimensions of data onto a series of parallel lines representing each dimension, and connecting the corresponding points with lines. Thus, each ‘solution’ is represented by a line comprising a visual ‘signature’ of its inputs and outputs. A variant of this – sometimes referred to as ‘radar’ or ‘spiderweb’ plots – places the axes radially, forming a polar plot, with an advantage of compactness, but a disadvantage of legibility, especially for values near the pole. In our investigations interactivity was introduced to parallel coordinate graphing by enabling: a) rearrangement of the coordinate axes’ sequence; b) highlighting or coloring of lines; and c) restriction of displayed data ranges via graphical selection and text-field based filtering.

Scatterplots are of course very commonly used for two- and sometimes higher-dimensional data, for example by plotting data points onto three ‘physical’ axes (e.g. X, Y and Z) or by plotting multiple series of points (connected by lines or indicated by bars, etc.) differentiated by hatching, shading and/or symbols. Interaction for scatterplots was achieved by a) giving control of the data dimensions to be
plotted on two axes, b) enabling highlighting of data ranges and c) restriction of data ranges via text fields.

3 EXPERIMENTAL APPARATUS
Our research involved application of supplemental data visualization techniques to a previously existing interactive evolutionary generative design system, as described below.

3.1 ParaGen
ParaGen is a framework which utilizes a variety of commercial and custom written software to aid the designer in the exploration of good solutions [20, 21]. The system uses heuristic methods to direct the search toward areas of the solution space which the designers defines as most desirable. The designer can describe “desirable” either through multiple performance objectives or by qualitative, visual selections. Applications of ParaGen to date have been focused on architectural design problems, and as such combine both qualitative and quantitative performance aspects of a problem solution. In order to deal with both qualitative and quantitative information, ParaGen harvests both a wide range of performance data (the quantitative) as well as an array of visual images and data depictions (the qualitative). Both types of information together can aid designers particularly in the early phases of design.

ParaGen makes use of parametric-associative modeling software to generate the geometry of the solutions, and then passes the digital model on to one or more simulation and analysis packages to determine the performance values. In the present work DIVA was used to evaluate daylighting and heat gain potential. Most modern simulation software also has the capability to display performance results in graphic form. For example Rhino/Grasshopper has many options for visual rendering that can include light level maps, interior and exterior perspectives, or other displays from various plugins. Most structural finite element software can image the deformed geometry under load or color coded stress information. Such images can convey valuable information to the designer in a qualitative way. Of course this same simulation software also produces quantitative performance values. ParaGen harvests both types of information and uploads it to a server where all quantitative data is stored in a database and linked with the various images that are also saved. In addition the different simulation models themselves as well as small animations or 3D VRML models can be saved and linked to the solution for more detailed inspection by the designer.

ParaGen makes all of this information accessible for exploration through a web interface. The main page shows an array of design/solution images that can be switched out for other views (any set of the saved images) by selecting the image type from a simple pull down menu. Figure 1 shows ten randomly selected design variations. The solutions shown can be filtered and sorted using another series of pull down menus on the web page. Using any of the design input parameters or performance values the designer can interactively select a desired set of solutions from the database. This selection can take the form of a simple max/min sort or a complex, multi-variable SQL query. The results are immediately displayed on the web page for inspection and further modification.

The search method used by ParaGen is a Non-Destructive Dynamic Population Genetic Algorithm (NDDP GA). It is non-destructive in that all solutions are maintained in a database and can be recalled or searched at any time by the designer. Being able to see both what makes a good solution as well as a poor solution aids the designer in learning about the problem. This is a valuable capability for early design exploration. Dynamic populations also aid exploration by allowing instantaneous or interactive production of breeding populations for the GA. Very importantly, in this way fitness functions can be interactively altered by the designer in order to explore different regions of the design space. This again offers the designer a true exploration of the solution space. In addition, other means to explore the performance data are also available in the form of interactive graphing tools.

Figure 1. Examples of different design solution images. Any images saved during analysis can be alternately displayed.

3.2 Interactive Graphing Methods
Two basic graphing methods were added to ParaGen for our present work: x-y scatter plots (with glyph control for a third level of information) and parallel coordinate plots, as described already in more detail above. The data plotted in both cases is controlled using the same sorts and filters which control the design/solution images. By plotting conflicting performance values, Pareto front optimality can be investigated. Figure 2 shows a plot of designs/solutions with average illuminance > 1500 lux and average irradiation < 2.8 W/m². Average illuminance (nominally to be maximized) is plotted against average irradiation (to be minimized). The red dots indicate the solutions with floorplate area above 200 m². The Pareto frontier is marked and two “red” solutions near the frontier are indicated. By clicking on any of the dots an image of the solution comes up. In this way the qualitative begins to be combined with the quantitative, and the graphing tools’ interactivity helps users of the system explore the data [3, 7] and test their ideas about underlying relationships within the data.
4 CASE STUDY AND EXPERIMENT

To test our hypotheses regarding usefulness of interactive data visualization in design space exploration and optimization, we constructed an example design problem illustrating a multi-(or many-) objective search for design solutions selecting among parameters of building massing, fenestration and shading, and evaluating these against criteria relating to (interior) daylighting, thermal gain and construction quantity/cost. To support early-stage design and conceptualization, emphasis was on relatively rapid modeling and analyses rather than more detailed ones.

4.1 Design Problem

The building model to be analyzed comprised a number of fixed and also variable parameters. These parameters correspond to design features, assumptions and constraints which would normally be considered within the process of design. For example, the total floor area of the building is constrained to a fixed value of 1000 m² (an approximation neglecting the small variation in size of vertical circulation and other shaftways for varying building heights). The number of stories in which the 1000 m² are distributed is an independent variable of the model. The floor plan shape is set to be a rectangle; one dimension of the floor is also an independent variable. The other dimension is based on the first dimension and on the distribution of the 1000 m² on the (independently variable) number of stories. Four independent variables regarding the number of windows regulate on each façade both the number of glazed modules and the number of shading elements. Specifically, each glazed module is connected with one horizontal and one vertical shading element. Total glazed surface does not increase proportionally to the number of glazed modules; instead, the proportion between the glazed surface and the opaque surface is constrained to a fixed value for each façade, but this could also be made variable. The dimensions of the shading elements are varied based on additional independent parameters, resulting – even when discretized – in a total number of possible designs on the order of $1 \times 10^{16}$, making a brute force search infeasible. (The complete list of parameters is omitted here due to lack of space but is available from the authors upon request.)

Performance criteria for evaluating the fitness of generated designs were defined in three main categories with sub-dimensions: daylighting, solar gain, and quantity/cost of construction. Daylight and solar gain were simulated for the location of Guangzhou (China). Daylight was measured based on illuminance values on the 21st September, h.14.00, with overcast sky; on a grid located on the entire top floor. It was evaluated for intensity and homogeneity (to be maximized). For evaluating the intensity, the average illuminance was calculated. For evaluating homogeneity, the ratio of maximum to minimum illuminance levels was calculated. Solar gain was assessed based on irradiation in a typical week, measured on the same grid as the illuminance. The solar irradiation was to be minimized. Costs were considered in reference to surfaces of the standard floor and its envelope (without differentiation of unit or area costs for different construction element types). Maximizing the floor areas, while minimizing the envelope area (including also shading elements) was one aim, and other performance criteria were also introduced, such as minimizing heat gain while maximizing homogeneity of daylighting. While recognizing that these represent a quite simplified assessment of a rather limited set of design variations, our aim was not to carry out a real architectural design investigation, but rather experiment with data visualization techniques applied to a plausible design investigation.

4.2 Design Process and Data Visualization

The data for the design problem described above were generated with Rhino/Grasshopper, DIVA, and ParaGen. ParaGen uses an NDDP GA (see section 3.1) to explore and
expand the data in different sections of the solution space in response to fitness criteria set by the designer. Changing the fitness function in a traditional GA is not generally an effective technique since once a population converges on one fitness function, diversity is lost which limits, or at least delays, the development of solutions in the direction of the new fitness. Because in ParaGen all solutions are retained, new populations can be dynamically created on the fly in response to changing fitness criteria [20]. In the problem described above, the GA was initialized with the generation of a little over 250 random solutions. This was followed by a series of explorations using different single and multiple fitness functions. After about 6000 solutions had been explored, it was decided to focus on a fitness function which described the desired illuminance and the distribution ratio levels. This was continued for the remainder of the run which generated some 8000 solutions. ParaGen can also adjust the breeding algorithm in a couple of ways to produce either more diversity or stronger focus on the fitness function. The basic breeding technique used is half uniform crossover, HUX, which uses a Gaussian distribution to find a new variable value between two being crossed [20, 21]. The sigma value of this distribution can be adjusted to allow either a looser distribution around two parent values or to focus the child solution more tightly between the parent values. The level of disruption caused by the HUX breeding can also be reduced by adjusting the ratio of crossed to non-crossed genes (variables) from the regular ratio of 1 out of 2 (50/50) to 1 out of 5. Both of these techniques were used in the later generations which focused on illuminance and the distribution ratio.

5 RESULTS

By assisting the designer in analyzing the population of design variations, the system helps to reveal relations between parameters and performance. This includes relations that are fairly obvious based on common sense or basic domain knowledge and also relations that are more difficult to predict. Various examples are provided below.

One basic relation is the association between the lowest average illuminance with the maximum depth of the floor and the minimum height of the story and windows. The system confirms this. Sorting the solutions based on ascending illuminance, the database shows that the first 52 solutions have one story only, with floor area of 1000 m²; while the first multi-story solution appears in position 53 (2 stories, each of which having a floor area of 500 m²). Most of the 52 solutions have a square floor plan. This is exemplified in Fig. 3, a screen capture of some of the sorted solutions and the parallel axis graph plotted for the solutions with illuminance lower or equal to 450 lux. Out of 20 solutions having the illuminance lower or equal to 450 lux, all have one story and 17 have the length of the building equal to 30 m, which is the length that gives a nearly square floor; while all the others have the length of the building near to 20 m. Looking at the parallel point graph, this is clearly shown. The parallel point graph makes visually evident also that all of the solutions have the lowest building height and number of stories (because the 1000 m² are in one floor only); shading elements set to high horizontal and vertical lengths; an orientation of -90° or -80°. Plotting then only the 5 solutions with illuminance lower or equal to 300 lux it also becomes evident that these are the ones having all shading elements set to their maximum horizontal and vertical lengths (all equal to 1 m) in all directions; and also with lower amounts of glazed surface facing south. (S orientation = 0°, to lower right.)

Figure 3. 15 solutions with lowest average illuminance. Top: screenshot of database, showing 15 solutions with lowest average illuminance, in isometric view. Bottom: parallel point graph plotted for 20 solutions having average illuminance lower than or equal to 450 lux. Height variable = 1 for all 20 solutions (circled).

Another basic relation confirmed by the system is the association between the highest average illuminance with the minimum depth of the floor and the maximum height of the story and windows, as shown in Figure 4. Plotting the solutions with illuminance higher than 2700 lux, the parallel point graph clearly shows that most of the solutions have the length of the building equal to 30 m; the others are very near to 30 m, which – when all solutions have a high number of stories (9) – leads to very narrow floors. Each
one of all stories has a resulting floor area of 111 m$^2$; has high height (4 m); and an averagely high number of shading elements in all directions. Figure 4 shows all of this. Further evidence regarding this relation can be gained by looking at the scatterplots, by plotting the generated data in pairs. For the 27 solutions with illuminance higher than 2700 lux, Fig. 5 shows the examples of illuminance vs number of windows facing south; and illuminance vs orientation.

Typically, in order to combine very high illuminance with maximum floor area, the only option (absent skylights, clerestories, etc.) is to have a very long and narrow floorplan of 1000 m$^2$ in one story only. This predictable relation is made evident both when sorting and filtering the views of the solutions and when using the parallel point graph, as shown in Fig. 6.

![Figure 4](image1.png)

**Figure 4.** Solutions with highest average illuminance. Top: The 8 solutions with highest average illuminance. Bottom: parallel point graph plotted for the 27 solutions having average illuminance higher than 2700 lux

![Figure 5](image2.png)

**Figure 5.** Scatterplots of the 27 solutions with illuminance higher than 2700 lux. Left: illuminance vs number of windows facing south. Right: illuminance vs orientation

Using the scatterplots, the fact that also shading on the north façade has some relevance in obstructing daylight emerges; the major relevance of high stories also is evident (having all points except one aligned on the maximum height of 4). This is illustrated in Fig. 7.

Similarly, looking at the highest average irradiation, the parallel point graph (plotted for the 17 solutions with average irradiation higher than 13.5 W/m$^2$ and illustrated in Fig. 8) shows that 13 solutions have the length of the building equal to 30 m, three solutions near to 30 m (29 m and 28 m) and one solution 25 m; all the solutions have the height of the building equal to 9 stories and the height of each story is 4 m for all except one (3.8 m); have an averagely high number of windows in all directions; and an averagely low shading; mostly an orientation of -90° to -80°. The resulting floor area per story is 111 m$^2$ for each.

![Figure 6](image3.png)

**Figure 6.** The image shows the solutions with average illuminance higher than 1150 lux and floor area of 1000 m$^2$. Top: screenshot of database, illustrating 8 of the 38 solutions matching this criteria, in isometric view. Bottom: parallel axis graph of the 38 solutions
Figure 7. Scatterplots of 8 solutions with illuminance > 1150 lux, floor area of 1000m². Left: illuminance vs horizontal length of north-facing shading elements. Right: illuminance vs story height.

Figure 8. Solutions with highest average irradiation, with parallel point graph plotted for the 19 solutions having average irradiation higher than 5.1 W/m². (Note: solutions similar to Figure 4).

Figure 9. Solutions with lowest average irradiation. Top: The 8 solutions with lowest average irradiation. Bottom: parallel point graph plotted for the 18 solutions having average irradiation lower than 0.65 lux.

Figure 10. The image shows examples of solutions having maximum irradiation higher than 8 W/m². Top: screenshot of the database, illustrating 6 examples, in isometric view. Bottom: parallel point graph plotted for the 6 solutions.

Looking at the minimum average irradiation, the parallel point graph (plotted for the 18 solutions with average irradiation lower than 0.65 W/m² and illustrated in Fig. 9) shows that all the solutions have floor area of 1000 m² and one story of low height (3 m); four have the length of the building equal to 20 m, three equal to 22 m, while the other 11 solutions have the length of the building equal to 30 m, which leads to a square plan; low number of windows facing south; mostly an orientation of -90° to -80°.

6 SUMMARY AND FUTURE WORK

We have presented a description of our work on applying various multi-variate/-dimensional data visualization techniques to a complex parametric-associative building model for design space exploration and multi-objective optimization. (Note that due to limitations of space, illustrations herein are reproduced at small sizes; for full images see: http://hdl.handle.net/2027.42/117408.) Our findings indicate that such visualization techniques do offer useful feedback in the use of such a model, aiding comprehension and modification of the design space [5, 9, 13] by introducing additional interactive data visualization.
components to the otherwise mainly automated operations of evolutionary visualization algorithms. We see too that multivariate interactive visualization aids in model verification, which is also important – even if not as glamorous as the discovery of unanticipated valid relationships in the data.

Further investigation of this approach should include development of improved and additional visualization and interaction capabilities, as well as experiments to compare the relative efficacy of the different visualizations and their combinations. These would be applicable both to conventional building types and to non-standard ones requiring more innovative designs for more ‘wicked’ situations. For example, one experiment could test the ability of the system’s users – e.g. students, practitioners – to predict the outputs (i.e. performance) of some solutions given only their inputs and a larger set of solutions evaluated also for performance. Another experiment would test the system’s support for reasoning from available patterns of inputs and outputs to interpolate or extrapolate other designs. In any case, we expect the graphing to aid pattern recognition, and such abilities would in turn increase the value of the system as a learning device for pedagogic purposes as well as more generally for reflective practice.

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REFERENCES
Folded Wooden Responsive Houses in hot arid climate

Alessandro Mattoccia1, Marco Giorgio Bevilacqua2, Francesco Lecce2, Michele Rocca2 and Rodrigo Rubio1

1Institute for Advanced Architecture of Catalonia. Barcelona, Spain
2University of Pisa, Department of Energy Engineering, System Territory and Construction. Pisa, Italy

ABSTRACT

Out of the architectural typologies that emerged in countries with a rough, arid and hot climate we synthesized the principles that laid the foundations of applied theories in bioclimatic and sustainable architecture. The accumulated experience is visible in their vernacular architecture, clearly showing the layers of attempts, adaptation and knowledge merging towards the best adaptive model of architecture to the harsh context. Some of the more prominent features of this type of architecture is constant search of cooling techniques, such as shading, designed to be protected by direct sunlight.

There has been little to none improvement to this type of architecture for a long period as no real value could have been added to this already functional ancient systems. But today, with the help of modern technology, one can use parametric design in order to further optimize this architecture and push it to an even more effective response to context.

Author Keywords

Parametric design, folding architecture, generative design, optimization, cellular automata, passive cooling.

1 INTRODUCTION

The paper uses the design of a wooden climatic responsive module for housing as a case study. The general argument is that digital technology can allow for customization and permits architecture to respond to geographical and environmental requirements, in contrast to the industrial-age paradigms of prefabrication and mass production [2]. The generative and controllable potential of digital tools, together with manufacturing progress, is opening new dimensions in architectural design. Clear understanding of the main problems and site surrounding conditions, which influence building design, increases the possibility of making environmental decisions in the early stages of design, even before a building form exists.

The project is located in the extreme hot dry climate of the Atacama Desert, Chile. The project was born out of a practical need: creating new settlements in places far from civilization but at the same time close to important human activities. The module we designed to respond to this request tries to combine principles from different fields (desert vernacular architecture, cellular automata and the art of folding) even to answer to our second aim, to create a comfortable environment in this extreme climate.

In the desert, ancient people knew very well how to avoid the harshness of the dry and hot climate and their knowledge hailed from centuries of experience and attempts. It was decided to combine this knowledge with computational techniques to try to parametrize these aspects in order to optimize and make them as effective as possible, allowing in this way to add something to what has been handed down. Among all the principles of this vernacular architecture, we will take into consideration how the patio works, how it cools the inner environment and which benefits it gives to natural ventilation.

To reproduce the traditional urban fabric of desert city, dotted of patios and characterized by a natural growing, we used the idea of Cellular Automata (CA). The strength of CA lies in the lattice’s uniformity as it facilitates the application of a particular type of state transformation within our module, but at the same time in its underlying recursive method that makes difficult to anticipate the future spatial form [5]. This offers an interesting and rich platform from which to develop possible architectural patterns.

The necessity of having a foldable structure arises from the need to build our houses as quickly as possible given the extreme climate in which our project takes place. The project is based on designing a foldable module, which arrives in a pack-state and which can be easily opened on site. With a developable surface we do not waste assembling time, achieving economic benefits, and we give immediately structural stiffness [1]. For a fabrication oriented design it gives more advantages, achieving a continuous surface that can adaptive to the environment.

The discussion is organized into the following five parts: an initial informative phase about the climate, the principles that reside in desert and the rules that govern folded architecture; a second simulation phase where we apply that we learn using a parametric approach; a third phase regarding the optimization process describing our zero organism and the objective function; a fourth phase where we analyze the family of solution we obtain, trying to understand which organism is the best one; the last phase where we develop the design of our module.
2 INFORMATION

2.1 Climate
The climate of the Atacama Desert is characterized by wide daily thermal fluctuations, with a high temperature difference between night and day. In summer, daily temperatures range from under 14°C to over 32°C, and in winter from 0°C to 22°C, with an average temperature difference of 20°C during the year. These conditions are accompanied by low daytime relative humidity, intense solar radiation and strong hot dusty winds, predominantly from South-East. During the year, there is very little rainfall, which causes a very low vegetation cover.

2.2 Desert Architecture

Town Planning
In the desert the passive cooling systems assume many forms: from an urban point of view, an important strategy is the agglomeration of buildings which limits the total surface exposed to solar radiation, reducing the heat absorption overall and the penetration of dusty winds [4].

The urban form of a traditional city is highly centralized, usually with a continuous pattern of courtyard building (Figure 1), joined each other by common walls and connected by a very diffuse network of narrow alleys departing from the main road system. These alleys work as the courtyard in the house; with long walls in clay they make shade and good thermal comfort conditions in the hot summers, because they avoid the overheating by direct radiation and create different temperature zones in the air which cause convective movements.

Figure 1. Continuous pattern of courtyard houses, Ghadames, Lybia

Courtyard House
The patio, in addition to play a central domestic function in the organization of the house, offers several climate advantages. It recreates the conditions of the chimney effect (Figure 2), which aspires hot air from inside the rooms and, with its walls partly in the sun and in the shade, it produces a beneficial air movement between the openings, to release fresh air from its lower layers [6]. A well-designed courtyard house is cool during the day when ambient temperature is high, providing shadow areas, and warm at night when it is low. Every courtyard is in relation to at least one house, but often more.

2.3 Folding Architecture
To respond to our request of building a structure as quickly as possible, we turned to folding architecture principles. With this tool we can improve the benefits of a prefabricated architecture. This is due to the fact of creating the outer skin in a single operation, working directly on the whole package (which will arrive complete of thermal insulation and finishing) and not on every single element, thus managing to save assembly time [8]. It even gives immediately a structural logic, being all the pieces linked each other.

Among all the patterns we could use, our choice fell on the famous Miura-Ori pattern (Figure 3), even inspired by the use of the dome in the desert whose purpose is to always have a shady and a light area. The folded pattern has a characteristic zigzag corrugation in two directions that allows extending and retracting the pattern in both directions [1]. This particular surface is composed of repetition of a basic unit, symmetric trapezoids, which form a herringbone tessellation.

Figure 3. Miura-Ori pattern: fundamental region of a concave polyhedral surface.

Mathematical Approach
To achieve better results through the optimization, we need something that can assume all possible shapes, not necessarily regular and symmetric, demanded by the environment. Since the rigid-foldability of known surfaces strongly relies on the symmetry of the pattern, the geometric constraints must be generally investigated to solve an inverse problem of obtaining a pattern from the resulting form.
The foldability conditions of generalized Miura-ori are presented by Tachi T.: considering a vertex (Figure 4) with 4 fold lines with 4 sector angles $\theta_i$ ($i=0,1,2,3$) and four folding angles $\rho_i$ ($i = 0,1,2,3$) between the sector angles, produces a one degree of freedom mechanism. To obtain a flat-foldable and developable surface, these angles have to respond to the following conditions [5]:

$$\sum_{i=0}^{3} \rho_i = 2\pi$$

$$\sum_{i=0}^{3} (-1)^i \theta_i = 0$$

Thus the sector angles satisfy the equations:

$$\theta_0 = \pi - \theta_2$$

$$\theta_1 = \pi - \theta_3$$

The fold angles $\rho_i$ and $\rho_j$ incident to the vertex are related as follows [5]:

$$\tan \left( \frac{\rho_i}{2} \right) = \begin{cases} 
A_{ij} \tan \left( \frac{\rho_i}{2} \right) & (i - j = 1 \text{ or } 3) \\
\pm \tan \left( \frac{\rho_i}{2} \right) & (i - j = 2)
\end{cases}$$

where the latter represents that pairs of opposite fold lines having an equal absolute folding angles. $A_{ij}$ is a coefficient between these two equivalent pairs determined by $\theta_0 \ldots \theta_3$ for instance intrinsic measure in the crease pattern independent from the folding angles.

If $|\rho_0| = |\rho_2| > |\rho_1| = |\rho_3|$, we obtained [5]:

$$|A_{0,1}| = \sqrt{\frac{1 + \cos (\theta_0 - \theta_1)}{1 + \cos (\theta_0 + \theta_1)}}$$

Using design methods based on computational geometry Tachi provides design variations of Miura-ori through an interactive design system in which a user can deform the surface freely while sustaining the rigid-foldability of the surface.

**Tectonic System**

The particularity of folded structures is the additional rigidity due to the inertia introduced by erecting the surfaces [7]. A thin horizontal surface can cover a large span but will bend under its dead weight. The folds give the surface the resistance to support loads. Each inclined face of the folded surface acts as a beam and it is horizontally supported by the adjoining face. The stability of the structure is guaranteed cooperative interaction of the folds (Figure 4).

In our design, the aim is to have a freestanding structure, a sort of valued roof, drawn following structural and energetic criteria.

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2.4 Cellular Automata

The term Cellular Automata (CA) refers to a rather broad class of computational system that have proved useful both as general models of complexity and as more specific representations of nonlinear dynamics.

Desert agglomerations are villages which grow spontaneously and without a plan. Cellular Automata can provide a high-resolution representation of this urban spatial dynamics. In particular they are able to replicate the various fractal dimensional of desert cities (Figure 5).

A CA can be defined as the following elements [6]: a discrete Cell Space together with a set of possible Cell States and a set of Transition Rules that determine the state of each cell as a function of the states of all cells within a defined Cell-Space neighbourhood; Time is discrete and all cell states are updated simultaneously at each iteration.

There are a number of common features, but the only universal property is that they are comprised of a number of discrete elements called cells. Hence a cellular automata consists of a regular lattice of cells. Each cell has a specific state, occupied or empty, represented by a marker recording its location. The transitional process begins with an initial state of occupied cells and progresses by a set of rules to each succeeding generation. The rules use a cell’s neighbourhood to determine its future [6]. The neighbourhood can be specified in two main ways, considering the left and the right cells or the eight cells all around the evolving one.

With this approach we can use an abstract concept, namely the CA, which can be specified in purely mathematical terms, to implement a physical structures.

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Figure 4. The structural behavior of thin corrugated surfaces.

Figure 5. Taos Pueblo, New Mexico, U.S.
3 SIMULATION

3.1 Geometry Modelling

In order to obtain a foldable surface which can communicate with the evolutionary solver, we have to generalize and then make parametric the Miura Ori pattern. We used the relation given by T. Tachi inside Grasshopper/Rhino, a parametric computational visual program language, to shape our starting module.

We here define the house module by the dimensions of its smallest constituent component, namely a parallelogram drawn using two sides, an inner angle and the dihedral fold angle. The inner angle is the one adjacent to the vertex in common to the four planes taken into account. Hence at the end we can change the length and the inner angle of each parallelograms, getting the folded angles with mathematical relations. The main steps of the algorithm are (Figure 6):

1. defining a starting point A;
2. defining a line AB giving the starting point A, its length and the azimuth angle A AB;
3. defining a second line BC giving the starting point B, its length and two angles, the vertical one B BC and the horizontal one B BC;
4. now we can define the first starting plane ABCD, giving the two previous lines and the inner angle BCD;
5. defining a third line giving the starting point B, its length and the vertical angle B BE;
6. defining the second starting plane BCFE, giving the line BC and BE and the inner angle BCF;
7. now we can find out the others two planes of the smallest constituent component CDHI and CHGF, using the relation gave by Tachi about the dihedral fold angles which are related to the previous inner angles BCD and BCF. Furthermore to get something can be repeated in the longitudinal direction the new inner angles CHI and CHG are given;
8. the last step is to continue the surface in the transverse direction, getting the two new planes EFML and MFGN always using the relationships of Tachi which link the dihedral fold angles and the inner angles.

This procedure was performed to obtain a surface composed of six to three elements (Figure 8) which they need to respond not only to matching edge conditions (giving for instance a surface domain) but even to developability and flat-foldability conditions.

3.2 Arranging the patios

In this section, we will use the concept of CA to choose the position of patios and loggias within our module, in order to obtain something more spontaneous and to reproduce the typical pattern formed by the courtyard houses, as we said before. We used Rabbit, a set of components within Grasshopper, where we can set all the basic parameter to describe the CA behavior.

Between the CA neighborhoods we chose the one-dimensional rectilinear one, composed by the right and the left cells. If each site has two possible values, there are a total of 2^n possible states, or configurations, for the complete finite cellular automaton. Having eight possibilities the rules we can have are 2^8=256.

We will use a grid of 42m for 14m composed of 12 for 4 cells, each one is a square of 3.5m, as shown in Figure 7, repeated for two storeys. The direction of growing follows the x axis. The “0” state in when the cell is empty and the “1” state is when the cells is full. It is often convenient to define some cell states as fixed, so while cells in these states can influence the state transitions of other cells, they are not themselves subject to changes of state.

![Figure 6. The steps followed inside Grasshopper to parametrize the Miura-Ori Pattern.](image-url)
About the rules the cells follow to evolve, for each level we have three different rules, hence in total we have six different rules which are in different grayscale in Figure 7. That is why in the evolution scheme the cells grow by group of three rows. By changing the combinations of the various rules and the points whose state is set to default, we get an infinite number of possible aggregations between which we can choose according to our needs.

Figure 7. Basic elements of our CA and the steps it does to grow following our rules.

3.3 Zero Organism
Finally we can get our zero organism. We obtained the latter joining the foldable module with the concept of CA, getting the position of the patios and loggias. Where CA has a void for two storeys we placed a patio, where the void is just at the second level, we placed a loggia covered by wooden lattice (Figure 8). Among all the solution we get from the CA simulation we chose the one has good advantages from a functional point of view (e.g. room distribution and size, people number, flats number).

Figure 8. How we obtain the zero organism.

4 NATURAL VENTILATION OPTIMIZATION
A customized design can be achieved by static and dynamic processes. Static customization is achieved during the design process by selecting the shape and size of the building to its particular use and location. Dynamic customization is accomplished after construction for instance by daylighting and shadow systems to control inner conditions. This research focuses on the static process to find an adequate shape configuration for housing.

To a certain extent, vernacular architecture can be seen as the result of a static adaptation process in which spatial and formal solutions are fine-tuned after years of evolution. Desert architecture, as we said, contains examples of static adaptation in which for instance courtyard house and compact fabric pattern are used to solve various problems and define spatial qualities. However, although the desire for responsive architecture is an old human desire, the advent of digital technologies brings increased opportunities. With the development of computer techniques, more powerful tools are now available for designing spaces that respond to users and the environment demands.

To reach this aim, we used Galapagos, which is a genetic and evolutionary solver inside Grasshopper. It applies the principles of evolution found in nature to the problem of finding an optimal solution. It starts by generating a population of random solutions, evaluating their fitness (objective function), and subsequently applying the basic genetic operators of reproduction, crossover and mutation. This generates a new population with higher average fitness than the previous one, which will in turn be evaluated.

4.1 Strategy
Among all the parameters we can optimize, we chose the natural crossed ventilation as shown in Figure 9. As we have seen before, the patios are crucial to make the ventilation effective. They work with the wind, but in the desert is hot and dusty, or with a difference of pressure due to different temperatures between the shady and the light parts. Therefore, we decided to maximize the shadow the roof casts inside the patios in order to have a large area where people can stay and to improve the ventilation during the day, reducing the cooling load.

Figure 9. Our aim is to improve the natural ventilation.

This concept largely depends on the solar geometry (the solar altitude and solar azimuth), so we need the basic elements of a specific site: date of year, time of day, location, building orientation and dimensions. Being our project made using a parametric approach, changing the weather data we can obtain a different shape perfectly adapted to the new condition, just modifying the inputs.

We considered the worst solar ray during the year and for the Atacama Desert it is the 21st of December at 2:00pm.
On this day the sun is high, so the shadow is very small, optimizing this situation we are sure to reach a comfortable condition during all the day. To reach this aim, we selected three criteria [2]:

1. to maximize the shadow cast from the roof (Figure 10a);
2. to minimize the difference between the patio’s area and the shadow area (Figure 10b);
3. to minimize the ratio between the previous quantities.

![Figure 10. The criteria used inside the algorithm to optimize the ventilation.](image)

We used these three criteria because using the first one we saw the organism was inclined to open itself independently from the patio’s area: it achieves big patio which has a big shadow area but not correlated to light area (e.g. organism 18 in Figure 11). Therefore we introduced the second criteria using the patio’s area, in this case the body tended to close regardless of the shade produced inside the patio: it creates very small patio, useless from a living point of view, to have them all in shadow (e.g. organism 20). To balance both the effects we launched the third criteria. With these criteria we have to solve a simply geometric projection rather than a time consuming solar radiation analysis.

### 4.2 Computer Simulation

All this process is set inside Grasshopper. The input of the algorithm are the angles and the lengths of the each parallelogram, the output is the roof surface which remains topologically the same. So aiming to have a developable surface, the algorithm analyses the latter and calculates the shadow inside the patios using a specific solar radiation with Ladybug, a set of components for environmental analysis, and the genetic solver, Galapagos, tries to reach the objective function modifying all the input parameters until the fitness is appropriate.

To set this process inside Grasshopper, we needed to fix the range of all the parameters, in order to get a structure that is possible to build and in which we have living spaces. Both for structural reasons concerning the resistance of the material and for the transportability of the folded structure, all the data ranges are set in order to have shorter panel lengths than 6m and a roof span shorter than 15m. The algorithm can change the angles and the length of each panel with the big constrain of obtaining a deployable roof at the end, so all the quantities are linked together with the Tachi’s relations explained before. In order to get a more uniform shape all the angles are linked together: the angle of each panel is obtained adding or subtracting a well-defined quantity to the previous one.

## 5 RESULTS

### 5.1 Set of Solution

After the simulation, a different population of surfaces was obtained, because we used different criteria and above all because the genetic solver is not a deterministic process. Each time we run an optimization we obtained a different result, with a different shape, even though only in the details (Figure 11). This set of solutions is related to the orientation: if we had chosen a different orientation at the beginning we would have obtained different solutions, one for each direction.

![Figure 11. A set of solution, different organisms, each one with different characteristics.](image)
As we can see in Figure 12, after the optimization we had different section types, because the roof tried to rise as much as possible with various configurations to achieve the most efficient shape. In theory all the shape are optimized, some ones more, others less but every ones reach the aim of improving the shadow inside the patio following a specific criteria. That is why in the next section we classify all the organism in order to understand which one is the best one.

### 5.2 Ranking

We have classified all the elements relying on each criteria: from the best to the worst, we assigned a score based on the standings at each element and at the end we produced a ranking by adding the scores obtained by each organism. Among the criteria in addition to energetic principles (three criteria explained before) a structural criteria was introduced (the maximum length of each panel). Before choosing the best organism, we analysed the solar radiation of all the organisms in order to decide on the best strategy. With this ranking, we are open to different solutions depending on the design strategy. For instance, for a hot climate, by analysing the solar radiation incident on any surface, we can choose the organism with the least amount to have less heat transmitted within the building. If we want to maximize the functioning of the solar panels (DHW productions or electricity generation) we can choose the shape with the best incident solar radiation. In our case, we will choose an organism that could follow the second strategy, to have a self-sufficient building, and that obtains the highest score between energy and structural criteria.

![Figure 12. Typological sections of the organisms.](image)

### 5.3 Best organism

After the optimization we obtained the best organism, namely the organism with the best energetic behavior according to the climatic conditions. The new element tries to rise and to get narrower the width of the patios (Figure 13), in order to have more shadow area but at the same time having a good relation with the courtyard area. Even though the shape is not so different from the starting organism, in Figure 14 we show how improved the shade produced by the roof is. At the beginning most of the courtyards had a sizable lighted part during the worst day of the year, now the courtyards are almost completely shady.

![Figure 13. Volumetric comparison between zero and best organism.](image)

We even show how decreased direct solar radiation annual exposure time of the patios is in percentage.

After we obtained the best organism we checked the structure. The material we used is a cross laminated timber to create a self-supporting structure. We run a FEM analysis using the self-weight, the wind and the live load. All the joints are considered fixed. The result is a thickness of 12cm for each panel.

![Figure 14. Improvements: a) Shadow Area comparison; b) Daily percentage exposition to the solar radiation.](image)

### 5.4 Design

The self-supporting roof system allows a free development of the floor plan. The proposed solution can accommodate eight families (Figure 15), the distribution being as follows: two flats for two people families, four flats for families of three members and two flats for the larger families of four. Every flat has a staircases matched with the bathroom and the kitchen, to keep the prefabricated logic of the building.

The access to the apartments is through the courtyards to protect them from the wind. Thus a private and protected network of pedestrian roads is created, semi-public spaces open to all occupants are shared to take part of the community life. At the second level, we have for each apartment a loggia covered with a lattice wooden panel, in this way shaded exterior areas provide a transmission between interior and exterior (Figure 16).

The reticular structure that can be seen on each patio arises from the need to replace a solid panel with a beam system which has the same inertia, however, being able to allow obviously air flow.

Interior natural lighting of the apartments is designed keeping in mind the daily shadow behavior. The main lighting sources are towards the courtyard, avoiding direct solar radiation and preventing heating the apartments. Other windows are placed towards the outside, which are very important for the ventilation but at the same time protected from direct radiation with wooden rods, repeated on all the facades to create a micro shadow able to protect the skin.
Figure 15. Ground and first floor plan.

About energy production, we selected the roof panel with the best solar radiation for square meter to produce both electricity, stored in battery, and the demanded hot water.

Figure 16. Perspective view underlying the main elements.

6 CONCLUSION

After the optimization of the foldable module, we analyzed the building in Ecotect, choosing all the comfort inner parameter (i.e. air temperature, relative humidity, air change rate). We used two data to see the improvement:

- too hot hours (degree hours): obtained by multiplying the difference between the inner temperature and the comfort range for the hours when we have this discomfort;
- cooling load (kWh): obtained considering a system with an efficiency of 90%. (comfort range 18-22 °C).

We compared the most efficient result with a simple prismatic volume to better underline the contrast of efficiency between a possible classical non-optimized architecture and the one provided through parametric design optimization (Figure 15).

At each step, we can see both the data decrease. In particular between the zero organism and the best one we have a 60% reduction of too hot hours and a 40% reduction of the cooling load.

With the informatics techniques explained, we were able to improve one of the oldest principles of vernacular architecture, the patio. Managing to calibrate the shape and the size of the latter, we can achieve appreciable improvements. For future works we want to explore the synergies of a multi-criteria optimization, trying to use more than one energetic parameters but even try to understand if a structural and energetic optimization can dialogue each other for this kind of shape.

Figure 17. Comparison between a prismatic volume with courtyards, our zero organism and the best organism.

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Nick Vlaun, Arend van Waart, Martin Tenpierik and Michela Turrin
Delft University of Technology
Delft, the Netherlands
{n.j.v.vlaun, a.vanwaart, m.j.tenpierik, m.turrin}@tudelft.nl

ABSTRACT
Optimizing the acoustic environment of open plan offices is a complex task due to the large number of design parameters that must be considered. In current practice, acoustic analysis – even in a simplified form – is not naturally integrated into the design process of office spaces. Applying digital acoustic simulation in architectural design currently requires a time consuming back-and-forth transition between geometric modelling programs and specialist analysis software. In this study, an acoustic ray tracer was developed within Grasshopper and coupled to Galapagos in order to optimize the acoustics of an open office space. This tool has been tested and validated through a case study performed on an existing office space in the Netherlands. This study demonstrates the possibility to computationally optimize open plan workspaces by way of acoustic analysis performed on a parametric model. In its current form the presented model is still limited in its features and calculation speed. Hence, further development of the tool is needed in order to facilitate a truly seamless iteration and hands-on evaluation of different design configurations (with respect to room acoustic performance).

Author Keywords
Parametric design; acoustic simulation; room acoustics; multi-objective optimization; performance-based design

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I.6.5 [Simulation and Modeling]: Model Development; J.5 [Arts and Humanities]: Architecture; J.6 [Computer-Aided Engineering]: Computer-Aided Design (CAD)

INTRODUCTION
Over the last two decades, modern non-territorial offices with large open work environments have seen a surge across Europe. Past research shows that user complaints tend to increase with the application of open planning in the workplace. Compared to small enclosed offices, workers generally experience a loss of privacy and tend to be distracted more easily in large open workspaces that they share with colleagues [2, 13]. Noise is identified as a root cause of these problems and often poses the most severe indoor environment problem in open offices [16]. Optimizing the acoustic environment of an open plan office is a complex task due to the number of design parameters that must be considered [5]. The very concept of open office planning itself already invites some level of acoustical compromise, since the conflicting requirements of good speech communication and good speech privacy are asked to co-exist in a single physical environment [2, 24]. In other words, the office space should facilitate good speech intelligibility so colleagues can effortlessly engage in conversation. At the same time, privacy may be desired because we want a conversation to remain confidential and not be understood by others. In other cases speech noise is seen as a main source of disturbance [6, 10, 25]. Direct person-to-person speech propagation in a room can be lowered by placing screens, the effectiveness of which increases with their size: essentially acoustic performance will improve the closer you get to a cell-type office. Altogether this poses a predicament which is deemed too complex for most architects and is thus left to specialists who get consulted in later stages of the design process.

The relation between acoustic performance criteria and building properties is described and assessed using terms such as reverberation time, which are typically expressed in the form of mathematical equations. A point of contention can be made that most architects do not innately utilize such formulas. A translation into geometric representation would be better suited for application in design practice. In other words, design team members could gain understanding for the implications of certain decisions if information on acoustic requirements is directly expressed in room shape and material properties [4, 24]. Currently there is a lack of appropriate toolsets which allow us to easily evaluate the acoustic quality of design proposals in an interactive fashion. Though specialized acoustic analysis software packages do exist, these currently do not offer seamless interoperation with popular 3-D modelling programs. Their application in office design is also far from commonplace.

This work is motivated by the idea that knowledge on room acoustics, relevant to the design process, can be made more accessible to design professionals if it is visualized directly in a (parametric) architectural 3-D model. It is of our contention that acoustic design guidelines are too generalized to account for the intricacies of any specific
applies for sound propagation in a free field condition over large distances, and vice versa. The inverse square law roughly translates into low sound propagation change in SPL detectable by human hearing, or ‘just-noticeable difference’ (JND), lies in the order of 1 dB [12]. For the most important frequencies the smallest normal level of human speech at 1 m distance is rated at 60 dB [3].

The main point here is that the results of acoustic simulation serve directly as feedback for the geometric and material reconfiguration of an architectural model.

TERMS AND PARAMETERS

Frequency and SPL
Sound consists of longitudinal pressure oscillations in air, which get meaning upon interpretation by human hearing. The sound wave is described by its wavelength and amplitude, which correlate to perceived pitch and loudness respectively. The frequency of sound determines the height of its tone (i.e. high frequencies correspond to high tones). In reality sounds are nearly always composites built up of many tones occurring at once. Human speech, for instance, contains frequencies in the range from 200 Hz to 5 kHz [3].

Sound pressure describes small positive and negative pressure variations in relation to atmospheric pressure we normally experience. Sound pressure level (SPL) is a logarithmic expression introduced to cover the wide range of pressure variations that can be detected by human hearing. It is a quantification related to the perceived loudness of sound, which is expressed in the decibel (dB) unit. The following equation applies:

\[ L_p = 10 \log \left( \frac{p_{eff}}{p_0} \right) \]  

\( p_0 \) is a reference pressure (20 μPa). SPL is not additive: a doubling of sound pressure equates to an increase of 6 dB. A normal level of human speech at 1 m distance is rated at 60 dB [3]. For the most important frequencies the smallest change in SPL detectable by human hearing, or ‘just-noticeable difference’ (JND), lies in the order of 1 dB [12].

Sound strength (G) is used to indicate the contribution of a room to the measured sound level from a sound source. In simple terms, this parameter effectively compares the sound level in a real room to the sound level an anechoic chamber with the same sound source [14].

Spatial decay rate of speech
The spatial decay rate (DL₂; D₂,S) indicates the decrease of sound with distance from the sound source. To be more precise, spatial decay is measured per distance doubling. A high decay roughly translates into low sound propagation over large distances, and vice versa. The inverse square law applies for sound propagation in a free field condition (outside without obstacles to reflect or block sound). The sound pressure of a spherical wave front, emitted by an omnidirectional point source, decreases by 50% each time the distance from the source is doubled: thus the spatial decay rate is 6 dB per distance doubling in this case. Target values for the spatial decay rate in an office depend mainly on the work activities, where tasks requiring high amounts of concentration will obviously lead to more stringent requirements. ISO/NEN 3382-3:2012 gives a general target value of D₂,S ≥ 7 dB for open plan offices with good acoustic conditions [15].

Absorption and scattering coefficients
These are numeric expressions for material and surface properties. When a sound wave encounters a structure part of its energy is absorbed, part is reflected and the rest is transmitted through the structure [9]. The absorption coefficient (α) denotes the portion of sound which is not reflected. Hard materials reflect more sound than porous materials, and thus have a lower absorption. The scattering coefficient (s) is that portion of the reflected sound energy \((1 – \alpha)\) which does not travel in specular direction. This portion, which increases according to the roughness of a surface, instead reflects diffusely in all directions, as illustrated in figure 1.

![Figure 1. Energy reflected from a corrugated surface into a scattered and specular reflected portion [28]](image)

DIGITAL SIMULATION OF ACOUSTICS

Sound wave theory, though correct from a physical point of view, is not deemed to be beneficial when it comes to dealing with practical issues in architectural acoustics. Computer simulations are instead typically based on the principles of geometrical acoustics: herein the concept of a wave is replaced by the concept of a sound ray [17, 28]. Analogous to light rays in optics, a sound ray is seen as a straight line along which a small portion of sound energy travels. Where sound in reality travels through a room from one person to another, rays in a simulation propagate from a defined source point to a receiver, interacting with the geometry of the room model along the way. The task in geometrical acoustics is to find the paths of sound connecting the source and the receiver [21]. Wave phenomena like diffraction and interference are typically neglected. Wavelength or frequency of sound is also not inherent to ray-based simulation models [22]. Ultimately geometric acoustics provides an approximation of the acoustical environment in a room. Its application is
however justified if the dimensions of the room and its walls are large compared to the wavelength of sound [17].

**Basics of ray tracing**

For the simulation of sound in large rooms two geometrical methods are generally distinguished: ray tracing and image source model. These approaches have contradictory (dis)advantages. This has led to the development of hybrid models that seek to combine the best features of both methods [21, 22], which are typically found in commercial acoustic analysis software such as CATT-Acoustic [11] and ODEON [20]. A pure ray tracing algorithm is utilized in this study, due to its relative ease to implement compared to more complex hybrid methods.

**Figure 2. The principle of ray tracing [17]: the method is used to find sound paths between a certain point A (the source) and one or several points B (receivers)**

In ray tracing a large number of rays are emitted from a source point in various directions (in our simulations we use an omnidirectional source emitting over 10,000 rays). Each ray carries a portion of the initial sound energy. Rays encountering the room boundary (walls) are subject to energy loss by absorption and will reflect and scatter as described further on. With each hit, rays lose energy according to the absorption coefficient of the wall. Tracing continues until a ray has no significant amount of energy left or a certain distance is reached. Counting volumes are used as receivers to record energy and elapsed time for every intersecting ray. Our model incorporates spherical receivers of variable size. As the use of receivers of constant size leads to systematic errors [18], the volume of a receiver is made a function of room size, source-receiver distance and amount of rays emitted by the source [29]:

$$V_{\text{receiver}} = \log(V_{\text{room}}) \cdot d_{\text{SR}} \cdot \sqrt[4]{\frac{4}{N}}$$  \hspace{1cm} (2)

**Modelling reflections**

The direction in which sound energy is reflected off a structure depends on wavelength of the sound in question on one hand; and the shape, roughness and materialization of the surface on the other hand. As previously illustrated in figure 1, two types of reflection are distinguished:

- **Specular reflections** – Essentially the behavior of sound bouncing off a smooth and hard surface is similar as light being reflected by a mirror. The angle of incidence is equal to the angle of reflection in this case;

- **Scattering** – In practical cases room surfaces mostly have an irregular texture. When a sound wave encounters a convex or rough surface a distinct portion of the reflected energy is scattered evenly, instead of being limited to a singular specular direction.

The distribution of scattered sound energy follows Lambert’s cosine law. This roughly comes down to the reflection of energy in all directions, the intensity of which is highest at a reflection angle perpendicular to the surface [17, 28]. From a computational perspective, generating new rays at each reflection point to model scattering is not feasible, as it would lead to an explosion of calculation time. For application in a computer model, one scattering angle is instead (randomly) chosen for each reflection at a time according to Lambert distribution. In our case we consider both specular and scattering reflections at the same time, applying a method for reflection modelling referred to as ‘vector mixing’ [8]. As shown in figure 3 a single resultant reflection direction is determined by directly combining specular and diffuse reflections through weighted vector addition. The scattering coefficient determines the weighting between the two, with a coefficient of 0 equating to pure specular reflection and 1 equating purely random scattering.

**Figure 3. Construction of reflected ray by weighted addition of a specular reflection and a scattering vector [8]**

The notion that scattering directions are chosen at random is important. An acoustic simulation can be performed twice with the same exact setup, but yield slightly different results between both runs. Though these differences are often not noteworthy in terms of human hearing, they are not small enough to completely ignore when we start to consider comparison of multiple design configurations. This inherently means simulation will be performed multiple times. This randomness issue has, at the time of writing, not been truly addressed.

**Implementation in the parametric model**

The process of software acoustical simulation consists of three subsequent elements [1]: source conception, the modelling method of the room (comprising the definitions for the geometric model and the tracing procedure) and modelling of the receiver. Our implementation of acoustic simulation in a parametric model follows the basic scheme of figure 4. The geometry and materials of the investigated
Figure 4. Principle of the acoustic ray tracing routine applied in an optimization process

Figure 5. Component network of the Grasshopper definition: the custom scripted components are denoted by the dashed line
design solutions, rather than a single solution. Out of this pool, individual solutions are selected according to their adjustment to performance goals. New solutions may be generated through mutations and crossovers of previous elites, which are those configurations displaying the most favorable traits with respect to the fitness criteria [19]. In Octopus solutions are plotted in real-time on a 3-D graph, in which each axis represents a predetermined design criterion. In all, our overall process is aimed at finding a set of configurations in which a vast improvement of room acoustic characteristics is balanced with a limited degradation in the open appearance of the indoor space.

**Model Validation**

In order to benchmark the accuracy of the developed definition, its results are compared to those of a full detailed simulation run performed in CATT-Acoustic 8. An existing office space in the Netherlands which, for purposes of anonymity, will be referred to as ‘office A’ (figure 6) serves as our case study. The investigated workspace exemplifies a typical Dutch office by its layout and activities.

![Rhino model of office A](image)

**Figure 6. Rhino model of office A**

Both simulations are based on the same Rhino model and the same measurement setup: a set of receivers placed in a straight line at fixed distances from a single sound source. The CATT-Acoustic program is set to utilize a detailed image source method with radiating surface sources for early specular and diffuse reflections, combined with ray tracing for late reflections. The simulations are assessed for the 500 Hz octave band only, with the material coefficients assigned to each surface as previously listed. Ray truncation time is kept consistent at 1 s, while the number of rays used within CATT is determined automatically by the program (amounting to over 18,000 rays in this particular instance). The results of the comparisons are shown in figure 7.

At two receiver positions deviations were observed between the measurements of CATT and Grasshopper which exceed just-noticeable differences. Upon inspection these receivers turned out to be partially intersecting with geometry. This a well-known detection problem of volume receivers [18]. The issue was corrected in a second run by moving the measuring line 0.3 m upwards. The differences for both SPL and DL₂ fall within the margin of error of the calculation in the corrected runs.

![Comparison of the results returned by the Grasshopper definition vs. CATT-Acoustic](image)

**Figure 7. Comparison of the results returned by the Grasshopper definition vs. CATT-Acoustic**

**EXPERIMENTAL SETUP**

The final optimization was performed using the model of office A. Within the modelled room a single source and several receivers are placed at a height of 1.2 m in fixed positions as indicated in figure 8.

![Floor plan of the ‘office A’ case study with measurement positions for acoustic simulation](image)

**Figure 8. Floor plan of the ‘office A’ case study with measurement positions for acoustic simulation**

Each time the design configuration is changed the SPL is measured at these receiver positions. The specific goal of the optimization runs is to maximize acoustic performance at places in the room where people might work (which equates in this case to a minimization of SPL). At the same time, the conflicting criteria of keeping the amount of added absorption and the size of placed screens to a minimum need to be satisfied. The following parameters are defined:

- Amount of absorption (minimized) – Calculated for each instance by multiplying the area of the surface with its absorption coefficient. All of the results are then summed for a room total;
Surface area of screens (minimized) – The amount and size of screens that are placed within the room are viewed as antithetical to the open nature of the space;

DL₂ (maximized) – Sound decay is measured across two lines of receivers. The first line is made up of receivers 01-03. The second line runs through receivers 11-15. DL₂ is obtained through linear regression of the measured SPL values at each consecutive receiver. This thus yields two values, one for each line, which are eventually averaged to a single value.

Variables
The starting point for the final model is the given space of office A in its current layout and material properties. The position of all the walls, the floor and ceiling, plus all furniture is fixed. The variables are as follows:

- Ceiling – The ceiling has been subdivided in 18 panels. These can have their absorption coefficient independently changed between 3 values (0.50; 0.70 or 0.90);
- Outer walls – The non-glazed portion of the façade is divided in 4 parts on each side according to the position of the desks. These parts can assume one of 3 values (0.10; 0.30 or 0.50) for its absorption coefficient. Glazed area remains unchanged;
- Internal walls – All of the glazed internal walls are parameterized. Every wall is divided over its height in three partitions. The middle portion is a closed panel with changeable absorption (0.10; 0.30 or 0.50), changeable dimensions and variable vertical position;
- Screens – Finally screens are placed in between and alongside the desks. Their height can vary in increments of 30 cm in the range of 0.9 m to 1.8 m. Their absorption coefficient is fixed to 0.30.

OPTIMIZATION RESULTS
The Octopus optimization presented here was performed on a custom built desktop computer, fitted with an i7-5920K CPU clocked at 3.8 GHz (calculations are single-threaded) and 8GB of RAM. Octopus’ settings were mostly kept to their defaults, applying HypE reduction and mutation. The population size was set to 250 per generation. The total execution time of the process amounted to 11 days. During this time 141 generations were completed, which brings the total amount of evaluated design configurations to 35,250, averaging a calculation time of 26.2 s per solution.

The solutions yielded from the optimization process are graphed in figure 9. Each dot represents a unique solution. The position it has in the chart determines the performance of the solution in question with respect to the given parameters. In a sense, the position of the dot in the graph mathematically describes which objectives are prioritized in that particular model configuration. Theoretically speaking, solutions plotted closest to the origin of the chart should exhibit the best overall performance. One thing that is evident from the given results, is that the solutions with the highest sound decay ratings (those lowest on the vertical axes of all graphs) always employ a combination of high absorption and most screen area, as expected. In comparison to the current office, practically all of the configurations on the Pareto front score better when it comes to sound decay. This is attributed to the fact that office A in its current state has no screens whatsoever placed in between the desks. None of the optimized design instances approach this extreme due to the solution space being constrained in that regard.

Figure 9. Pareto optimal solutions of the final generation of the optimization graphed

Upon further inspection it is also striking that the model instances with the highest DL₂ values have the absorption of the ceiling maximized closest to receivers 02 and 03. We found this to be one indication that the distribution of absorption given by the optimization, is dependent on the acoustic parameter being optimized and its method of
measurement. Figuring out the exact relation between the used calculation method, applied parameters and the outcomes subsequently produced by the optimization process requires more in-depth scrutiny of the data.

One design alternative is finally selected for purposes of feedback and validation. As illustrated in figures 9-10, most of the given solutions do not reach the ISO-standard target value of $D_{L_2}$: $D_{2,5} \geq 7$dB. For the final selection the solution is chosen which barely satisfies this criterion, with the smallest amount of screen area obstructing sightlines: this gives us ‘solution 144’. Said configuration is firstly characterized by a screen height of $h = 1.5$ m. Keeping in mind that the source and receivers are placed at a height of $h = 1.2$ m; increasing the screen heights further (to 1.8 m) leads to configurations that outperform solution 144, although not by much. The effect of this increase is for instance far less evident than the same increase made between 1.2 m to 1.5 m screen height.

DISCUSSION
The developed ray tracing algorithm is a very simple implementation of acoustic analysis with parameterization capabilities and provides a basic framework that can and should be built further upon. In its current form sound pressure levels (and other parameters derived from SPL) can be analyzed in a given closed space. Through alteration of geometric entities and material properties, measured sound levels can be lowered, which should bluntly equate to an improvement of acoustic quality in the space.

The current model is still in its infancy and requires further development on several points. Key areas of improvement include increasing the reliability of the script and its results, making the definition faster in terms of calculation time and streamlining its use through the creation of a more intuitive user interface. First, evolving the script from a pure ray tracer into a hybrid model should prove to be beneficial for the accuracy of the results. Second, the current implementation could be made more efficient in a few ways. Due to the workings of the Grasshopper definition, the ray tracing process always starts over if any of the input variables are changed. This is however not necessary when only material properties are altered and room geometry stays the same. Furthermore, Grasshopper does not innately recognize cases in which two model instances with different inputs produce similar geometry. As a result, several evaluated configurations may look alike and thus return rather insignificant differences in terms of acoustic performance. In some cases a solution might even be evaluated twice or more. Calculation time can be greatly reduced if such unnecessary operations are taken out of the equation. Especially in parametric search, where multiple model configurations are assessed, increasing calculation speed is of paramount importance. Altogether, a more fundamental question is raised of whether evolutionary algorithms will ever be suitable in a practical application of acoustic optimization. As it stands, solutions returned by the optimization process are primarily presented by their individual performance in regard to the objectives. Comparing the visual and parametric characteristics of each solution is however done manually. This naturally constrains the amount of alternatives that can be inspected within any reasonable time frame and, in a sense, defeats the purpose of generating many design instances in the first place. An integrated form of statistical analysis could help to uncover relevant relationships between geometric or material alterations, and subsequent acoustic performance.

The optimization process in this study was performed with a measurement setup using a single stationary source at a time. Offices are however multi-talker environments: noise in the workplace is produced by several employees, whom are seated at different places in the room, who tend to move around and may speak simultaneously. An efficient measurement method that is more representative for this natural situation has yet to be developed.

CONCLUSION
Within this study it is observed that the computational optimization of open office environments is possible by integrating principles of acoustic simulation in a parametric model. Said model needs further development to become a viable and accessible tool in the arsenal of an architect or building physics consultant. Besides making improvements
to the simulation algorithm itself, we have identified the necessity of including graphical post-processing features, so the results of the optimization process can be interpreted more effectively.

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TOWARDS RATING OF GENERATED TYPOLOGIES BY MEANS OF ADJACENCY COMPARISONS

Gabriel Wurzer and Wolfgang E. Lorenz
TU Wien
Vienna, Austria
{gabriel.wurzer|wolfgang.lorenz}@tuwien.ac.at

ABSTRACT
Applying different typologies to the same building yields a number of options concerning extensibility and circulation. However, it is hard to rate and compare these in order to find the most fitting one for a specific building task at hand. In this paper, we wish to work towards this goal using a showcase in which we generate and rate a large number of buildings in order to find out whether certain typologies prevail among the fittest solutions. On a technical level, we contribute (1.) a simple cell-space grammar that generates building volumes, given a preference for different axes in which form can develop - orthogonal, diagonal and vertical, (2.) a rating procedure which infers a fitness for every solution, based on (a.) the assignment of functions to parts of the generated building and computation of adjacencies between these and (b.) the extensibility of the building along its axes. Typologies are attributed in a post-step, as part of a manual analysis. Our results show a preference for the compact/central building type, as dictated by the use of adjacencies for rating a building.

Author Keywords
Typology; Grammars, Adjacency Comparison.

1 INTRODUCTION
Typologies are useful for describing a building from the standpoint of circulation and extensibility. Especially in buildings which serve a large amount of users and need to be adapted often - e.g. hospitals or airports, it makes sense to consider this topic early-on. Thinking about possible options (some given in Figure 1) can lead to a form that allows for short paths between adjacent zones and makes future extensions possible. However, this is a highly intuitive process: One can never say for sure whether a certain typology is adequate or even "optimal" given circulative requirements (expressed as adjacencies between zones, e.g. near, average, far) and possibilities for extension (constrained by the building spot). Furthermore, we never deal with "pure" typologies but always mixtures (refer again to Figure 1, left to right, top to bottom): The "T"-type is contained within the "I"-type, which also contains the "C"-type. "C" is also contained twice in the ring ("O"-type), as is the "L" type. The "Y" type is a "T" with diagonal instead of orthogonal axes.

Figure 1. Typologies give options for circulation and extensibility.

To rate and compare such typologies even in the light of such ambiguities is the main goal of our approach. To do that, we proceed in three phases:

1. We first give up the notion of typologies altogether and simply talk of spatial arrangements which we generate through a grammar, without loss of generality: All typologies seen in Figure 1 are generated by our program, and we may always name the most fitting one using a post-rationalization step (see Section 3, 'Generating Typologies').

2. We attribute zones to the generated spatial arrangement and compute their adjacency relationships. The calculated values are compared to a preset adjacency matrix and forms the first part of the generated building's fitness. The second part comes from the number of possible extensions of the building in relation to perimeter and area left on the building spot (which forms a constraining boundary). Because all of these points require assumptions that are specific for a building type and site, we use the concrete case of a

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hospital as example (see Section 4, 'Rating by Adjacencies').

3. By iterating generation and rating, we find the most fitting building size and spatial arrangement for the given requirements. The post-hoc attribution of typologies still remains subjective/ambiguous, however, we can now discuss them in the light of an objective measure (see Section 5, 'Results').

2 RELATED WORK
We use a three-dimensional grid grammar [1] to generate spatial arrangements. As always when dealing with grids and update rules, the transition to Cellular Automata (CAs) is fluent, two important differences being: (1.) Our update proceeds sequentially, one placed element after another, while cellular automata update in parallel, and (2.) our elementary element is a 3x3 arrangement of cells, while CAs consider a single cell. Our actual algorithm can be compared to Mitchell and Dillon's work on floor planning [2] (notably also in hospitals!) which agglomerates cells on a grid. By contrast and as novelty, our generation explicitly considers the direction in which this agglomeration evolves (vertical axis, orthogonal axes, diagonal axes). This also works for spatially constrained building spots, meaning that the algorithm takes whatever cell is available if there is none along the preferred direction.

After generation, we subdivide the building vertically into a 'public' part at the bottom (typically used for outpatient departments) and a 'private' part (used for wards). Such a subdivision has also been conducted e.g. by Lopez et al. [3], who also "grow" areas within the building design up to a specific preset size. Doulgerakis [4] furthermore assigns functions ad-post to generated spaces ("embryology"), which might be used for placing sub-departments within the public and private zone in future work.

During our rating step, we compute the farness from every cell of an area into every other cell. The reciprocal value of farness is closeness, a measure commonly associated with Hillier and Hanson's integration analysis [5] within their Space Syntax model. Other methods for computing centrality (e.g. eigenvector centrality/random walks) are slowly beginning to catch on the field (see e.g. [6]), however, closeness ("integration") and betweenness ("choice") remain the predominant techniques employed.

Because the (weighted) farness measures between areas are crisp values and not linguistic terms (near, average, far), we need to fuzzify as previously described in [7]. We can then compare the computed adjacencies to a preset adjacency matrix, in order to assign a fitness to each generated solution.

Evaluating fitnesses is a common process in Evolutionary Algorithms (EAs) and optimization. For this study, we have used a brute force approach (parameter sweep) rather than looking into more efficient ways of searching. Admittedly, this is one of the areas we have to look into in future work (a good starting point being e.g. [8]).

3 GENERATING TYPOLOGIES
We use a 3D grid grammar which with only one element, a Megacell consisting of 3x3 cells (refer to Figure 2). We have six cell states, empty, regular, circulation, diagonal connector, orthogonal connector and vertical connector. A Megacell has a circulation in its middle, surrounded by 8 regular cells. This area is the so-called built area, which is surrounded by connector cells that extend into directions where a next Megacell could be placed. We have four orthogonal connectors, four diagonal connectors and one vertical connector that is situated above the Megacell's center cell.

A cell has no physical size per se - this has to be attributed a posteriori and is only important for the later rating step.

Before our generation, we set a building budget in cells that is not to be exhausted. Every time a Megacell is built, we deduct 9 cells (i.e. the built area) from that budget.

Our generation (see Figure 3) starts with a single Megacell, always situated in the origin of the grid, which we assume is also the center of the building spot. Then, we consecutively place new cells using Step A-C:

Step A chooses a connector by probability: We have three probabilities, \( P_o, P_d \) and \( P_v \) corresponding to preference for orthogonal, diagonal or vertical connectors. All three are independent, one could in principle also choose 100% probability for all three of them. Typically, though, one will want to use these three global parameters to specify the type of building to generate - a high-riser or flat building complex, more orthogonal (90°) or with 45°-diagonals.
As a side-note, this step only considers connectors from which it is possible to build; extending beyond the grid, for example, is not possible. Furthermore, all types of horizontal connectors must check whether there is a Megacell underneath (we currently allow a maximum of 1 cells empty space to allow for cantilevers; an exception is the ground floor, on which we can always build).

Step B retrieves the cell C lying adjacent (and in "the direction" of) the connector. In the example shown in Figure 3, this is the cell east of the connector.

Step C Places a new Megacell with center C into the grid. Any overlaps between connector cells and built cells are turned into circulations.

The process is repeated as long as the cell budget is not exhausted (i.e. there are still 9 units left).

As finalization step, we clear all connectors to obtain the final spatial arrangement which can now be post-rationalized, naming the set of typologies that fit. Figure 4 gives examples of the generated spatial arrangement and shows that this is not always easy: While the left building is clearly a high-rise with type "C" base, the right building is a mixture between lots of types such as "Y" and Ring.

Figure 4. Examples of buildings generated by our approach

Figure 5. Private/public zone split using a histogram approach
4 RATING BY ADJACENCIES

This step is essentially occupied with transforming the spatial arrangement into a adjacency (half-)matrix and comparing that with preset requirements to compute a fitness. However, until this point the algorithm knows nothing about zones which it needs in order to form the adjacency matrix. We need to attribute such zones to the built, which is of course specific for every type of building. In our case, we chose a hospital with only two types of zones: the public (basement) zone in which outpatient care takes place, and the private zone above in which wards are placed. Our attribution proceeds by forming a histogram containing the number of cells per floor (refer to Figure 5). We go through this histogram from the lowest to the highest floor and test if the difference in the number of cells exceeds a given threshold \( \alpha \) or the sum of cells until here exceeds a threshold \( \beta \). If that is the case, we have found our split.

In each zone’s gravity center, we place a node (bubble) and connect that via an edge (adjacency relation; see Figure 6) which we now compute via a circulation graph. In each built cell, we place a graph node which we connect to each built neighbor's node in the same level, assigning a weight of 1 to the edge. Circulation cells additionally check whether there is a vertically adjacent circulation cell to which it then connects using a weight of 2 (penalty for vertical travel). As a side-note, the vertical connection algorithm also enforces a (configurable) minimum separation between vertical connections, as in elevator and stair shafts.

In the circulation graph, we compute the \textit{farness} between each pair of zones, including the zone and itself:

- All nodes of the source zone compute the average shortest path lengths to all nodes of the target zone, giving an average \textit{farness per node}. However, path lengths are not abstract, so we multiply this with an assumed cell length (8m in our case).
- The \textit{average farness} between source and target zone is computed by averaging the average farnesses of all nodes contained in the source zone.

The computed values are quantities and not qualitative statements (near, average, far). Using three \textit{linguistic membership functions}, we can find the most plausible term with which to describe the obtained average farness (see again Figure 6: near < 100m, average around 100m, far >100m). Admittedly, these values are based on the estimation of an advisor in the hospital we are working on rather than proper data in a large survey of building users. To be accurate, we would need to perform such a survey with many users, and from different perspectives (patients [capable of walking, wheelchair, in bed] and staff members).

We have two constituents for computing the fitness of a solution:

\textbf{Adjacency fitness}. We compare the computed adjacency matrix to a preset adjacency matrix (which in our case was set to Private-Private: near, Public:Public: near, Private-Public: average). For scoring, we represent near as -1, average as 0 and far as 1, and apply the following algorithm to each computed/preset adjacency pair:

\[
\text{diff} = \text{preset} - \text{computed}
\]

\[
\begin{align*}
\text{if } \text{computed} &\leq \text{preset} \text{ then} \\
& \quad \text{fitness} = \text{fitness} + \max(1, \text{abs(diff)}) \\
\text{else} \\
& \quad \text{fitness} = \text{fitness} - \max(1, \text{abs(diff)}) \\
\end{align*}
\]

\textbf{Algorithm 1: Comparing computed/preset adjacencies}

\textbf{Extensibility}: A building needs to be able to grow over time. We take the building’s base floor for checking this. There are two different types of extensibilities, (1.) the ratio between extension points and perimeter and (2.) the area covered by extensions versus the total area left for extension.

\textit{Ratio extensions to perimeter}. We count the perimeter of the building at ground floor by first counting all cells surrounding the building (depicted red in Figure 7). Then, we go through each connector at the ground level, testing for two different criteria:

- Is the cell at the opposite side of the Megacell built?
  Example: For a north connector, there must be a Megacell, in order to emphasize the circulation axes of the building when extending.
- When shooting a ray in the connector’s direction, there must be no intersections with the building. This is to ensure that extensions are not filling up holes between parts of a building but continue naturally along given axes.

Connectors surviving these two tests are counted, their number is divided by the number of perimeter. This ratio is invariant to scale (e.g. the ratios of the two "C"-types shown in Figure 7 are the same).

\textit{Ratio extensions to area left}.

For a concrete building site, we have to consider not only potential extensions but also how well they cover the remaining area on the building spot. By using a flood-fill algorithm, we are able to get all cells that are still open for development. Shooting a ray through each available connector in the direction it is pointing to, we count the cell area that would be covered until either a) the site boundary or b) obstacle is hit. We divide the number of covered cells through the number of cells available for development to give this ratio. In short, this determines how well the building's extensions fit into the building site.
5 RESULTS
We have conducted a parameter sweep experiments in three scenarios, using the values provided in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (building budget)</td>
<td>50, 100 or 150 cells</td>
</tr>
<tr>
<td>Po (orthogonal probability)</td>
<td>10%, 50% or 100%</td>
</tr>
<tr>
<td>Pd (diagonal probability)</td>
<td></td>
</tr>
<tr>
<td>Pv (vertical probability)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Parameter settings used in the sweep experiments.

For the first scenario, we used adjacency and the ratio extensions to perimeter as fitness (n=761 experiments total, 10 repetitions per parameter setting). The results shown in Figure 8a clearly indicate that the adjacency measure keeps the building shape compact (i.e. "O"-type with two levels).

For the 50-cell spatial arrangement, this is most clear (the ideal arrangement is always the same "O"-pattern, even though rotated). As we go into 100- and 150-cell arrangements, there are additional diagonal arrangements protruding from the central building. However, these are not formulated out so as to fit into any other typological category than the central type.

Another striking result of the adjacency measure is that the building is always two levels high. Anything else would be penalized the weight that was added to the vertical circulation, in order to simulate lifts and stair movement. The choice of adjacency matrix as well as the rather strict fuzzy membership functions further contribute to the preference for compact, flat buildings.

In scenario 2 (n=243 runs, 3 repetition per parameter setting), we have thus chosen to not take the adjacency into account but only rely on the ratio of extensions to perimeter. In that case (Figure 8b), the grammar is allowed to build higher structures (see rightmost building in the 150-cell category), however, it still seems to avoid these in favor of a large building base which translates into many extensions (and thus higher ratio).

Taking adjacency and both ratios into account leads to scenario 3 (Figure 8c; n=243 runs, 3 repetition per parameter setting): While similar to scenario 1, we see more diversity even in low cell budgets. Furthermore, the ratio extensions to area left seems to prefer diagonals (more directional freedom to claim the remaining area of the building site), it seems.
Figure 8. Top 5 spatial arrangements for cell budgets 150, 100 and 50 (top-down), in descending order of fitness (left-right).
Under these circumstances, it is hard to infer different "typologies" that are ideal - adjacency really dictates that the building should be a sphere, and the ratios furthermore work towards a ground floor of maximum extensibility. In order to allow for results as given in Figure 4, one would need to relax the required adjacencies and shift the fuzzy membership functions to allow for greater distances.

Comparing all three scenarios (see Figure 9), we can see that Scenario 2 has a relatively minor, positive range. Adding adjacency (Scenario 1) makes the fitness range oscilate between +/- 4. The second ratio is an additive term, hence Scenario 3 is shifted upwards.

CONCLUSION AND OUTLOOK
We have presented an approach that is capable of generating spatial arrangements resembling typologies, based on three-dimensional grid grammars. Rating each generated solution by adjacency and extensibility, we wanted to see whether the same typologies appear in all of the highly-rated buildings. Our current results show a high preference for compact/central building types, as dictated by the use of adjacencies during the rating process.

However, results could differ in cases where the building spot is highly constrained by pre-existing buildings and/or regulations. Since this is nearly always the case during real projects, our next step is to apply these concepts in practice.

Another future extension, which is currently being developed, is concerned with using building physics calculations as additional fitness criterium.

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ABSTRACT
This paper discusses Hong Kong’s 2015 ‘ZCB Bamboo Pavilion’ as a methodological case study for the design and construction of light-weight, bending-active, bamboo gridshells using digital simulation and physical prototyping. It covers the form-finding methods, physics simulation engines, and methods for construction documentation that were developed in response to the volatile nature of bamboo.

The ‘ZCB Bamboo Pavilion’ is a twelve meter tall public event space that spans thirty seven metres. It is built from bamboo poles, manually bent onsite, hand-tied with metal wire, and covered with a composite tension membrane. The project’s design and implementation pivot around formulating strategies for dealing with onsite imperfections and setting-up of protocols concerning unavoidable error.

The paper starts by addressing the design sequence for form-finding the bending-active structure. This sequence combines digital physics simulations with testing through physical model making. It then discusses the construction sequence which was iteratively developed through simulation and physical prototyping. It continues by analysing the construction documentation methods and notation systems set up for implementation of structure and skin without traditional architectural drawings.

The paper concludes by discussing the necessity for digital architecture to proactively operate within the field of real-world indeterminacy, highlighting applied design priorities, assumptions, risks, and probabilities.

Author Keywords
Bamboo; bending-active gridshell; physics simulation; form-finding; indeterminacy.

ACM Classification Keywords
Architecture; Computer-aided design (CAD)

1 INTRODUCTION
The virtual reality of building information models (BIM) is actually more precise than the material world. Since there will always inevitably be a gap between both, the question is: how big a gap should there be and is this gap potentially advantageous? (Willis & Woodward, 2010) This research project explores alternatives to attempting the building of architecture in the image of ideal, perfect digital models.
forms, and construction methods for their materialisation. This makes Cantonese bamboo scaffolding craftsmanship rather limited in architectural scope.

The ‘ZCB Bamboo Pavilion’ showcases how architectural innovation is possible when digital design tools for form-finding and construction documentation are introduced into pre-existing construction methods. Additionally the project fuels conversations on how bamboo can be suitably employed as an environmentally friendly and sustainable structural material in permanent buildings.

2 DIGITAL AND PHYSICAL MODELLING

2.1 Form-finding tools

Pioneering engineers like Frei Otto employed physical models, such as hanging chain models or soap films, as ‘physical computers’ to generate a structure’s optimal form for resisting specific design loads. The design of the ‘ZCB Bamboo Pavilion’ follows this tradition, but additionally incorporates digital real-time physics simulation engines in the workflow to define a suitable form for a bending-active gridshell.

Bamboo is a tall grass that gains its strength from its structurally highly efficient pole section. It is built up of cylindrical cells separated from one another with diaphragms. This geometry makes the material not only strong but also very flexible. The form an elastically bent bamboo pole takes can easily be discovered using physical models. Similarly, virtual spring-particle systems allow us to find this form by simulating material behaviours digitally.

This project applies Kangaroo as a digital form-finding tool. Kangaroo is a plug-in for Rhinoceros® and Grasshopper®. Kangaroo operates using a particle systems in which points (often called nodes, or particles) respond to applied forces following laws of physics. Hooke’s law, for example, states that the force exerted by a spring is directly proportional to the amount its length differs from its natural or rest-length. By breaking an object down into an interconnected network of points and subjecting these points to specific forces, such as gravity or spring forces, its macro-scale behaviour can be mimicked.

![Spring-particle simulation of an elastically bent discretised curve.](image1)

The natural bending of curves can be simulated in these environments through discretisation (See Figure 3). A curve is subdivided into segments. Each segment operates as an individual elastic spring with a rest-length to which it constantly tries to return. A bending force is applied in between each curve segments aiming to straighten them. By moving the end points of the curve closer to one another, this set-up relocates the central points until an overall force equilibrium is reached. This shape approximates the one a continuous curve or rod would take when bent elastically. Similarly, a single-curve setup can be expanded into a network or grid of interconnected discretised curves.

2.2 Structural concept definition

Unlike wood, steel, or concrete, bamboo is a material that is rarely used in construction as a structural material. At the start of the design of the ‘ZCB Bamboo Pavilion’, documentation, let alone building regulation, on how to use natural bamboo in the bent fashion as a primary structure were insufficiently available. The architectural and structural design of the project therefore resorted to the rigorous use of both physical and digital models to simulate the overall structural behavior of the pavilion prior to construction (See Figure 4).

![Design sequence using digital and physical models](image2)
The project started off with a design and build workshop where participants, backed up by digital physics simulation tools, built physical models to test out design options. The project brief was to design a covered public event space in an open park area capable of housing two hundred people. Four teams worked in parallel on different design concepts. At the end of the workshop the final selected project had been developed through a series of five prototypes made from split bamboo sticks at 1 to 20 scale. Each model iteration aimed to solve encountered structural issues until a structurally sound and architecturally satisfying end result was found (See Figure 5).

Unlike most of Frei Otto’s designs that employ a singular structural concept, the workshop outcome applied a hybrid of various simultaneously operating structural systems. The digital simulation tools, needed for the extraction of eventual construction documentation, had to be reworked in order to accommodate this.

3 DIGITAL SIMULATION OF FORM FINDING

A bamboo pole cannot be deformed beyond its natural varying properties when cold-bent onsite. Therefore any digital or physical model can be but an approximation of the eventual outcome. We prepared for a level of ‘form-finding’ to take place during construction similar to what we observed during the making of the physical models in the design workshop, albeit at a much larger scale. Nonetheless, digital models were needed to allow for the automated production of the construction documentation.

The following paragraphs describe the digital setup that was put in place.

3.1 Step 1: physics simulation input geometry

The first step involves the definition of the geometry that will be used as input for the physics simulation engine (See Figure 7).

The input geometry definition starts by generating the triangulated diagrid that defines the doubly curved top shell of the structure (Zone A in Figure 6). For this, first the onsite locations of the footings are fixed. Three locations in the grass area surrounding the wooden decking are selected. Circles of five metres in diameter are drawn and their centre-points are used as a basis for the creation of a hexagonal grid (see diagram 1 in Figure 7). This hexagonal grid is then extended and divided into eighteen subdivisions in each of its UVW direction (see diagram 2 in Figure 7). This variable number was intuitively selected from an iterative series of test simulations as it resulted eventually into onsite triangles of a manageable dimension with edges between 1 and 2 meters.

The three pavilion legs that emerge from the top diagrid are formed by folding extensions of the diagrid curves onto themselves. Trial and error in both the digital and physical realm revealed that an appropriate length for these extensions in the simulation can be found by intersecting them with arcs that extend from the boundary line (see diagram 3 in Figure 7). These extended boundary lines will later be wrapped and folded to make up the bottom side of the legs. Their endpoints are the points that touch the concrete foundation.
Figure 7. Physics simulation input geometry: diagram 1. Foundation positioning defines triangular grid orientation; diagram 2. Triangulated grid; diagram 3. Grid curve extension for legs and ‘belly’ area; diagram 4. Force anchor point definition.

The intersection points of overlapping folded geometry (zone B in Figure 6) need to be pulled together. The anchor points for these forces are found by splitting the extensions with a second arc and dividing the remains into equal segments (see diagram 4 Figure 7).

3.2 Step 2: input force definition

Three types of virtual forces are internally applied onto the structure to fold the legs together. In our setup, the force magnitudes form a numerical abstraction of real-world forces. It is their relative value that is crucial – not the actual numerical values, which affect the speed of reaching equilibrium only, but not the outcome.

1. Spring-From-Line forces: every line segment aims to keep a certain rest-length by having an elastic spring force applied between its end points. This force strength is set relatively low in the overall setup. Every curve is broken up into line segments at intersection points with other curves. In areas with free-hanging curves (Zone D in Figure 6) the curves are subdivided according to their length. As the planar input geometry (see diagram 4 in Figure 7) is larger than the final geometry, we iteratively found the appropriate rest-length to be 76% of the drawn input.

2. Bending forces: all adjacent line segments within each curve have a bending force applied to them, aiming to straighten out each overall curve. This force strength value is relatively set to be very high.

3. Inverse gravity: in order to initiate the deformation out of the drawing plane, all intersection points are subjected to a very weak upward unary force. This force is slightly larger in the central area in order to have the pavilion’s folds to ‘flip’ into the right downward direction.

In addition to these internal forces, outside forces are applied to pull the structure onto its foundations. For this a relatively very high Spring-From-Line force strength is applied to line segments that connect the permanently fixed foundation anchor points with the corresponding points of the flattened input geometry. Similarly the overlapping points in Zone B (See Figure 6) are pulled together to make the quadrangulated grid in the legs. Both of these strong spring sets have their rest-length set to zero.

3.3 Step 3: repeated physics simulation

Once the physics simulation engine is set in motion the input geometry transforms until equilibrium is reached between all the forces that simultaneously act on the particles. The outcome is a close approximation of the final form with all curve geometry resulting primarily from the applied bending forces (See Figure 8).

Figure 8. Geometrical outcome of digital physics simulation

The Spring-From-Line forces with rest-length zero do not result into single points: a small curve remains in the final force equilibrium. Kangaroo does not allow for particles separated at the start of the simulation to merge completely during the simulation. This, however, is needed as the pavilion’s folded leg geometry needs to be connected similar to the curves in the triangulated areas on top.

In a separate step these problem points, found at the foundation and in Zone B (See Figure 6), are merged and
the updated geometry is subjected a second time to the physics simulation engine. This time only the foundation points are anchored and all line segments only have Spring-From-Line forces and Bending forces applied to them.

The outcome of the second iteration is an interconnected curve network in which the geometry of all lines, including the free-hanging curves (Zone D of Figure 6), are the resultant of elastic bending.

4 PROJECT CONSTRUCTION

With the overall geometry digitally defined, the next steps involve developing this model further to a point where the necessary information for manual construction can be extracted. This information had to incorporate the fact that onsite construction would use bamboo poles of varying diameter, length, and flexibility, tied together by hand using metal wire.

The development of the construction documentation for this happened in the following steps.

4.1 Intersection mark-up

The interconnected bamboo poles had to be bent in shape by hand and tied into place onsite, up in the air from the top of temporary bamboo scaffolding. No traditional architectural drawings or measurement tools could practically be carried up into the scaffolding to allow for accurate positioning, meaning a system needed to be devised allowing all necessary preparatory annotation work to be done on the ground.

The method developed for this was remarkably basic. A drawing set was produced in which each individual curve was straightened out, and the intersection points with the crossing curves were marked up from the curve’s starting point. A long ruler was laid out on the ground, and poles of varying length were laid out next to it and tied to one another with sufficient overlap. Using the ruler all intersections were marked.

Once all intersection points were marked onto each individual pole, the remaining onsite tasks to rebuild the overall geometry were to roughly lift the poles into place, position them onto the correct foundation points, and fix the correct corresponding connection points between different poles. With each connection, the geometry slowly took shape and became stiff. Vertical projections of selected intersection points onto the ground were marked up ahead of time, allowing for the correct positioning of these points during buildup. Eventually the overall form automatically emerged as each pole found its appropriate bent form.

For all prototypes (See Figure 4) this annotation was done by hand. For the final construction transparent sticker labels were used that had all the necessary node connection information printed onto them.

4.2 Installation sequence

The first prototype, made from solid bamboo sticks at 1 to 30 scale, revealed issues with the installation sequence. The stiffness of the individual sticks made it impossible to ‘weave’ them randomly into one another. The final structure would similarly require the poles to be installed in overlapping zones where certain directions would cover the bottom layer, and others would go in the middle, or on top. However, the three directions needed to be installed simultaneously to allow for the form to start defining itself from the very beginning through the first connections. Additionally, the size and complexity of the final structure required the construction of a dense temporary scaffolding underneath the entire pavilion, meaning poles needed to be laid up from the outside only, rather than placed from within.

Figure 9. Pole installation sequence

The final iteratively tested solution consisted of breaking the installation sequence into separate phases based on the three groups of curves (See red (A), blue (B) and green (C) curves in Figure 9). First the top poles from A and B were roughly fixed into place with support from the scaffolding underneath. Then two additional poles from each were installed to define the most central compression arches of the overall shape, carefully placing B on top of A. Then half of the remaining poles from group A (the poles that define compression arcs) were installed underneath the already installed poles of group B to define the bottom layer. Then the compression arcs of B were added on top, followed by all the compression arcs of group C. At this point a relatively stable structure was formed defined by quadrangulated grids and free-hanging curves.

Then all the remaining curves were installed consecutively, first for group A, then B, and then C. These final curves triangulated the quadrangulated structure on top, acted as tension members towards the edge, and defined the belly geometry of the structure.

This layering method was included in the digital model, and all the up-until-now intersecting curves were separated onto three layers placed 120mm apart — the anticipated average thickness of a bamboo pole. Intersection mark-ups were
updated accordingly and a second prototype, this time from rattan sticks and at 1 to 4 scale, was made.

This installation sequence prevented the localised tight bending radii that weaving would need, and gave the final pavilion its distinctive striated look by day where you see certain directions pushing through the taut membrane (See Figure 1).

4.3 Pole length variation
The intersection mark-up method in principle allowed for working with members made from poles with undetermined pole lengths. While preparing for the final construction, however, it became clear that due to transportation restrictions the individual bamboo pole lengths would not vary as much as originally anticipated and that we would work with a fixed maximum length of 7.2 meters. This allowed us to design the pattern that would result from the visibly thicker overlaps of bamboo poles.

This algorithmically designed pattern was developed with the following considerations in mind. As three members often cross in a single point, theoretically six bamboo poles could need to be joined in one point, if three overlapping areas coincided. This would make hand-tying very difficult. The pattern therefore avoided overlaps in different directions from crossing through single points. The pattern was also designed to favor individual pole continuity at the very top of the dome where the structure was meant to read as light as possible. Also, continuous members were placed in areas with the tightest curvatures as overlapping areas are stiffer than single poles (See Figure 10). Furthermore, overlaps were avoided at the foundation.

4.4 Membrane
The pavilion needed to be covered with a waterproof rain and sun screen for both programmatic reasons and in order to protect the bamboo from direct rain and UV exposure. A non-elastic, translucent, glass-fibre reinforced composite tension membrane was selected for this.

The digital model allowed easy separation of this membrane into developable strips for fabrication. These could then be stitched back together into one single tailor-made ‘sock’. This method was tested in the skinning of the first three prototypes for which a stretch fabric was used. An elastic membrane, however, was not appropriate for the full-scale pavilion and the finally selected tension membrane required accurate measurement of the as-built pavilion.

During construction, onsite measurement could not be done through 3D scanning as the complexity of the scaffolding underneath would make it impossible for the scanners to isolate the structure from its support. Instead the following manual method was developed. As all onsite workers carried Smartphones, a Google Doc spreadsheet was set-up in which each bamboo edge of the structure was identified according to the 3D model. Each fabric triangle edge was measured onsite using a simple tape measure and the coordinates were instantly punched into the shared spreadsheet. Triangles were digitally drawn up from these edge lengths and were then connected into long strips (See Figure 11).
Figure 12. These strips could then be connected together to make up the complete cover of the structure.

A 1 to 50 scale paper test model was made to check the accuracy of the measurements, fine-tune the triangulation pattern in the non-triangulated belly areas, and to see if the overall shape was met. Once satisfied the triangles were cut from fabric using a large-scale CNC (computer numerically controlled) cutter, and welded together into one non-elastic tailor-made ‘sock’. This ‘sock’ was then unrolled over and manually fixed to the bamboo structure (See Figure 13).

Figure 12. Membrane cutting pattern, based on on-site measurements by hand.

Figure 13. Membrane installation on top of bamboo substructure

5 AS-BUILT ASSESSMENT

The bamboo structure was erected in less than two months, and the fabric matched the structure closely. The annotation system worked very well and the sequencing and overlapping did not cause any problems. The capabilities of the bamboo poles to be manually bent onsite were slightly overestimated and the five poles with the tightest curvatures had to be locally notched to allow for the appropriate bending. As for the membrane, only one triangle dimension at the base was wrongly measured and had to be fixed onsite.

In order to assess the structural behaviour of the pavilion the most crucial piece of information will be its permanent deformation over time under changing climatic and wind load conditions. A first 3D scan of the pavilion has already taken place to document this process.

This scan also allows us to evaluate how closely the as-built structure approximates the digital models (See Figure 14). This analysis reveals that the largest deviations occur in the areas where curvature is minimal for two of the three members. Here the third direction seems to be incapable of preventing the other two directions from straightening out more, resulting in a slight flattening of the area. At the time of writing, this deviation from the digital model does not seem to affect the overall structural integrity as the overall synclastic nature of the geometry is maintained.

Figure 14. Top and bottom view of 3D scanned fabric vs. originally designed fabric. Red = less than 50mm deviation. Blue = more than 1000mm deviation.

6 FUTURE RESEARCH

Bamboo poles vary substantially in terms of geometry and build-up, making it a challenging material to use in construction in its natural form. Yet, as shown, protocols can be set up to allow for the management of this volatility. For bamboo architecture to gain in applicability, especially in its bent form, the largest unknown is the structural strength of the individual pole connections. Although the hand-tied metal wire connections that were used allow craftsmen to respond onsite to material variations, their required skill is of crucial importance. A rigorous testing is needed of the strength of the various connection types in order to be able to re-assess the safety factors taken into consideration during the project’s structural calculation.

7 CONCLUSION

Common architectural practice leaves little room for construction deviations or for feedback from onsite challenges. Instead most procedures favour set-ups where responsibilities and tasks are defined and delineated in a top-down manner. Especially with the capability of the latest digital design tools for the very precise virtual simulation of future projects, the industry is being pushed in a direction where construction is asked to build in the image of a perfect digital model.
The ‘ZCB Bamboo Pavilion’ illustrates how this model can be overturned and showcases how the ‘virtual’ can more proactively operate within the field of real-world indeterminacy. It reveals how digital design tools can be used to engage in a productive dialogue with both materials and construction industries. Protocols were set up to allow for an unusually complex and innovative form to be built using an only slightly adapted pre-existing imprecise construction method. Indeterminacies, such as changing material properties, geometry deviation, and low-tech construction inaccuracies, were tested and balanced by combining physical and digital simulations and prototypes. Latent material properties, such as the bending force of bamboo poles, have thus been made accessible, allowing here for the realisation of beautiful, light weight, ecological architecture.

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Design research team: Principal Investigator, CUHK: Prof. Kristof Crolla; Co-Investigator, CUHK: Mr. Adam Fingrut; Research Assistants, CUHK: Mr. IP Tsz Man Vincent, Mr. Lau Kin Keung Jason; Consultants: Dr. Goman Ho and Dr. Alfred Fong (Structural Engineering), Mr. Vinc Math (Bamboo Consultant); Authorised Person: Mr. Martin Tam; Registered Structural Engineer: Mr. George Chung; Project Documentation: Mr. Ng Ka Hang Kevin, Mr. Grandy Lui, Mr. Michael Law and Mr. Ramon van der Heijden

CIC/ZCB Client Project Team: Executive Director, CIC: Dr. Christopher To; Publicity, ZCB: Ms. Yan Ip; Technical Services, ZCB: Dr. Margaret Kam


REFERENCES
Form-Finding Methods of FaBrick and its Application to Morphogenetic Design

I-Ting Tsai1, Somdatta Majumdar2, Xixi Zheng2 and Yiru Yun2

University College London, UK
i-ting.tsai.13@ucl.ac.uk

The Bartlett School of Architecture
UCL Faculty of the Built Environment

ABSTRACT
The thesis aims to explore the limits of fabric in a three-dimensional form. It introduces a novel technique of using felted fabric coated in resin to create architectural elements. The objective is to examine the possibility of applying the fabric and the concept of origami to morphogenetic design. The discussion centers on how the fabric takes advantage of its characteristic to form interesting geometry and how it changes the morphogenesis in fabric design. To develop its material system, different simulation methodologies of fabric behavior and design languages were studied to scrutinize the transformation process from a two-dimensional pattern to three-dimensional geometry. By applying fabric simulation engine and crease modeling plus mathematical deformation, we could simulate the traveling seams and tubes of geometry and generate volume to achieve intricate fluid space afterwards. The idea the façade and structure merged into one material system leads to a new typology of fabric construction.

Author Keywords
FaBrick; form-finding; material behavior; fabric simulation; morphogenetic design; pattern; geometry.

1 INTRODUCTION
FaBrick is a potentially exciting research project, which may change the way fabric is perceived in the field of architecture. In comparison with rigid materials, fabric that could be transformed into soft ethereal spaces in architecture has more potential and wider implications in spatial creation. However, the material has not been fully exploited in spite of the various advanced techniques we have today. The FaBrick project developed a self-supporting system for creating a complex three-dimensional form from a flat sheet, using the traditional art of stitching. With the crafting technique and its material behavior, the geometry of the fabric could support its own weight to form a mold-less fabric construction without any support from a second material. Fabric architecture and furniture have long existed but the invention of a composite that makes fabric the main structural material is unique.

This paper explores a suitable form-finding method to the intersection of crafting techniques and computational design for textile morphogenesis. In order to create structurally strong and interesting geometries in morphogenesis, different simulation methodologies of fabric behavior and design languages were studied to understand the transformation process from a two-dimensional pattern to three-dimensional geometry. (Figure 1.) The parametric design methodology generally saves time and could be utilized to adjust and enrich the design to a better level [5]. In FaBrick, not only various mathematical deformation methods are required to form different design languages, but the workflow from digital simulation to physical fabrication is also designed for building larger fabric structural scenarios.

2 INSPIRATION AND MANIPULATION OF FASHION DESIGN
The inspiration of FaBrick came initially from fashion design. It has already been proven in fashion industry that the act of sewing and stitching provide fabric itself with volume and strength. (Figure 2.)

2.1 Construction and Volume
Garments are built by bringing pieces of fabric together with seams, ties and so on. They are three-dimensional forms which involve a process of building [16]. A fabric...
may collapse vertically to the direction of the hem with accumulated weight. Strategies such as origami folds, pin tucks, pleats, shirring and smocking, could be utilized to control fabric volume [16]. Construction means constriction as well. Construction techniques, such as darts, flares, gathers and pleats, can also be used as controllers to add and subtract volume or fabric area wherever desired in a garment, while creating surface effects like curves, folds, lines, ripples and ruffles simultaneously [16].

2.2 Application in FaBrick
The fashion design cases in Figure 3 demonstrate the strong relationship between the structure and morphogenesis of fabric. Since fabric’s inherent properties could be implemented to form a structure to support its own weight, the form-finding process may be achieved via the application of basic fashion construction techniques, such as stitching, to control the geometry. (Figure 3.)

Figure 3. (Left) Stitched curvatures; (Right) stitching craft

Different parts of the design object have various functions in the project, just as the volume of fabric would affect the function of the garment. While seams and tubes may be transformed into stiff edges for supporting purposes, flat surface may deform into flexible and sheltering areas. Nevertheless, the fabric structure in architecture is different from that in garment in terms of complexity and size because it has to support a holistic human-scale space structure.

3 MATERIAL RESEARCH AND STUDY
Material investigation on various textiles was carried out via experiments combined with different techniques, such as stitching and folding. Studying their characteristics and understanding the design possibilities assist in creating complex structures. (Figure 4.) We choose felt as the developing material of the design project, since it is a thick material of which form could be fixed easily and of which volume could be created after being stitched.

Figure 4. Fabric characteristic experiences; softness, elasticity, permeability and shaping test of the felt

4 PHYSICAL MODELING AND DESIGN
The technique of designing two-dimensional patterns that fold up to the final object is like the idea of ‘fabric origami’. In order to understand the link between two-dimensional pattern and three-dimensional volume and develop the design, we analyzed the cutting patterns and physical behaviors of the fabric. (Figure 5.)

Figure 5. Examples of analyzed patterns and geometry forms

4.1 Design Languages
We developed various prototypes with three formal languages: tube, seam and surface with slits.
1. Tube: Legs, formed through cutting and stitching a sheet, can be connected to each other with interweaved behavior. (Figure 6.) Tubes of different thickness provide different self-supporting strength.

Figure 6. Prototypes design with tubes

2. Seam: The fabric surface bends along the two stitching curvatures. The seams are the element providing the structural supporting function to the form. (Figure 7.) It offers us a better idea how the fabric deforms from a flat sheet into a self-supporting volume.

Figure 7. Prototypes design with seams

3. Surface with slit: The cutting patterns with slits on the surface were studied in order to understand the way they deform the fabric. (Figure 8.)
4.2 Fabric as Brick in the Physical World

We designed prototypes with different languages in furniture scale by cutting and stitching one piece of fabric to form a chair or a stool to show the development. In the above physical modeling experiments, almost all prototypes were created from a sheet ninety centimeters wide and one-hundred-and-sixty centimeters long. (Figure 9.) To fully manipulate and control the shapes, forms, and details of the stitched pattern and geometry, the size of the sheet is the most reasonable one based on the results of these experiments.

Under the condition of material behavior and size constraint, we decided to apply the component-based method to construction in the project. We made different kinds of components and systemize them into linear and non-linear types based on the above experiments of design languages. The linear components were defined as structural elements and non-linear components as ornamental elements. Through the process of defining structural curvatures of each component, ornament components would be attached to different sections of the structural components depending on the design of their seams and tubes. The morphogenesis would change depending on the way components are attached.

The diverse experimenting results offered us an idea of how different design languages could be seamlessly combined. We deal with fabric transformation from tubes to seams and then to surface to achieve a fluid space with certain complexity. (Figure 10.) The transition between each language could be illustrated in the two-point-five-dimensional transformation of the geometry.

4.3 Structural Performance Test

The claim that a structural system can support itself was tested in a loading test. Two prototypes, tube stool and seam stool, were created digitally and physically for testing the bearing capability of the fabric structure. In Figure 11, it demonstrates that the seam stool with holes is weaker in terms of structure than the tube stool. The restraints on the four legs and loads from top-down were fixed beforehand. Depending on the amount of surface in between the seams, different levels of supporting strength would be offered. Therefore, we decided to use tube language as its structure, seam language as a transitional part to maintain the shape of the design, and surface language as the ornament depending on the design requirements.

In the physical prototype, we also experience different three-dimensional forms with concrete canvas since it is a material that has been recently used for architecture. Concrete Canvas, a construction material called Geosynthetic Cementitious Composite Mats, is a flexible, concrete-impregnated fabric that hardens on hydration to form a thin, durable, waterproof and fire-resistant concrete layer [1]. We had successfully fabricated a physical prototype of which geometry could structurally support the fabric itself, which is made of concrete canvas. The stool consists of three identical parts which were fabricated from two-dimensional patterns stitched together and hardened by water spread to the canvas. It is able to bear an adult’s weight as it shows in Figure 12. Although fabric origami structure could be created with concrete canvas, it is too heavy and would cause manufacturing difficulties. With the composite of felt and resin, the same form and function could be created into a light-weight structure in an easier way.
Figure 12. (Left, Middle-Left and Middle-Right) A 2D pattern to a 3D stool prototype made of concrete canvas that bears an average human weight; (Right) the stool made of felt and resin that bears an average human weight

4.4 Fabrication Process
The larger scale object was fabricated in several stages. We created individual components from two-dimensional patterns which were cut out on a flat sheet, using a laser cutter and stitching curvatures with a sewing machine to form the three-dimensional volume. After this, we started to aggregate them by intertwining, looping, and stitching the connections of these components by hand or with a handheld sewing machine. (Figure 13.) The fabric would then molded into pipe-like structures that could support the weight of the object. (Figure 14.)

We developed a composite material of felt and resin that could be stitched together to create works of furniture and architectural elements. We have been experimenting with various hardening materials, such as cement, sand, foam, and different kinds of resin on the prototypes. Eventually, it involved the calculation of the precise ratio of resin mixtures which could be added to felt without weighing the fabric down. A temporary frame would be necessary for better stabilizing the three-dimensional form since it has to be hardened with certain points being hung on the frame. After the form is shaped, the resin is ready, partly or entirely, to create a stronger structure with varying levels of rigidity from soft to stone-like hard. The chair was created through the fabrication procedure within two weeks, including 2 days for hardening.

Figure 13. Fabrication process of the fabric chair

Figure 14. Fabric components become the legs, seat and backrest of the chair, constructed from tubular sections that resemble a bundle of tangled roots

4.5 Comparable Methods of Manufacture
While the materialization technologies such as 3D printing and robotics facilitate the rapid design and materialization of such products and environments, the tactile interaction with form and matter throughout the design and fabrication process would be increasingly scarce [12]. This project seeks to explore hybridized designs and fabrication strategies in which digitally controlled techniques of form-finding and manufacturing naturally blend with existing crafting techniques and low-tech ways of making.

The digital models were specifically created depending on fabric behavior in this research. Therefore, other materials, such as metal and plastic, or other fabrication process, such as 3D print, are not in current discussion. Since almost everything and each material that can be powdered to a proper particle size could be 3D-printed to replace hand-carved models [10], the fabrication method has little to do with the material system. Reshaping and redefining the boundaries of fabric’s material behavior is what we aim to extract here.

5 DIGITAL DESIGN OF FORM FINDING
Mario Carpo [5] mentioned an idea that forms are not designed or determined in traditional ways but found. Architects and designers may have a logical idea of generation, but they do not have a clear target of the design outcome [5]. In the form finding method, architects and designers do not create the final form, but design it through computational generation based on algorithms or various parameters [5]. Through self-organizing, an object may find its natural form in unpredictable ways.

The form finding method is a key tool that could deal with complicated architectural problems, since it may include an abundance of information simultaneously in the design process [9]. The form is not seen as the result, but as the morphology, the collection of processes related to generation, materialization and physicality in operation [11]. Digital simulation is capable of making and breaking more models in a few seconds than a traditional craftsman could in a lifetime. It makes form finding a perfectly viable design strategy [5].

5.1 Self-generation of Fabric
Antoni Gaudi’s hanging model for the Colonia Güell church is an example of adopting a self-generating process performed on a physical model to determine the complete structural form of the whole building [17]. Also, Frei Otto has systematically developed strategies based on self-generating processes performed on physical models, such as the numerous tents and the wide-spanned tensile structures [17]. (Figure15.) Tent skins that are stretched equally in all directions correspond to the minimal area of the fabric and it shows the link between form and structure [13]. This physically self-generating process is considered essentially natural by Otto and the shape of the building is justified in the self-shaping process [17].
Simulation, and fabric surface discretization [8]. The quality of computer models varies with several implementation of algorithms and numerical methods [8]. Successful fabric simulation relies on an adequate surface languages along with four different simulation simulated a part of our physical models in tube, seam, and modeling began with simulating small patches. We also structure in FaBrick to tent structures, we may regard the tension-loaded parts of the tent as the structural curvatures of the FaBrick model and the rest areas of minimal surface as the non-structural ornaments.

6 DIGITAL SIMULATION

Digital experiments were done in parallel with physical modeling in order to form the fabric systematically and enrich the design. The digital simulation method of FaBrick is a different procedure from the cases mentioned above. To understand how fabric behavior forms volume, our digital modeling began with simulating small patches. We also simulated a part of our physical models in tube, seam, and surface languages along with four different simulation methods.

Successful fabric simulation relies on an adequate implementation of algorithms and numerical methods [8]. The quality of computer models varies with several predefined parameters such as fabric properties, mechanical simulation, and fabric surface discretization [8]. Mechanical properties here mainly refer to elasticity and viscoelastic parameters. The simulation should also be performed in high dynamic situations [8]. The bending properties are one of the most influential parameters [8]. The bending fabric model with seams that involves wrinkling and folding would significantly improve the realism of fabric simulations [8]. In the following experiments, we try to figure out reliable simulation methods for developing the simulation workflow.

6.1 Explicit Modeling

The first application of fabric simulations was to digitally replicate the physical model. Initially modeled with the manual explicit modeling method, the digital model could be almost identical with the physical model. (Figure16.) All kinds of shapes and languages could be modeled digitally. However, the material system of fabric could not be demonstrated well with this method since the modeling process is very different from that in the real world. Besides, the modeling process is time-consuming.

Figure 15. (Left) Gaudi’s hanging model for the Colonia Güell church [17]; (Middle) Soap film model for a tent [13]; (Right) Form-finding Model for the ‘Multihalle’ [17]

Since material intelligence could provide textile itself with structural functions, we could offer shapes to define its structures and provide variations to its morphogenesis at the same time. Nevertheless, most of the current textile buildings have two construction systems and are made of two materials: a structural system made of steel, concrete, or wood; the other system made of soft fabric served as the shelter covering the rest of the space. Unlike most of the fabric architecture cases of which structural systems are based on the suspended points, the fabric structure in this project is supported by the continuous curves of seams and tubes that we created in the geometry. Comparing the fabric structure in FaBrick to tent structures, we may regard the tension-loaded parts of the tent as the structural curvatures of the FaBrick model and the rest areas of minimal surface as the non-structural ornaments.

6.2 Fabric Simulation Engine

nCloth system as the fabric simulation engine in Autodesk Maya was selected for fabric simulation in this project. The simulation of fabrics’ behavior using both the geometrical and physical methods provides very good realistic presentations of fabrics within a virtual environment [8]. The nCloth system was originally designed to make dynamic cloth simulation easier for creation and animation [14]. An nCloth object is simply a polygon object that has had its vertices converted to particles [14]. A system of virtual springs connects the particles and helps maintain the shape of nCloth objects [14]. The objects automatically collide with other dynamic systems, such as nCloth, nParticles and rigid bodies, which are connected to the same Nucleus solver. The behavior of the object could also be controlled via the application of nConstraints, which is used to attach vertices of objects together in nCloth [14]. Special materials, for instance, a semi-rigid material, could be designed according to particular presets [14].

Parameters for different fabric behavior were set randomly for testing realistic virtual simulations of real fabrics based on previous experience, since it requires a considerable degree of user intervention [8]. In the simulation process, 2D patterns and divisions were modeled and divided at first. By applying nConstraints to part of the vertexes of the model and resetting its rest length scale, the different strength of physical stitching and tearing behavior could be simulated digitally. (Figure17.) Various patterns were stitched in digits for developing different three-dimensional volume. The process simulates the fabric behavior as the physical fabrication process. However, the geometrical-physical modeling process is computationally very expensive. The more modeling time is spent, the more accurate and physically-similar model would be created. The fabric needs to be simulated step by step for the controlling of the stitch and fold digitally. It may cause a lack of complexity in digital model in comparison with physical models if no sufficient time were spent on. Thus, if complex looping and intertwining tubes or surfaces were physically modeled inside the object, it would be difficult to simulate the geometries with the same complexity.

Figure 16. A section of the built physical model (Left) with tube language and its simulation in the computer model with explicit modeling (Right)
Figure 17. (Top) Fabric simulation engine modeling process; a section of the built physical model (Bottom-Left) with surface language and its simulation in the computer model (Bottom-Right)

6.3 Generative Modeling Tool
We tried to digitalize tubular language with a generative tool based on particle spring system, since the material behavior could be customized freely. The data of the basic geometry could be imported into the digital environment. With the update of the physic parameters, fabric behavior could actively change with time and environment to create complex geometries that contain a better and natural replication behavior.

We imported the particle and spring data of the tube element into the tool. Locked particles could run while unlocked particles also moved naturally behind them depending on the particle attraction setting. Geometries were duplicated to loop and intertwine with each other. (Figure 18.) Although the physical fabrication process is not well demonstrated digitally, we may still explore complex structures and surfaces in a short time by using this tool. Nonetheless, it is difficult to create continuous surface languages since the surface would be duplicated into many separated ones.

Figure 18. (Top) Generative modeling process; a section of the built physical model (Bottom-Left) with tube language and its simulation in the computer model (Bottom-Right)

6.4 Crease Modeling plus Mirror Cut Generation
Since our design languages had strong characteristics of traveling seams and pipes around a volume, crease modeling technique might be a good solution to the digital design. The geometry of something as simple as lower solution polygon could be analyzed and re-constructed digitally. We reversed this process and designed the desired geometries in low poly to find the two-dimensional seam pattern afterwards. In the digital process, we applied series of mathematical deformations on a base geometry with designed crease curvatures. We can also track back the previous operation and change the result intuitively. (Figure 19.) The smooth and wrinkled surfaces could be reformed with the addition of more divisions. It is thus easier and more efficient for us to design and achieve a larger architectural scale proposal. Tube, seam, and surface languages can then be created with this modeling method.

Figure 19. (Top) Crease tool plus mirror cut modeling process; a section of the built physical model (Bottom-Left) with seam language and its simulation in the computer model (Bottom-Right)

7 DIGITAL DESIGN TO PHYSICAL MODELING
In the previous research, we try to simulate physical fabric languages in digits based on the existing physical models. Various simulation methods could not only demonstrate different focusing on finding forms but also inspire designers with interesting volumes. For a large-scale scope, digital models are indispensable for analyzing its structure and behavior before creating the physical models. Moreover, it is essential to figure out a suitable and logical computational simulation workflow not only for approaching fabric structural curvatures and volumes but also for physical fabrication. Therefore, the simulation method and outcome that could be analyzed and decomposed into two-dimensional patterns for physical fabrication is crucial. Since our physical material system deals with the transformation from a two-dimensional pattern to three-dimensional geometry, we wanted to extract the relationship between the two. The following are the two methods we utilized for decomposing the digital geometry.

7.1 Workflow Decomposed via Fabric Simulation Engine
It begins with a digital two-dimensional pattern and then simulates its folding into a three-dimensional object. nCloth system is applied to simulate the fabric behavior. Step by step, with the simulation of stitching behavior of which constrain has been previously fixed, the physical fabrication process could be exactly simulated in digits. Therefore, the three-dimensional volume could be decomposed if it is traced back to the previous steps. (Figure 20.) The simulation process could be traced back to the initial pattern as the thread was removed in the physical model. Each step was recorded digitally and therefore physical models could be stitched like how they can be in the digital world. The only drawback is that it is computationally expensive since
it would consume a great amount of time to stitch every single vertex together.

Figure 20. The workflow of how a digital 2D pattern transforms to a digital 3D geometry and then is decomposed backwards for the production of physical fabrication

7.2 Workflow Decomposed via Crease Modeling Plus Mirror Cut Generation

With crease modeling plus mirror cut generation modeling method, three-dimensional volume could be modeled in a short time. Starting with a very simple geometry such as a box or a cylinder with minimal polygon, the geometry could then be modeled into a complex three-dimensional object and create its pattern afterwards. By adopting the tool of crease and mirror cut, more divisions and deformations could be added during the forming process. Besides, a low-poly model with complex form could be created in the same time. By analyzing the traveling seams and pipes of the completed three-dimensional geometry, its folded curves could be transformed into two-dimensional pattern. Fabric could then be cut into the same pattern and stitched along the analyzed curves for forming the same geometry physically. (Figure 21.) Although digital modeling method is different from physical fabrication process, the digital result could still be analyzed for physical manufacturing. However, if the digital model is too complex with a great number of tubes and surface intertwining and looping inside the volume, the analysis of the geometry would be difficult and more time-consuming.

Figure 21. The workflow from a low-poly model to a decomposed 2D pattern for the production of physical fabrication

7.3 Fabric as Brick in the Digital World

Since the three-dimensional geometry modeled with the application of the above two methods could be decomposed into two-dimensional patterns, we decided to utilize both methods for creating different components. Depending on the complexity and languages of the design, components with more intertwining tubes would be modeled with the utilization of fabric simulation engine; on the other hand, components with more seams on the surface would be generated with the use of crease modeling plus mathematical deformation tool. Digital fabric forming generation is not able to implement singular mathematical descriptions because of the interesting forms that fabric behavior could create. We may use both simulation methods at the same time, since fabric simulation engine would be easier for creating the fabric-like wrinkles and folds. (Figure 22.) The different design language typologies can be categorized into structural and ornamental elements. Each component with different elements could then be combined and merged digitally for demonstrating a larger spatial scenario afterwards. Each component could then be fabricated physically and attached to each other based on the digital design to form a large fabric structure. (Figure 23.)

Figure 22. The outcome of mathematical generation plus deformation shows the idea of transformation from 2D to 3D

Figure 23. Design evolvement: the design of digital components for the physical fabrication of the column

8 CONCLUSION

Current examples of textile architecture in the world, such as Zenith Music Hall Strasbourg, the O2 London, and Munich Olympic Stadium, all demonstrate that the
structural and non-structural parts of one building can be separated into two distinguished material systems despite the fact that structure and morphogenetic design are physically integrated. The biggest difference between FaBrick and other fabric projects is that we implemented fabric itself as the structural material based on its material behavior while still retaining its softness at specific areas. The material system can be strong enough for self-support with the application of low technology such as stitching. With stitched structural seams and tubes, not only could the morphogenetic design and structure be created simultaneously, but the supporting curvatures would also be defined in the geometry for creating a unique form.

In digital design, it is difficult to simulate fabric behavior and generate intricate forms simply via implementing singular mathematical descriptions. The more design languages that material behavior could create, the more difficulties the FaBrick project would face during the design developing process. We experimented with different computational tools in order to extract the link between two-dimensional patterns and the three-dimensional volume. Ultimately, we conclude that with the application of fabric simulation engine and crease modeling plus the mathematical deformation tool, design languages of tube, seam, and surface could be well simulated. We can then combine and merge different languages and components afterwards. The digital three-dimensional geometry can be analyzed and decomposed into two-dimensional patterns for physical fabrication. Feedbacks of the workflow can enrich the design and achieve a certain physical, spatial quality.

Instead of material efficiency, the focus of FaBrick is on the interesting geometries that fabric can form due to its material behavior. The large physical prototypes done in this research prove that adopting the material and the forming method is a genuinely feasible attempt in producing products and medium-sized constructions with fabric structure. In large-scale architectural construction, however, the complexity of geometry could be potentially minimized with its interesting forms still remained. The research not only defines the fabric forming logic, but also changes the way morphogenesis in textile design is perceived.

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Modelling Natural Formations: Design and Fabrication of Complex Concrete Structures

Elif Erdine¹, Alexandros Kallegias²

¹Architectural Association (AA)  
School of Architecture  
London, United Kingdom  
elif.erdine@aaschool.ac.uk

²Architectural Association (AA)  
School of Architecture  
London, United Kingdom  
alexandros.kallegias@aaschool.ac.uk

ABSTRACT
The paper aims to address techniques directed towards the integration of form, structure, and singular material systems through a series of simulation-based design tools acting in correlation with digital fabrication processes for the realization of one-to-one scale architectural prototypes that have been designed and produced as part of the Architectural Association (AA) Summer DLAB Visiting Schools 2014 and 2015. The case studies described investigate concrete and its inherent fluid materiality through various physics-based simulations derived from generative form-finding methods, Finite Element Analysis (FEA), and innovative modes of digital fabrication processes. The first case study, Callipod, correlates rules extracted from branching and bundling systems in nature with a fabrication process based on earth scaffolding and fabric formwork for the production of a concrete shell structure. The second case study, In.Flux, investigates doubly-curved complex geometries through form-finding simulations and robotic milling techniques for the design and construction of a concrete wall. The discussion points at the progressive inter-relationship between different simulation software in recognizing ways of integrating architectural criteria with structural performance.

Author Keywords
Concrete; Physics-based simulation; Processing; Object-Oriented; Agent-based system; Structural analysis; Robotic fabrication.

ACM Classification Keywords
D.1.5 OBJECT-ORIENTED PROGRAMMING; I.2.9 ROBOTICS (e.g. Manipulators); I.6.5 MODEL DEVELOPMENT (e.g. Modeling methodologies); I.6.8 TYPES OF SIMULATION; J.2 PHYSICAL SCIENCES AND ENGINEERING (e.g. Physics, Engineering); J.3 LIFE AND MEDICAL SCIENCES (e.g. Biology); J.6 COMPUTER-AIDED ENGINEERING (e.g. Computer-aided manufacturing (CAM)).

1 INTRODUCTION
Advancements in computational processes and digital fabrication techniques enable seamless workflows for architects in order to enhance decision making procedures throughout the entire design, fabrication, and assembly processes. In the 21st century, it is a well-known fact that architects and designers need to be equipped with the necessary knowledge and tool-building capacity towards the conceptualization and realization of innovative architectonic spaces and spatial experiences. One of the constituents of this process entails re-inventing the capacity and behavior of material systems which have long been employed in construction. In this respect, concrete has proven to capture the attention of architects for many decades due to its fluid materiality, durability, and strength.

The research presented in this paper is part of an ongoing series of investigations on design and fabrication techniques with concrete by coupling custom-made computational simulation tools in conjunction with innovative modes of digital fabrication processes. The investigations are conducted as part of the Architectural Association (AA) Summer DLAB Visiting Schools in 2014 and 2015. The theoretical framework of the research situates itself within the complexity paradigm, whereby rules abstracted and extracted from natural systems serve to formulate guidelines for an integrated approach to design and fabrication. Natural systems demonstrate interrelated levels of complexity by recycling their materials, allowing for change and adaptation, and utilizing energy [1]. Nature folds various functions into basic material systems through differentiation. The systematic diversity in the observed and microscopic world of nature occurs due to the ways in which basic materials, such as cellulose and chitin, re-order and self-organize themselves to form complex constructions of varying scales. Diversity in nature does not emerge from which materials to use, but how to use available materials [2]. As such, the complexity that is observed in natural systems provides inspiration and methods for the integration of form, material, and structure by mapping careful correlations between the various parameters pertaining to the performance of each system.

The research presented in this paper investigates methods of realizing computationally generated self-organizing systems on a one-to-one scale with the employment of a singular material system. The design brief for both case studies entails the design and construction of a one-to-one scale pavilion made from concrete in a forest located in AA’s Hooke Park premises in Dorset, United Kingdom, within a limited time.
frame, three weeks. The objectives of the research are two-fold. While real-world constraints through the implementation of advanced physics calculations in computational simulations are taken into account, attention is also given to how the digital paradigm and physical materiality can inform each other during design and fabrication processes.

2 CASE STUDY 01: CALLIPOD

2.1 Computational Methodology

A research methodology has been developed in order to test the research objectives. The design brief is to propose and construct a one-to-one scale concrete shell pavilion that can accommodate humans. Initially, real-time generative form-finding methods based on branching and bundling systems in nature have been developed and simulated in the open-source programming environment Processing. The key influence in working with branching systems has been their structural capacity coupled with the motivation to contextualize the design outcome in the natural environment of the forest.

In nature, branched structures can be found in abundance throughout various plant systems. Materialized direct path systems can be observed in umbels, and materialized minimal detours systems can be viewed in bushes and shrubs. The difference between branched constructions in architecture and nature lies in functionality. Whereas the branched structures built by humans are mainly designed to carry a structural function, the branched constructions of nature have the property of multi-functionality. In the case of plants, the branches need to transport water, minerals and products of photosynthesis for survival as well as maintain the necessary structural resistance against the various forces applied to the leaves [3].

In biological systems, self-organization refers to the process where pattern at the global level emerges from the interaction between lower-level components. The rules specifying the interactions between lower-level components rise from local information, without the interference of external directing instructions [4]. Swarm intelligence, a concept mainly used on research about Artificial Intelligence, is the behaviour exerted by natural or artificial self-organized systems, being made up of boids/agents which interact locally with each other and their environment. These interactions lead to the emergence of complex systems demonstrating intelligent behaviour on a global level [5]. The inspiration for generating swarm intelligence mainly come from biological systems, such as bird flocking, fish schooling, ant colonies, and bacterial growth. In the computational paradigm, agent-based models are used to create decentralized, self-organized behaviour. These computational algorithms simulate the local interactions of agents in order to evaluate their complex behavioural patterns leading to swarm intelligence [6].

In the context of this research, self-organization refers to form-finding methods directed at optimizing the load bearing capacity of structures through a process where the amount of material of the system is decreased as its strength is increased, while simultaneously having the ability to make local adjustments according to preferred architectonic qualities. As such, the digital simulations present a progression from the analogue-optimized path experiments of Frei Otto due to additional design constraints relating to gravitational forces, levels of adjusting bundling intensity on a local scale, and the ability to follow free form three-dimensional shapes. During the simulation processes, various iterations have been generated. The iterations vary according to the amount of paths, intensity of bundling force, the minimum and maximum distance ranges which bundling forces can influence, as well as the starting geometrical form. Initially, a starting geometrical form is created in a three-dimensional modelling software, McNeel Rhinoceros, and its iso-curves in the U and V directions are extracted. These curves are then divided into a specific number of points. The point coordinate data is then exported from Rhinoceros as a text file and imported into Processing. In Processing, these points are defined as nodes which are connected to each other via particle-spring systems; therefore, it is now possible to create real-time dynamic interaction between them. At this instant, the mathematical description of minimal detours system as a function of proximity is applied to the nodes. If the nodes are within a maximum neighbouring distance to each other, then a force which bundles them together is created. The force is described mathematically as the average vector from each of the nodes towards the neighbouring nodes; therefore, the nodes within the neighbouring range begin to move towards each other. This force is applied until the distance between the nodes reaches a minimum amount specified as a parameter. The maximum amount of magnitude for the bundling force is determined as a parameter in order to limit the strength of bundling. This magnitude grows by an increment of $5 \times 10^{-3}$ as the z-coordinate of the nodes increases, in order to provide for more openings in the higher ranges of the form. The calculation of the bundling force is repeated for every frame of the simulation, whereby the particle-spring system reaches its resting position after all the nodes are bundled together.

Figure 1 demonstrates instances of the Processing simulation during its course, starting with the paths in their initial position and finally concluding when all the paths reach their resting position as a result of the applied forces. It must be noted that a shell form has been opted for after initial tests with free-form surfaces, as concrete's strong compressive capacity makes it suitable for shell structures, a system containing mainly compression forces. After various iterations, a design option is selected according to criteria including the desired number of openings and anticipated structural stability.
The outcome of this stage, visualized as curved geometrical elements, is exported from Processing as a text file comprising the coordinates of points which form every curve element. This data is then imported to McNeel Rhinoceros and given structural thickness. The radius of each branch in the model is 15 cm. The model is evaluated via FEA analyses in Rhinoceros’ plug-in Scan&Solve. Scan&Solve is a linear solver that automates basic structural simulation of Rhino solids without pre-processing algorithms, such as meshing, simplification, healing, and translating [7]. The structural analysis is carried out as a solid volume analysis, the selected material properties belong to high strength concrete (C90/105), and the model is analysed under its own self-weight. The total displacement values gained from initial FEA analyses serve as inputs for re-adjusting the parameters of the Processing algorithm through various iterations. It is observed that nodes where several branches come together perform inadequately due to buckling. Therefore, in the final iteration the maximum neighbouring distance has been decreased to generate 2 branches per node in order to decrease buckling. The final parameters related to bundling can be viewed in Table 1. Figure 2 illustrates the resulting configuration of optimized path members generating the pavilion and the corresponding total displacement values, which range between 0.15 mm and almost zero.

<table>
<thead>
<tr>
<th>Number of divisions</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Bundling Distance</td>
<td>0.1 m.</td>
</tr>
<tr>
<td>Bundling Force</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**Table 1. Parameters of branching / bundling operation in Processing.**

Figure 1. Instances of Processing simulation demonstrating the applied forces in the initial path network.

Figure 2. Total displacement values on the final output as a result of FEA.

### 2.2 Fabrication and Assembly

The objective of the next stage is to transform the three-dimensional geometry into a two-dimensional layout which can then be cut from fabric. For this purpose, the final geometry has first been sliced radially into 12 pieces. Each piece is flattened via the Rhinoceros Squish command,
which is developed to flatten non-developable surfaces. The parameters of the command are adjusted to match those of an elastic material in order to control the compression and stretch amounts realistically. Figure 3 shows one of the slices of the final output, both as a three-dimensional geometry and two-dimensional pattern with the corresponding compression and stretch amounts, which have minor numerical values. The resulting two-dimensional outputs of this stage are then marked on fabric via CNC router and stitched together, thereby creating the fabric formwork for concrete casting.

In the concluding stages of the process, the scaffolding for the pavilion is assembled from earth in the forest (Figure 4), forming a second point of integration with the environment of the context. The overall form in the digital simulations is adhered to by the inclusion of timber ribs serving as guidelines during the earth scaffolding construction process. The fabric formwork is then laid on top of the earth scaffolding, followed by the process of concrete casting (Figure 5). The structure is made of a special concrete mix with fiberglass additives which has enabled it to be cast, dried and held strongly in place in a period of several hours without being limited by the constraints of applying conventional reinforcing systems such as rebar. Finally, the earth scaffolding is removed and reunited with the surroundings (Figure 6). Being 2.1 meters tall and 4.4 meters wide, the fabrication and assembly of the pavilion has been realized within a period of one week.

3 CASE STUDY 02: IN.FLUX

3.1 Computational Methodology

The design goal for the next case study has been focused on the production of a concrete wall through the exploration of complex form-work. The employment of complex formwork for concrete structures has the potential to yield morphologically interesting and materially efficient assemblies. In the initial stages of design development, real-time generative form-finding methods have set the correlations between the computational process of design with the physical world of fabrication and materiality. Recent developments in robotic fabrication techniques offer designers with the capacity to fabricate complex geometrical configurations thanks to their multi-axis freedom. As such, the major objective of this case study has been directed towards the coupling of doubly-curved complex geometrical assemblies informed by structural analysis and their realization through robotic milling processes.
One of the major design goals in this case study has been the integration of structural analysis in the initial stages of design in contrary to its conventional employment as an error-checking/optimization tool succeeding conceptual design development. In this respect, a preliminary wall design has been modelled in McNeel Rhinoceros as a NURBS surface. While the upper section of the wall has been linear in top view, the bottom section follows an S-curve in order to provide stability, as the wall will not be supported by additional walls or structural members. The dimensions of the preliminary design are 4 meters in length and 2.2 meters in height. The surface has not been given any depth at this stage as the intention has been to test the optimum value for depth through FEA processes. The FEA analysis has been conducted in Karamba, a parametric environment for Grasshopper enabling the finite element analysis and optimization of spatial trusses, frames, and shells [8]. The initial geometry has been analyzed as a shell structure; and the material properties of high-strength concrete (C90/105) have been selected. After various tests with shell depth, a value of 5 cm. has been selected in regard to keeping displacement values at an optimal level (Figure 7).

The output mesh model of Karamba has then been connected to the ‘ForceFlow’ component, another native component of Karamba, which enables the visualization of force flow lines in a shell in the global direction provided. As the structural analysis has investigated the performance of the wall under its self-weight, the Z coordinate has been selected as the global direction for the force flow lines. The generation of the force flow lines has been design-oriented, with the aim of achieving wall openings which do not interfere with the transfer of loads throughout the global geometry. As such, the FEA stage has been concluded with the creation of a 5 cm. deep shell split by openings following the direction of force flow within the wall.

The next stage in the computational design process entails the generation of doubly-curved geometries following the initial shell model as an input. The purpose of this investigation is two-fold, pertaining to structural performance and exploration of robotic milling techniques. A computational tool in Processing has been developed in relation to the above-mentioned goals. The tool is structured as a combination of agent-based simulation and mesh relaxation techniques with the purpose of creating a doubly-curved geometrical aggregation that increases in density towards the bottom section of the wall. The agent-based system is initiated from the edges of the openings of the input mesh, exerting flocking behavior defined by cohesion, separation, and alignment which constitute the basic behavioral rules of such systems. Simultaneously, the agent system moves down in the Z direction towards the ground plane while at the same time keeping contact with the vertices of the input mesh through proximity-based rules. As the agents travel according to flocking and proximity, the vertices of the input mesh are subjected to forces which act in the perpendicular direction to the wall’s primary axis as a result of their interaction with the agent system. More specifically, as the Z coordinate value of the mesh vertex decreases, its neighboring mesh is subjected to mesh relaxation which in turn gradually deforms the wall and adds increasing depth. With the resulting tapering effect, the final outcome of the simulation has more structural load-bearing capacity (Figure 8).
3.2 Multi-Axis Robotic Milling and Assembly Process
As it has been described above, the second goal of the simulation process has been to test robotic milling processes with the purpose of experimenting with complex curvatures for form-work building. In this respect, the choice of form-work material and robotic milling time have served as major inputs for the fine-tuning of applied forces in the Processing simulation.

The material for the form-work has been selected as medium density fire retardant grade expanded polystyrene (EPS) blocks, as EPS offers a suitable compromise between milling time and strength for form-work construction. Several iterations investigating the increase of surface area in relation to milling time have been generated in Processing. The final output model demonstrated in Figure 8 is the result of this iterative process, providing a conclusion that the total amount of milling time would approximately be 30 hours.

The next stage of design development has involved the creation of the necessary form-work files for robotic simulation followed by the milling process. The output mesh generated in Processing is exported as a text file into McNeel Rhinoceros, becoming the negative geometry for the preparation of form-work geometry. In Rhinoceros, each form-work is created by taking into consideration material dimensions and tolerances. The dimension of each EPS block is 200 cm in length, 125 cm in height, and 50 cm in depth, resulting with the employment of a total of 8 EPS blocks. As the fabrication and assembly processes need to have high precision for desired outcomes, the placement of steel bars connecting the form-work elements on two sides has been calculated in Rhinoceros as well. The location of the steel bars follows the distribution of the openings of the final wall structure (Figure 9).
The end-effector for the robot, a milling tool, serves as a design means that aids in the generation of surface textures in the EPS boards [9]. After the completion of the milling process that lasted 30 hours in total, the areas of contact between the scaffolding and concrete have been treated with a mixture of silicone and mold releasing agent in order to assist with the de-molding process (Figure 10). Accordingly, the EPS foam boards have been connected and secured with steel bars and plywood panels to enhance their stability. It is important to note that the structure is made of a special concrete mix with fiberglass additives which has enabled it to be cast, dried and held strongly in place in a period of several hours without being limited by the constraints of applying conventional reinforcing systems such as rebar. The only location where rebar has been used in the final fabrication has been along the foundation of the wall, bearing a depth of 30 cm.

![Figure 10. A section of EPS form-work after it has been treated with silicone and release agent.](image10.png)

The final stages of assembly has involved the casting of the concrete in the EPS form-work, followed by the waiting time for curing, approximately 12 hours, and the de-molding process (Figure 11). The overall fabrication and assembly of the final wall structure has been completed within a period of one week (Figure 12, Figure 13).

![Figure 11. Casting of concrete on site.](image11.png)

![Figure 12. Final wall structure, overall perspective.](image12.png)

![Figure 13. Final wall structure, detail displaying surface textures.](image13.png)

### 4 DISCUSSION

The two case studies described above share common attributes in relation to form-finding methods and design development processes. The design and fabrication processes have demonstrated the strong independence between the digital and physical paradigms in design. The computational simulations have taken real-world constraints into account, with the implementation of physics behavior in the first structure and the integration of structural analysis in the second structure. Nevertheless, it must be noted that in the first case study the material properties of concrete and the correlations between earth and concrete have been some of the critical aspects which could not have been predicted via the simulations. Due to the humid conditions in the forest environment, the earth scaffolding became condensed which in turn restricted the settling of the fabric and concrete while concrete was being poured. Therefore, future work needs to incorporate CFD (Computational Fluid Dynamics) simulation of concrete in the digital environment in order to allow for more precise control of the final physical output. It has also been
witnessed that the density of the fabric formwork is crucial in manipulating the behavior of concrete. An ideal formwork setup would comprise fabric with less density, in other words more openings, in the lower parts of the scaffolding in order to accelerate the curing speed of concrete. Furthermore, the connection between the digital simulation and final structure in the second case study has been more accurate due to the choice of material for formwork and the precision of robotic milling. As such, it must be noted that the degree of association between digital simulation and physical outcome also depends highly on the amount and extent of manual labor during fabrication and assembly processes.

Data exchange between Processing and McNeel Rhinoceros has been smooth due to the utilization of the import and export functions in Processing as a text function. As such, the output model has the advantage of high portability; it is essentially a geometrically precise 3 dimensional spatial model of nodes, lines, and mesh faces connecting with data attached.

In current research processes, the role of robotic fabrication techniques are moving away from a direct design-to-production approach towards the integration of robots with the design process itself as a result of embedding robotic systems with various sensors. Therefore, future research in the field will incorporate the exploration of robotic concrete deposition informed by structural performance criteria and deposition of material informed by real-time scanning processes.

Throughout the design, fabrication, and assembly processes, the interactive associations between different simulation software has been a key driver in recognizing the ways of integrating architectural criteria with the structural performance of the two pavilions. Furthermore, the comparison between the digital simulation of the architectural output and the final output, the pavilion itself, provides useful information to be considered and embedded in the future digital simulations. Overall, the research aims to illustrate the architectural possibilities of using concrete in a non-conventional way, directly connecting computational design methodologies with digital fabrication processes.

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Robotic Setup: Pradeep Devadass.

REFERENCES
Robotic Motion Grammar
Ardavan Bidgoli
Pennsylvania State University.

Heterogeneous Atelier Community. Socio-Economic Lattice Structure
Ali Farhan, Abdulmalik Abdulmawla
Dessau International Architecture School (DIA).
Application of industrial robots in digital fabrication has expanded rapidly during the past decade, generating a wide interest among designers, artists and architects. Being generic, these machines can be modified to host a wide range of tools and execute various fabrication methods. However, utilizing these machines are among the most complex tasks that a user can encounter. In this research, I have investigated the affordances of a rule-based logic to simplify the robotic fabrication procedure through visual computation, shape grammar, and visual programming. In this system, the proposed Motion Grammar is the core engine to generate forms based upon the characteristics of a specific Robot-Tool-Material system.
Heterogeneous Assemblages of Atelier Industries
Ali Farhan, Abdulmalik Abdulmawla
Dessau International Architecture School (DIA).

The debate of this project starts from understanding an important district of Istanbul, which have significant importance from Byzantine time and used to be a metal industry and later turned as Sishane light manufacturing industry in Ottoman Empire time. In this time sishane district inhabitants used to share common interests and feed each other with their socio-economic, socio-cultural and socio-political values. Project is about exploration and analyzing the existing urban situation in terms of socio-economic activities of existing network of production and their associated group of craft people in production line process, then proposing perfect scenarios of communication, interaction environment as lattice through an optimization process of core values like relationships, dependency and proximities among Agents. The process of design is defined through simulating values. Beside Different stages within the project define the process of simulations.
Presenting Author Biographies

Aly Abdelalim

Aly Abdelalim is currently a Ph.D. candidate in Environmental Engineering program at Carleton University (CU). He is also a team member in HBI (Human Building Interaction) Lab. His research focuses on developing a multi-scale approach to exploiting measured and modelled building performance data to improve campus operations, which could yield greater insights about opportunities for operational improvements and retrofits. Before joining CU, Aly worked as a teaching assistant at the British University in Egypt. He acquired his Bachelor from ASU (Ain Shams University) and Master’s degree in Architectural Engineering & Environmental Design from AAST (Arab Academy for Science and Technology) from Egypt.

Jawad Altabtabai

Jawad Altabtabai is a Ph.D. Candidate at the College of Architecture at Texas A&M University. His research interest includes parametric and performance-based design, Building Information Modeling (BIM), virtual reality, simulation, and architectural representation. He holds a B.A. in Architecture from the University of North Carolina at Charlotte and a Master of Science in Advanced Architecture Design from Columbia University. Altabtabai’s current research proposes a real-time dynamic presentation method for parametric-BIM-based models, which may simultaneously engage representations of tangible and intangible qualities of architectural design problems.

Tatiana Alves

Tatiana Alves is a registered architect and an assistant professor at Centro Universitário Una in Brazil where she teaches disciplines related to sustainable construction and building energy performance. She holds BA and MSc degrees in Architecture and Building Energy Performance. Currently, she is a Phd student at Universidade Federal de Minas Gerais in Brazil and an exchange student at Plymouth University, UK. Her research area is environmental building, particularly building stock modeling and building performance analysis. Moreover, as a registered architect she is part of a team in an architectural practice called ACTA – Arquitetos e Consultores Técnicos Associados focused on commercial building design which the portfolio can be seen on the website www.actaarquitetura.com.br.

Ricardo Andrade

Ricardo Andrade received his Diploma in Architecture at Pontificia Universidad Católica de Chile in Santiago 2002 and his MSc in Adaptive Architecture and Computer Science at The Bartlett, UCL in London 2014 with distinction. He has worked towards the integration of social media data in space syntax methodologies for navigation systems design and human mobility research. He is also interested in the way architectural visualization and digital technologies can contribute to the study and revaluation of visionary ideas from the past. His work experience has ranged from being a 3D artist, to a designer in an architecture firm, and to a project manager in a construction company. He is currently a lecturer at Universidad Andrés Bello and a research assistant at Instituto de Economía, Innovación y Emprendimiento at Universidad Gabriela Mistral in Santiago de Chile.
Ramtin Attar

Ramtin received his Masters of Architecture with a focus on digital media, architectural design, history and philosophy. He is the recipient of various awards including the Royal Architectural Institute of Canada Medal, Association of Computer Aided Design in Architecture’s award of distinction and Canadian Architect’s Art of CAD award. Ramtin has joined Autodesk Research with an extensive experience in design research, practice and education. Ramtin has led and worked on various high profile architectural design projects and winning design competition entries. In addition to his role as a research scientist at Autodesk Research, Ramtin also works closely with researchers outside of Autodesk to develop strategic partnership and projects. He is currently participating in a number of funded research projects involving academia, government and industry. Ramtin has taught and lectured on digital media and design at four Canadian Universities. He currently holds an honorary Research Professorship from the school of architecture at Carleton University where is deeply invested in a number of projects that deal with community revitalization, sustainability, and life-cycle assessment of built environment. He is also a founding member of SimAUD conference; a newly established conference on Simulation for Architecture and Urban Design. Recently Ramtin has been selected as a DiverseCity Fellow: The Greater Toronto Leadership Project funded in part by the government of Ontario. As a passionate city-builder, Ramtin has joined a diverse cross-section of rising leaders from business, government, and community organizations who will work together to strengthen the economic and social prosperity of the Greater Toronto and Hamilton Area. Ramtin is also the founder of Imagine My City; a non-profit organization that he is working to grow by helping important regional issues through collective leadership coupled with tools of imagination.

Ardavan Bidgoli

Ardavan Bidgoli is a Ph.D. candidate at Stuckeman Center for Design Computing at Penn State. His research is focused on computational design and digital making. His recent studies explore the affordances of virtual reality in architectural robotics to bridge the gap between thinking and making in real-time. He also works on the possible merger of virtual reality systems with architectural robotics pedagogy.

Kristof Crolla

Kristof Crolla is a licensed architect who combines his architectural practice “Laboratory for Explorative Architecture & Design Ltd.” (LEAD) with his position as Assistant Professor in Computational Design at the Chinese University of Hong Kong. After graduating Magna Cum Laude as Civil Architectural Engineer at Ghent University in 2003, he practiced in Belgium and built his first project, House for an Artist. He moved to London in 2005 to attend the Architectural Association School of Architecture, London (AA)’s Master of Architecture program Design Research Laboratory, from where his student work was exhibited at the 2006 Venice Architecture Biennale. Following this he worked for several years as Lead Architect for Zaha Hadid Architects, while teaching in parallel at the AA and other institutions worldwide. He is currently based in Hong Kong and is best known for projects “Golden Moon – 2012 Mid-Autumn Festival Lantern Wonderland” and “ZCB Bamboo Pavilion”.

Angelos Chronis

Angelos is a PhD Candidate, as part of the InnoChain program at the Institute of Advanced Architecture of Catalonia, Barcelona, Spain. He teaches at IaaC and at the Bartlett School of Architecture of University College London. Previously he has been working as an Associate for the Applied Research + Development group at Foster + Partners. He holds a diploma in Architecture from the University of Patras, Greece and an MSc in Adaptive Architecture & Computation from the Bartlett School of Graduate Studies, UCL, with distinction. He is a registered Architect both in Greece and in the UK. His main research interest lies in the integration of simulation, optimization and performance drive in the design and fabrication process with a deeper expertise in computational fluid dynamics (CFD) but he has worked across many fields including virtual & augmented reality, interactive installations, 3D scanning, spatial analysis and parametric design. He is also actively involved in scientific committees as an author, reviewer and organizer as well as participating in lectures, workshops and architecture crits internationally. He is currently the program chair of SimAUD 2016 which is going to be held in UCL, London.
Ryan Danks
Ryan Danks is a senior engineer in the Building Performance team at RWDI Inc. in Guelph, Canada. His work focuses on the research and development of tools and methodologies to better simulate the interaction between the built and natural environments in order to help engineers, architects and urban planners create climate aware designs that emphasize energy efficiency, outdoor comfort and walkability. This requires leveraging a wide variety of computational modeling techniques, including computational fluid dynamics (CFD), solar radiation modeling, particulate matter transportation and human physiological response modeling to understand how local wind, solar and rain patterns influence the livability of urban spaces.

Antonio D’Aquilio
Antonio D’Aquilio is currently working as Engineer at Arup Amsterdam. His field of interest is the envelope performance optimization and energy efficiency in buildings. After obtaining a Bachelor Degree in Architecture Sciences in Rome (Italy), he moved to the Netherlands where he graduated from the MSc in Building Technology, TU Delft. As a researcher in TU Delft Antonio focused on the benefits of incorporating natural ventilation into the early architectural design as well as the use of computational optimization. As Engineer in Arup, he is currently working on energy modelling, façade optimization studies and systems design.

Aymeric Delmas
Aymeric Delmas is a PhD Candidate in the Physics and Mathematical Engineering for Energy and the Environment (PIMENT) Laboratory, Reunion Island University. He is also working as a Research Engineer at IMAGEEN. Aymeric has a multi-discipline background of engineering, research and teaching in building science and simulation. His current research interest is in the development of comprehensive design tools based on simulation. In this task he is focusing on bridging the gap between early-design tools and micro-scale models to design zero energy neighbourhoods. He aims to integrate microclimate analysis with parametric modelling for supporting bioclimatic design and optimisation at the urban scale in the tropics.

Elif Erdine
Architect, designer, and researcher. Currently, she teaches at the Architectural Association (AA) School of Architecture, Emergent Technologies and Design Graduate Programme. She is the Programme Director of AA DLAB Visiting School and AA Istanbul Visiting School. She has worked for Zaha Hadid Architects during 2006 - 2010. She received her B.Arch. degree from Istanbul Technical University in 2003 (High Honors), and M.Arch. degree from the AA Design Research Lab (AA DRL) in 2006 (Project Distinction). Her projects have been printed widely in international and national architecture publications. Her research interests include the role of the individual building within complex urban systems, and the exploration of various flows in the urban environment as design drivers, and biomimicry. She has presented her research in eCAADe 2013, eCAADe 2014, eCAADe 2015, ACAJIA 2015, among others.

Filipe Gaspar
Filipe Gaspar is a Ph.D. student in Computer Graphics and Computer Vision at ISTAR/ISCTE-IUL and a software engineer at MLDC/Microsoft, both in Lisbon, Portugal. He received his B.Sc. and M.Sc. in Computer Science and Telecommunications Engineering from ISCTE-IUL, with academic emphasis on vision-based 3D tracking techniques for virtual reality environments, in 2007 and 2009, respectively. Until 2012 he worked at ISTAR/ISCTE-IUL as a researcher in several European projects focused on object/facial 3D reconstruction and biometrical facial matching for people authentication and assisted living. His current research embeds one of the current challenges in vision-based augmented reality applications: simultaneous tracking and reconstruction of arbitrary 3D scenes using commodity RGB-D sensors such Kinect.
David Jason Gerber

Dr. David Jason Gerber is an Assistant Professor of Architecture at the University of Southern California and holds a joint appointment in the Viterbi School of Engineering at USC. He has held executive positions for design technology start-up and mature companies, and was a Vice President at Gehry Technologies Inc., a global innovator in Building Information Modeling and building industry technology consulting. Dr. Gerber has worked as an architect in the US, Europe and Asia, for the Steinberg Group, Moshe Safdie, Gehry Technologies, and as a project architect for Zaha Hadid Architects. Dr. Gerber has been awarded research fellowships at MIT’s Media Lab, Harvard University Graduate School of Design and as a Harvard University Frederick Sheldon Fellow. He was full time faculty at the Southern California Institute of Architecture (SCI Arc) from 2006-2009, a technical tutor at the Architectural Association’s Design Research Laboratory in London, and held lecturer positions at UCLA’s AUD, Stanford University, Innsbruck University, the EPFL Switzerland, Te de Monterrey Mexico, and Tsinghua University China. At USC he instructs students in design research seminars and design studios and leads a multidisciplinary research team focused on innovating at the intersection of design with computation and technology. His research is funded by the National Science Foundation as well as industry sponsors. David Gerber received his undergraduate architectural education at the University of California Berkeley (Bachelor of Arts in Architecture, 1996). He completed his first professional degree at the Design Research Laboratory of the Architectural Association in London (Master of Architecture, 2000), his post professional research degree (Master of Design Studies, 2003) and his PhD (Doctor of Design, June 2007) at the Harvard University Graduate School of Design.

Joel Good

Joel Good is an Associate and Consultant with the Building Performance Team at RWDI. Joel has an M.A.Sc. in Environmental Engineering and a B.Eng. in Mechanical Engineering. Joel’s current work and research is focused on using and improving energy, daylight, solar, and reflected light modelling tools to achieve high-performance, comfortable built environments. Joel has collaborated on building and masterplan design teams in a wide range of climate types: from his home in Vancouver on the moderate west coast of North America to the cold and hot extremes of Northern Russia, Western China and the Middle East.

Caroline Hachem-Vermette

Dr. Caroline Hachem-Vermette is an assistant professor at the University of Calgary, in the Faculty of Environmental Design. Dr. Hachem-Vermette and her group at U of C carry out investigations on the design of net zero energy /energy positive mixed-use solar communities. These solar communities will combine energy efficiency measures with effective solar technologies, for electricity, heat generation and thermal storage. A specific area of research that constitutes an additional focus of Dr. Hachem-Vermette group is the design issues of building envelope, for improved energy performance of different types of buildings (high-rise commercial and residential, various type of commercial buildings such as supermarkets, greenhouses, etc.). Her research is multidisciplinary, it plays a bridging role between building engineering and architectural and urban design. She is a member of the International Energy Agency IEA Task 51, Solar Energy and Urban Planning, and has been involved in the feasibility studies of several solar community designs, in various areas of Canada. Dr Hachem-Vermette is recipient of numerous grants and awards including: The Building Excellence Research and Education Grant, various NSERC grants (e.g. Discovery grant, Engage), IBPSA-Canada eSim 2012 Outstanding Contribution for Innovative Directions in Modeling, and the IASS (International Association for Shell and Spatial Structures) 2005 Hangai Prize for young researchers.

Sean Hanna

Sean Hanna is Reader in Space and Adaptive Architectures at UCL, Director of the Bartlett’s MSc/MRes programs in Adaptive Architecture and Computation, and Academic Director of UCL’s Doctoral Training Center in Virtual Environments, Imaging and Visualisation. He is a member of the Space Group, noted as one of the UK’s highest performing research groups in the field of architecture and the built environment in the 2008 RAE and supported by three consecutive EPSRC platform grants. Prior to academia, his background is in architecture and design practice, in which his development and application of design algorithms includes major projects with architects Foster + Partners and sculptor Antony Gormley. Sean’s teaching is primarily on the AAC courses, leading the Computational Analysis and Computational Synthesis modules and workshops on parametric modelling and associative design. He also shares the Design as a Knowledge-Based Process module with Sam Griffiths and the MSc AAS. Sean supervises a number of PhD and EngD researchers, as well as dissertation projects from both the MSc AAC and Bartlett Diploma programmes.
Christina Hopfe

Christina Hopfe is a Senior Lecturer in Sustainable Building Design and is the Programme Leader for Low Carbon Building Design and Modelling at Loughborough University, England. She is a Director of the International Building Performance Simulation Association (IBPSA-World), a board member of IBPSA England and is the Editor of ibpsaNEWS.

Jie-Eun Hwang

Jie-Eun Hwang is an associate professor at University of Seoul. Her research interests include spatial information representation, digital tectonics, design media and interface, open data. As an educator, new media experiment and alternative education are also recent challenges. She pursued various research projects, including: developing participatory mobile augmented reality contents, developing a spatio-temporal timeline system for monitoring public space, developing index system for monitoring UNESCO heritage. Art galleries: Gallery Factory, Gwangju Design Biennale, Culture Station Seoul 284, and Kumho Gallery, have invited her for media art installations that represent social commons.

Didier Josselin

Didier Josselin has been a Researcher in Quantitative Geography with the French National Research Center (CNRS) since 1998 and Director of Research since September 2010. He defended his PhD in 1995 and his HDR thesis (research supervision accreditation) on robust spatial analysis in April 2010 at UMR ESPACE in Avignon (southern France) which he joined in 2003. He has already coordinated several interdisciplinary projects (Computer Science - Geography – Maths – Ecology), especially on transportation and networks. He has already (co-)supervised 16 (post-)doctoral students in Geographical Information Science, Spatial Optimization and Modelling. He has published about 30 articles in international journals, more than 50 papers in Proceedings of international conferences with review committees and a few book chapters. He has (co-)organized 4 international conferences (AGILE'2012, 250 participants) and edited 6 collections of articles (in journals or conference proceedings). https://cv.archives-ouvertes.fr/didier-josselin/

Alexandros Kallegias

Alexandros Kallegias is an architect currently teaching at the Architectural Association (AA) (2011-current). He is the Programme Director of AA Greece Visiting School, AA Athens Visiting School, and AA Summer DLAB. He has also taught in the University of Liverpool (2013-2015). Alexandros is a Senior Architect at Zaha Hadid Architects (2011-current), acting as the BIM Coordinator in various international projects. He received his MArch degrees from University of Patras in 2000 (High Honors), and AA Design Research LAB (DRL) in 2011. He is a registered architect in the UK and Greece.
Lemonia Karagianni

Lemonia Karagianni is an architect and facade engineer focused on the potential of Additive manufacturing in the building sector and how it can affect envelope performance. Therefore, her research focuses on digital fabrication and customized solutions by computational design tools. She holds a MSc degree in Building Technology from TU Delft University of Technology, The Netherlands (2015), and she received the Diploma degree in Architectural Engineering from the Aristotle University of Thessaloniki (AUTH), Greece, in 2012. She has professional experience in architectural offices based in Greece and Spain and she currently combines her work at a building façade consultancy multinational company in Barcelona with her research career.

Nesrine Mansour

Nesrine Mansour is a Ph.D. student in Architecture at Texas A&M University, College Station, Texas. Originally from Tunisia, Mrs. Mansour holds a Bachelor in Environmental Design and worked for few years on daylighting design with an emphasis on dynamic facades as well as participating in an EPA project investigating passive daylighting systems. She is currently researching the inter-relationship between religion, media, and architecture and the expression of the spiritual experience in a sacred virtual space. Her inquiry focuses on the correlation between light and sacred architecture in a virtual realm. Her research unfolds around sacred architecture, building technology, environment, and computation.

Alessandro Mattoccia

Alessandro Mattoccia is an architect focus on building environmental design. He is currently collaborating with the department of “Project for the Self-Sufficient City” at the Institute for Advanced Architecture of Catalonia (IAAC) and with the studio MargenLab, Barcelona. He graduated with honours in 2015 at University of Pisa, Italy, with a master degree in “Building Engineering and Architecture”. He has particular interest in the relationship that computational design and digital fabrication processes can have in the development of more climate-responsive environments, integrating simulation and performance optimization methods in the architectural process. He has work experience in energy modelling to predict and ultimately reduce energy consumption in buildings. He has participated in the design, analysis, prototyping and construction of environmental feedback projects.

Manuel Muehlbauer

Manuel Muehlbauer is an architectural engineer, researcher and educator and PhD Researcher at Spatial Information Architecture Lab (SIAL, RMIT University) in Melbourne with a specialization in design computation and architectural technologies. In his professional activities he integrates practice, education and research in architecture into interdisciplinary research trajectories at the intersection of architecture, engineering and computer science. His research focuses on architectural simulation, generation and evaluation in early design stages of architectural design, aiming for improved resource efficiency and resilience of architectural products. At this stage Manuel Muehlbauer is applying his skills on international research projects dealing with custom-optimisation, encoding strategies for multi-criteria optimization and simulation of complex designs of building components.

Josef Musil

Josef Musil is currently part of the research group Specialist Modelling Group within Foster + Partners in London and focuses on applied research, application of new technologies and algorithmic design to complex architectural and geometrical challenges. He also specializes on application of small robotics within the office and his academic research. Josef studied as a Fulbright scholar at the University of Pennsylvania, where he received his MArch degree, and at the Czech Technical University, where he recently took classes in computational intelligence after finishing a professional degree in architecture there. Josef is enthusiastic about bridging computer science or other sciences with architecture. Josef worked as a researcher or a tutor at UPenn, USC, UCL and AA Visiting School.
Pirouz Nourian

Pirouz Nourian is a PhD candidate, researcher, and lecturer at TU Delft, Faculty of Architecture and Built Environment, the Department of Architectural Engineering + Technology, the Chair of Design Informatics. He is a computational design researcher and a developer specialized in developing mathematical and computational methods for spatial analysis and spatial layout. Pirouz has developed methodologies and toolkits for design and analysis of spatial configurations, namely SYNTACTIC (Space Syntax for Generative Design) and CONFIGURANIST (Cheetah for Urban Configuration Analysis). He is currently developing a new generation of spatial accessibility models for walking and cycling using Fuzzy Logics, Spectral Graph Theory and Markov Chains.

Yannis Orfanos

Yannis Orfanos is a Research Associate at Harvard Graduate School of Design (GSD). At the Zofnass Program for Sustainable Infrastructure, he is leading research on the integration of data analytics, infrastructure systems and the urban environment, while has been the Computational Design Lead at the Health and Places Initiative. Yannis has worked within a number of international design practices in London, Barcelona, and Athens, including KPF Associates and Pollalis Inc. where he was the project manager for the new DHA City Karachi for 600,000 people. Yannis is an Envision Sustainability Professional & Trainer by the Institute for Sustainable Infrastructure. His education includes a Diploma in Architectural Engineering and MSc from the National Technical University of Athens, and MArch in Architecture and Urbanism from Architectural Association Design Research Lab.

Ulrike Passe

Ulrike Passe, Dipl.-Ing., is Associate Professor of Architecture at Iowa State University (ISU) USA and Director of the ISU Center for Building Energy Research. She received her Diplom - Ingenieur in Architecture from the Technical University in Berlin, Germany in 1990. A licensed architect and founding partners of Passe-Kaelber Architekten, Berlin with 15 years of architectural practice she specializes in energy efficient buildings and passive design strategies. At Iowa State University she teaches sustainable architectural design and environmental technologies. Her multidisciplinary research projects span from ‘CFD for natural ventilation’ to ‘sustainable cities decision making’, some are funded by the US National Science Foundation. Ulrike has published and lectured widely internationally and her book co-authored with Francine Battaglia "Designing Spaces for Natural Ventilation: an architect’s guide" was published by Routledge in April 2015. Ulrike is president-elect of the Society for Building Science Educators (SBSE).

Siobhan Rockcastle

Siobhan Rockcastle is a PhD candidate in the Architecture and Sciences of the City (EDAR) Doctoral Program at the Ecole Polytechnique Federale de Lausanne. She received her professional BArch from Cornell University in 2008 and her SMArchS degree in Building Technology from MIT in 2011. She has taught full-time at Cornell and Northeastern University, where her courses include studio design, environmental systems, and special topics in architectural technology. Her professional work experience includes two years of project management at KVA matX and internships at Snohetta, Epiphyte Lab, and MSR design. She currently consults on daylight design integration for a number of architectural and urban-scale projects in Switzerland. As a continuation of her work at MIT, Siobhan’s PhD proposes new quantitative models that predict the perceptual impacts of daylight dynamics on visual interest in architecture using experimental data and an applied simulation based-approach.
Davide Schaumann

Davide Schaumann is an Architect and Ph.D. Candidate in the Faculty of Architecture and Town Planning at the Technion – Israel Institute of Technology. He holds BA and MSc degrees in Architecture from the Politecnico di Milano in Italy, and has worked for emerging architectural firms in Italy, Spain, Canada and Israel. Schaumann’s research explores the mutual relations between a physical setting, the people who inhabit it, and the activities they engage in, to devise methods for designing settings that better meet people’s needs through the use of Computer Aided Design and Building Information Modeling tools. In particular, Schaumann’s research involves: human behavior simulation in built environments; spatial knowledge representation for architectural design; development and application of ethnographic data collection methods to correlate user activities with the built environments in which they are performed; and use of video game engines and virtual reality tools to support evaluation and communication in architectural design.

Marc Aurel Schnabel

Marc Aurel Schnabel is an Architect and Professor in Architectural Technology at the School of Architecture, Victoria University of Wellington, New Zealand and Visiting Professor at School of Architecture, Sheffield University, UK. As Programme Director in Architecture at VUW he is leading research and education in the field of Architectural Design and Technology. As (Past) Presidents of CAADRIA, Industry Advisory Board of Autodesk and Architectural Science Association, he is affiliated with various professional bodies and scientific committees. He taught and worked in Germany, Australia and Hong Kong for over twenty years and is highly recognised for his research in the areas of computational design environments. He has established the Digital Architecture Research Alliance, DARA, and the online social network Urban Digitalics connecting professionals and researchers of innovative digital spatial design.

Rusne Sileryte

Rusne Sileryte has been working as a researcher in TU Delft, Faculty of Architecture, focusing on the development of customized tools for the multidisciplinary, multi-objective optimization of large sports buildings especially for exploring design alternatives and supporting the decisions made in the early stages of a design. Previously she has acquired a BSc in Architecture in Vilnius Gediminas Technical University, experience of working as an architect and a MSc with honors in Geomatics Engineering for the Built Environment in TU Delft. Currently she continues working in academy as a visiting researcher at the University of Lisbon, Design and Computation Group.

I-Ting Tsai

Following her B.Arch studies in Taiwan and China, I-Ting Tsai has graduated from the M.Arch program at The Bartlett School of Architecture at University College London in 2015. Her research encompasses hybridized design of physical fabrication and digital simulation through tactile interaction with materials and forms. She is particularly interested in the integration of computer controlled design and manufacturing operations. Her work, the FaBrick project, is the recipient of the Sir Peter Cook Award as well as the Silver Award within the architecture faculty. She is currently working at EDS International as an architectural designer on projects located in East Asia.
Michela Turrin

Michela Turrin is an Assistant Professor at the Chair of Design Informatics at TUDelft. From 2006, she developed research, taught and coordinated MSc courses at the Faculty of Architecture, Delft University of Technology, for the Chair of Design Informatics. In 2012 she was Marie Curie Fellow at Beijing University of Technology, as part of the Urban Knowledge Network Asia. She collaborated with international companies and worked at Green World Solutions Ltd in Beijing. She taught in a number of international events, among which the iFoU Summer School 2012 in Beijing and Winter School 2013 in Hong Kong. In 2013, she was awarded a grant by the Urban Systems and Environment, joint Research Centre between the South China University of Technology and Delft University of Technology; at South China University of Technology, in 2014 she has been awarded a grant as Excellent Oversea Instructor and a research grant by the Key State Laboratory of Subtropical Building Science. From September 2012 to January 2015, she held a position as senior lecturer at Yasar University in Izmir-Turkey, where she has coordinated the collaborations with Delft University of Technology and has been involved in joint practice-related architectural design projects. Among recent and current activities at TUDelft: as port-doc researcher, she works on the STW granted project ADAM, on acoustics by additive manufacturing; as initiator, she was awarded a grant by 3TU for preliminary studies on a novel lightweight translucent and adjustable trombe-wall system; as co-applicant, she was awarded a grant by STW for further studies on the system; as project leader, she was awarded a grant by the Urban Systems and Environment and a grant by the TUDelft Sports Engineering Institute for parametric design and optimization of sport buildings; as initiator she was awarded a grant by 3TU for preliminary studies on a 3D printed façade component allowing movable thermal mass. Since 2003, she has lectured in workshops, symposia and international conferences; and she has co-organized international scientific conferences. Some of her publications has received international awards. Since 2011, she has peer-reviewed a number of journal papers and conference papers. As a practicing architect, she has been working on international projects.

Nick Vlaun

Nick Vlaun is currently a Building Physicist at ABT Consulting Engineers in Delft, the Netherlands. His daily work covers digital simulation of architectural and environmental acoustics, daylight modelling and assessment of building energy performance. He received a BSc in Architecture, Urbanism and Building Sciences (2012) and a MSc in Building Technology (2015) from the TU Delft. For his graduation research he investigated the merits of parametric modelling for the purpose of integrating acoustic analysis and optimization into the architectural design process of office spaces. During his studies, Nick also worked as a teaching assistant for the chair of Design Informatics.

Gabriel A. Wainer

Gabriel A. Wainer is Professor and Associate Chair for Graduate Studies the Department of Systems and Computer Engineering, Carleton University (Ottawa, Canada). He is the author of three books and numerous research articles; he edited four other books, and helped organizing various conferences, including being one of the founders of the Symposium on Theory of Modeling and Simulation, SIMUTools and SimAUD. Prof. Wainer was Vice-President Conferences and Vice-President Publications, and is a member of the Board of Directors of the SCS. He is Special Issues Editor of SIMULATION, member of the Editorial Board of IEEE Computing in Science and Engineering and Wireless Networks (Elsevier). He obtained Carleton University’s Research Achievement Award (2005, 2014), the First Bernard P. Zeigler DEVS M&S Award, the SCS Outstanding Professional Award (2001), Carleton University’s Mentorship Award (2003), the SCS Distinguished Professional Award (2013), and the SCS Distinguished Service Award (2015). He is a Fellow of SCS.

Gabriel Wurzer

Gabriel Wurzer is a researcher focusing on early-stage hospital planning using agent-based simulation. Having been trained as a computer scientist, he switched over to architectural sciences, a field in which he has gotten his PhD. and Habilitation (tenure track accreditation in German-speaking countries, equivalent to associate professor). He is currently researching both at TU Wien and the Vienna University of Economics and Business. Furthermore, he is involved in establishing a study programme on healthcare facilities, as part of a joint effort between TU Wien and the Medical University of Vienna.
Ding Yang

Ding Yang is currently a joint Ph.D. Candidate in the Department of Architectural Engineering & Technology at TUD (Delft University of Technology) and in the School of Architecture at SCUT (South China University of Technology). He received his B.Arch and M.Arch from SCUT, and has worked as an Architect at Sun Yimin Studio of SCUT since 2009, mainly focusing on the design of sports and recreational buildings. His recent research, in collaboration with Arup in Amsterdam and ESTECO in Italy, aims at developing a performance-based design approach for the conceptual envelope design of indoor sports buildings. The proposed approach is able to improve multiple building performances, including daylight, thermal, energy and structural performances; and support the trade-off decision-making by utilizing multi-objective and multi-disciplinary design exploration and optimization techniques.
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