2015 Proceedings of the
Symposium on Simulation for
Architecture and Urban Design

Edited by
Holly Samuelson, Shajay Bhooshan, and
Rhys Goldstein
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Contents

Preface 1

Session 1: Human Behavior 5

Simulating Human Behavior in Not-Yet Built Environments by Means of Event-based Narratives 7
Davide Schumann, Yehuda E. Kalay, Seung Wan Hong, and Davide Simeone
Technion - Israel Institute of Technology; Inha University; Sapienza University of Rome.

Session 2: Building Information and Data 15

Capturing an Architectural Knowledge Base Utilizing Rules Engine Integration for Energy and Environmental Simulations 17
Holly Ferguson, Charles F. Vardeman II, and Aimee P. C. Buccellato
University of Notre Dame.

Digital Campus Innovation Project: Integration of Building Information Modeling with Building Performance Simulation and Building Diagnostics 25
Zixiao Shi, Aly Abdelalim, William O’Brien, Ramtin Attar, Peter Akiki, Katie Graham, Barbara van Waarden, Steve Fai, Alex Tessier, and Azam Khan
Human-Building Interaction Lab, Carleton University; Carleton Immersive Media Studio, Carleton University; Autodesk Research.

Forensically Discovering Simulation Feedback Knowledge from a Campus Energy Information System 33
Clayton Miller and Arno Schlueter
Institute of Architecture, ETH Zurich.
Session 3: Design Optimization

Multiobjective Optimization of Structure and Visual Qualities 43
Kirk Martini
Department of Architecture, University of Virginia.

Decomposition Strategies for Building Envelope Design Optimization Problems 51
Steve Barg, Forest Flager, and Martin Fischer
Stanford University.

Optimizing Creatively in Multi-Objective Optimization 59
Yassin Ashour and Branko Kolarevic
EVDS, University of Calgary.

A Multi Agent System for Design Simulation Framewok: Experiments with Virtual Physical Social Feedback for Architecture 67
David Jason Gerber, Evangelos Pantazis, Leandro Marcolino, and Arsalan Heydarian
University of Southern California.

Session 4: Occupant Tracking and Visualization 75

Exploratory Sequential Data Analysis for Multi-Agent Occupancy Simulation Results 77
Simon Breslav, Rhys Goldstein, Azam Khan, and Kasper Hornbæk
Autodesk Research; University of Copenhagen.

Occupant-Aware Indoor Monitoring for Enhanced Building Analysis 85
Dimosthenis Ioannidis, Stelios Krinidis, Anastasios Drosou, Dimitrios Tzovaras, and Spiridon Likothanassis
Computer Engineering and Informatics, University of Patras; Centre for Research & Technology, Hellas Thermi-Thessaloniki.
A System for Tracking and Visualizing Social Interactions in a Collaborative Work Environment
Mani Williams, Jane Berry, Asha Rao, and Nathan Williams
Spatial Information Architecture Laboratory, RMIT University; School of Mathematical and Geospatial Sciences, RMIT University; Qinlao Design.

((MODYPLAN)) - Early Stage Hospital Simulation with Emphasis on Cross-Clinical Treatment Chains
Gabriel Wurzer, Wolfgang E. Lorenz, Matthias Rössler, Irene Hafner, Niki Popper, and Barbara Glock
Vienna University of Technology, DWH Simulation Services.

Session 5: Impact Minimization

Yair Schwartz, Rokia Raslan, and Dejan Mumovic
University College London.

Optimization of Passive Cooling Control Thresholds with GenOpt and EnergyPlus
Alexandra R. Rempel and Stephen J. Remington
School of Architecture, Rensselaer Polytechnic Institute; Department of Physics, University of Oregon.

Toward Pre-Simulated Guidelines for Low-Energy High-Rise Residential Design in Megacities
Holly Samuelson, Apoorv Goyal, Sebastian Claussnitzer, Alejandro Romo-Castillo, Yujiao Chen, Arpan Bakshi
Graduate School of Architecture, Harvard University; LMN Architects; SOM.
Session 6: Fabrication and Architecture  

A Digital Design and Fabrication Library  
Stylianos Dritsas  
Singapore University of Technology and Design.  

Aware Design Models  
Martin Tamke  
CITA: Centre for Information Technology and Architecture.  

Curve-Folded Form-Work for Cast, Compressive Skeletons  
Shajay Bhooshan, Vishu Bhooshan, Ashwin Shah, Henry Louth, and David Reeves  
Zaha Hadid Architects.  

Session 7: Computational Fluid Dynamics (CFD) and Ventilation  

A Physical and Numerical Simulation Strategy to Understand the Impact of the Dynamics in Air for the Design of Porous Screens  
Mani Williams, Rafael Moya, Daniel Prohasky, Mehnoush Latifi Khorasgani, Simon Watkins, Mark Burry, Jane Burry and Philip Belesky  
RMIT University; University of Melbourne.  

Assessing the Energy and IAQ Potential of Dynamic Minimum Ventilation Rate Strategies in Offices  
César Porras-Amores and Spencer Dutton  
Technical University of Madrid; Lawrence Berkeley National Laboratory.  

A Comparative Study of Mixed Mode Simulation Methods: Approaches in Research and Practice  
Priya Gandhi, Gail Brager, and Spencer Dutton  
Center for the Built Environment, UC Berkeley; Lawrence Berkeley National Laboratory.  

Session 8: Solar Shading

A New Approach to Modeling Frit Patterns for Daylight Simulation
Mostapha Sadeghipour Roudsari and Anne Waelkens
Thornton Tomasetti | CORE Studio.

Remote Solving: A Methodological Shift in Collaborative Building Design and Analysis
Matthew R. Naugle and Mostapha Roudsari
Thornton Tomasetti | CORE Studio.

ComfortCover: A Novel Method for the Design of Outdoor Shades
Christopher Mackey, Mostapha Sadeghipour Roudsari, and Panagiotis Samaras
Massachusetts Institute of Technology; University of Pennsylvania; University College London.

Session 9: Design Methods

Simulating Human Visual Experience in Stadiums
Roland Hudson and Michael Westlake
Universidad de Los Andes; Populous.

Self-Organizing City: Experiments Using Multi-Agent Model and Space Syntax
Ming Tang
University of Cincinnati.

Computing Curve-Folded Tessellations Through Straight-Folding Approximation
Suryansh Chandra, Axel Körner, Antiopi Koronaki, Rachelle Spiteri, Radhika Amin, Samidha Kowli, and Michael Weinstock
Zaha Hadid Architects; University of Stuttgart; AA School of Architecture.
Session 10: Energy Modeling

Analyzing Indoor Comfort Conditions through Simulation and On-Site Measurements
Raghuram Sunnam, Annie Marston, Zhuzhou Fu, and Oliver Baumann
Baumann Consulting, Dept. of Civil and Environmental Engineering, Carnegie Mellon University.

Approaching Biomimetics: Optimization of Resource Use in Buildings Using a System Dynamics Modeling Tool
Mercedes Garcia-Holguera, Grant Clark, Aaron Sprecher, and Susan Gaskin
McGill University.

Development of a Modeling Strategy for Adaptive Multifunctional Solar Energy Building Envelope Systems
Nicholas Novelli, Justin Shultz, and Anna Dyson
Rensselaer Polytechnic Institute.

Presenting Author Biographies

Organizing Committee

Sponsors

Cover Image Credits

Author Index
Preface

It has been our pleasure to chair the sixth Symposium on Simulation for Architecture and Urban Design (SimAUD 2015), in Alexandria, Virginia, near Washington DC. SimAUD continues to bring together top researchers and practitioners in the fields of architecture, urban design, urban planning, building science, visualization, and systems engineering, with the overarching goal of achieving a positive and lasting impact on society though the simulation-aided design of compelling and sustainable built environments.

This year saw outstanding participation from the community: a record 103 abstracts were contributed; among these a record 63 manuscripts were completed and peer-reviewed, several of which featured accompanying data sets or videos; and a full program of 30 papers were ultimately accepted and included in the proceedings. Top international universities such as UCL, RMIT, the Technion, ETH Zurich, EPFL, SUTD, Stanford, Berkeley, MIT, Harvard, and many others are represented in the final program. Also prominently featured in the accepted works are design schools such as the Architectural Association and CITA, and design and engineering practices such as Thornton Tomasetti, Zaha Hadid Architects, LMN Architects, Populous, SOM, and Baumann Consulting. Among the program’s highlights are several papers on optimization from both the design and engineering domains; new design methods for solar shading, experimental prototypes and fabrication, cities, and stadiums; ground-breaking work on energy modeling and ventilation; new developments in building information and performance data; and a number of contributions which investigate various aspects of human behavior.

We are excited to have Darren Robinson give this year’s SimAUD keynote, on “Stochasticity in Building and Urban Simulation”. We are also delighted to have last year’s chair David Gerber return as an author and presenter. We thank David as well as past chairs Liam O’Brien, Lira Nikolovska, Ramtin Attar, and SimAUD founder Azam Khan for their committed efforts and valuable guidance in preparing this year’s event. We also thank John Yee for assembling this proceedings book and
providing ongoing administrative support. The SimAUD 2015 scientific committee featured an impressive panel of 72 outstanding experts from architecture, engineering, and computer science, who volunteered numerous hours carefully evaluating all manuscripts and providing the authors with useful and well-informed feedback. We sincerely thank this year’s peer reviewers. We also thank Autodesk for sponsoring the symposium, and the SCS and ACM/SIGSIM for co-sponsoring the 2015 SpringSim Conference where SimAUD takes place.

Most importantly, we wish to thank all of this year’s authors for their hard work, ingenuity, and participation. We are confident that future SimAUD events will continue to build on this year’s success in presenting cutting-edge research from around the world, and continue to forge ever-strengthening ties across disciplines, research and practice.

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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

“Stochasticity in Building and Urban Simulation”

Darren Robinson
University of Nottingham

Professor Darren Robinson is Chair in Building and Urban Physics at the University of Nottingham’s Faculty of Engineering where he heads the environmental Physics and design research group (ePad) and directs the cross-faculty Laboratory of Urban Complexity and Sustainability (LUCAS). His personal research activities lie at the intersection between social physics (people), building physics (buildings) and urban physics (city): people | buildings | city; in particular building and urban energy microsimulation, incorporating stochastic models of peoples’ presence, activities, behaviours and comfort.

In recent years Darren has held teaching positions at EPFL (2004-2011), the Architectural Association (2002-2004) and Cambridge University (1998-2000), and worked in industry as an Associate with BDSP Partnership (2000-2004).

He has over 100 refereed scientific publications to his credit including the book “Computer modelling for sustainable urban design”. He sits on the editorial advisory boards of the Journal of Building Performance Simulation (JBPS), the Building and Environment (BAE) Journal and the online journal Sustainability. Darren is a recipient of the CIBSE Napier-Shaw Medal and the JPBS Best Paper Prize, and a two-time recipient of the BAE Best Paper Award.
Session 1: Human Behavior

Simulating Human Behavior in Not-Yet Built Environments by Means of Event-based Narratives
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Technion - Israel Institute of Technology; Inha University; Sapienza University of Rome.
Simulating Human Behavior in not-yet Built Environments
by means of Event-based Narratives

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ABSTRACT
Current Computer-Aided Architectural Design (CAAD) systems fail to represent buildings in-use before their realization. This failure prevents testing the extent to which a proposed setting supports the activities of its intended users. We present a novel approach to human behavior simulation based on a thorough representation of end-user activities by means of events – computational constructs that simulate users’ individual and group activities to achieve a specific goal. Human behavior narratives result from a combination of top-down (planned) and bottom-up (unplanned) sequences of events, as a reaction to time-based schedules and to social and environmental stimuli, respectively. A narrative management system orchestrates the narrative developments and resolves conflicts that may arise among competing events.

Author Keywords
Event-based model; Virtual users; Human behavior simulation; Building design evaluation.

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INTRODUCTION
During the design process architects and clients need to determine in what ways a building will support end-user activities; a building that does not meet its user needs will suffer in terms of lack of functionality, waste of space, delays in task accomplishments, and user dissatisfaction. Nevertheless, predicting and evaluating such building performance is a complex task: user behavior is driven by work-related tasks within an organization, by social and environmental aspects related to the surrounding context, and by individual desires and motives, mediated by perceptual, cognitive as well as cultural and social factors.

Current approaches to human behavior simulation mainly rely on the Agent-Based Modeling (ABM) paradigm, which focuses on assessing specific responses of human inhabitants to social and environmental stimuli, such as fire egress situations [8] and pedestrian movement [5]. Nonetheless, ABM has shown conceptual and technological limits in representing more comprehensive buildings’ spatial use patterns, involving both scheduled activities and more serendipitous one (e.g. social interactions), despite the fact that both types of activities are the bulk of everyday functioning of a building.

To overcome such limitations, Simeone & Kalay [17] proposed a simulation model based on the notion of event: a 3-tuple computational structure that combines actors, activities, and spaces into a single, holistic unit. This model proved its capabilities in simulating top-down pre-planned logical sequences of events. We aim at expanding the capabilities of the model to afford intertwining top-down scheduled sequences of events with a bottom-up lists of events not scheduled ahead. Bottom-up events are performed in relation to agents’ individual traits (e.g. an agent’s health condition) or to groups’ serendipitous situations (e.g. social encounters). These aspects are of critical importance especially for representing human behavior in complex, social environments such as hospitals. Within these settings activities due to social and contextual occurrences may have serious consequences for the function of the environment, and may result in diversions from usual work processes [14].

In this paper we elaborate on the notion of events as computational behavior units, and we propose a narrative management system to simulate both planned and unplanned activities in hospital environments.

STATE OF THE ART
Human behavior in built environments
Architects’ domain of expertise lies within the realm of configuration and prefiguration of physical settings. The built environment, in turn, considerably influences the behavior of its users. Several research practices investigated the relationship between people and their physical environment, including the field of Environmental Psychology. Barker, one of its founders, proposed a comprehensive approach to investigate the dynamic interplay between people’s goal-oriented activities and the environment in which they are performed [3]. The approach relies on the notion of behavior setting: a bounded, self-regulated system that involves both human and non-human components synchronously interacting to carry out behavior...
units, defined as temporal and logical sequences of events [21]. Behavior units are aggregated in observable standing patterns of behavior dependent on the social “program” of the setting rather than on people’s individual decision-making processes. Furthermore, these behavior patterns represent a consistent activity system that adapts to changes in the composition and number of participants, or in relation to the spatial features of the physical setting.

Following Barker’s theory of behavior setting and Alexander’s pattern-based approach [1], we argue that standing patterns of behavior commensurate with environmental, social, and cultural contexts can be computationally represented along with the physical settings in which they occur. These patterns, after being observed in real environments and computationally formalized, can be used to test by means of simulation the affordance of a setting to support or hinder the performing of the related activities.

Simulating behavior narratives

Human behavior narratives can be defined as logical, time-based activity structures evolving in time in a coherent fashion. In the architectural field, current methods to simulate human behavior narratives involve two opposite approaches: the first consists in a top-down deterministic definition of time-based schedules to simulate building spatial utilization processes [18], buildings’ occupant behavior in relation to energy use [10, 12], and designer-user communication [15]. The second consists in a bottom-up approach to provide agents with simple rules of behavior in response to environmental and perceptual stimuli [19].

In the video game industry, instead, much effort is dedicated to mix the two aforementioned approaches by creating intelligent Non-Player Characters (NPC) that follow a general narrative script, and that are capable of dynamically adapting their actions in reaction to a player choices. Central narrative management systems orchestrate a narrative development according to agent goals, and environmental conditions and properties [4, 13]. However, drawbacks involve the complexity of encoding narrative management rules, and high computational costs. Alternatively, hybrid narrative management systems distribute decision-making tasks between a narrative manager and semi-intelligent characters [7, 20, 9]. This approach advocates a division between a top-down story-level control system and a bottom-up character-level system. The integration between these two levels can occur by means of small-granularity story units, which represent individual and group behaviors [2, 11, 16].

In this paper we elaborate on a model proposed by Simeone & Kalay [17], which adopted video game hybrid narrative management strategies to simulate human behavior narratives in not-yet built environments. The model, designed to overcome the limitations of previous ABM approaches, trades some aspects of single agents’ decision-making abilities in favor of a centralized direction mechanism, affording authorial control over the performing of complex operations such as group activities and agent collaboration. The model relies on the notion of event—a computational structure that embeds the knowledge required to perform individual and collaborative tasks in virtual settings. When triggered, an event temporarily reduces the autonomy of the involved agents to direct them through a series of actions in a coordinated manner.

This narrative-oriented interpretation of the word “event” is consistent with previous work in the video game industry [16]. A somewhat different interpretation is found in the discrete-event simulation literature, where an “event” is still a representation but occurs at an instant of time. However the self-contained nature of an event is common to both discrete-event simulation and the narrative-oriented context of our work. Furthermore, the two primary event-triggering mechanisms in discrete-event simulation—the scheduling of events and the receiving of new information—are analogous to the planned and unplanned events described in this paper.

EVENTS AS BEHAVIOR UNITS

Events combine three types of information: the actors that populate a setting, the activity they do, and the space they use. By juxtaposing entities among these non-homogeneous information domains events define behavior units with context-related semantics, and describe segments of the use processes that occur in buildings in relation to their function (Figure 1). For instance, an event describing a common activity within a hospital setting could be: “visitors” (actors) “talking to patient” (activity) in “patient room” (space).

![Figure 1. Event coordination mechanism](image)

**Figure 1. Event coordination mechanism**

**A distributed intelligence approach**

To reduce events’ computational efforts in managing the performing of a behavior pattern, each of the aforementioned event constituents, namely the actors, spaces and activities, presents dynamic calculation capabilities. The event—acting like an “orchestra director”—provides top-down management of the aforementioned involved entities to assure the achievement of the goal.
Space
To support human behavior simulation, we propose to augment the spatial representations afforded by current Computer Aided Design (CAD) and Building Information Modeling (BIM) tools by adding semantic and environmental information. Such information is continuously updated in accordance with the activities and environmental conditions prevailing in each space at a given time.

Recent attempts to encode space semantics in a static fashion (e.g. through IFC models) have been proven inadequate for the dynamic simulation of user activities within predefined space boundaries (e.g. a room, or a specific area within a room). Rather, a time-dependent representation is required, since a specific space may assume different meanings depending on the nature of the activity that occurs in it, or the composition of the actors performing that activity. For instance, if an event called “patient check,” which involves a doctor and a nurse checking a patient, is performed in a hospital room, the character of the space becomes akin to a clinic, which excludes visitors. Once the “patient check” activity is over, visitors may be allowed, since the character of the space changes into “patient room.”

A pre-coded list of possible semantics defines each space affordance in terms of supporting a discrete number of activities. During the simulation process, space entities are responsible for detecting the activity performed within their boundaries, and selecting the corresponding semantic value, therefore updating their own properties. Conflicts among competing semantic values attributed to the same space in relation to multiple activities are solved by means of a rules-based system, which determines the current space semantics in relation to multiple parameters such as event priorities, as well as social and environmental factors.

Environmental data is added in the form of data-maps, dynamic databases that represent environmental properties such as noise, light, smell, and density of people. Data-maps are updated at specific time intervals during the simulation process in response to environmental conditions, and are queried by events to determine whether the conditions required to perform a specific behavior are fulfilled. Changes in both space semantics and data-maps values can, in fact, cause an event to adopt a different strategy to achieve its goal, or even be cancelled if an alternate plan is not available.

Actors
Anthropomorphic goal-oriented virtual users mimic end-user behavior in a virtual setting [19]. Each agent, called actor, embeds geometrical properties, a semantic role he/she occupies in the organization (e.g. doctor, or nurse), and physiological and psychological traits whose values remain fixed during the simulation process (e.g. age, gender, experience) or vary dynamically according to the activities performed (e.g. tiredness, stress, hunger). As with spatial semantic information and data-maps, event entities access information stored in actor profiles to trigger or adapt the performing of an activity in relation to individual features.

Actors are capable of low-level decision-making to perform activities such as path finding and walking towards a target. For instance, to move through a virtual setting agents rely on their physical and psychological condition, as well as on their role in the organization (e.g. a doctor, or a nurse), which affects their environmental knowledge.

Environmental perception and cognition are not encoded in actors themselves, but rather are mediated through a spatial “awareness” system that detects actor and object presence in spatial zones. For example, to determine whether two agents are present in the same room, an event communicates with the “room” entity itself: the room has the capacity to detect which agents are located within its boundary, in a manner that is simpler than endowing each agent with spatial awareness capabilities. This approach ignores sight lines and gaze direction, as is done in other research projects at a much higher computational cost [6]. We consider this approach an acceptable trade-off for the purposes of our simulation.

Basic constructs involving actor groups are managed by event entities, which can for instance coordinate the behaviors of patients’ family members while visiting their relative. In this case, the semantic role of the group members and the relationship between them play an active role in performing the task.

Activities
Activities provide a set of actions and procedures that direct agents toward the accomplishment of individual or group tasks. They consist of methods/functions that are called by events, and that take as arguments at least an actor entity and a space entity associated with the same event. Parametric values guide the performing of activities, and allow them to be reused in different circumstances by multiple actors. For example, the activity “talk to” takes as arguments the actors involved (at least two), the semantics of the space in which the activity can be performed, and the duration of the action. Performing activities that involve an agent movement through space, such as path finding, obstacle avoidance, and speed of motion, rely on each agent individual capabilities. In case of activities involving a group of actors moving towards a target, the event entity coordinating their behavior selects a “group leader” who will share with the other group members his/her path-finding capabilities.

Event performing structure
Events are implemented as self-contained autonomous routines with decision-making capabilities in relation to the status of the entities involved, the social and physical
context, and stochastic processes. They include pre-conditions, a set of performing procedures, and post-conditions.

Pre-conditions specify the requirements for an event to be triggered. They might be related to the activity, space, or actor entities involved in the event, or to more general constructs, such as time. Preconditions concerning space, for instance, might check for the space semantics, data-maps values, or other information detected by the spatial awareness mechanism.

After verifying the compliance with the preconditions, a set of performing procedures guides the event execution. Such procedures are provided by an event’s activity component. An activity success test notifies the event about a task achievement when terminating conditions are satisfied.

Upon termination, events update the status of all the entities involved in its execution (such as actors, spaces, furniture) by means of post-condition instructions.

In case the preconditions of a sub-event are not met, the event seeks for an alternative plan stored inside its performing procedure to achieve the same task. If such plan cannot be found the event is aborted.

**EVENT-BASED NARRATIVES**

By combining events into larger compositions we generate human behavior narratives related to how buildings are used by their occupants. Narratives provide a logical plot structure that unfolds during the simulation process according to event preconditions, as well as to stochastic processes. To define narratives we use a system of nested events, assembled in logical structures.

**Event nesting**

Events can be nested within other events in a tree-like manner (Figure 2). This approach aims to increase the level of detail in representing behavior units, and to make the complexity of a building use-process more manageable. The nesting system allows defining behaviors as a composition of sub-behaviors whose performing eventually leads to a task achievement. A parent event is responsible for orchestrating the performing of its children events so that sub-events do not need to be aware of their siblings. In this manner, parent events are able to make informed decisions about the performing of their sub-events. This system affords a hierarchical control mechanism in which rules and properties encoded in a parent event propagate to the children. The nesting system allows representation of behaviors at different levels of abstraction for the purpose of managing increasing complexity and adapting to the level of detail required by the simulation to describe human behavior phenomena.

**Event assembles**

Multiple sub-events are nested within the performing procedures of a parent event. We define this composition as event assembly. Event assemblies define the execution logic of a structured set of events to achieve a task stated by the parent event. Within the assemblies, events are combined by means of logical operators, which are embedded in the parent event, and describe the rules to perform the children events. Logical operators are of three kinds: sequence, parallel, and selection (Figure 3).

The sequence operator defines a logical and temporal sequence among events that occur one after the other. The parallel operator assembles two or more events that are triggered at the same time. This type of operator is useful to synchronize two activities starting at the same time.

The selection operator indicates a choice that has to be made at the parent node about which sub-events to trigger next. The selection is realized by evaluating the event preconditions and priority values. A stochastic mechanism can also be applied to randomize the selection process. In case of an event’s failure to complete a task, an alternative plan to achieve the same task can be stored within the parent node, and selected by means of this operator type.

**Figure 2. Event nesting**

**Figure 3. Logical operators to define event assemblies**
Example: “Patient Check” event
To illustrate the concepts of event performing, nesting and assembling, we discuss the “patient check” event (Figure 4), which is a common event in a general hospital ward. “Patient Check” is considered the parent node of a nested event assembly comprising a sequence of two events (1.1 & 1.2). Event 1.1 is in turn the parent of two sub-events (1.1.1 & 1.1.2), combined by a parallel operator. These events direct a doctor and a nurse (actors) through a specific space type (a corridor), towards the room of the patient (another actor) who needs to be checked (activity). The space type defines the required semantics to support the activity performing. Sudden emergency situations taking place in the corridor might in fact change the semantics of the space through which the doctor and the nurse are moving, obliging the actors to look for an alternate route to reach their target (or abort the “patient check” event in favor of engaging in an emergency event). After completing Events 1.1.1 & 1.1.2, the “move to patient bed” event (1.1) is fulfilled, and the narrative proceeds to Event 1.2, which comprises two nested events (1.2.1 & 1.2.2) connected by a selection operator. After evaluating both event preconditions, Event 1.2 decides which one of the two sub-events to trigger. Event 1.2.1 involves both doctor and nurse checking on a patient in a space whose semantic value is “clinic”. As mentioned before, any changes in the space semantics, such as a visitor talking loudly in the same room can prevent the patient check event from being performed. If the conditions to perform Event 1.2.1 are not satisfied (e.g. the patient is not in the bed), the event will be aborted. After navigating the event graph till its end, the control is brought back to the root event (Event 1). The root event updates a loop counter stored within its performing procedures indicating the patients that have already been checked, and the ones that yet have to be checked. Event 1 therefore re-triggers the same sub-events for the next patient to be checked, until all patients have been visited.

NARRATIVE MANAGEMENT
A hierarchical event composition structure is used to simulate use-process narratives in buildings (Figure 5). The system consists of a distributed decision-making mechanism that involves actors at a lower level (operational), events at a middle level (tactical), and a narrative manager at the higher level (strategic). At the operational level, behavior is directed by actors’ individual traits, such as walking speed, and path-finding capabilities. At the tactical level, events coordinate actors’ behavior to accomplish a task. At the strategic level, a narrative management system directs the evolution of the simulation narrative in a coherent fashion by determining which event to perform next. For management purposes, events are classified according to whether they are planned or they are selected due to impromptu circumstances, and whether they are performed by individuals or by groups of actors.

Planned events are scheduled in time (e.g. a meeting), and they represent the procedures that designers aim at simulating and evaluating. Unplanned events are triggered in relation to contingent situations (e.g. users’ physiological needs, social interactions, or emergency situations), and they lead to deviations from the performing of planned events. Individual events involve a single agent and are performed without interacting with others, whereas group events involve several agents with a shared common goal.

This system organization allows distributing decision rules at different levels of the narrative to resolve conflicts that arise among competing events. Higher nodes in the event tree solve conflicts among events in the lower hierarchy level by means of a rule-based system that indicates which event to perform among two competing ones.

Planned events
Planned events are encoded in the form of a top-down comprehensive time-based schedule. Events starting at the same time are nested within a higher-level event that triggers all the sub-events by means of a parallel operator, when the time preconditions are satisfied. When an event time preconditions are satisfied, a daemon triggers the respective event(s).
The higher-level event (Event 1.1 in Figure 5) combines the information encoded in the children nodes to generate a comprehensive time-based schedule that accounts for both individual and group behaviors. Furthermore, Event 1.1 consolidates decision-making capabilities involving both group and individual schedules, such as rescheduling an event due to conflicts or delays.

**Unplanned events**

Unplanned events are encoded in the form of a list of possible behaviors that may be performed when determined preconditions (involving spatial, environmental, or social stimuli) are satisfied.

Unplanned group events (1.2.1) stipulate that actors must collaborate in order to achieve a joint task. Social interaction events (1.2.1.1), for example, can be triggered when two actors are within a predefined proximity of one another. To verify this condition, a daemon constantly monitors a proximity data-map, which detects the position of actors in space. When the conditions are fulfilled, the daemon will notify the event.

Instead, a list of unplanned individual events is defined for each actor, and nested within a parent event (1.2.2.1 & 1.2.2.2). Such events can be triggered in two ways: the first when a daemon notices some conditions, and requests other events’ interruption. For instance, a medical emergency (so-called “Code Blue”) event is triggered when a daemon that monitors the vital signs of each patient detects a health-threatening situation (Event 1.2.2.2.1). This event involves directing a team of doctors towards the patient to initiate resuscitation procedures. The second way is when an actor is not involved in any other planned event. In this case, to perform a selection, the parent event, which resembles individual actors decision-making capabilities, checks the children-events’ preconditions accounting for the individual agent’s drives and motives (e.g. doing his job, assisting others etc.). In case where two or more events are suitable for performing, the parent event will evaluate the events’ priority values.

**Narrative Manager**

A narrative manager oversees the performing of all the events, and manages information that is shared among different levels of the events hierarchy, such as the time parameter and daemons’ actions. Due to its root position in the narrative hierarchy, the narrative manager resolves conflicts that arise between competing planned and unplanned events. To resolve a conflict, a rule database, which is stored within the narrative manager’s performing procedures, is consulted. Rules define which event to perform among competing events, and under which conditions. For instance, if the conditions to perform a social interaction event are satisfied while an agent is already performing another event, the narrative manager detects a conflict. Its resolution depends on many parameters, including event priorities and the actor individual states (e.g. stress, tiredness). The evaluation of these parameters will determine if a social event can be triggered (e.g. the doctors will pause to talk to each other), and, if so, for how long.

![Figure 5: Narrative management system defined by Planned & Unplanned events, and by Group & Individual events.](image)
This conflict resolution mechanism aims at obviating the cumbersome procedure of dynamically adapting event priorities during the simulation process in relation to the status of the actors involved and of the environment in which they operate. While event priorities remain constant, more rules can be added that relate to different aspects of the environment, to make more informed decision in resolving conflicts.

CASE STUDY
The following case study is offered to elucidate the simulation model described in this paper (Figure 6). The simulation involves four actors in their daily routines. The setting consists in a simplified hospital environment where activities typically adhere to strict time-based schedules, interrupted by unexpected events. The spatial layout comprises several semantically different zones. No planned activities are scheduled at the beginning of the simulation. Rather, each actor autonomously selects which event to perform (Figure 6a). At the appointed time, the planned event “patient check” is activated. It directs a doctor and a nurse to go to the patient room, where a patient is talking to a visitor. The arrival of the doctor and the nurse at the patient room causes a change in the room semantics, from being a patient room, to a clinic. This change causes the event “patient talking to visitor” to stop, and the visitor to leave the room. When the doctor and nurse are close to the patient bed and the related preconditions are satisfied, the “patient check” event takes control of the three actors to perform the collaborative activity (Figure 6b). After completing the event, each actor goes back to resume his/her previous task. On the way to his office, though, the doctor passes close to the visitor, who is waiting in the lobby. The spatial awareness system of the space zone “i” detects the proximity of the two agents and communicates it to a “social interaction” event, which tests additional preconditions concerning the doctor’s state of stress, and the visitor’s anxiousness value. Since the conditions are verified, the event is performed (Figure 6c).

This simulation was facilitated by a host of computational tools: Autodesk Revit allowed the physical setting’s geometrical data modeling; Autodesk 3DS Max allowed actors’ geometrical data modeling and animation generation; Unity 3D—a video game engine tool—provided a simulation environment with dynamic visualization capabilities. Data-maps, semantics, agent profiles, activities, and events were also scripted in Unity.

CONCLUSIONS AND FUTURE DEVELOPMENTS
During the design process, architects rely on their own, partial and biased experience to foresee the impact of a physical setting on future human behavior. The research presented in this paper outlines a model to simulate human behavior in buildings before construction, for evaluation purposes. The model relies on events—self-contained behavior units that are assembled into larger narratives accounting both for top-down (planned) and bottom-up (unplanned) activities. A hierarchical control system controls the progression of human behavior narratives, and resolves conflicts between planned and unplanned events. The simulation accounts for the effect produced on the activity performing due to changes in environmental properties and semantic meaning. We argue that the model allows for a better management of human simulation narratives, guaranteeing flexibility in behavior design, and allowing increasing level of detail.
Further work is required at all levels of the model: at the agent level, the enhancement of visibility calculations; at the event level, the development of better strategies to evaluate which event to perform among a list of options in relation to probability considerations and utility functions; at the narrative level, the definition of the appropriate size of event assemblies to guarantee an optimal management system.

Future developments will involve the creation of a more comprehensive system to include other state-of-the-art simulation methodologies, and the application of such system to simulate other facility types, such as schools, airports, or museums. More generally, we look forward to develop a computational platform test the impact produced by a built environment on its inhabitants, implementing human behavior knowledge deriving from multiple research fields, such as Cognitive Science, Social Science, and Environmental Psychology.

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ABSTRACT
The era of “Big Data” presents new challenges and opportunities to impact how the built environment is designed and constructed. Modern design tools and material databases should be more scalable, reliable, and accessible to take full advantage of the quantity of available building data. New approaches providing well-structured information can lead to robust decision support for architectural simulations earlier in the design process; rule-based decision engines and knowledge bases are the link between current data and useful decision frameworks. Integrating distributed API-based systems means that material data silos existing in modern tools can become enriched and extensible for future use with additional data from building documents, other databases, and the minds of design professionals. The PyKE rules engine extension to the Green Scale (GS) Tool improves material searches, creates the opportunity for incorporating additional rules via a REST interface, and enables integration with the Semantic Web via Linked Data principles.

Author Keywords
Expert Systems; Sustainable Data; Linked Data; Big Data; Semantic Web; Ontological Knowledge Engine; PyKE; OWL; SWIRL; REST; SPARQL; RIF; Green Scale Tool; Knowledge Based Rules; Machine Learning.

ACM Classification Keywords
Algorithms, Design, Experimentation, HCI, Performance, Reliability, Standardization, Verification.

INTRODUCTION
Between the years of 2013 and 2025 U.S. electricity consumption from buildings is expected to increase from 72% to 75% [20], part of the 40% of domestic primary energy usage for which buildings account [12]. In addition, domestic carbon dioxide emissions that result from building services make up 40% of the total [8]. Annually, 26% of all non-industrial waste derives from construction, demolition, and renovations of our buildings [5]; this is a drastic figure representing hundreds of thousands of building projects [6]. As a result of these trends, strategies for achieving building sustainability are needed from the beginning of the architectural design process [4] because our design choices have long-lasting impacts on the environment. This research is aimed at bringing real solutions to the professional community that can be used readily and will have positive impacts in the early stages of production. However, full environmental analysis currently requires specialized expertise and software to quantify impacts, and even those programs that are available are limited in scope and accuracy. These shortcomings are due to a restricted understanding of computational models, but more so because of incomplete material property data used in the calculation processes, if available at all. Consequently, this limited data means that decisions are made by humans considering a smaller scope of parameters and criteria than could be possible by utilizing Big Data practices and modern computing power applied to that data.

This developing concern for the future of the built environment means that tools will absolutely need to be robust enough for multi-metric energy analysis to remain advantageous in the architecture and engineering fields. Single-metric analysis programs that are widely used today will not be sufficient in the near future as the quantity of available data increases to unparalleled amounts. Unfortunately, many of the commonly used AECO models and tools (Revit®1, Ecotect®2, Athena Impact Estimator®3, Green Building Studio®4, U. S. Department of Energy (DOE-2)5, and the U. S. Department of Commerce (BEES 4.0)6) are limited to manual entry of building data and/or material properties values. Thus the data deficit which modern energy applications are subjected to requires attention and strategies to not only collect this data but to do so in a manner that is adaptive and scalable enough to keep pace with rapid advances in the field.

1 Revit ®: www.autodesk.com/products/
2 Ecotect ®: usa.autodesk.com/ecotect-analysis
3 Athena ®: www.athenasmi.org/our-software-data
4 GBS ®: www.autodesk.com/products
5 DOE-2: http://energy.gov
6 BEES: www.nist.gov/el/economics/BEESSoftware
Most of the simulation tools in use today will usually only perform data analysis on a single design metric, but in the Big Data era, tools will have to be able to run efficiently enough to handle several metrics at once over a large quantity of design choices. To reach an optimal level of usefulness, modern multi-metric comparison tools will not only have to perform well making their calculations, but will now have to do so when tens of thousands of material options are available from an interdisciplinary set of data related to all aspects architectural material manufacturing and usage.

Green Scale (GS) Research [19], and by extension the GS Tool7 efforts, work to discover efficient methods to aggregate and process multitudes of material data without harming the performance of a multi-metric application, explore how these methods could communicate beneficially with the larger semantic web - partially via a PyKE Rules Engine, and ultimately seek solutions that will positively impact the way that the built environment is conceived and executed. Furthermore, the GS tool is an excellent example of a multi-metric energy analysis tool that can be used to implement experimental methods of rules communication needed for handling the quantities of data used in proper multi-criteria decision analysis while gaining access to the larger semantic web utilizing linked open data principles.8 The following work analyzes the GS Tool with and without the implementation of a PyKE based Rules Engine (for architectural material choices, geometry discrepancies, and best practice “rules of thumb”). The structure of the paper is as follows: motivations for creating a Rules Engine Layer, the architecture of the GS Tool with the rules layer implementation, methodology of the project and creation of the rule types, results of the rules layer implementation, implications for future computer science, future research, related work, and concluding thoughts.

RELATED WORK
Projects have worked towards similar visions of knowledge-enhanced applications. SAFegress [7] is a similar type of rule-based approach for egress simulations instead of material data leading to decision support. Design Elevator [16] was an approach to integrating knowledge into an application for influencing early stages of the design process; however, new technologies make this process more adaptable and extensible. Solibri Model Viewer9 is a tool developed to address a vision of easier data sharing and model viewing possibilities with BIM and IFC data types. These are widely used and relevant data types as well but our research works to become reliant on a data methodology that supports all building data, regardless of source and structure.

Other relevant work is more specifically in the area of building material name matching related to energy analysis and includes projects where an IFCXML is the chosen file format for handling data to decrease erroneous input [14] or to create software implementations for shareable data between several design fields related to building systems [22]. While currently there are several fragmented computer science areas of research related to the architecture and engineering professions including other knowledge sharing system for sustainability sciences [15], the goal is to have a complete and interactive decision system for architecture applications similar to the UFIT ontology-driven knowledge-based system for enhancing physical fitness [18]. At that point, architecture-related ontology patterns can be applied to the data as well, such as those that represent building material transformations [21] for more accurate lifecycle inventory analysis [1] and perhaps advances can be made to the GS database with known methods of modeling semantic data [2] [3].

MOTIVATION TO IMPLEMENT A RULES ENGINE LAYER
The Green Scale Tool (see Figure 1) was built to be integrated with the workflow of an architect and provide a broader perspective of the environmental impacts caused by the built environment through a multi-metric comparative analysis including BEAM [23] thermal heat flux model and Embodied Energy life cycle inventory model [4]. Development of the tool has been done in close consultation with architect practitioners and architecture students to integrate rules into a computational design environment that can be utilized on a daily basis. The tool heavily utilizes the existing Revit interface, and thus is largely tied to whatever usability advantages and disadvantages Revit provides. Further iterations of the research would include testing with a wider community outside the original development collaboration team.

In this paper, the GS tool is used as the base framework for applying a PyKE10 based rules engine enabling Decision Theory [13] models to be incorporated such that architects will make better material choices for the built environment. Within certain existing simulation tool databases, there is

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7 Green Scale: www.greenscale.org
8 Linked Data: www.w3.org/standards/semanticweb/data
10 PyKE ®: pyke.sourceforge.net
syntactical and semantic ambiguity that is not adequately addressed by application of regular expressions or even generating the correct nominal values for material data. By extension, adjustments in energy calculations are often overlooked due to the misinterpretations because of the structural nature of Open Green Building XML (gbXML)11 based schemas as implemented in common architectural design tools and the limited explicitness to interpret XML tag structured data. A PyKE rules engine, however, means rules can be adaptively constructed to fix discrepancies and be extrapolated for use with other rule engines and applications.

Past and ongoing research related to rule-based expert systems include the development of the Python based rules engine presented at PyCon in 2008 [9], which was the foundation of this project. PyKE is a knowledge-based inference engine inspired by Prolog12 but implemented completely in Python. This method of logic programming allows the free exchange of Python expressions and customized expert system rules while improving the availability and quantity of code reuse. A distributed API-based system can be added after the rules are implemented as traditional python functions via PyKE. Stored in a designated location away from pre-existing code, the knowledge base is now portable, easily editable, and accessible for adding new rules over time.

The proposed rules layer resolves problematic or often missing XML tags and, combined with regular expressions, these XML files can now be efficiently and more accurately parsed within the architectural simulation tool (with minimal interventions aside from deliberately adding new rules to the knowledge bases). Additionally, rules capturing “rules of thumb” tacit knowledge known to the architecture practitioner can be triggered based on conditions detected in XML data structures. This PyKE implementation builds on the Green Scale Tool using a flexible framework for mapping regular expressions to conditions and finally to an associated action for several types of architectural decisions (material choice, geometry discrepancies, and architectural best-practice rules), all of which are encountered through using this example application. This framework constructs a mapping between the architectural approximation rules and the GS model data, which usually has computational processes and code sequences that require more analysis than the standard simulation tools allow for accuracy in the calculations. These methods often include strings, regular expression matching, and other numerical data.

Varying architectural perspectives and experience can be leveraged in order to gather a broader set of rules and expand the existing collection. The resulting knowledge base can then be used to benefit the larger community and be applied as Linked Data via SPIN13, SPARQL14, and the PyKE rules engine. Using REST15 type interfacing and web services, the accessibility on wireless devices can be increased and the system can be effective in cloud-computing environments. This means the final implementation would be able to interface with other applications thus more usefully connecting all the system elements. The rules layer and ultimately the knowledge base communicate with the PyKE rules engine; once it is moved to the Cloud, it can be extended and improved by Machine Learning [11]. Additionally, SPIN rules can be integrated with SPARQL for generating inference based connections with relevant methods in the expanding knowledge base. Additionally, SPIN could provide mechanisms for data consistency and integrity checks within the knowledge base.

TOOL ARCHITECTURE AND RULES ENGINE

The Green Scale Tool Architecture

The GS Tool is implemented as a Revit 2014 Plug-In and has an architectural design presented in Figure 1. After the Plug-In launches, the user is then required to choose surfaces from the architectural model of at least one construction type. Next, the GS user interface is presented from which the Python energy models are called. This is a windows application that handles locating all the construction types for a particular surface, generating a gbXML for each type found, presenting a list of these possibilities to the user, and processing the Python models once for each choice selected so as to create an iterative and extensible simulation tool. This processing loop can be repeated as desired by the user. From the Windows Application layer, the Python based analysis models are launched individually enabling potential parallelism and extensibility and currently include modules for computation of life cycle inventory based Embodied Energy and Thermal Heat Flux metrics for a given architectural design [19]. Individual modules also require connections to additional data sets and external entities; for example, the thermal model would need access to Energy Plus climatology data. A SQLite316 database called the “GS Material Property Database” is queried from within the running Python models via a Django17 based RESTful web service running on a remote Linux server.

Once each one of the Python modules has completed execution for all assembly versions selected for comparative analysis, the collected calculation results are transferred back to the Revit Plugin via standard output. These results are reported and visualized using text tables.

11 gbXML: http://gbxml.org
12 Prolog: http://www.deransart.fr//prolog/docs.html
13 SPIN: http://spinrdf.org
14 SPARQL: http://www.w3.org/2009/sparql/wiki
16 SQLite3: http://sqlite.org
17 Django: https://www.djangoproject.com
charts, graphs, PDFs, etc. As a result, the application is an ideal modular framework for implementing computational rules because it already facilitates multi-metric calculations and comparisons to be analyzed simultaneously. As modules are added and the database expands, the application will be able to connect to other databases that conform to a RESTful API, collecting new material data on-the-fly as needed by the models. The data aggregation can even extend to cloud-based or crowd-sourced datasets as the community expands. The inherent nature of all of these goals will benefit long-term from rule-based processing of properly structured data (see Figure 2).

**Addition of a Rules Engine and API Framework**

We have implemented an extended architecture that allows the execution of a rule set and knowledge base to be used with design evaluation models, potentially in distributed computing environments as design complexity increases. The focus of this work is the addition of the PyKE based Rules Engine for the GS Tool (see Figure 2). Figure 2 demonstrates the existing GS Tool, the new additions made as a result of the implementation of the PyKE rules engine, and the elements to be added through future research. The rules are incorporated as an extension of the python modules lying within the previously described main application architecture. This works in conjunction with a set of .kfb, .krb, and .kqb extension files that represent a fact base, forward and backward chaining rules and a “question base” respectively, that have Prolog inspired syntax. Because PyKE is a hybrid of python and a formal logic language that provides a knowledge-based inference engine, it allows communication from any existing module for easy intermingling between Python expressions and the expert system rules [9]. This also means that the decoupling of rules from the main body of source code is now a functional possibility.

By integrating a rules engine directly into a multi-metric application architecture, we have created a bridge that is extensible in terms of encapsulating and transferring rules and knowledge bases between GS platform instances. (see Figure 2). Mechanisms for crowd-sourcing can be constructed within the GS tool user interface allowing data and tacit knowledge to be gathered from a variety of sources not only to build up the data in the GS Material Property Database itself, but to add rules to the PyKE base files for the rules engine to utilize. We envision the GS tool will be able to use additional logic and machine learning to automatically incorporate these rules and infer decisions using semantic web based technologies creating a truly distributed computational architecture. At this point, a SPARQL endpoint can be added that to facilitate distributed queries and inferencing from a web of Linked Data, increasing the variety of data from architects, manufacturers, construction contractors, and governmental organizations to be incorporated in a rules based decision support system. The PyKE rules engine can potentially be connected to formal Ontologies and Ontology Patterns implemented in the Web Ontology Language (OWL) that allow larger expressivity based on first order description logics creating an architectural design knowledge base for isolated calculations such as robust and highly accurate multi-criteria decision analysis.

![Figure 2. Existing and Future Application Architecture](image)

**METHODOLOGY**

**Application Restructuring for a Rules Engine**

Current tools are using a very limited amount of data to make calculations or are reliant upon inaccurate user input for results. This means that all of the source code (often if-else or switch statements) is able to handle potential data combinations; in the Big Data era, continuously updating source code to add new cases or storing all potential logic in the source code files is impractical for performance in the very least.

The rules layer created for the GS activates only once within the GS tools main routine and from this point the individual rules are called as needed based upon the type of rule needed and what associated pieces of the knowledge base are required. This process introduces some initial overhead, but the benefits of having decoupled rule sets far outweigh the change in processing times (For more see: Rules Aiding Decision Theory Frameworks). Throughout the source code, entire sections of nested if-else logics were replaced with only one or two rules to achieve the same model outputs for all case studies.

As the architectural design documents increase in complexity or number of surfaces, it is likely more inconsistency in XML data will be encountered due to data quality [10] or inconsistent naming of materials,
assemblies, dimensions and novel design geometries that have not been accounted for in analysis modules. We have observed that gbXML files alone can have several types of errors that need the use of rules to be resolved so that the python models calculate accurately. Incorrect tags, values, strings, and/or missing versions of the same types of data are some of the most problematic XML problems encountered from the Plug-In export from Revit. For example, data may be arbitrarily concatenated into strings that are then output from Revit and available to use in certain cases instead of a structured set of material property data and values using an appropriate schema. Cases such as these result in a complex set of conditional statements that are difficult to manage in a purely procedural language implementation; this is why gbXML alignment is necessary. The rules engine is a more flexible and singular solution for these data structures.

**Three Types of Architectural Rules Considered**

After exploring a large set of architectural models that are typical of a standard architectural workflow and studying the tendencies of the Revit outputs, it was observed that most of the code that would benefit from being executed utilizing a rule language could be divided into three distinct rule categories: material choice, geometry discrepancies, and architectural best-practice rules-“rules-of-thumb.” Although some rules need to be used in combination, given a particular analysis model calculation type, the concepts are maintained throughout the source code and the knowledge base files. The belief is that as the rule base grows, the more comprehensive the rule answers will be since they will derive from a greater body of knowledge.

While outside of the scope of this work, the addition of new rules over time could potentially be achieved by automated processes where information is extracted from design documents and analysis during their creation. Rules can be created and extended due to the modularity of the GS Tool, including ones to capture historic, regional, resilience, and user preference data. Because the rules base is encoded in plain text files, rules can be readily exchanged. These rules could be aggregated through reliable methods such as properly sourced databases, experts and other standards (i.e. written by a domain expert via the correspondence of architects and their knowledge) to give assurance of rule quality. Lastly, application of natural language based rule entry using the existing GS tool interfaces, which could then use semantic technologies such as SPIN [17] to map to formal rules. In the following section, conceptual and data levels are outlined as the method for bridging the gap of various data description types. Natural Language Processing (NLP) and SPIN would be able to take user input and translate entries into variables and then rules for automatic code generation as illustrated in Figure 3.

![Figure 3: Example Rule Implementation](image)

**Material Choice Rules**

As the name indicates, this category of rules is used when there is a question about what type of physical material identity is most appropriate for a calculation or what type of surface to assign within the python analysis models to produce the most accurate end results. Some of the rules that appear in this category for the GS application implementation include a sequence that determines a default door or window type with associated material data (density, thickness, etc.). There is also a rule set that determines a surface type and construction ID when only a descriptive string is provided through the gbXML serialization. A similar rule initializes missing data when columns are present in a space by determining between round and square shapes as well as cross-section areas and construction descriptors.

**Geometry Discrepancy Rules**

Apart from material choices, there is a large category of inconsistencies that are now resolved by rules where the geometries of a surface, material, or other object are assigned values for material properties from a Revit materials database through the gbXML transfer mechanism, but those values are incorrect, or more general that would be desired for a given analysis type. In certain common situations, the geometries are more easily exported by estimating instead of handling all possible geometric cases. This makes the Revit® export process easier and faster at times, but creates issues that rules can now appropriately resolve for the external energy simulation calculations. These rules include volumetric adjustments when certain strings are present including walls that have an alternating stud and insulation type of assembly, adjustments to insulation volumes and coefficients depending on insulation types, and certain structural elements.

**Architectural Best-Practice Rules**

Architectural best practice rules are representing a type of tacit knowledge that most architects and engineers have accumulated through education, experience and specialization best practices. We can now provide a possible mechanism by which some of this tacit knowledge can be captured and used analytical or decision support models. These rules can include factors for reducing the embodied energy to get embodied water, handling the calculation of the thermal conductance of a material (C-
value), and swapping back and forth between temperature units and conversions for the thermal model. Tacit knowledge “reported” back by constructed buildings via embedded sensor networks is another data source and knowledge base scenario that can contribute to other rules.

Combinations of Rules
Interestingly, as seen in the previous section, there can be situations where rules seem to fit in more than one rule category. For these cases, there can be a best fit determination based upon how the rule is being used, or eventually there could be a pattern layer on top of the rule sets that flag them automatically into certain categories based upon what a user enters into either Revit and/or a Rules Entry User Interface. For example, the determination of volume reduction on a stud wall assembly can use the best practice rule of 15% structure and 85% insulation when the gbXML indicates both materials as taking up 100%. This would be one rule type that requires a material decision rule about the studs and insulation, followed by an adjustment in the volume of both of these materials. This second rule can be of a geometry or a best practice type, but since it is changing the volume for calculations, it is grouped with geometry discrepancy rules, for this situation.

The Use of a Rules Engine at a Larger Scope
A PyKE layer allows for further extensions to the existing analysis modules and beyond the application layer of the tool. PyKE specifically was chosen for this type of application because the source code is already implemented in the Python programming language. Using a rules engine that is coded in the same language makes this addition more interoperable and cohesive with the existing multi-metric application. There are also less problems communicating with the GS Material Property Database than there might be if another language were introduced, and this creates the effect of a less problematic bridge between the application and incorporating LD, DT, and/or the Semantic Web.

Without a separate knowledge base and rules, all of these nested, ever-growing statements would be completely stored in the source code, creating an overly complex logic that makes the python models slower and/or too complicated to truly capture architectural knowledge from the limited data available in the gbXML files. It would also keep the code in an impossible state for end-users to be able to understand where to enter their own additional conditions for materials, geometries, and best practices. If this logic were to remain in a purely procedural form, it would also make the models eventually very inefficient and prone to possible errors as multiple people want to add more conditions to the models. Therefore, the rules engine employed now provides a better solution to capturing this logic, processing for semantic decisions, and application extensibility. It also allows for the possibility of self-consistency checking and monitoring data quality.

RESULTS OF A RULES ENGINE WITH THE GS TOOL
One of the goals of this rules layer implementation was to understand the implications of a more expressive rules language to the overall run time of the program. Our team felt that there may be some advantages for several reasons: 1) the application will no longer need to filter through long lists of conditional string comparisons, 2) the creation of a simpler process of interaction as new rules are added means general users can add rules, and 3) potential interoperability with the semantic web exists as an extensible application feature since rules are now all stored in a single location and format. For the set of seven building models tested (see Figure 4), the full implementation of rules in the current version of the GS Tool was the first experiment conducted and shows a slight increase in the processing time (see Figure 5). This indicates that the simplicity of the architectural models and consistent materials used therein are not yet overcoming the overhead of activating the rules engine and processing the rules in this manner. This is not a deterrent to a rules based approach, however, because currently the rules are based upon a subset of the potential possibilities a fully developed database and surface set would provide (See the following section).

Figure 4: Test Set of Architectural Models
To study processing time relative to building model complexity, the aforementioned seven architectural models (see Figure 4) were run through each of the two python analysis models (embodied energy and thermal heat flux) both before and after the rules were implemented into the code (see Figure 5). The embodied energy model shows a modest increase in run time for the simpler architectural models (0.102 seconds overall for the single room model of 6 surfaces on ground level) and a slightly higher increase in run time for the larger ones (4.59 seconds overall for the largest tested model of 841 surfaces spanning two stories). This is due in part to certain types of rules (see Figure 6) requiring more execution time to run than others and due to the fact that the GS Material Property Database is sparse resulting in shorter processing time compared to having to search tens of thousands of entries at full capacity with fuller collections of data. The increase in raw run time for the thermal model is almost negligible 0.45 seconds for the single room model and 25.82 seconds for the largest tested model—which is still only a 5.91% increase over the original, and will become more negligible as architectural model size increases and varies in complexity. For the thermal model, the percent of time increase is 6.49% for the single room model and only 5.91% for the largest model, suggesting that the increase in overhead time will be
overcome as the models and database become more complex and the architectural models become larger in scale. It should be noted that while it can be true that run time correlates to number of surfaces to process, often numbers of surfaces are not directly proportional to run times due to the variation in surface types and assembly components throughout a building.

Figure 5. Comparison of Traditional Models with Rules

Additionally, with the rules set into the different categories described above, it is possible to compare and see what types of rules are causing the most benefit and the most time increase in the overall program (see Figure 6). One possibility is that dynamic rule sets could be chosen given user criteria for accuracy vs architectural model complexity allowing rules that offer the most benefit for a given function to be instantiated.

**BIGGER SCOPE BEYOND THE RULES ENGINE**

**Future Work and Additions to the Rules Layer**

After the development of a working Rules Engine Layer, the next steps to improve energy simulation tools would involve applying an extension to data aggregation in the GS Material Property Database. This can be better achieved via crowd-sourcing and/or automated web-crawling since the amount of data does affect the decision making quality. To further these future improvements, there are extensions that would help to materialize these pursuits faster and easier. For example, a secondary interface used for the purposes of gathering database data and rules would help aggregations run more smoothly and reach a more diverse group of users. Thus, the simulation tool could accumulate a more diverse range of rules and knowledge via crowdsourcing, individual, and automated use.

**Rules Aiding Decision Theory Frameworks**

We believe as the GS Material Property Database grows, the potential efficiency will improve relative to a procedurally structured code and by creating de-coupled rules sets for more maintainable source code, improving interoperability, facilitating data collection via crowd-sourcing, maintaining further compatibility with Python, and setting up rule-type organization and optimization. Methods such as crowd-sourcing provide the basis for DT to become operational. Ideally, for proper multi-criteria decision analysis, all of these interconnected extensions of the application would aid in generating sets of decisions or choices and the most accurate application output.

The rules create a degree of flexibility for certain methods of decision analysis that if-else/switch statements simply are not capable of generating. For example, a knowledge base that is established at the time the program is instantiated provides data in one place such that rules can simultaneously select parameters based on a combination of minimizing cost, shipping, and energy consumption. In reference to the modest increase in run times mentioned in the previous section, it is obvious by this point that optimizing decision suggestions over such an extensive collection of data is a real concern. Since the change in run times of the tested models showed that there could be a decrease in time as the code and model complexity increased, a second experiment was conducted with a basic set of conditional statements to see at what point the rule structures could overcome the traditional conditional lines of code. For a set of 10 searches using a basic naming system (i.e. one string example is: ‘Brick, Common: 10 1/2’), it took between 6,400 and 12,800 conditional statements for the rules to perform better. At first glance, this may seem like a rare circumstance, but it should be noted that this is not only for the most simplistic structure for a basic string search in each of the 10 cases, but it also processed with a minimal version of our material data strings that would become quite complex in time as product manufacturer data is incorporated. In reality, the necessary conditional structures will be far more complex in terms of the number of lines of source code and therefore without a more sophisticated processing schema, the complexity will only increase with growing communication abilities across the semantic web. Additionally, 12,800 comparisons is not that unrealistic to determine rules to be a good option.
because in a real database scenario, there could easily be tens or hundreds of thousands of options for each rule, making the 12,800 baseline well-worth the effort of PyKE rule implementation (as well as the other discussed benefits of rules). Rules structures also give a larger degree of expressivity through formal logics, do not have the complications of the old procedural approach, and have computational advantages.

CONCLUSION
Regardless of data optimization preferences, building sustainability measures will become increasingly accurate as more data becomes available from which to make design choices. Architectural tools, which are currently relying on limited or local data collections, are suffering in the advent of Big Data possibilities. The larger the database grows and the more that Linked-Data principles are integrated into the data sets, the more efficient and accurate architectural PyKE rules will perform thus improving our multi-metric energy simulation tools. This is the future of energy simulation in a global world functioning within the semantic web environment and it will enable multi-criteria decision analysis in an unprecedented fashion.

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Digital Campus Innovation Project: Integration of Building Information Modelling with Building Performance Simulation and Building Diagnostics

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Abstract

Building Information Modelling (BIM) has emerged as a powerful technology that creates a central hub for managing building energy and resources at all phases of the building life cycle. Without it, many tools that lack interoperability are used, thus massively under-exploiting the efforts of other building design and management parties; this largely describes the status quo. However, despite the power of BIM, it has not been readily adopted by industry, and especially not at the community and campus scale. Digital Campus Innovation (DCI) is a large multi-year and multidisciplinary project involving development of a methodology for use of BIM for operation and maintenance of a portion of Carleton University’s 45 interconnected buildings. Major elements include: (1) development of highly-detailed BIM models for site and buildings; (2) conversion from BIM models to building performance simulation (BPS) models; (3) model validation using measured data; (4) building Fault Detection and Diagnostics (FDD) using advanced algorithms and calibrated modelling; and (5) advanced building performance data visualization on top of 3D BIM model. This paper will describe the methodologies that are being developed while demonstrating the ongoing processes by a case study of Canal Building, a part of DCI project. While the project is only one year old, impactful examples have already demonstrated BIM as an invaluable technology that improves indoor environment quality, reduces energy costs, and has a potential application for asset management.

Introduction

In Canada, buildings are responsible for about 50% of total electricity use, 35% of total greenhouse gas emissions, and 15% of total water consumption [25]. Canadian Universities have an average energy usage intensity of 2.59 GJ/m² per year, 68% more compared to commercial and institutional buildings’ average [24]. Carleton University campus has an annual utility cost of $12 million, an average of $30/m² or $400/student. Carleton University Facilities Management and Planning Department has suggested that numerous opportunities exist in building operation to significantly reduce energy consumption.

Past research showed that proper commissioning and maintenance can reduce energy use by 20% or more [23], with payback period ranging from several days to years [26]. Although often conducted as a one-time performance assurance activity, the commissioning process can also extend throughout the operation phase to solve operational problems and improve performance [22]. Past projects have shown continuous commissioning can reduce energy cost as much as 25% [22]. Thanks to the development of building sensor network and data storage, building operation data can be used to largely automate the continuous commissioning process. Thus there is a tremendous value to provide better access to building performance data and building information.

An efficient and easy-to-use information infrastructure was not available in the past, but in recent years Building Information Modelling (BIM) is becoming as a powerful technology to establish a comprehensive multi-faceted digital model of physical and functional aspects of buildings that can support data communication, analysis and commissioning activities throughout the building life-cycle [4, 14]. Integrating BIM in building operation and maintenance can decrease operation risk and costs, as well as maintain facility management quality [7], though this application is rarely seen in practice, especially for university campus. Building information from BIM models can feed to the automated continuous commissioning process to improve the information flow and reduce manual input.

Thanks to the interoperability of BIM, Building Performance Simulation (BPS) can also be added to the picture. BPS provides quantifiable analysis to evaluate various aspects of building systems, and over the past 50 years has been developed into a variety of programs performing simulations such as energy consumption, thermal comfort and lighting [10], although it is still rarely used in maintenance and operation due to intensive labour requirements and costs [6]. Integrating
BIM, BPS and building performance data with proper interoperability could reduce the cost barrier and fully exploit the BPS analysis, but more research is needed for large scale implementations [8].

With the help of BIM technology, BIM-enabled Information Infrastructure (BIM I²) for fault detection and diagnostics (FDD) proposed by Dong et al. can be adopted [13]. FDD is used to identify problems in building systems for continuous commissioning process. Compared to conventional FDD used in many existing Building Energy Management (BEM) systems, which often focus on controls and mechanical equipment, FDD based on BIM I² uses a holistic approach that covers all building system and improves information flow and diagnostic effectiveness [13]. The extra data made available by BIM and BPS also enables more feature extractions and complex model-based diagnostic algorithms. To better visualize the building performance and diagnostics results, tools like Project Dasher [3] makes it possible to generate hierarchical and spatio-temporal representation of the building performance from space level to whole building level by using data from BIM model.

**Digital Campus Innovation Project**

In early 2014, Digital Campus Innovation (DCI) project started its pilot phase of integrating all the above-mentioned technologies into BIM-enabled information infrastructure on a campus scale. Similar projects on a building scale have been investigated recently by other research teams, such as an office building in Toronto [2] and a two-story recruit barrack in Illinois [13]. The main objective of DCI is to apply an integrated BIM, BPS and the continuous commissioning process on a campus scale, providing a useful platform for building operators and other stakeholders such that they can make informed decisions and efficiently explore operational improvement strategies. The team will also generalize its methodology for widespread implementation in the future. The vision is to have a common model that exists and continuously evolves from design to construction and throughout the operation and maintenance phases, until the reuse or demolition of the buildings. Figure 1 shows the current structure of the DCI project. Besides building models, other campus infrastructure will also be digitized and in the future campus-level analysis and diagnostics will be performed. This paper will focus on the building level of the DCI project. The highlighted parts in Figure 1 will be discussed in the paper with the case study of Canal Building.

The Canal building was one of the first buildings to be modelled in DCI. It is a seven-story mixed-use building with total floor area about 7700 m². The building began its operation in 2011 and includes 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 two small air-handling units (AHU) designated for the mechanical rooms; the rest of the building is conditioned by two separate air-handling units. The heating system uses campus steam generated at a central plant and the cooling system uses a water glycol loop which also supplies another building. The air distribution system is single-duct VAV with reheat and radiant panels to reduce cold surfaces. The windows of this building are double-glazed with air gaps of 13.5mm, and the exterior walls have varied R-values ranging from R-12 to R-24. The building is also equipped with more than 2500 sensors to collect data needed in the DCI project. Since the Canal Building represents typical education buildings on campus with comprehensive documentation and abundant sensor data, it serves as a good starting point for the DCI project and helps to set up a framework for all other buildings on campus.

**BUILDING MODEL DEVELOPMENT**

Models for several recently constructed buildings, including the Canal Building, are constructed first in Autodesk® Revit 2014 which is the main tool for architectural and analytical model development. Figure 2 illustrates the entire building model development process. EnergyPlus 8.1 was selected as the BPS tool in place of DOE-2 used in Green Building Studio in Revit, due to its versatility and capability of simulating complex building system and its continuous development of new simulation modules [13]. To achieve interoperability between BIM and BPS tools, gbXML was selected as the primary file format for modelling and data storage due to its simplicity and capability for fast prototyping [12].

**Architectural Model Development**

The architectural model created in Revit serves as the foundation of BIM I² for DCI project and therefore affects the results of all the analysis in later steps. To achieve good accuracy of the model, the team checked and compared layouts and plans provided by the facility management department of Carleton University. Any discrepancy found across the drawings was
resolved through site visits, photography or laser scanning if possible. Figure 3 shows a comparison of the exterior view of Canal Building between a photo of the actual building and a combined image of Revit model and BPS model.

Figure 3. Real image (left), Revit model (top right) and BPS model (bottom right) of Canal Building

Although Revit is highly capable of developing detailed and complex models, there is a good possibility that high polygon models may not be translated to gbXML format or rejected by BPS tools. The team had to find a balance between the level of detail and the interoperability of the Revit model in order to achieve a smooth transition of the model from Revit to the BPS tool. Strategies used in similar projects for this purpose were reviewed and tested in DCI project [11, 5]. The following major modelling strategies were adopted by the team during the development of architectural model:

1. Simplify complex geometries
Most BPS tools have problems interpreting surfaces (like walls, roofs and floors) or sub-surfaces (like windows, doors) with irregular shapes or round shapes. Therefore building components with irregular or complex surfaces and large number of surfaces were modified in order to simplify geometry, preventing system crashes, errors and long simulation time.

2. Properly define curtain walls
A curtain wall that makes up a whole building façade is usually modelled as a single unit in Revit. However in EnergyPlus, fenestrations can only be represented as sub-surfaces, which means that the curtain wall has to be modelled as a window inside a wall. The team therefore translated the curtain wall elements to windows (with frame) with equivalent thermal and optical properties so that this design can be correctly interpreted by the BPS tool.

3. Properly define non-space bounding elements
Not all elements need to be input into the BPS tool. For example structural elements such as beams and columns in interior spaces often have minimal influence over thermal performance and should not be included to the building energy model. With simulation requirements in mind, the team identified elements that can be neglected and set their properties as non-space bounding.

Analytical Model Development
After the Revit model was properly developed, the team prepared the analytical model in order to output it as a gbXML file that is compatible with the BPS tools. The analytical model translates information of "rooms" in architectural model to "spaces and zones", which are used in the simulation later. To prepare the analytical model properly, the team adopted the following practices:

1. Properly define spaces
In cases where spaces are not bounded by actual structures, such as large open spaces controlled by separate HVAC terminal units, space boundary lines were manually defined to separate the space into appropriate compartments with corresponding thermal interfaces. In some rare cases, where several rooms use the same controller and if the rooms are very different from each other, each room is defined as separate space.

2. Properly define space boundaries
The boundaries of each space were properly defined to ensure the accuracy of the geometric model in BPS. In EnergyPlus, space dimensions are defined from the interior surface, thus the space boundaries in the analytical model were calculated from the interior side of each surface.

3. Space volume computations
A space volume computation method was used for the analytical model to accommodate the varying height of each space.

Model Checking and Conversion
Before exporting the analytical model as a gbXML file, the team performed following checks to ensure the model was interoperable:

1. Proper enclosure of all spaces
If a space is not properly enclosed in the model, most BPS tools will reject it and simulation cannot carry on. If a building space has disjoint surfaces, surface boundary lines must be drawn to enclose the space.

2. No nested spaces
Current gbXML format does not support nested spaces, i.e. a space wholly contained within another space. If this situation occurs, it was resolved by separating and dividing the surrounding spaces of the nested space using manually defined space boundary lines.

When the analytical model passed all the checks, it was exported as a gbXML file. The gbXML file was checked for its validity before it was input to BPS tool - EnergyPlus in this case. The BPS model was tested for its functionality; error and warnings from EnergyPlus simulation results were used to adjust the analytical model and gbXML file. The process was repeated for several iterations to finalize the BPS model.

The conversion process from the Revit architectural model to the BPS model was largely manual due to the different and even conflicting requirements for these two different types of models. The team has been continuously searching for better practices of model development and model conversion and experimented with different model techniques during pilot phase of DCI project. As more buildings are added to DCI, a standardized guideline for developing and converting Revit models will be developed and refined.
When the BPS model is completely set up and the corresponding weather file is selected, a simulation is performed, and results produced. Simulation results can be significantly different from measured building performance [29], which makes model calibration a crucial step to verify and improve the BPS model [21] so that the simulation can produce meaningful results for building analytics, fault detection, and predictive simulation. Two calibration methods were proposed for this project: an evidence-based method by Raftery et al. [27] and an analytical optimization method by Sun et al. [28]. Evidence-based method uses a manual input calibration procedure that relies on evidence obtained from design drawings, measurements, sensor readings, etc. [27]. This method proposed a hierarchy of evidence reliability and a version control strategy, but can be time consuming and enough evidence is not always available for all inputs. On the other hand, the analytical optimization method uses a mathematical and statistical procedure to automatically determine the input value, and has better performance than pure stochastic processes. However, tweaking high number of unknown parameters can still yield unsatisfactory results, so some form of input parameter calibration before analytical optimization is required [28]. To combine the advantages of both methods, a joined evidence-based and analytical optimization method was developed by Coakley et al. [9] and was adopted in DCI project. The team has decided to conduct an evidence-based calibration with available data and follow up with analytical optimization method to determine input values for variables that cannot be supported by evidence. This paper focuses on the evidence-based part of the calibration that has been carried out for Canal Building at this stage of the project. With each iteration of the calibration process, BIM model and BPS model were updated and version managed.

Weather data calibration is the most important step of evidence-based calibration [27] and should be performed before building model calibration. Using historical weather data corresponding to the performance data instead of a standard weather file can greatly remove the weather factor from the discrepancy between the simulation results and actual data. Weather data was obtained from a weather station located on the rooftop of the building. It measures weather data at five-minute intervals from four temperature sensors, one humidity sensor, two wind speed/direction sensors and six pyranometers with different tilt angles. Diffuse radiation is not directly measured and was extrapolated from different pyranometers. The weather data was automatically compiled to EnergyPlus weather file format and used in simulation.

The evidence-based calibration method is applicable for most parameters in the building model since this project has a large and growing pool of evidence, lots of effort has been dedicated to this ongoing calibration process. Since each zone has independent schedules and internal load parameters, each zone was calibrated individually first to improve the accuracy of the calibration, and then the overall building-level calibration was performed.

One source of evidence for calibration is from design documents. Most of this information, such as architectural, structural, and construction drawings, was already incorporated in the Revit model. Then the model was updated based on newly available as-built document from Facility Management. However, even the as-built documents may be different from actual condition and not all the system information required by BPS were included in those documents. Direct observation through on-site audit, a more reliable evidence source than design and as-built document, was used to update the model so that it reflects the actual condition of the building.

Abundant sensors installed in Canal Building provide building operation data, which could also be used as a source of evidence for calibration. For example, the schedules provided by Carleton University were used as inputs for occupancy schedules in classrooms and teaching labs. For faculty offices, due to the variation of schedules from day to day and from person to person, occupancy schedules have to be extrapolated from the building sensor network. With data from occupancy sensors in individual faculty offices, an average occupancy schedule for weekdays was extrapolated (Figure 4) and used in the model. Although sensor data is good evidence as it reflects some actual building usage values, sensor calibration and data noise reduction are necessary steps to take before calibration. For the above example, occupancy durations shorter than 30 minutes were filtered out from the data, since those readings were likely noises caused by sensor error, cleaning staff or other transient occupancy.

In cases where the values of some parameters could neither be obtained from design documents nor sensor data, an on-site audit was required. For instance, equipment power density depends on the number and types of equipment used in each zone; this information is not documented and there is no sub-metering in individual rooms and labs. Therefore a walkthrough of all major rooms in Canal Building was carried out to assess equipment power ratings. For special equipment such as laboratory equipments, specifications were obtained from name plates. Special attention was also given to spaces that hold large amount of equipments (e.g. computer lab) or special equipments (e.g. research lab). For parameters whose values cannot be verified through auditing, analytic calibrations will be performed later.

To compare the results from calibrated model and actual energy consumption, it is preferable to have hourly and sub-
metered utility data [27]. Unfortunately, only part of the utility data was available at this point and the limited number of data points was not enough for fine-tuning the building model input. The utility data available were building plug load (equipment) electricity consumption and building lighting electricity consumption. Other utility data such as cooling energy consumption and heating steam consumption are still in the process of calibration.

Figure 5 compares the measured and simulated results of annual plug load and lighting consumption. The lighting energy consumption calculated based on lighting fixtures design in BIM file and campus schedule produced an over estimation of 32% while the simulated plug load has a better agreement with the measured data with an error of 7%. The plug load inputs were calibrated through audit as mentioned above, while the lighting load inputs were calibrated using document only. This confirmed the importance of selecting more direct and reliable evidence for calibration. Figure 6 compares measured and simulated daily plug load for the Fall Semester in 2013. EnergyPlus uses fixed weekly schedules and the simulation results do not reflect daily variations and small events such as exams that significantly lowers the average occupancy rate. These variations due to stochastic behaviours of occupants could have huge impact on energy use on space level [16] and therefore are important when performing space-level diagnostics using calibrated BPS results. One approach to improve this is to use stochastic occupant schedule [17] and will be investigated in the future.

BUILDING DIAGNOSTICS

There are three major types of FDD methods: quantitative model-based, qualitative model-based and process history based [20]. The goal of DCI project is to employ all three methods, but in this phase of the project a combination of qualitative model-based and process history based FDD is used. Qualitative models such as rule based models are qualitative relationships from knowledge of the system. Process history method is purely based on historical data, sensor and BIM model data in our case. The team developed a FDD module that analyses the data from both sensor and BIM model, performed qualitative analysis to extract extra features from the data. A graphical user interface is under development, allowing user to manually generate or to schedule a diagnostic report. Figure 7 shows the structure of the FDD module. FDD in the DCI project is focused on three areas: sensor reliability, energy performance and thermal comfort. In this paper diagnostics of thermal comfort problem in the Canal Building will be presented.

Thermal comfort is an important design goal of the HVAC and control system but can only be verified and studied during the operation and maintenance phase of the building lifecycle. Of all 215 buildings surveyed in U.S., Canada and Finland, only 11% have more than 80% of the occupants satisfied with thermal comfort [18] while the ASHRAE Standard 55-2013 and ISO standard 7730:2005 both require 80% of the occupants to be satisfied with thermal comfort [19, 1]. Some thermal comfort problems are results of over-cooling, over-heating, or malfunctioning HVAC equipment and therefore, accurate and prompt detection of the thermal comfort problem could often detect energy performance issues. Continuous monitoring and maintaining proper thermal comfort could ensure that productivity of the students and faculties are not negatively affected.

Thermally uncomfortable conditions of a building over an operation period should be quantified first in order to perform the diagnostics. One methodology is the degree-hour method proposed in European Standard EN 15251 [15]. This method uses the product of time and temperature difference outside
comfort range to aggregate the degree of over-cooling and over-heating over time. Another metric used is degree outside comfort range of each room weighted by its area, floor area weighted temperature provides a more accurate representation of the whole building than average of all thermostat data. The data used for the analysis is from Nov 1, 2013 to Oct 31, 2014 on 3-minute intervals. Only reliable sensor measurements within regular office hours were used. The comfort range is assumed to be 21°C – 25°C during office hours.

Based on preliminary analysis, overall temperature of the Canal Building tended to be too low. Over the whole year during occupied hours, over 35% of the time at least one room is below the thermal comfort range, and for every room on average 13% of the time, the temperature is below 21°C. This has been further verified by on-site visit and surveys of occupants. Low indoor air temperatures can be caused by either over-cooling or under-heating. Over-cooling often indicates improper HVAC control and resulting in energy waste; whereas under-heating indicates that the heating system is too small to handle the building heating load. Over-cooling could be possibly fixed by control tweaking; while under-heating might need equipment upgrades.

Figure 8 separates over-cooling and under-heating occurrences of the whole building by plotting the floor area weighted temperature difference under 21°C (y axis) against the outdoor temperature (x axis) for each operating hour of the whole building. Green dots represent data during the cooling period, red crosses during heating period, and black squares for hours when heating is required but not supplied. As shown in the Figure 8, under-heating (red crosses) occurs mostly at very low temperatures (<-15°C) and the average air temperature were above 20°C most of the time, so the under-heating problem is not significant. On the other hand over-cooling (green dots) was significant in the building. Since dehumidification process is handled by the cooling coil and there is no reheat coil in the air handling units, dehumidification may also cause low supply air temperature and result in the over-cooling of the building. A further analysis found that dehumidification process had no meaningful correlation with the over-cooling problem.

To further understand the over-cooling problem observed, the team investigated whether the problem was associated with a specific room parameter in this mixed-use building. Figure 9 shows annual degree-hour over-cooling of each room verses room type, room area, room orientation and window to wall ratio (WWR) with correlation coefficient (r) values plotted in the title section. The room parameters were automatically calculated from the BIM file. No significant correlations have been found between over-cooling and room parameters, except North facing rooms have slightly more over-cooling than other rooms. This may be caused by variations of solar radiation and/or Air Handling Unit One (AHU1) which conditions only the north facing rooms, whereas Air Handling Unit Two (AHU2) conditions all other rooms. Since the over-cooling problem is not likely associated with room properties, it’s more likely related to HVAC issues.

Upon further analysis the correlation between the over-cooling and various HVAC sensor data we have found that over-cooling problem was caused by high supply air flow and over-pressurizing of the building. Figure 10 shows some of the selected plot between floor-area weighted building average over-cooling temperature and several HVAC parameters including return air CO2, outdoor air temperature, fresh air energy flow which is a combined effect of indoor/outdoor enthalpy difference and damper position, and cooling coil chilled water supply. The building tends to over-cool more when there is higher occupancy indicated by more return air CO2, and since supply air temperature is constant for the VAV system, the over-cooling is likely caused by high supply air flow. The two AHUs are identical, but AHU1 conditioned 15% less floor area and controls the space where receives less solar radiation, thus showing a stronger correlation (higher r value) with outside air temperature and fresh air energy flow than AHU2. Since AHU1 conditions north facing spaces with lower return air temperature, AHU1 has less need to cool the air with cooling coil, making its over-cooling points shifted towards lower chilled water supply. Upon checking building control, we confirmed this diagnostics: supply air flow controlled by both AHUs were using the same proportional control logic designed for full building occupancy based on supply air CO2 and temperature, whereas almost half of the building was still unoccupied; the decreased internal heat gain made the building over-cooled and lowered thermal comfort.

BIM enabled FDD process shows promise and provides in-depth analysis of the building performance, but the process is still not fully automated. In the future, quantitative based models and calibrated BPS models need to be implemented to achieve fully automated diagnostics and improvement suggestions.

**FUTURE WORK**

During the next phase of the DCI project, the team will complete the following tasks at the building level:

1) Acquire and calibrate sensor data and hourly sub-metered utility data for further evidence-based calibration and analytical optimization calibration.
2) Develop diagnostics algorithms for sensor data mining, quantitative FDD, and predictive simulation for performance improvement.

3) Apply model based FDD techniques.

4) Standardize the procedures and add other buildings in DCI to BIM platform.

5) Perform advanced building performance visualization using Project Dasher.

CONCLUSION
One year into the DCI project, the team has set up the framework with BIM technology. The impact of integrating BIM and BPS into the operation and maintenance of building was promising. The BPS model development and calibration process and sensor data exploiting processes benefited from BIM tools like Revit. The process of model development, conversion and calibration reported in this paper could be implemented for other buildings in the DCI project. Thermal comfort diagnostics using BIM and BAS data already discovered over-cooling problems in the Canal Building; solving this problem can improve both thermal comfort and energy performance of the building. In the future, DCI project will focus on acquiring more reliable data and provide quantitative results of evaluating improvement options by using a calibrated building model. Next, the methodology will be generalized from the pilot building and be applied to more buildings on Carleton University campus.

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Forensically Discovering Simulation Feedback Knowledge from a Campus Energy Information System

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ABSTRACT
Simulation model calibration has been long identified as a key means of reconciling the consumption and efficiency characteristics of buildings. A key step in this process is the creation of the actual diversity factor profiles for occupancy and various energy end uses such as lighting, plug-loads, and HVAC.
Creation of these model inputs is conventionally a tedious process of site surveys, interviews or temporary sensor installation. Sometimes measured energy data can be used to create these schedules, however there are many challenges, especially when the sensor network available is large or unorganized. This paper describes a process applying a series of knowledge discovery filters to screen data quality, weather sensitivity, and temporal breakouts from large nonresidential building performance datasets collected by building management and energy information systems (BMS/EIS). These screening techniques are used to qualify the desirability for calibrated model diversity schedule creation from a forensic perspective. A diurnal pattern filtering technique is then applied that automatically extracts frequent daily performance profiles, which can then be normalized and used as model inputs according to conventional industry techniques. The process is applied on a raw dataset of 389 power meter data streams collected for eight years from the EIS of a campus of 32 higher education buildings. The results are discussed in the context of time and effort savings for creating urban and building scale simulation model inputs.

Author Keywords
Knowledge discovery; Measured building performance; Simulation feedback; Diversity schedules; Temporal data mining; Visual analytics

ACM Classification Keywords
J.5 [Arts and Humanities]: Architecture.; H.4.2 [Information Systems Applications]: Types of Systems Decision Support.; H.5.m [Information Interfaces and Presentation (e.g. HCI)]: Miscellaneous.

INTRODUCTION
Modern commercial buildings contain an ever-increasing amount and complexity of sensor systems designed to control and monitor the performance of energy consuming systems [7]. Building owners are starting to see the value in the storage and processing of this time-series data through the use of various analytics and monitoring techniques [6]. In addition, multiple commercial product and service providers are creating a new market on these technologies. One key focus in leveraging this data is design phase feedback through measurement and verification plans and calibration of the whole building energy models (BEM) [10]. Commissioning and operations experts are focusing the analysis of performance achievement as a means of getting the building off to a good start and maintaining optimal performance through the life of the building. A common scenario when leveraging the sensor data is when an analyst is forensically searching the stored dataset for general characteristics and anomalies as a basis for further investigation. The primary question of an analyst at this phase is: “What insight can we achieve at this point with the raw data available?”

Based on the authors’ experience and through several industry and professional reviews, key challenges have been identified in the initial level of analysis of common BMS/EIS systems [5]:

- An unorganized data storage structure that impedes the analyst’s ability to explore multiple data streams
- Indecipherable or forgotten point labeling schemes that make it difficult to semantically model the data
- Poor sensor accuracy or data storage quality
- Poor characterization of the influence of data streams on each other or from external factors such as weather, occupancy, etc.
- The sheer size of the database and number of sensors is often beyond the capabilities of most energy analysts’ tools, which are often simply spreadsheets

The literature in commercial building model calibration treats temporal knowledge extraction from sensor data lightly and often focuses on the actual process of calibration once all of the inputs have been determined. One set of inputs that are crucial for model calibration are diversity factor schedules which inform the model of the approximate percentage of people, lighting or miscellaneous loads at a given point...
in time. Very often diversity factor schedules are only determined through labor-intensive site surveys, questionnaires or additional temporary sensors [4]. Another method of schedule creation is the use of measured energy performance of weather-independent end uses. One of the largest reviews of industry-standard diversity schedules creation relies on transforming measured energy performance data in this way [1]. Lighting and plug load meter data is transformed through manual analysis and normalization for the creation of diversity factor schedules. The techniques reviewed in this study rely on an in-depth understanding of the measured dataset and are restrained from implementation in other projects by the previously identified BMS/EMS challenges. The process of calibration on a campus or large portfolio EIS/BMS systems increases the challenge as the scale and complexity of the systems is larger. Recent research projects attempt to remedy these challenges such an example of automated utilization of measured data for autotuning simulations [9].

In this paper, a data screening process is defined that is designed for an analyst to dissect, characterize and acquire knowledge from BMS/EIS data repositories that are relevant to the diversity factor schedule creation procedure for non-residential buildings. Nonresidential buildings are targeted due to the similarity in the data collection capabilities and relatively systematic nature of load profiles as compared to residential. This process uses statistical techniques to filter relevant information as part of a forensic investigation of past data. The paper will stop short of the full transformation process of creating diversity schedules as these techniques are covered widely in the literature [1]. The forensic process is implemented on a large campus case study dataset that is in the process of analysis for calibrating a coupled urban-scale and whole building energy simulation.

**A Screening and Knowledge Extraction Process**

In this paper, the development and implementation of a knowledge discovery process is discussed that addresses the context-specific challenges outlined. This process utilizes the following steps to explore a large, real-world case study dataset:

1. Data quality screening - Evaluation of the completeness and rough accuracy of the data in terms of gaps and extreme outliers
2. Weather sensitivity screening - Classification of each stream according to its influence from outdoor air temperature conditions
3. Breakout detection screening - Split each data stream according to subsets of continuously similar statistical behavior
4. Compared evaluation of metrics - Clustering and evaluation of the data streams available according to the combination of their metrics from the screening process
5. Typical daily profile filtering - Utilize a clustering process to extract and group similar performance profiles

### Table 1. Data quality metric description and thresholds

<table>
<thead>
<tr>
<th>Quality Metric</th>
<th>Description</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Missing Data</td>
<td>Data loaded as NaN as compared to other data stream availability</td>
</tr>
<tr>
<td>1</td>
<td>Flat-lined Data</td>
<td>Exact same value recorded for an entire day</td>
</tr>
<tr>
<td>2</td>
<td>Outliers</td>
<td>Individual data points as detected by Seasonal Hybrid ESD (S-H-ESD) algorithm</td>
</tr>
<tr>
<td>3</td>
<td>Normal</td>
<td>Data points that don’t fit in the above criteria</td>
</tr>
</tbody>
</table>

**METHODOLOGY**

**Data Quality Screening**

General sensor data quality is defined in terms of the factors of temporal completeness, meaningful sensor output, and presence of significant anomalous behavior. Temporal completeness pertains to the absence of gaps in the dataset. These gaps are most often related to sensor failure, in which a sensor stops sending readings to the central repository. Meaningful sensor output pertains to the sensor stream’s reading matching the expected behavior of the phenomenon. For example, a sensor that is constantly reading the same value for long periods of time is likely not giving meaningful information. This particular situation is often noted as “flat-lining” and it is defined as recording the exact same value for a 24 hour period for performance measurement data streams. Significant anomalous behavior is detected using a Seasonal Hybrid ESD (S-H-ESD) anomaly detection algorithm as implemented in the AnomalyDetection R library [12]. This library was developed by the web-based social media company, Twitter, as a means of finding interesting or anomalous behavior in the postings of their users online. This algorithm can be used to detect both global and local anomalies and it was developed with a focus on temporal datasets with potentially non-normal distributions and seasonal and other cyclical attributes.

In this screening process, four general classifications of data quality and completeness are created. The data set is first divided into these classifications based on various statistical thresholds. It should be noted that these thresholds were chosen for the dataset used in the implemented example and tuning may be required for implementation on other data sources. These levels with description and threshold definition are found in Table 1. Figure 1 illustrates the data quality screening process for 310 days taken from a commercial building. The initial 15 days have no data available and the next approximately 120 days have a flat-lined zero reading for the meter. This flat-lined behavior of this meter shows that the measured system is off or the meter is malfunctioning. Most of the remaining data are considered normal except for a peak towards the end that is classified as an anomaly. This anomaly is detected through time series decomposition and robust statistical metrics contained within the applied library.
Weather Sensitivity Screening

Data stream influence characterization is the process of roughly classifying the dataset into streams and subsequences based on weather conditions sensitivity. This evaluation is important in understanding what measured performance is due to heating, cooling, and ventilation systems (HVAC) responses to outdoor conditions and what is due to schedule, occupancy, lighting, and miscellaneous loading conditions which are weather independent. Performance data that is influenced by weather can be used to better understand the HVAC system operation or be weather-normalized to understand occupant diversity schedules. Non-weather sensitive data streams are used with less pre-processing to create diversity schedules and to calculate miscellaneous and lighting load power densities.

In this filtering step, the Spearman Rank Order Correlation (ROC) is used to evaluate the positive or negative correlation between each performance measurement stream and the outdoor air dry bulb temperature. This technique has been previously used for weather sensitivity analysis [3]. The ROC coefficient, $\rho$, is calculated according to a comparison of two data streams, $X$ and $Y$, in which the values at each time step, $X_i$ and $Y_i$, are converted to a relative rank of magnitude, $x_i$ and $y_i$, according to its respective dataset. These rankings are then used to calculate $\rho$ that varies between +1 and -1 with each extreme corresponding to a perfect positive and negative correlation respectively. A value of 0 signifies no correlation between the datasets. This $\rho$ value for a time-series is calculated according to Equation 1.

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$  \hspace{1cm} (1)

The difference between the data stream rankings, $x_i$ and $y_i$, is signified by a difference value, $d_i$, and the number of samples compared in each dataset is signified by $n$. Figure 2 illustrates the calculation of the ROC coefficient, $\rho$ for three examples. The cooling sensitive data set shows a strong positive correlation between outside air temperature and energy consumption with a $\rho$ value of 0.934. As the outside air temperature increases, the power consumption measured by this meter increases. The heating sensitive dataset shown has a strong negative correlation with a $\rho$ of -0.68. A weather insensitive dataset is shown in the middle which has a $\rho$ of 0.0, signifying no weather correlation, which is obvious due to the four levels of consumption which are independent from outdoor air conditions.

Breakout Detection Screening

Breakout detection screening is a process in which each data stream is analyzed according to the tendency to shift from one performance state to another with a transition period in between. Breakout detection is a type of change point detection...
that determines whether a change has taken place in a time series dataset. Change detection enables the segmentation of the dataset to understand the nonstationarities caused by the underlying processes and is used in multiple disciplines involving time-series data such as quality control, navigation system monitoring, and linguistics [2]. Breakout detection is applied to temporal performance data to understand general, continuous areas of performance that are similar and the transition periods between them.

In this process, an R programming package, BreakoutDetection, is utilized, which is also developed by Twitter to process time-series data related to social media postings [13]. This package uses statistical techniques which calculate a divergence in mean and uses robust metrics to estimate the significance of a breakout through a permutation test. BreakoutDetection uses the E-Divisive with Medians (EDM) algorithm, which is robust amongst anomalies and is able to detect multiple breakouts per time series. It is able to detect the two types of breakouts, mean shift and ramp up. Mean shift is a sudden jump in the mean of a data stream and ramp up is a gradual change of the value of a metric from one steady state to another. The algorithm has parameter settings for the minimum number of samples between breakout events that allows the user to modulate the amount of temporal detail.

The goal in using breakout detection for building performance data is to simply find when macro changes occur in sensor data stream. This detection is particularly interesting in weather insensitive data to understand when modifications are made to the underlying system in which performance is being measured. Figure 4 shows eight years of data from a weather insensitive data stream. Each color represents a group of continuous, steady-state operation and each change in color is, thus, a breakout. These breakouts could be the result of schedule or control sequence modifications, systematic behavior changes, space use type changes, etc. Creation of diversity factor schedules should target data streams which have few breakouts and the data between breakouts is the most applicable for model input.

**Compared Evaluation of Metrics**

Comparison and evaluation of the individual metrics is necessary in order to understand which data streams are more applicable for extraction of diversity schedules related to the occupancy or load characterization of the building. In this step, the InCHlib (Interactive Cluster Heatmap library) is used to apply Wards hierarchical clustering with Euclidean distance to the metrics [11]. This clustering groups similar data streams according to similarities in the screening metrics. The data streams are qualified according to groups, or regions, of sensors with similar characteristics according to simulation data feedback.

**Typical Daily Profile Filtering**

The final step in the process is to characterize the data according to similar groups to understand the general modes of performance. This characterization divides the data into typical daily consumption profiles and further divides these diurnal sets into frequent patterns, or motifs, and infrequent patterns, or discords. This process has been implemented in previous case studies for performance characterization and is known as the DayFilter technique [8].

Up to this point, the previous steps are considered filters that are qualifying the data for inclusion or exclusion in the simulation data generation process. For example, an analyst may make decisions on whether to include certain types of outliers from the data quality test as they seem relevant to distinguishing discord patterns in this phase. Another decision might be to divide the dataset up into difference regions of analysis according to the breakout detection steps.

The DayFilter process starts by using Symbolic Aggregate approXimation (SAX) to distinguish patterns and then divide them by user-defined thresholds into motifs and discords. Discords are to be investigated further in order to understand infrequent behavior that may be caused by performance problems. The motifs are then clustered according to similarity using the k-means algorithm to create typical performance profiles.
IMPLEMENTATION

The filtering process is implemented to exemplify knowledge discovery for simulation according to a real-world case study. Typical model calibration processes of single buildings may only have a few sub-meters worth of data. These filtering and characterization techniques are applied to a relatively large dataset from a whole campus of buildings. This approach will show the value of filtering and visualizing large amounts of time-series data quickly and more accurately than more manual methods.

The case study chosen is a university campus with a large energy and building information system and a long log of data acquisition. The campus consists of 32 buildings located in a temperate climate. This campus has been modeled extensively in past projects using the EnergyPlus whole building simulation engine and the CitySim urban-scale modeling software. The intent at this point is to utilize the measured dataset from the campus EIS to tune and calibrate those models. Figure 5 illustrates the number and type of data streams available in the EIS of the campus. The key focus for simulation model calibration is the heating, cooling, and electricity consumption metrics, however the other streams can be processed to provide supporting evidence for model tuning decisions. Many of the older buildings on campus have very few automated measurement systems, while many of the newer or recently-renovated systems have a large number. Building 0 is home to the chiller and boiler plants for the campus and therefore it has the largest number of sensors. This project is within the scope of the goal of taking a large, relatively-unstructured dataset and forensically filtering the value and structure of the data out as it pertains to the model calibration objectives. Eight total years of data from January 1, 2006 to January 1, 2014 were collected from over 1200 sensors that were stored at 5-60 minute frequency intervals.

In order to show the filtering and characterization steps visually, a subset of the EIS data is selected to apply the various filters and visualize them using a color mapping technique designed to show a high-level of information about the entire dataset as a whole without overwhelming an analyst with detail. The subset of data chosen for inclusion in this paper is 389 sensor streams measuring hourly energy readings in kilowatt-hours [kWh]. This dataset includes both electricity and thermal energy measurement devices from the heating and cooling systems. The intermediate screening steps are used to qualify the individual data streams for inclusion in the diversity profile generation step at the end of the process.

The first screening technique to be implemented is the data quality tests to calculate metrics according to data availability and general accuracy. Figure 6 shows an overview color mesh map of these tests applied to the 389 targeted energy measurement streams. The streams are sorted from bottom to top by increasing quality according to a summation of the metrics. Streams 0 to 130 contain a mixture of data streams with various types of gaps. The first obvious observation is that there are several streams at the bottom of the map in which a majority of the data is missing for much of the entire eight year time-span; insight that may be valuable to fix those particular sensors. Subsegments of the data can also be seen which have “flat-lined” either due to sensor failure or to the measured phenomenon being turned off completely. Several groups of streams in this region can be observed which appear to have been installed at various stages in the last eight years.

The next screening process is the division of the streams according to weather sensitivity. This general application to the dataset can be seen in Figure 7 as a color map in which the Spearman Rank Correlation coefficient, ρ, is displayed for all data streams from -1, or highly negatively correlated, to +1, or highly positively correlated. The coefficient for each month has been calculated independently of the rest of each data stream and averaged across 6 months in order to visualize correlation across the entire year. This map has also been sorted from bottom to top according to increasing ρ to show the range of phenomenon occurring in the dataset. Approximately the bottom 70 data streams are highly correlated with heating; e.g., as the outdoor air drybulb temperature decreases, the energy consumption increases. The top 120 streams are positively correlated with cooling and seem to have more prominent seasonal correlation with weather. There are many non-weather sensitive streams in the middle which are not often as complete quality-wise.

The last screening process is the breakout detection. Figure 8 illustrates this step applied to the remaining data streams. The minimum span between breakouts is set to six months due to wide time range of eight years. This color map is sorted according to number of breakouts detected over the time range with the streams with more breakouts at the top and less at the bottom. This visualization shows that there is a wide range in terms of breakout behavior amongst the dataset from frequently changing sensors which show breakouts at every 6 month minimum to ones that are consistent across all eight years.

![Number/Type of Sensors in EMS](image-url)
In order to analyze the strengths and weakness of the data streams based on the screening process, the metrics are combined and the values normalized to create a matrix of data-stream attributes. Those attributes are then clustered to pinpoint subsets of data that are ready for typical schedule creation for simulation input. Figure 9 illustrates a hierarchical clustering of the data streams according to the mean of the quality metric, the mean weather sensitivity, and the max value of breakouts across the eight year time span. Prominent groups of sensors become apparent through this analysis as annotated on the figure. Region 1 includes data streams that are of low quality, mostly weather sensitive and have few breakouts. Region 2 are streams of high quality, varying weather sensitivity, but many breakouts. Region 3 has varying quality, is a majority weather insensitive, and has a moderate numbers of breakouts. Region 4 has varying quality, is mostly weather insensitive, and has a lower tendency for breakouts.

Region 3 and 4 are the most advantageous group of sensor data streams to investigate for this data are generally complete across many seasons (quality), not highly influenced by weather and have little need for normalization (weather insensitivity), and are relatively consistent over time (breakouts). These two sets of data streams are to be targeted in creation of diversity schedules for simulation feedback. The other regions have their strengths and weaknesses which need to be addressed through further analysis.

An example data stream from Region 4 is selected to illustrate the typical profile creation process. A set of optimal streams is queried from this region and a kWh meter is chosen that has a mean quality metric of 2.63, a mean weather sensitivity of 0.11, and 4 breakouts across the eight year time span. This meter is also measuring a fairly large power load as its mean power consumption reading is 108 kWh. The process of SAX aggregation, discord and motif filtering is completed, and follow-up clustering is performed on the mo-
A subset of the data is chosen from July 1, 2011 to January 1, 2014 as this data fits between the breakouts detected. Figure 10 illustrates the averaged daily profiles for each cluster across a 24 hour period. Figure 11 illustrates the resultant five typical profiles across the time range. The weather insensitive nature of this data stream is apparent as the daily totals modulate independent of the season. The profiles from this power meter follow a fairly conventional occupied versus unoccupied schedule. Figure 12 shows how the profiles are distributed across the days of the week. There are strong weekend clusters of type 0 and 1 and strong weekday clusters of types 2, 3, and 4. However, there are a few of these clusters that fall outside the conventions and are likely holidays. This example is now ready for further transformation into a simulation model input according to industry standards [1]. The revelation of these typical profiles is automatic and uninfluenced by infrequent daily patterns from the larger dataset.

CONCLUSION

A process of knowledge discovery is shown that is designed to automatically evaluate the applicability for simulation feedback for measured data streams within a large, raw EIS dataset. The analysis is shown of 389 power meters streams collected across eight years of data at a frequency of 60 minutes. The total data collected from these sensors is over 22 million measurements, an amount far beyond the capability of manual analysis. The novelty of this work is it showcases techniques which empower an analyst to screen this data before more manual approaches and before further data collection is planned. All of these screening steps can be imple-
mented by setting only a few parameters and the speed is only limited by the computational power in running the algorithms. While precise computation times were not kept for this study, it took approximately 30 minutes for all the screening steps to execute on a Mac OSX laptop computer for the 389 data streams. This process should save a lot of manual analysis and give more insight into the available dataset.

The dataset analyzed will continue to be developed as part of a larger study to model the campus with an urban scale modeling tool. Many of the Region 3 and 4 data streams are to be converted into diversity schedules for this simulation process and the comparison between manually generated simulation inputs and those created automatically in this process will be compared.

**Process Replication**

The data, code and additional explanation of these steps are available for download from http://www.datadrivenbuilding.org. Replication is possible using a series of IPython notebooks and a sample anonymized subset of the data.

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**REFERENCES**


Session 3: Design Optimization

Multiobjective Optimization of Structure and Visual Qualities 43
Kirk Martini
Department of Architecture, University of Virginia.

Decomposition Strategies for Building Envelope Design Optimization Problems 51
Steve Barg, Forest Flager, and Martin Fischer
Stanford University.

Optimizing Creatively in Multi-Objective Optimization 59
Yassin Ashour and Branko Kolarevic
EVDS, University of Calgary.

David Jason Gerber, Evangelos Pantazis, Leandro Marcolino, and Arsalan Heydarian
University of Southern California.
Multiobjective Optimization of Structure and Visual Qualities

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ABSTRACT
The paper describes and demonstrates an optimization tool that combines methods developed independently in the fields of structural engineering and fine art. Optimization has a long history in structural engineering. Most commonly, structural optimization seeks a configuration that minimizes material volume, subject to constraints on strength and stiffness. Metaheuristic search methods, such as genetic algorithms, have been widely applied to structural optimization problems. Such methods have also been applied in the field of evolutionary art. This field seeks to produce aesthetic images or objects through an iterative search, guided by visual, rather than functional objectives. The paper presents the Variable Evolutionary Strategy for Pareto Optimization (Vespo), and demonstrates its use to integrate visual objective functions like those in evolutionary art with technical objective functions and constraints in structural optimization. The goal is to aid a designer in developing an efficient structure with desired visual qualities. The work is motivated in part by the prominent trend in contemporary architecture toward randomized, free-form structures.

Author Keywords
Optimization; structural design; evolutionary art.

BACKGROUND
Overview
Visual randomness has emerged as an important theme in structures and architecture. Buildings such as Toyo Ito’s Sendai Mediatheque and Rem Koolhaas’s CCTV Building use configurations which lack traditional modular regularity. This trend adds to the challenge of architects and engineers to develop a structural system which has the visual properties sought by the architect, with the structural effectiveness sought by the engineer. Engineers from Arup describe this challenge in the design of the Northwest Corner Building at Columbia University [1]. Arup engineers implemented a random generator to generate options for bracing configuration that would be structurally efficient, but also visually random. They then presented these options to architect Rafael Moneo to select. Similarly, structural engineer Mutsuro Sasaki describes the shape design process for the Florence New Station where the engineer, architect, and a structural optimization program form a three-way partnership. The computer algorithm generates alternatives that are structurally confirmed by the engineer, and visually assessed by the architect [12, p. 81]. Sasaki notes the design process was a repetitive sequence of operations wherein a theoretical solution that satisfied the given mechanical conditions and design parameters was calculated inside a computer, while designers outside gave feedback by amending the design variables until a satisfying shape was obtained.

This paper describes and demonstrates an optimization tool intended to support this type of design process; that is, a process that integrates measures of structural performance with those of visual appearance, particularly visual randomness. The discussion is organized into the following four parts: a review of related work; a description of the key features of the optimization tool and its implementation; a demonstration of the tool on an architectural design project; and conclusions.

Related work
The work presented in this paper is derived from two fields which are largely distinct: structural optimization, and evolutionary art. In structural optimization, the great majority of published research addresses the problem of finding a single combination of parameters defining a structural model to achieve a design which minimizes structural weight. Since the 1990s, much of this work has employed population-based metaheuristic methods such as genetic algorithms and particle swarm optimization. Hasancibi et al [8] provides an overview of these algorithms in structural optimization. Several researchers have noted the potential of population-based optimization algorithms to generate a range of alternatives, allowing a human designer to account for aesthetics and other considerations in choosing among alternatives [2, 11, 14]. Some researchers have introduced explicit quantitative measures of visual properties into the optimization algorithm. Shea et al [13] used the standard deviation of
member lengths in a dome framework as part of a composite objective function. Felkner et al [5] used deviation from a designer-supplied truss profile as an optimization constraint.

While a few researchers in structural optimization have introduced visual measures into metaheuristic algorithms, the field of evolutionary art is devoted to that task. As defined by den Heijer et al [4] “Evolutionary Art (EA) is a field that investigates ways to apply methods and ideas from Evolutionary Computation (EC) in the domain of generating aesthetically pleasing content.” Here, the term Evolutionary Computation refers to genetic algorithms and other metaheuristic optimization methods. Visual measures in evolutionary art commonly include statistical quantities to assess distribution of color properties, symmetry, regularity, and other aspects of appearance and composition. Galanter [6] gives a concise overview of the development of the field.

The tool described in this paper is similar to the structural optimization work of Shea and Felkner, in that it uses quantitative measures of visual properties, but it treats those properties differently. Rather than including visual measures as a part of a composite objective function, or including them as constraints, the proposed method treats the visual measures as independent objective functions alongside material weight to find a Pareto optimal set of solutions, which is explained below. This approach is similar to den Heijer’s [4] treatment of visual objective functions in evolutionary art.

THE VESPO OPTIMIZATION TOOL

Formulation of the optimization problem

The algorithm works on a parameterized model of a structure. The parameters are called decision variables, and a collection of particular decision variable values is called a solution. A solution is sometimes called a solution vector, where each decision variable is a component of the vector. The algorithm seeks to minimize the values of multiple objective functions, whose values are calculated based on the values of the decision variables. Structural self-weight is a common objective function in structural optimization, because it is closely related to cost. In cases where the intent is to maximize a function, the function is multiplied by -1; minimizing the negative value of a function, maximizes the function.

With multiple objective functions, it is common that some objectives may conflict with others; that is, solutions which minimize one objective tend to maximize others. In this case, it is not possible to identify a single best solution. Figure 1 illustrates the situation. The axes of the graph represent values for the two objective functions $f_1$ and $f_2$, and the points represent different solutions. Solution $B$ is clearly better than solution $1$, since its values for $f_1$ and $f_2$ are both less. Solution $C$ is better than solution 2 because its $f_1$ value is better, and its $f_2$ value is equal. This relationship is described as dominance: i.e. solution $B$ dominates solution 1, and solution $C$ dominates solution 2. Similarly, solution 3 is dominated by both solutions $C$ and $D$.

Considering the solutions $A$ and $B$, neither dominates the other. $A$ is better in terms of $f_2$, $B$ is better in terms of $f_1$. This relationship is termed non-dominance. Solutions $A$, $B$, $C$ and $D$ compose a set where no solution dominates any other. Such a set is called a non-dominated front, or a Pareto optimal set [3, p. 31]. The algorithm searches for a diverse and well distributed Pareto optimal set. The solutions in this set reflect the tradeoffs of one objective relative to the other.

The optimization process also includes constraint functions. Like objective functions, the values of constraint functions are calculated from the decision variables. While objective functions determine which solutions are desirable, constraint functions determine which solutions are acceptable. In structural optimization, constraint functions are commonly based on limits of material stress and structural deflections. Constraints are mathematically formulated so that values less than or equal to zero are acceptable, and values greater than zero are not acceptable. A solution is called feasible when all its constraint functions have an acceptable value.

The definition of all decision variables includes an upper limit and a lower limit; the difference between them defines the range of the variable. There is also an option to define an increment for any variable. Defining an increment limits the values of a variable to the sum of the lower limit and an integer multiple of the increment. This option reduces the search space and can be used to reflect practical concerns. For example, if the value of a variable represents an overall dimension of a large building, there is little meaning to differences of less than 1 cm. The increment feature is also

![Figure 1: Dominance and the Pareto optimal set.](image)
used in variables that define standard cross sections by having the value of the variable represent the index of a predefined list of cross sections, and setting the increment of the associated value to 1.0; this effectively limits the variable to integer values.

The optimization algorithm and its implementation
The optimization algorithm is a variant of an evolutionary strategy (ES), called the Variable Evolutionary Strategy for Pareto Optimization (Vespo). The term variable refers to the algorithm’s ability to work with solutions with varying numbers of decision variables, i.e., solution vectors of varying length. The term evolutionary strategy refers to a family of optimization methods which are related to genetic algorithms (GA). Like a GA, An ES begins with a random population of solutions, generates and evaluates new solutions, selects better solutions for the next generation, and repeats. The primary conceptual difference is that an ES generates new solutions only through mutation; that is, imposing a small change to a single existing solution, so a solution in an ES has only one “parent”. This feature distinguishes ES’s not only from GA’s but from many other metaheuristic methods which generate new solutions by combining multiple solutions [3].

Vespo’s most novel extension of a conventional ES is the ability to support solutions with differing numbers of decision variables. This is accomplished by organizing all decision variables into groups, where each group has a parameter that defines its number of variables. This parameter can be constant for all solutions, or can be calculated based on the value of other decision variables. A decision variable that determines the number of decision variables in a group is called a guide variable. An example in structural design would be the optimization of a conventional rectangular frame where one of the decision variables is the number of bays in the frame, and a design variable group represents the cross sections for the columns. A solution with more bays will have more columns, and will hence need more column cross section variables. In this case, the number of bays would be a guide variable, used to calculate the number of variables in the column cross section group. Variables belonging to a group whose size is determined by guide variables are called follower variables. Variables which are neither guide variables nor follower variables are called rider variables.

Vespo is implemented as a collection of components in the Grasshopper plugin [7] of the Rhino modeling program [10]. Structural analysis is performed with the Karamba extension to Grasshopper [9]. This environment makes it possible for the design team to build a parametric model which establishes the relationships among guide variables, follower variables, and the parametric model. A variable group is represented by a single Grasshopper component, as shown in figure 2. The component includes the following inputs:

- **pre**: A string prefix used to name each variable in the group.
- **num**: The number of variables in the group.
- **intvl**: The interval for the variables in the group, defining the upper and lower limits of the variable value.
- **inc**: The increment for the variable value. The value of any variable in the group is coerced to the sum of the lower limit and integer multiples of the increment. The default value is zero, meaning the variable value is continuous.
- **inVal**: The initial value of the variable. This is normally ignored by the optimization algorithm, but is needed to initially build the model.
- **isGuide**: A boolean parameter that identifies whether the variable is a guide variable.

In the case where the num parameter is greater than 1, the inVal parameter must be a list, and the outVal output of the component will also be a list. In the figure, the num variable is a static value, which will always be true for a guide variable or rider variable, but for a follower variable num is calculated based on the values of guide variables. Before optimization starts, outVal simply equals inVal. During optimization, the algorithm sets outVal when it generates a new solution. The following describes how a solution is modified when mutation creates a need to add or remove variables.

Handling mutation of guide variables
Normally, mutation of a variable value involves adding to the value a normally distributed random value, with an expected value of zero and a standard deviation equal to a control parameter called the mutation strength. That approach applies easily to follower and rider variables, however when the value of a guide variable is changed, it changes the number of variables in the solution; follower variables will need to be either added or removed from the existing solution to get the new length of the solution.
vector. Vespo uses the following procedure. If a guide variable is mutated, recalculate the number of variables in all groups. If the number of variables in a group needs to be decreased, then remove the required number of variables at random. If the number needs to be increased, then repeat the following procedure as needed:

- Select two decision variables from the group at random.
- Calculate the average of their values, and the difference of their values.
- Generate a new value as a normally distributed random value, with an expected value equal to the average calculated above, and a standard deviation equal to half the difference calculated above.

This procedure ensures that the new value is in the neighborhood of other values in the variable group, but not exactly the same. With this extension, Vespo can mutate a new solution which has a different length than its parent solution. The discussion now proceeds to the application of the Vespo tool to an architectural design problem.

EXAMPLE: RIVERFRONT CANTILEVER BUILDING

Overview

Vespo was applied in developing a schematic proposal based on a design competition. Figure 3 gives an overview of the building, which cantilevers over a river to the south. The primary structural system comprises three story-deep truss-like frames, with one frame on the building centerline, and one each on the east and west facades. The three frames are integral to both the structure and the architecture of the building. Structurally, the frames enable the large cantilever. Architecturally, the outer frames define the building’s most important façades. With the west façade allowing more open views, and the east façade providing more screen-like visual density. The central frame needs to accommodate openings for internal circulation. The design intention was to make each frame distinct and responsive to its architectural context, while still using the same compositional vocabulary.

The process began by setting up a parametric model for the frames in Grasshopper. Figure 4 shows the framework geometry. The frame members are divided into two parts: a common part shared by all solutions, and a varying part, which can be different among solutions. The common part includes the two sloping chord members and the four verticals. These verticals occur at the transitions between the tiered floor levels. The roof and floor framing are arranged to bring all their loads to the four vertical members of the framework. In the parametric structural model, the members of the common part are modelled as hollow rectangular plate sections. The decision variables determining their geometry include the following: 1 variable for the width of all the members; 1 variable for the depth of the two chords; 1 variable for the depth of the four verticals; 1 variable each for the thicknesses of the top chord member, the bottom chord member, the two verticals on the left, and the two verticals on the right (4 total). This makes a total of 7 decision variables for the common part.

The varying part comprises two sets of diagonals, each at 45 degrees to the sloping bottom chord member. The location of the diagonals is determined by diagonal generator lines, located by their horizontal distance from the lower left corner of the framework. The number of diagonals in each direction is a decision guide variable, with a range of values from 3 to 12. The position of each diagonal and its cross section are then decision follower variables. Cross sections for diagonals are selected from a list of 296 UK RHS and SHS hollow rectangular and square sections. The material for all members is S275 steel.

As described above, the number of decision variables in a solution varies depending on the guide variables. There are 7 variables for the common part, these are all rider variables. There are 2 guide variables, 1 each for the number of diagonals in each direction. For each diagonal, there are 2 follower variables, one for position, and one for cross section. In the minimal case with 3 diagonals in each direction, a solution has 21 decision variables, and the maximum case with 12 diagonals in each direction, a solution has 57 decision variables.

Concerning structural modelling, all members are connected at points of intersection. There is a pin support at the base of the second vertical from the right as shown in

Figure 3: Overview of Riverfront Cantilever Building.
Figure 4, and a roller support at the base of the first vertical from the right. The analysis considers gravity loads only, based on the following loads: permanent, roof 4 kPa, floor 6 kPa; variable, roof 1 kPa, floor 4 kPa. Two models were created, one for the outer frames, and one for the center frame, which carries twice as much superimposed load as the outer frames because of the arrangement of roof and floor framing.

Objective functions and constraints
The model includes objective functions and constraints commonly used in structural optimization. Structural self-weight is one objective function, and constraints include member strength criteria according to Eurocode 3, and a deflection limit at the tip of the cantilever, equal to L/180.

The model also includes less conventional objective functions and constraints. Among the constraints is one establishing a minimum horizontal distance between parallel diagonals, \( d_{\text{min}} \), of one meter. If the horizontal distance in meters between adjacent diagonals is \( d \), then the constraint is evaluated as \( 1 - (d/d_{\text{min}}) \). This keeps adjacent parallel diagonals from overlapping, and facilitates constructability. In addition, there is a constraint which limits the self-weight of the structure. Such a constraint is unnecessary for single-objective optimization to minimize weight, since the algorithm always rejects heavier solutions in favor of light ones. In multiobjective optimization, however, an algorithm may accept extremely heavy solutions if those solutions minimize some other objectives which keep the solution in the Pareto optimal set. The weight constraint prevents the algorithm from pursuing solutions where the weight is unacceptably high.

Concerning the outer frames, the optimization employed two additional objective functions to influence their visual properties. The first of these objectives was the total number of diagonal members. The second objective was the regularity of spacing between parallel diagonal members, measured in each direction as the standard deviation of the horizontal distances between adjacent parallel diagonals. These objective functions were used differently according to the visual goals for each frame. For the west frame, the goal was to achieve a visually open frame to allow large view areas. To support this goal, the optimization was set to minimize the number of diagonals, and to maximize the irregularity of their spacing. In contrast, the east frame used opposite objectives, maximizing the number of diagonals, and minimizing irregularity in order to achieve its goal of higher visual density.

The configuration of the center frame was guided by constraints of architectural function. Circulation in the architectural program required clearance for openings at
three locations in the framework. Rather than employing the visual objectives above, the design process used only weight as an objective, and added a constraint calculated as the total length of diagonal structural members occurring inside the clearance openings, normalized by the diagonal length of the largest opening. With this constraint, only solutions which left the openings unobstructed were feasible.

**Results**

A separate optimization run was performed for each of the three frames, using the distinct combinations of objectives and constraints described above. Each optimization run used a population of 100 solutions, and ran for 500 cycles, for a total of 50,100 model evaluations. Figure 5 shows results for the east and west frames. For each frame the figure shows the least weight solution for the optimization run, plus an alternative selected from the population. The figure shows the contrasting visual effect achieved by setting the objective functions towards visual density for the east frame, and visual openness for the west frame. Figure 6 shows the least weight configuration of the center frame, with grey rectangles marking the required clearance for circulation. The weight of the frames is roughly double that of the outer frames, which is consistent with the frame carrying twice as much superimposed load.

The prototype software includes a simple interface which allows the designer to browse the final population of solutions using parallel coordinates, as shown in figure 7. The dialog box on the right side of the figure includes a graph with a vertical axis for each objective function; the objective values are normalized so that the smallest value corresponds to 0, and the largest value to 1. The solutions can be sorted by any of the objectives, and a slider can navigate through the population in order of the current sort. For example, a designer can browse through the solutions by order of weight, by order of spacing irregularity, or by order of number of diagonal members. The currently selected solution is highlighted on the graph with a thicker line.

The optimization was performed on a laptop computer with 6 Gb RAM and an Intel i5-2450M 2.5 GHz processor running Windows 7. The run time varied with the complexity of the model. For the relatively sparse west frame, the run time was 59 minutes; for the more complex west frame, the run time was 135 minutes. The longer run time for the west model logically results from its greater number of nodes and elements.

These solutions produced by the algorithm are preliminary and schematic. In an actual project, these would be further refined, either by more specific optimization, or through manual iterative analysis and adjustment. At this preliminary stage of design, the purpose of the tool is to identify viable alternatives, rather than produce a completely refined design.

**Notes on objective functions and constraints**

Many of the constraints and objective functions in the above example are highly specific to that example, and are in no way general purpose: e.g. the objective function concerning the regularity of spacing of the diagonal members. This raises the question of the applicability of this approach to other projects. The author believes that such special-purpose goals and constraints are inherent in architectural design. Each project will have its own visual, spatial, and functional qualities of interest that can guide technical optimization. An optimization system to support such design needs a flexible way to create constraints and objectives that are tailored to the demands and circumstances of a particular project. This process is reasonably straightforward in the Grasshopper environment, since it is possible to implement such constraints and objectives as custom script components. For example, the component to calculate spacing irregularity of diagonals is 13 lines of C# script. The component to calculate the constraint for circulation clearance in the center frame is 8 lines of C# script, combined with a few built-in components. The environment enables the creation of simple scripts to model both objective functions and constraints customized to particular design situations.

**CLOSURE**

The paper has described a Variable Evolutionary Strategy for Pareto Optimization (Vespo), and demonstrated its application in optimizing with structural, visual, and
functional objective functions and constraints. Previous research has addressed architectural and visual qualities either through constraints alone or through a composite objective function. This treatment of structural, visual, and functional objectives has the potential to enhance the three-way creative partnership between engineer, architect, and computer in developing an effective design, particularly a design that uses randomness in its configuration.

In addition, the paper has introduced the application of variable-length solution vectors in metaheuristic structural optimization. Typically, the application of metaheuristic methods, such as genetic algorithms, has used fixed-length solutions vectors. The variable-length method enables the application of optimization to a broader range of structural and aesthetic design challenges.

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REFERENCES
Decomposition Strategies for Building Envelope Design Optimization Problems

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ABSTRACT
The design of a building’s envelope, including exterior walls, glazing and shading elements, has a significant impact on the life-cycle cost and environmental impact of the facility. Computational Design Optimization (CDO) methods have been developed to assist architects and engineers to systematically search through large numbers of design alternatives to identify high-performing building envelope solutions. This paper presents a method to quantitatively compare different CDO approaches in terms of solution quality and computational efficiency. To demonstrate the method we compare four CDO methods: two single-level genetic algorithms, a single-level gradient-based algorithm that maps continuous solutions back to discrete options, and a bi-level decomposition with a gradient-based algorithm operating on continuous variables nested within a genetic algorithm operating on discrete variables. The example chosen for benchmarking purposes is a midrise apartment building in Chicago. The results show that the all-in-one multiple objective genetic algorithm is the most computationally efficient and produced superior solution quality. The limited breadth of the current results does not allow general conclusions about the methods, but does demonstrate a methodology for further evaluation of optimization techniques.

Author Keywords
Building design; decomposition strategies; building envelope.

ACM Classification Keywords
G.1.6: Optimization.

1. INTRODUCTION
A building’s envelope serves several critical functions: it protects occupants from the elements, helps to regulate temperature and modulates light and views to the outside. The capital cost of the envelope is significant, representing between 10-20% of the overall construction cost for a typical building [1]. The envelope also has an important influence on a building’s operational performance; including indoor air quality, peak heating and cooling loads used to design mechanical systems, energy consumption and associated greenhouse gas emissions. The design of high-performing building envelopes is a critical step in improving the life-cycle economic and environmental performance of our built environment.

The design of building envelope components, including exterior walls, glazing and shading elements, has appropriately received a great deal of attention from the architecture and engineering community. Typically, the architect will take the lead role in the envelope design and will be supported by engineering specialists responsible for other subsystems (e.g., structural, mechanical) [2]. These subsystems are often tightly coupled, meaning that design decisions for the building envelope often have major implications for these other subsystems [3]. In addition, many decisions result in trade-offs between competing design objectives. One simple example is illustrated by the amount of glazing, which allows outdoor views and natural lighting, but come at the expense of solar heat gain and increased thermal conductivity.

In conventional practices, design teams collaborate on design alternatives, which typically involve the development of one or more computer models to assess multidisciplinary performance (e.g., structure, energy). However, manually generating, analysing and coordinating different options is time consuming, leading to only few design alternatives being evaluated [4]. This method is labor intensive and does not guarantee that an optimum design is reached. It could also be less convenient as extensive manual effort is required to manipulate the input parameters and carry out the analysis [5]. A need exists to increase understanding of the performance trade-offs inherent in different design alternatives in order to create optimized building envelopes considering multiple criteria.

Computational Design Optimization (CDO) methods enable architects and engineers to leverage computer processing power to systematically search the design space for optimal design solutions. Researchers have developed a variety of CDO approaches to support the design and specification of building envelopes, however, there is currently a lack of measureable comparisons between these strategies. This paper presents a method to quantitatively evaluate existing CDO approaches in terms of solution quality and computational efficiency. Section 2 of this paper provides a summary and classification of CDO approaches. Section 3 describes the method as well as the benchmarking case study and the existing CDO approaches used to demonstrate the method. The results of the comparison are presented in Section 4 and Section 5 discusses the implications of these conclusions on theory and practice as well as future work.
2. RELATED STUDIES

Computational Design Optimization methods can be generally classified according to how the design problem is decomposed as well as the type of algorithm used to generate new designs. Decomposition methods provide a systematic approach for dividing large engineering systems into smaller, coupled subsystems. Several factors can motivate problem decomposition, including the obvious need to distribute work over many people or computers to compress task calendar time. An equally important reason for decomposition is to more fully exploit the capabilities of specialized engineers and/or algorithms [6]. There are two primary types of decomposition strategies: single-level and bi-level. These approaches can be further classified as single-objective or multi-objective method based on the type of algorithm used to generate new designs.

2.1. Single-Level Methods

The most basic type of problem decomposition is referred to as single-level because one optimization algorithm is used to operate on all design variables simultaneously. Although the analysis may be distributed, a single optimization algorithm makes all design decisions. The vast majority of CDO methods that have been applied to building envelope design problems are single-level approaches.

Cheung et. al. [7] developed a method to minimize building operational energy intensity for a high-rise apartment building in Hong Kong considering several key building envelope parameters including window area, wall insulation level, glazing type and the length of shading elements. It involves performing a one-dimensional parametric analysis for each design variable across a range of input values and then relying on engineering judgment to select an optimal configuration using that information. Yu et. al. [8] developed a similar approach that involved a slightly different set of variables that was applied to a six floor residential building in Changsha, China. One of the limitations with these approaches is that it does not help to predict the complex interactions between design variables [9] and there are often too many combinations to perform a full factorial analysis of every possible combination.

To address this limitation, researchers have applied gradient-based optimization algorithms to automate the searching process for similar problem formulations [10]. Peippo et. al. [5] used a gradient-based approach coupled with pattern search to minimize the construction cost of a building envelope for a single family residential house and office building given a constraint on the maximum permissible annual energy consumption. The gradient-based techniques described above require continuity of the design variables. When a discrete solution is desired, e.g., when selecting glazing types or exterior wall assemblies from a finite list of standard products that are available from a manufacturer, approximation techniques can be used to generate continuous performance functions from discrete product data. Researchers have shown that these approximations can result in solutions that are sub-optimal or even infeasible [11].

Heuristic techniques such as genetic algorithms are capable of handling both discrete and continuous variables simultaneously, and can also accommodate multiple design objectives. Several researchers have applied multi-objective genetic algorithms to identify Pareto optimal solutions considering both cost and energy consumption [4, 12]. Flager et. al. extended this work to also consider the impact of envelope design on the building’s life-cycle carbon footprint [13]. Finally, Shea et. al. [14] applied a multi-criteria ant colony optimization method to select discrete wall and roof panel types to minimize cost and solar gain while maximizing daylighting at various locations throughout the building.

Diakaki et. al. [15] compared different multi-objective optimization techniques, including compromise programming, a global criterion method, and goal programming to optimize building envelopes in consideration of capital cost and energy consumption. However, this research focused on investigating the feasibility of applying each technique rather than quantitatively comparing the methods in terms of solution quality and computational efficiency.

2.2. Bi-level Methods

Bi-level problem decompositions employ more than one optimization algorithm, with each algorithm operating on a specific set of variables. As discussed above, these methods make it possible to distribute work to more fully exploit the capabilities of specialized engineers and/or algorithms compared to single-level methods.

The authors of this paper are not aware of any applications of bi-level methods specifically to building envelope design, however, a number of such methods have been applied to the structural design of buildings and civil infrastructure. Kripakaran [16] and Flager [17] both proposed bi-level hierarchical formulations that utilize different algorithms to operate on discrete member size and continuous node position variables, respectively, for steel truss and frame structures. These methods compared favourably to single-level methods in terms of solution quality and computational efficiency. Balling [18] applied collaborative optimization to decompose an example bridge design problem between two groups – a superstructure design group and a deck design group. The disciplinary groups are allowed to search over different design concepts and formulate the design variables and constraints for each. A system-level group manages the autonomy of the two subgroups to ensure that overall system objectives are met and coupling is properly accounted for.

3. METHODOLOGY

This section describes a methodology to quantitatively compare different Computational Design Optimization
(CDO) approaches in order to assess their suitability for building envelope design. To illustrate the methodology, a representative design problem has been identified for benchmarking purposes. The essential features captured in the example problem include the multi-objective nature of the problem and the mix of discrete and continuous variables common to design problems of this type. The CDO techniques chosen for this study include gradient-based and genetic single-level algorithms, and one bi-level method. The techniques are evaluated on the basis of computational efficiency and solution quality. The limited scope of the four CDO approaches evaluated for this paper is to demonstrate the methodology more than making general statements about the results. Further research will expand on the results, using the same methodology, to evaluate more approaches and propose trends.

### 3.1 Example Problem

This study evaluated a building with fifteen design parameters related to its envelope, see Table 1. The number of unique designs possible for the given variables is $2.5 \times 10^{14}$ (assuming 75mm gradations for the continuous dimensional parameters). Cost and energy analyses were performed to evaluate the objective functions of life-cycle cost (LCC) and carbon footprint. When a single objective function was required, either for an optimization method or for processing results, the social cost of carbon (SCC) was used to calculate a combined monetary result for LCC and SCC.

The building type chosen for the envelope optimization is a midrise apartment building in Chicago. The energy model is built using the building parameters for the midrise apartment Department of Energy (DOE) reference building [20]. For the baseline design, ASHRAE prescriptive roof, wall, and window properties are used with 40\% Window-to-Wall Ratio (WWR) [21] with spandrel-glass solid-wall sections. The figure below shows the building attributes.

![Figure 1](image.png)

**Figure 1.** Chosen DOE Reference Building. Four-story, 3132m² apartment building in Chicago, climate zone 6A. Daylighting controls applied and all living units within perimeter zones. Split system DX cooling and gas furnace heating. Shading elements shown, but not included for baseline analysis.

The design variables for this study include the window properties, depth of overhang and fin shading elements, and the level of insulation for the roof and walls. All wall, window, and shading parameters are independent for each wall orientation and the building is oriented with its long axis parallel to the east and west direction. Reasonable constraints are placed on the level of insulation, depth of shading element, and glazing properties.

### Table 1. Example problem design variables.

Details of the design variables for the envelope are shown in Table 2, Table 3, and Table 4 for the continuous variables, wall variables, and glazing variables, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window Fin and Overhang Depth (cm)</td>
<td>0-61</td>
<td>$19.68/m for anchorage and $64.55/m² for material costs</td>
</tr>
<tr>
<td>Roof U-Value (W/m²K)</td>
<td>0.009-7.28</td>
<td>$211.73/m³</td>
</tr>
</tbody>
</table>

**Table 2.** Description of continuous variables. Roof insulation is varied by the thickness of expanded polystyrene insulation installed above the deck. For the baseline design, there are no shading elements and 33cm of continuous roof insulation (approximately R-20).

<table>
<thead>
<tr>
<th>Exterior Wall Constructions</th>
<th>U-value (W/m²K)</th>
<th>Cost (USD/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6mm Spandrel Glass with 25mm Insulation board, 12mm gypsum</td>
<td>0.83</td>
<td>247</td>
</tr>
<tr>
<td>6mm Spandrel Glass with 50mm Insulation board, 12mm gypsum</td>
<td>0.52</td>
<td>283</td>
</tr>
<tr>
<td>6mm Spandrel Glass with 50mm Insulation board, R9 Batt insulation, 12mm gypsum</td>
<td>0.38</td>
<td>318</td>
</tr>
<tr>
<td>6mm Spandrel Glass with 50mm Insulation board, R13 Batt insulation, 12mm gypsum</td>
<td>0.35</td>
<td>353</td>
</tr>
<tr>
<td>6mm Spandrel Glass with 50mm Insulation board, R19 Batt insulation, 12mm gypsum</td>
<td>0.33</td>
<td>377</td>
</tr>
</tbody>
</table>

**Table 3.** Wall design options. The assembly U-values are taken from ASHRAE Table A3.3 [21]. The baseline design is 50mm of continuous insulation and R-13 batt from ASHRAE Table 5.5-6 [21].
Table 4. Glazing options. LT: Light transmittance ratio. SHGC: Solar heat gain ratio. The baseline option is #17, which is closest to ASHRAE requirements in Table 5.5-6 [21].

The two objective functions for the optimization are:

- **Life-cycle cost.** These costs include the capital costs for the building and the operational utility costs. This objective is formulated with just those values that are varied by the envelope components, so only a portion of the building capital costs are included, the remaining are those that are considered constant for all design variables. The capital costs included in the objective function are roughly 8% of the total cost of the entire building and half of the building envelope components. In addition to the direct capital costs associated with the design variables, the cost of the building heating, ventilation, and air conditioning (HVAC) system is varied dependent of the maximum cooling and heating load demand reported from the energy analysis. Operational costs include all utility costs but no maintenance, repair, or replacement costs. Cost parameters are listed in Table 5.

- **Carbon footprint.** The carbon footprint for the building is measured by CO₂ equivalent global warming potential. The embodied carbon of the envelope components considered is only ~1% of the operational carbon, so is excluded. Carbon intensities for the utilities are also listed in Table 5.

- **Combined LCC and SCC.** The combined LCC with SCC is used to establish certain metrics and for a single objective function on the gradient-based algorithm.

Table 5. Cost and carbon objective function parameters.

3.2 Description of CDO Techniques

The algorithms chosen to evaluate are two genetic algorithms (GAs) and the gradient-based design explorer algorithm (DE).

**Darwin GA.** Phoenix Integration’s Darwin GA is the first GA evaluated as an all-in-one single-level optimization that works on all design variables simultaneously. The Darwin algorithm functions similarly to MOGA and other GAs, in that it starts with an initial population, which is evaluated against the objective functions, and then crossovers and mutations are used to create the variables for the subsequent generations. The parameters for the Darwin GA include a generational population size of 103 designs, multiple elitist selection, and a 5% mutation rate.

**MOGA.** The next single-level GA evaluated is DAKOTA’s Multiple Objective GA (MOGA). DAKOTA is an optimization toolkit developed by Sandia National Laboratory [22]. MOGA utilizes a variable population size, elitist selection, and a 5% mutation rate.

**Design Explorer.** DE is a robust optimization toolkit developed by Boeing [23][24]. The method samples the design space to create an approximate regression of the objective function. Gradient optimizations are performed on this surrogate model, and then global and local minima are explored with additional simulation runs, which are used to refine the surrogate model and the search for a global optimum. The process is repeated until some stopping criterion is met, which can be a convergence criterion or maximum number of iterations.

To perform this gradient-based optimization, the discrete variables had to be converted to continuous variables. This is done by converting the discrete wall type to a continuous wall-insulation-level variable. The discrete glazing type is converted into three variables: U-value, LT, and SHGC, all are independent variables with an added constraint on the ratio of LT:SHGC to restrict the selection to realistic ratios.
See Figure 2 below for a regression of typical glazing LT and SHGC ratios, which is used as the constraint. These conversions to continuous variables are mapped back to actual discrete assemblies by assigning the nearest discrete value and analyzing. For the glazing types, the nearest type is chosen by the method of least squares on the three glazing variables.

Bi-Level Method. The bi-level optimization utilizes the DE optimization on the continuous variables within an inner optimization loop, while the MOGA optimization works on the discrete variables in the outer loop. This decomposition allows the algorithms to operate on a much smaller number of variables, but this is balanced by the need to perform a complete gradient-based optimization for every function evaluation of the GA optimization. The convergence criterion for the DE was loosened to 1 percent for the inner loops. And the initial population size of the MOGA was reduced for the smaller set of variables.

3.3 Evaluation Metrics

Algorithm Efficiency. To evaluate the efficiency of the methods, the single objective of combined LCC and SCC is used. The design from all of the methods that resulted in the lowest combined LCC and SCC is designated the best design for comparison purposes. The 90% convergence level is measured on the scale from the combined LCC and SCC of the baseline ASHRAE design to the designated best design. So the efficiency metric for each method was the number of simulations required to reach this 90% convergence level. The number of simulations is a surrogate for computational time since design evaluation is the dominant factor for computation time and the analyses are conducted on workstations with varied processing power. On average, analysis is performed at 10sec per simulation or 2.8hrs per 1000 simulations.

Algorithm Solution Quality. The quality of the methods is measured for all methods at a common stopping point of 8000 design simulations. The first criterion of quality is their level of convergence toward the designated best design at 8000 simulations, reported as a percentage from baseline design. The second indicator of quality is the completeness of the Pareto optimality for the dual objectives of LCC and carbon footprint. Completeness is measured by the hypervolume indicator of the Pareto measured from the reference lines defined as two standard deviations from the mean for both objective functions. The hypervolume indicator is in units of million USD – mt CO2e and is the area of the Pareto optimality on the LCC v carbon footprint plot. This measurement allows for objective comparison of results with multiple objectives.

3.4 Implementation

The workflow for the methods utilizes two main software applications. ModelCenter by Phoenix Integration is used to wrap the analysis components and its preloaded algorithms are used for optimization. DOE2, developed by James Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory, is used to perform the energy analysis. The pre- and post-processing are performed using Matlab scripts that evaluate the cost and environmental impact functions, and build the energy model input file with the defined variables.

Most of the cost data is taken from RSMeans [22] using the installed prices. The wall costs included an additional $0.40/cm of wall thickness to account for the added building footprint for the same leasable floor area required for the thicker insulation. The cost of the curtainwall support framing is considered constant for all options and therefore excluded.

The glazing costs are based on COMFEN data [27] for the material costs, and RSMeans for the installed costs. For specific glazing types not priced in COMFEN, the generic prices for single or double glazed, clear or tinted, costs from RSMeans are used. Only 6mm panes are considered for consistency and the glazing alternatives were chosen from...
the DOE2 library of materials [26] to provide the range of available properties.

4. RESULTS

Table 6 below shows the results for the different optimization methods. Figure 4 and Error! Reference source not found. Figure 5 show the Pareto and convergence plots for the methods, respectively. The designated best design is from the MOGA method, which reduced the combined value of the LCC and SCC from the ASHRAE baseline value of $1.693 million to $1.520 million, or a 10% reduction.

All the single-level methods reached the desired precision of 90% toward the absolute optimum. The MOGA algorithm is the most efficient, and also led overall for both quality indicators. The advantages of the GA methods also include general applicability and ease of implementation.

As expected for the single objective algorithm, the DE resulted in a much less complete Pareto as demonstrated by the hypervolume indicator and the Pareto plot. This is a consequence of the simple fact that the algorithm was not looking to expand the dual objective Pareto.

The combined LCC and SCC single objective is dominated by the LCC, so the Pareto shows how designs closer to the minimum on that axis were explored further than toward the carbon minimum. The DE also did not prove as computationally efficient as the MOGA, so there is no tradeoff that would suggest using the DE if that was a dominant concern. The DE also required the additional setup time required to establish the discrete-to-continuous variable mapping.

<table>
<thead>
<tr>
<th>Evaluation Metric</th>
<th>Darwin</th>
<th>MOGA</th>
<th>DE</th>
<th>Bi-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations until 90% convergence</td>
<td>3280</td>
<td>1160</td>
<td>366</td>
<td>--</td>
</tr>
<tr>
<td>Hypervolume Indicator</td>
<td>148</td>
<td>153</td>
<td>97</td>
<td>122</td>
</tr>
<tr>
<td>Convergence at 8000 simulations</td>
<td>97.1%</td>
<td>100%</td>
<td>96.4</td>
<td>99.0%</td>
</tr>
</tbody>
</table>

Table 6. Results of the comparisons. The hypervolume indicator is in units of million USD – mt CO2e and is the area of the Pareto optimality on the LCC v carbon footprint plot. The results show the number of simulations required to reach 90% of the distance from the ASHRAE design to the absolute optimum LCC inclusive of SCC. The convergence at 8000 simulations is the percent toward the absolute optimum at a common stopping point.

Figure 4. Pareto optimality charts for each method at the 8000 simulations with hypervolume area shaded.
The bi-level optimization does not compare favorably with the single-level optimizations, which required much more than 8000 iterations to reach the 90% convergence level. Even adjusting the convergence criterion to speed up the inner-loop, the DE did not converge quickly enough to make up for the many iterations required for the outer GA loop. Future investigation into alternative bi-level processes are recommended to more fully evaluate the potential for bi-level formulations. One possible solution is to further decompose the problem by optimizing the glazing and wall properties for each facing orientation separately in parallel. This would greatly reduce the number of variables for the optimizer.

5. CONCLUSIONS
This methodology for evaluating algorithm efficiency and solution quality is useful for quantitative comparisons. The workflow demonstrated is also an efficient process for exploring envelope designs and establishing optima. The number of possible designs evaluated in a CDO is several orders of magnitude greater than a parametric study due to the reduced design cycle time, while also opening up the design space for broader exploration. The result of this design data is not only that solution quality is greatly improved, but also greater insight into the nature of the problem and the consequences inherent in the design decisions. This information allows the designer to integrate the search for an optimal into a successful design strategy.

Further research is recommended to explore the effect of the size of the design space on the algorithm comparisons. Another recommendation is for the integration of a building’s massing and orientation into the evaluation. When looking at these additional building design variables holistically, there is the prospect for much greater impacts on LCC and carbon. This broader design problem also has more potential for decompositions to improve both computational efficiency and design team performance.

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ABSTRACT
Designers will always face the challenge of designing well-performing buildings using what are often conflicting and competing objectives. Early stage design decisions influence significantly the final performance of a building and designers are often unable to explore large numbers of design alternatives with respect to the performative criteria set for the project. This research outlines a ‘creative optimization workflow’ using a Multi-Objective Optimization (MOO) engine called Octopus that runs within Grasshopper3D, a parametric modeling tool, and simulation software DIVA for daylight factor analysis. The workflow utilizes a ‘creative optimization tool’ which allows the designer to explore, sort and filter solutions, and analyze both quantitatively and qualitatively the trade-offs of the resultant design solution space. It enables the designer to visually compare alternative solutions in a gallery and subsequently analyze trade-offs through a radar-based chart, parallel coordinate plot graphs and conditional domain searches. This feedback tools allows the designer to quickly and efficiently identify potential solutions for either design development or to select preferred solutions for further optimization, i.e. ‘optimizing creatively’. A retrospective design case study, the ‘De Rotterdam’ building, is used to demonstrate the application of the tools. The workflow demonstrates the ability to reduce design latency and to allow for better understanding of design solutions. Additional research is needed to better understand the application of MOO in the early stages of design; and the further improvement of the creative optimization tools to accommodate the designer’s need for a more dynamic and synergistic process.

Keywords
Multi-Objective Optimization (MOO); performance-based design; generative design

INTRODUCTION
Current Computer-Aided Design and Engineering (CAD/CAE) tools offer more rapid design iterations via quick visualization, modification of geometry and by simulating many different aspects of building performance [1, 7, 15, 18]. However, manually simulating many design alternatives and analyzing them can be a very time consuming endeavor, so designers are often forced to select from a narrow set of solutions. Researchers have used several optimization methods based on Genetic Algorithms (GA) to rapidly generate and evaluate multiple design solutions especially in the early stages of design [4, 6, 27, 28]. Architectural design, however, involves a great deal of complexity and requires judgment and decision making, along with an understanding of trade-offs [5, 9]. Rigorous analysis of the design solution space using both quantitative and qualitative criteria becomes essential to identify ‘sub-optimal’ solutions. Yet, performance feedback latency exists in the current tools, hampering decision making, invariably leaving a significant area of the design solution space unexplored. Recent research has explored the automation of performance feedback loops through the use of Multi-Objective Optimization (MOO) by coupling geometry visualization with Pareto-ranking and quantifiable performance metrics using Revit and Green Building Studio (GBS) [18]. However, the application of MOO with an automated performance feedback loop has not been fully developed in Grasshopper3D.

This research describes a ‘creative optimization workflow’ which combines a MOO engine (Octopus – a plugin for Grasshopper3D) with parametric design, a financial model, program area definition, views score and daylight analysis (using DIVA) to accelerate the design cycle and systematically generate, evaluate and explore design options faster than what current conventional design processes would allow. Through one platform (Rhinoceros3D), parametric modeling and a GA-based optimization engine, this research enables rapid design exploration considering aesthetics, better understanding of the correlation between disparate objectives, quick visualization of the cause and effect of quantified trade-offs, and overall reduced design latency given the automation of the generation and evaluation of the resultant design solution space.

This body of research is unique in aiding the designer to explore and evaluate more quickly and efficiently the design solution space in Grasshopper3D. The aim of the research is to explore sub-optimal solutions with their trade-offs i.e. “explore” and not aim to find a singular optimum solution (i.e. “exploit”). The ‘creative optimization tools’ make MOO results more accessible to designers and enable the designer to sort and filter designs based on performance metrics while simultaneously evaluating the aesthetics (form) of those solutions. Qualitative relationships between
the objectives can be ascertained from the parallel coordinate plot graph and the radar-based chart which help the designer in addition to the graphical aids in Octopus to carry out sensitivity analysis. With the coupling of the ‘creative optimization tools’ and Octopus, the designer is able to fully apply Octopus’ ability of preference searching and its adjustable optimization settings to optimize interactively in a ‘creative’ fashion.

Grasshopper3D provides an extensible and flexible platform for designers upon which to combine disparate domains of expertise such as financial models, daylight analysis, to structural and energy analysis among other domains through the array of free plugins available online. Overall, this automated workflow considers aesthetics as an objective in the optimization process; aesthetic considerations are ignored in optimization models as they are particularly difficult to quantify mathematically [3, 5, 9, 22, 28]. Aesthetics, however, have an influential role in the negotiation and re-negotiation of the trade-offs of the design solutions.

BACKGROUND & REVIEW

This section provides an overview of the current design technology used in performance based design. In addition, it discusses problems associated with the currently available design technology.

Multi-Objective Optimization (MOO) refers to optimization methods used to solve design problems which have multiple, often conflicting objectives to find solutions that satisfy these multiple objectives [8]. Genetic Algorithms (GA), first introduced by John Holland in the 1970s is a method inspired by biological mechanisms, and is used for solution generation in MOO. GAs have traditionally been used to solve optimization problems; in addition they can be used as design aids [19]. Evolutionary architecture based on the application of GA was initially experimented with in the late 1980s and early 1990s by John Frazer in optimizing multiple performance criteria [14].

Even with the increasing use of MOO in the building industry, it has yet to be fully embraced as a vital part of the design process [13]. There are several reasons for the slow assimilation of optimization tools in design. Designers must visually identify solutions resulting from MOO in order to fully evaluate design trade-offs along with quantifiable goals, preferences and constraints [9, 16, 21, 22, 24]. Lack of real-time analysis and feedback between performance metrics and geometry in MOO design is another obstacle [25]. In addition, the comparison of sub-optimal designs through their associated myriad of data is fundamental in further defining the design objectives as well as the understanding of the nature of the ‘optimal’ solution [3, 9, 28]. The tools and processes are not fully developed to support quick evaluation of alternative design solutions [16]. Therefore, the majority of designer’s time is spent managing design information, manually integrating and coordinating design information in their task-specific format and coordinating solutions [16]. A pattern was identified through interviewing practitioners that use MOO in their design process, found that through badly designed user interfaces and inflexible data exploration and visualization tools, designers have a difficult time understanding the design solution space [6].

A performance-driven generative tool that would produce a range of design solutions based on a set of multiple performance targets was envisioned by [17]. The design solution space would then be evaluated through a performance feedback system based on both quantitative and qualitative performative criteria. Interactive tools were created that combined together GA-based optimization tools with modeling and simulation tools; through an interactive tool, the designer is then able to edit objectives/constraints during or after the optimization process [4, 9, 20, 21, 22, 28]. Other research included the use of off-the-shelf software such as modeFrontier by [3, 4] for the optimization of a generic skyscraper. Eiff
d developed by [26], comprising of a generative structural design system, an associative modeling system and an optimization engine, with an immediate performance feedback system.

“CREATIVE OPTIMIZATION” WORKFLOW

The workflow (Figure 1) includes the use of existing plugins in Rhinoceros3D: Grasshopper3D for parametric modeling, Octopus for MOO and DIVA for daylight factor analysis. The unique functionality of the automated workflow is the ability to represent, manipulate, sort, and filter design solutions based on performance metrics using Grasshopper3D and displaying the results in Rhinoceros3D (radar charts, parallel coordinate plot graphs and 3D solution meshes).

![Figure 1. Creative Optimization Workflow.](image)

Parametric design tools such as Grasshopper3D (GH) allow the designer to design with pre-defined constraints and parameters to quickly generate alternative design solutions through changes in the geometry. Hard constraints such as plot dimensions and height restrictions are defined in GH. Building information data (quantitative) such as program areas (office, hotel, residential & retail), profit calculations and geometry definitions are established in GH. Simulation
plugins such as DIVA for daylight analysis can be used in the definition among other plugins based on the user’s preferences and cognitive abilities.

During the optimization process, Octopus plots in real-time the results on a 3-dimensional graph, with each axis representing an objective; color is used for the fourth objective and size for the fifth objective (Figure 2). Recorders are used in GH to record both the 3D mesh of the solution and its respective performance values during the optimization process. Following the optimization run, all the relevant quantitative data is then streamed into a spreadsheet in Microsoft Excel, and subsequently imported into GH using an Excel importer component (a plugin called Lunchbox). The solution space results can then be sorted, filtered and analyzed via the ‘creative optimization tool’.

**Octopus: multi-objective optimization engine**

Octopus’ algorithm is developed by Robert Vierlinger in cooperation with C. Zimmel and Bollinger Grohmann Schneider ZT GmbH. It uses Pareto-based optimization technique, which is currently the leading multi-objective search technique based on the work of economist Vilfredo Pareto [3, 10]. All solutions that form the Pareto front are mathematically equivalent – ultimately they are a set of well-performing solutions [3, 10]. According to [23], Pareto optimization “is more realistic and useful for design because it allows subjective criteria to be taken into account”.

Octopus utilizes Strength Pareto Evolutionary Algorithm (SPEA-2) reduction in combination with the Hypervolume Estimation Algorithm for Multi-objective Optimization (HypE) algorithm for mutation (population method). Octopus provides flexibility for the designer to choose between two different reduction strategies and between three different mutation strategies based on the population size and number of objectives respectively. The GA engine uses a non-dominating sorting to find the Pareto front [30, 31]. Elitism, mutation probability, mutation rate, crossover rate, population size and maximum generations can be set by the designer manually before or during the optimization, to accommodate the designer’s preferences and the scale of the design problem.

The evolutionary search is an iterative process; in each iteration a solution set is created. In GA terms, the solution set is called a generation which consists of a population of solutions that have different genes (design variables). The first solution set is generated randomly. The following generations are generated by an algorithm, emulating the biological reproduction by pairing solutions. After each iteration, the genes of the two of the best performing solutions are combined to create a new set of genes. These genes form the design variables of new generations [30]. This process mimics natural selection in a limited sense; the fittest solutions survive, however, they are not necessarily the fittest solutions within the context. Solutions that fit the required objectives (fitness criteria) will be considered the highest performing designs. In order to prevent the algorithm of getting stuck in local optima, a chance of mutations is defined in the algorithm, meaning that the generated population has more diversified offspring [30].

Three graphs aid the designer in identifying convergence of solutions: Hypervolume graph (Figure 2-1) is a history graph representation of the mathematical measure for the spread of solutions, the higher the value, the better: when the line begins to flatten out, the solutions are converging as their fitness value cannot be maximized any further. Parameter distance graph (Figure 2-2) is similar to the genome graph in Galapagos (a single-objective engine native to GH), where each polyline represents a solution with its genetic variation; as the solutions converge, the polylines begin to re-iterate close to each other (i.e. become denser). Each convergence graph (Figure 2-3) represents one objective scaled to a domain of 0 to 1; light grey represents the elite solution domain and the dark grey represents the Pareto front domain and is updated for each generation for each objective. A completely dark grey graph means that the algorithm has found that all elite solutions are also the Pareto-non-dominant solutions as well. The changes in the graph through the generations is a representation of the truncation of the Pareto-front results, which is done by the reduction strategies [29, 30].

During the optimization process, Octopus plots the results in real-time on a 3D graph with every cube representing a complete solution (Figure 2). In other words, each cube is a mathematical representation of the performance of that particular design. The solutions that form the Pareto front are represented as red solution cubes. Instead of maximizing all objectives, Octopus minimizes the objectives; therefore the performance numbers are adjusted accordingly in advance before the optimization process begins, to achieve the required objective of either maximizing or minimizing [30].
CASE STUDY AND ANALYSIS RESULTS

A case study, the ‘De Rotterdam’ building (Figure 3) designed by OMA (Rem Koolhaus) is used as a test case to both design and evaluate the effect of the workflow and to critically examine the role of MOO in the design process. De Rotterdam, located in Rotterdam, Netherlands, is described as a ‘vertical city’ by Rem Koolhaus; it is a mixed-use building with the main aim of maximizing efficiency and profit. De Rotterdam consists of three stacked and interconnected towers via a plinth with a total area of 160,000 m² and a total height of 150 m [2].

Two optimization runs were conducted with the aim of increasing the Floor Area Ratio (FAR), financial profit, average daylight factor and views. These parameters were chosen because they are relevant to many mixed-use buildings, where ultimately the main aim is efficiency and maximum profit as well as they are easy to quantify. In addition, the same optimization settings such as the mutation rate were used for both optimization runs to ensure consistency.

The first optimization run involved beveling of the individual towers (Figure 5) in the belief that it would increase views and natural daylight; however, significant area was lost and thus profit. Other issues with this run were the resulting form, the beveling based on the authors’ opinions did not yield any aesthetically pleasing solutions. The aesthetics resulted in exploring an alternative parametric definition and thus an alternative formal language. The second optimization run divided the individual towers into four stacked blocks (Figure 10) to create a more dynamic looking building and as a way of mitigating loss of floor area resulting from the first optimization run.

De Rotterdam Parametric Replica

A replica of the De Rotterdam (Figure 4) was parametrically modeled using GH with the exact realistic plot dimensions, building height, number of floors, orientation of the building and the respective areas of the four main program functions (retail, office, residential and hotel). The financial model was based on the difference between the construction costs and selling prices per square footage in Rotterdam for each program function, for example, retail and hotel have different construction costs and subsequently selling prices [11, 12]. The financial model is adaptable and can be made more comprehensive by including expected operation and maintenance costs. The views score was evaluated using a component called ‘IsoVist’ in GH which projects points radially, with those not striking nearby geometry returning a ‘false’ Boolean value; their count provides the “views” score (the higher the value, the better the score).

First optimization run (beveled towers)

The first run involved the beveling of the towers (Figure 5) with the hypothesis of increased daylight factor and views score. This in turn would translate to increased revenue from the increased views score and the increased daylight would translate into less use of artificial light, hence less energy use. In total 60 genes or design variables were manipulated; in total 1500 design solutions (offspring) were generated, with an average individual run-time of about 30 seconds for each solution.

By simply using number sliders in Grasshopper3D, conditional domain searches (in terms of either objective ranges or percentiles) (Figure 6) within the design solution space are feasible and allow for subset exploration based on
the user’s preferences and aesthetic sensibilities. Parallel coordinate plots are helpful in carrying out sensitivity analysis with the help of the graphical aids in Octopus. Sensitivity analysis is necessary in identifying how influential each objective (fitness) is compared to and on other objectives. This may cause the designer to modify the parameters under evaluation, identify bottlenecks in the search process or explore alternative optimization settings such as different mutation rates.

Using conditional domain searches, the designer can filter design alternatives from different perspectives; for example, from an owner’s perspective the main concerns would be profits and an iconic design (Figure 6). Other perspectives can be explored such as from the architect’s or from the public’s perspective, etc. The designer can further refine the search for potentially ‘good’ solutions by selecting preferred solutions from the gallery to further explore via the radar-based chart and thus evaluate comprehensively (Figure 7). The parallel coordinate plot graph can also be coupled with the radar-based chart to explore individual solutions that were identified as potentially ‘good’ solutions (Figure 8).

Overall, the higher FAR, the higher the daylight factor, but lower the profit and views score. There were certain exceptions where the highest FAR also resulted in a very high profit and views score, but significantly low average daylight factor (Figure 9). The authors’ hypothesis of improved daylight and views score was correct, however, the aesthetics of the designs were not particularly better according to the authors’ opinions.
All the solutions, including those on the Pareto front, can be explored and analyzed (Figure 11 & 12). Selection of the satisfactory/preferred solutions by the designer could be further optimized in Octopus by mating them to create more sub-optimal solutions (i.e. “optimizing creatively”) or alternatively can be used for design development. The results forming the Pareto front (Figure 11 & 12) are spread out mainly between the second and third quartiles of each objective. The daylight factor appears to be an influential limiting objective; profit will take precedence over other objectives as it is larger in range (341 to 458 million), meaning it will have a larger influence on choice of solution over other objectives.

Overall, in this optimization run, the solutions followed the same trend as the beveling solutions; profits, however, did not increase as expected from the change in geometry, in fact, the minimum and maximum bounds of the profit were nearly the same. Again, the same trend is observed similar to the beveled iteration for the upper quartile for daylight factor (Figure 13 & 14), where profit is in the bottom half with the views score and FAR from the mid to upper quartiles.

Comparison between the optimization runs and the De Rotterdam parametric replica
Using MOO, the generation of a greater number of solutions ultimately leads to improved building performance results as shown in Table 1. The results are not conclusive figures because many other domains are not taken into account such as structural analysis and energy use analysis among others. They are, however, representative of the overall trend of the possible design solutions that can be taken into consideration for design development. The qualitative analysis also led to important correlations between the different objectives. Some objectives seem redundant (least influential) such as FAR and others may be seen as influential such as profit. These derivations were necessary to formulate a quick understanding of the design solution space. Across all domains, there were considerable improvements (Table 1):
The parallels of the trends of the two optimization runs may be because of multiple conflicting objectives or that due to hard constraints such as the height restriction led to no significant quantitative differences between the runs. With this mind, the flexibility of Grasshopper in modifying parametric definitions and in the ability of Octopus tailoring the optimization settings or strategies based on the design problem may have arguably yielded better solutions [30]. It is, however beyond the scope of this research paper to explore the influences of the varied optimization settings in Octopus on the MOO process.

The ‘creative optimization tools’ enable qualitative interactions by the inclusion of aesthetics as an objective. The vital role of aesthetics in the optimization process led to a different formal exploration process (second optimization run). It is the difficulty in quantifying aesthetics or other qualitative objectives, that a decision maker is necessary, for example, in identifying potentially good solutions or a bad optimization trajectory. The tools aid the designer to contemplate multiple solutions and substantiate any optimization decisions such as changes in the mutation rate that may lead to alternative solutions. The overall process is analogous to the design process itself and in this case, where MOO is used, the design decisions are not solely based on quantifiable metrics such as FAR.

### Table 1. Comparative improvements (%) over De Rotterdam parametric replica.

<table>
<thead>
<tr>
<th></th>
<th>De Rotterdam parametric replica</th>
<th>Bevel (%)</th>
<th>Stacked blocks (%)</th>
<th>Average (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAR</td>
<td>22.43</td>
<td>10%</td>
<td>11%</td>
<td>10.5%</td>
</tr>
<tr>
<td>Daylight Factor</td>
<td>5.1 %</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Profit</td>
<td>$347,390,493</td>
<td>17%</td>
<td>21%</td>
<td>19%</td>
</tr>
<tr>
<td>Views Score</td>
<td>372</td>
<td>17%</td>
<td>22%</td>
<td>19.5%</td>
</tr>
</tbody>
</table>

CONCLUSION AND FUTURE OUTLOOK

One of the main goals of the research described in this paper was to reduce the design cycle latency through the integration of parametric design, MOO, simulation, and feedback loops. By using and tightly integrating off-the-shelf software and by automating the workflow using a common platform, some of the commonly encountered data exchange and interfacing issues were avoided.

The purpose of the ‘creative optimization workflow/tool’ is to provide a flexible real-time feedback loop with 3D geometric representation in order to influence early design decision making from both a quantitative and qualitative perspective as well as the aesthetics point of view. The tools offer improved accessibility to MOO results for the designer and the ability to sort, filter, comprehend the solution space with consideration of overall design performance. Grasshopper3D provided a common platform for added functionality in design development by the combining of multiple disparate domains via free plugins according to the designer’s preferences and cognitive abilities. Grasshopper3D will move its platform to support 64-bit computing and parallel processing, hence augmenting the performance of MOO runs. Essentially, with a more powerful GH, overall design latency will be reduced even more notably in the near future.

We believe the potential of the described workflow is significant early in the design development. It can be made more efficient, smart and flexible with additional tools/components for Grasshopper3D that can be used by practitioners and students. The intent of these tools/components is to allow designer’s to generate complex geometry, explore and evaluate a large number of alternatives quickly through the integration of multiple domains and to reduce overall design latency. Too many solutions may devalue the understanding of the design solution space [6], the tools will aid the designer in the overwhelming task of comprehending and cognitively determining which solutions are suitable.

REFERENCES


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ABSTRACT
This paper presents research on the development of multi-agent systems (MAS) for integrated and performance driven architectural design. It presents the development of a simulation framework that bridges architecture and engineering, through a series of multi-agent based experiments. The research is motivated to combine multiple design agencies into a system for managing and optimizing architectural form, across multiple objectives and contexts. The research anticipates the incorporation of feedback from real world human behavior and user preferences with physics based structural form finding and environmental analysis data. The framework is a multi-agent system that provides design teams with informed design solutions, which simultaneously optimize and satisfy competing design objectives. The initial results for building structures are measured in terms of the level of lighting improvements and qualitatively in geometric terms. Critical to the research is the elaboration of the system and the feedback loops that are possible when using the multi-agent systems approach.

Keywords
Generative Design; Parametric Design; Multi-Agent Systems; Architecture; Multi-disciplinary Design Optimization; Immersive Virtual Reality; Design Performance.

INTRODUCTION
The rapid evolution of computational design tools such as associative parametric modeling [1], algorithmic and generative design methods [2], and multi-disciplinary design optimization methods have provided designers with a new set of design exploration possibilities that can aid them to actively collaborate with other disciplines and to more rapidly explore design alternatives, and manage the complexity of design problems inclusive of human, environmental and structural feedback loops [3]. As part of this rapid industry evolution simulations are used increasingly in design practices for evaluating different performance aspects of a design including for factors such as risk, cost, energy, structural efficiency, lighting, and social utility [4].

Our work situates itself amongst a body of research that investigates the applicability of Multi-Agent Systems (MAS) in architectural design, building engineering and construction [5-7]. It proposes an integrated approach for architectural design where agent-based algorithms are researched for their ability in simulation to negotiate across multiple design objectives including geometry, material properties, fabrication constraints, environmental factors and human preferences. This approach attempts to go beyond the limitations of current computational design techniques that are restricted to either simple parameter sets or single optimization strategies. One main objective of our work is to investigate the applicability of a custom MAS framework for the design of building components and structures which challenge and enhance the existing capabilities of Multi-disciplinary Design Optimization (MDO) and MAS methods. The proposed approach combines design data, optimization routines and analysis with real time data collected from users where the MAS is conceived not purely as a swarm or flock. Furthermore, we aim at extending the capabilities of MDO which can often be limited to pre-determined and top down driven solution spaces with simple geometries and similarly simple optimizations based on reduced analysis and objectives.

The research seeks to test the hypothesis that the MAS framework will lead to informed design variation and solution spaces that are larger and pre-optimized where geometric and performance complexity are not marginalized nor simplified. The multiple inputs and datasets from performance analysis, illustrated in Figure 1, are used for the design of specific agent behaviors that compose an integrated design system for design with increasingly large and complex set of design objectives. These include virtual, physical, and social objectives in conjunction with structural and constructability parameters. As the use of simulation for form finding and optimizing geometry is rapidly becoming a common practice in architectural design it is an essential component of our process [8]. One key innovation of the research, seen in Figures 1 and 2, is that it bridges the virtual-physical divide.
through the linking of the MAS to an immersive virtual environment (IVE). An IVE setup is used to collect user data that enhance the agents’ behaviors. Another key innovation of the research is the learning from computer science social choice and voting techniques in addition to flocking behaviors of the agents in order to improve upon design products and decision making processes [9]. The paper presents the state of development and testing of our MAS for design framework as well as the initial experimental results and next steps. The paper provides background and literature review as a means to highlight initial gaps and analysis. The experimental design and results presented include: 1) the development of the MAS for simulating a light diffusing building component that takes into account environmental analysis as well as user data; and 2) a second scenario where agents, guided by environmental analysis, emerge a geometric structure. The paper lastly enumerates a research plan and next steps for the incorporation of an expanded set of architectural, geometric, and social objectives experimentally.

BACKGROUND & REVIEW
An overview of MAS in architecture and engineering, are described in brief highlighting the limited and nascent nature of the field. Secondly, given our research methodology an introduction into the use of Immersive Virtual Environments (IVE) in the fields of architecture, engineering and simulation for design decision-making is described. Third we relate our current work back to research on Multi-disciplinary Design Optimization (MDO) and finally highlight the gaps in need of addressing.

Multi-Agent Design Systems
Multi-Agent Systems (MAS) have generated a growing number of experimentalists in architecture in recent years [10]. These include researchers, units, and practitioners such as Cecil Balmond, Achim Menges, and RMIT in Australia as well as practices such as at Zaha Hadid Architects [11]. These approaches are arguably becoming a new paradigm for conceptualizing design, exploring design solution spaces more efficiently and for solving complex problems [12]. Much of this development in architecture has originated from the seminal work of Craig Reynolds [13]. The introduction of MAS in architectural design is albeit relatively new and has focused mostly on a specific type of agent algorithm known for being able to generate complex self-organizing geometry.

Figure 1: Overview of the proposed Multi Agent Design Framework. The diagram illustrates the geometry and environmental inputs and parameters, the linking of the digital to physical environments, the analysis engines, and the agent IDE.
Thus behavioral design methodologies such as an MAS framework enable a shift from the direct invention of form or organization to intensive intrinsic, bottom up, collectively intelligent processes for exploring morphology and the generation of form and lastly optimization and rationalization for performance criteria and constructability [14].

Different studies have identified the applicability of MAS in different stages of the architectural process but in aggregate illustrate a noticeable gap: the majority of the precedent work has been limited by investigating only specific behavioral models such as Reynolds’ flocking. As a result these precedents also highlight a focusing mostly on the generative and formal aspects of the simulations and not on the impacts of performance criteria nor on the incorporation of human and real world data for informing the simulation behavior.

Our work couples simulation environment agents (the virtual) with material systems (the physical) with human agency (the social) through bringing to the agent algorithms some exposure to social choice and voting based Artificial Intelligence (AI) techniques. This occurs through an accumulation of real world behavior both from human and environmental and physics based sources which are then feedback into the agent probability distribution functions (PDFs) discussed in later sections.

![Figure 2: Example of participant navigating an Immersive Virtual Environment (IVE) with a head-mounted display.](image)

**Immersive Virtual Environments**

The second area of precedent research relates to an invention of our design methodology, the incorporation of human data to inform our MAS in conjunction with a version of rules defined by Reynolds. Immersive Virtual Environments (IVE) have been brought to the design research for both practical reasons of enabling more expansive and cost effective data capture and experimentation but equally as a means to develop iterative feedback for machine learning across the virtual physical social divides. There is significant research to date on informing agents through human data in the domains of security, economics and game theory but little work has been done in the arena of design exploration or architectural performance [15, 16]. Some of our previous research has suggested not only that participants perform similarly within IVE as they do in physical environments, but they also feel similar feelings of presence within such environments [17]. The IVE allow the design researcher to control for all potentially confounding variables and to properly isolate the variables of interest for measuring statistical variance and significance. Prior research has also demonstrated that participants often try to act in a “virtuous” way in front of an experimenter [18]. In studying social behavior research usually starts with inputs and assumptions from real-world settings including human tendencies, contextual data, and the complex interactions allowing for simulation outputs which can be analyzed iteratively and in a feedback loop within the MAS framework. Further background in the development and use of IVE’s for design alternative and human preferences can be found at [17, 19].

**Multi-Objective Design Optimization**

A third area of background is that of our previous and continuing research into the combining of associative parametric design models and the automation of performance driven solution space generation and ranking. In previous work we have illustrated the value of harnessing high performance computing and cloud based procedures to generate expansive solution spaces while simultaneously optimizing across aligning and contradicting objective functions [20]. However our MDO research to date works in isolation from human centered inputs and is only generative within a predetermined solution space [21]. One hypothesis is that simulation can be improved by the combining of MDO research with that of the MAS framework once informed by the capturing of user data from IVEs in conjunction with MAS approaches incorporative of social choice. It is evident in the literature and contemporary discourse that interest into MAS approaches in architecture is growing. However it is also clear that there are few precedents to illustrate the development of MAS techniques beyond simple flocking algorithms within architecture. While there is incredible development in computer science of agents they have yet to trickle down to the design field. Our work uniquely is learning from social choice based MAS for architectural design decision making [9]. Furthermore what is also evident is that the use of agents considering performance criteria beyond material and geometric aspects remains in a very nascent state.

Related work in the fields of design, with few exceptions, has shown interest mostly for the generation of geometric complexity and less for addressing design problems holistically and requisite of environmental and human factors. Our research methodology and resultant framework is in part a response to these identified gaps: 1) the lack of sophistication of the agent models in use in architecture; 2) the lack of existing MAS to negotiate highly coupled and complex multi-objective design scenarios; and 3) the lack of linkage and crossing of the virtual physical social systems and data sources.
RESEARCH METHOD & EXPERIMENTAL DESIGNS

The objective is to evaluate whether the proposed MAS design framework can provide designers with an alternative design approach that incorporates bottom up strategies and data for informing agents that optimize architectural designs. This work attempts to develop a versatile and extensible MAS that supports and synthesizes environmental, structural, and user agencies by linking interdependent agent based sub-models into a MAS. Hence, our framework assumes multiple levels of agency. We are working towards agent classes, each responsible for different design requirements. In this paper we present two classes: one responsible for creating a window panel that controls the amount of light that enters a room; and another responsible for generating a shell structure with different degrees of porosity that allow the direct radiation of sun light under the structure. The creation of more agent classes and the definition of how exactly these classes will interconnect and negotiate multiple aspects of design are our next steps into implementing this framework. We are currently exploring voting as a negotiation mechanism, as presented at [9]. Due to space constraints, in this paper we focus on the definition of two agent classes.

Our proposed agent classes are based on agents with locally defined rule sets that emerge into global form using a bottom-up approach. Such shape is within a larger context of an assembly, and can be measured according to well-defined performance criteria. Performance criteria include and anticipate environmental, structural and material constraints as well as user preferences. These performance criteria obtain different weighting factors depending on the type and scale of the design space, or the preferences of the designer.

Our algorithms currently use sun radiation analysis data to inform the agents while generating a surface. They can also be parameterized, in order to attend preferences of a user concerning the amount of light inside a room. We are currently using an IVE system to directly obtain a user’s preference. Such information can then be used to dynamically adapt and change the surfaces in our proposed framework, by changing the algorithms parameters accordingly, but this feedback loop is still under implementation. We now proceed to explain the two agent classes, and in the next section we show our experimental results.

Experiment 1: Agent 1.1 Light diffusing Panel Agent

The first experiment investigates the combination of environmental analysis data, specifically solar radiation and luminance with user preferences for light intensity within an office environment. We are currently working in a novel algorithm where an agent grows a window panel according to these two factors.
The developed algorithm has two phases to date. In the first phase, an agent iteratively grows 2d lines in the panel surface. In the second phase, the lines are transformed into 3d surfaces (i.e., linear extrusion), finalizing the realization of the window panel. A number of parameters affect the behavior of the agent, which can be set according to the user preferences. For the first phase, the parameters are: \( L \), which defines the length of each line; \( p_1, p_2, p_3 \), the probabilities of each agent behavior (which is clarified further below). For the second phase, the user specifies \( d \), the maximum extrusion length; and \( \theta \), the maximum extrusion angle. Hence, the lines are not only transformed into 3d surfaces according to a certain length, but also rotate. All these aspects affect how the sun light enters the room, changing the illumination inside.

We now explain our algorithm in detail. Figure 3 (a) shows the first phase. The agent starts in a corner of the panel, and performs a series of iterations. At each iteration, the agent grows one line from its current position, and moves to the end of that new line. The agent can grow three different types of lines, according to three different behaviors: straight, left-curved or right-curved, as shown in the figure. In the beginning of each iteration, the agent picks its next behavior randomly, according to the probabilities \( p_1, p_2 \) and \( p_3 \). However, the agent must also obey two constraints: the new line must not intersect a previously constructed line and the agent must not leave the boundaries of the given surface. If the randomly chosen behavior would violate these constraints, a new behavior is selected until valid. More specifically, the agent checks the history of all previous selected behaviors and changes to the behavior that has the ratio furthest away from the desired one according to the probabilities \( p_1, p_2 \) and \( p_3 \) (which naturally induce a ratio). This phase terminates after a pre-specified number of iterations. In the second phase, shown in Figure 3 (b), (c) and (d), the lines are extruded in 3d geometries. For each line, a length and angulation are chosen according to the following equations:

\[
\begin{align*}
d' &= d \times w; \\
\theta' &= \theta \times w,
\end{align*}
\]

where \( 0 \leq w \leq 1 \) is a weight given by the current sun radiation entering the panel in the position of the line.

Hence, each line will have a different \( d' \) and \( \theta' \), but bounded by the preference of the user. Moreover, the user can specify two different types of extrusion: uniform or non-uniform (Figure 3 (b)). The uniform case follows as just described, while in the non-uniform case the user can also specify a “control point”, which affects the degree of the curves, which generate the surface as shown in the figure. Finally, these parameters define the aperture \( \alpha' \) between surfaces (Figure 3(d)), which in turn influences the amount and type of light that enters the space.

**Experiment 2: Agent 2.1 Reciprocal frame porosity Agent**

In our second experiment, we are going towards a system of agents that grow a geometric structure. The idea is to allow porosities in the structure which serves as apertures for sun light. Figure 4 (a), (b) and (c) present our initial algorithm. We start with an initial form found geometry (that is generated with a mesh relaxation algorithm) input by a user. This geometry is then analyzed to obtain the amount of sun radiation on the surface (Figure 4 (a)). We, then, uniformly distribute a set of agents on the surface.

![Figure 4: Diagram illustrating the geometry, analysis and agent behavior of our second experiment, II) Constraints and behavior of the reciprocal principle configuration and the statics graph of a frame with n=4 sticks.](image-url)
attraction force towards the initial geometry, thus allowing a user to influence the final shape. Each agent is repelled by the sun radiation, forcing them to avoid areas with high solar radiation values. Therefore, the agents create a structure with openings in the areas of high solar-exposure, allowing the interior of the geometric structure to be well illuminated. The relative weights of these forces are specified by the user.

Eventually the agents reach an equilibrium state, where their velocities are close to 0. The algorithm, then, changes to a different phase, illustrated in Figure 4 (c). Each agent grows geometric “trees”, by growing “branches” according to an L-system algorithm. This is executed for two reasons: first, to ensure that the final structure is connected; second, in our next step we plan to use these branches to create reciprocal frames structures (as illustrated in Figure 4 (II)). Finally, we consider all agents’ paths and branches in a voxelized 3d space. We consider each voxel where there is either a deposited material from an agent’s path or part of an agent’s branch as full (while other voxels are empty), thus generating the final surface. With this final surface we then expect to further explore, through the agents self-organizing reciprocal frames where the non-uniformity is a negotiation of structural efficiency, and the need for porosity based on the environmental conditioning, and user profile preference data.

RESULTS & ANALYSIS
The initial results of our experiments serve as a proof of concept for the proposed framework. We start by discussing Experiment 1, where an agent grows a window panel. The experiment included running daily and annual radiation analysis of 30 different design outcomes of an office space over a specific time-period (9pm-6am) with parametrically varied glazing ratios (20-90%) of the façade (Figure 5 (a)). We use these results as a baseline, in order to compare with our agent class. Specifically, each analysis measured: a) daylight factor (DLA) in Lux; b) central daylight autonomy (CDA) as a percentage of area with light values above 300 lux and c) useful daylight illuminance (UDI) as percentage of area with light values between 300 and 800 lux.

We then run our agent system to generate window panels for the same office space. We test 25 different parametrizations of our algorithm, and in Figure 5 (b) we show the results of a subset of those. As can be seen, our algorithm was able to generate façade panels that provide the same amount of useful daylight illuminance as the baseline, but critically while bringing down the direct radiation. Hence, our method is more energy efficient. Moreover, in comparison with the baseline, there is a 5% increase of the area that has a Continuous Daylight Autonomy for the tested time period (9:00pm -17:00am). Selected design outcomes, expressive of our desired geometric intricacy, can be seen in Figure 6 (a). The research also included gathering human data for light preferences, from 20 participants that experienced an office space environment through a virtual reality head mounted display (Oculus Rift) and the IVE. The participants were asked to adjust the lighting levels through either the blinds for altering the glazing ratio or turning more artificial lights on in order to perform a specific office related activity (see Figure 2). As a next step the user preference information will be used to automatically adjust the parameters of our system, allowing a feedback loop that automatically adjusts the system according to the user and the current environment condition.

Finally, Figure 6 (b) shows our initial results for Experiment 2, where a swarm of agents emerge a shell structure with permeability that allow the direct radiation of sun light. The figure shows the geometric variations and complexity that can be obtained by different parametrizations of our algorithm, allowing a user to then choose according to her preferences with greater understanding of the performance of the structure. The evaluation of the performance of these designs in terms of DLA, CDA and UDI is still work-in-progress.

DISCUSSION AND FUTURE WORK
For the two experiments, we explicitly selected two different approaches for developing the MAS in order to observe differences in the implementation of tools, and in the evaluation of the design alternatives that the system provides across two objectives: geometric intricacy and design performance (in terms of measurable illumination performance). Our next immediate step is to introduce a feedback loop for both agent classes proposed, allowing the human preferences to directly influence the design outcome. User preference data sets are currently being collected to include not only lighting levels but also heat, sound/noise and viewing preferences.

Concerning our second agent class, which builds a shell structure with gradient porosity, we are currently exploring how to use the output of our algorithm to build reciprocal frames (in order to realize the proposed structures). In particular, using the branches (L-systems) constructed by the agents is our current means to guide the construction of the reciprocal frames. At this stage the quantitative evaluation of the algorithm results is still a work in progress. In addition, materializing the results of both agent classes at varying scales, in order to further empirically test the design outcomes is currently being developed through 3d printing experiments.

Finally, while in this paper we presented two agent classes, our vision is an integrated multi-agent framework where many agents negotiate across multiple aspects of design. Therefore, as next steps towards fully implementing the frameworks’ vision, more agent classes must be implemented, and the actual negotiation and coordination mechanisms must be defined, refined and evaluated. As mentioned, we are currently exploring voting mechanisms for architectural and performance objectives in building design [9].
In conclusion, we would suggest that the research as a whole is contributing to a greater understanding of the myriad of optimization and MAS techniques being deployed, in design and architectural research. Uniquely the work will continue to argue for the crossing of the virtual, physical, and social divides as a means to inform the agent based simulations with environmental, structural and user preference data, driving our design processes toward managing real world complexities.

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Session 4: Interactive Environments

Exploratory Sequential Data Analysis for Multi-Agent Occupancy Simulation Results
Simon Breslav, Rhys Goldstein, Azam Khan, and Kasper Hornbæk
Autodesk Research; University of Copenhagen.

Occupant-Aware Indoor Monitoring for Enhanced Building Analysis
Dimosthenis Ioannidis, Stelios Krinidis, Anastasios Drosou, Dimitrios Tzovaras, and Spiridon Likothanassis
Computer Engineering and Informatics, University of Patras; Centre for Research & Technology, Hellas Thermi-Thessaloniki.

A System for Tracking and Visualizing Social Interactions in a Collaborative Work Environment
Mani Williams, Jane Berry, Asha Rao, and Nathan Williams
Spatial Information Architecture Laboratory, RMIT University; School of Mathematical and Geospatial Sciences, RMIT University; Qinlao Design.

((MODYPLAN)) - Early Stage Hospital Simulation with Emphasis on Cross-Clinical Treatment Chains
Gabriel Wurzer, Wolfgang E. Lorenz, Matthias Rössler, Irene Hafner, Niki Popper, and Barbara Glock
Vienna University of Technology, DWH Simulation Services.
Exploratory Sequential Data Analysis for Multi-Agent Occupancy Simulation Results

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ABSTRACT
In this paper we apply the principles of Exploratory Sequential Data Analysis (ESDA) to simulation results analysis. We replicate a resource consumption simulation of occupants in a building and analyze the results using an open-source ESDA tool called UberTagger previously only used in the human-computer interaction (HCI) domain. We demonstrate the usefulness of ESDA by applying it to a hotel occupant simulation involving water and energy consumption. We have found that using a system which implements ESDA principles helps practitioners better understand their simulation models, form hypotheses about simulated behavior, more effectively debug simulation code, and more easily communicate their findings to others.

Author Keywords
Exploratory sequential data analysis; agent-based simulation; multi-agent simulation; occupancy simulation; visual analysis; debugging; tagging; annotation.

ACM Classification Keywords
I.6.6. [Simulation and Modeling]: Simulation Output Analysis; H.5.2. [Information Interfaces and Presentation]: User Interfaces – Graphical User Interfaces.

INTRODUCTION
Simulation development is an iterative process typically beginning with model design and programming, followed by the execution of a number of simulations, generating streams of results that may be analyzed. As simulation is based on the advancement of time, simulation results are typically sequences of time series data that are concurrent in simulated time. These parallel time series may be analyzed for scientific purposes, such as the generation and testing of hypotheses about the phenomena under study; design purposes, such as performance evaluation of various design options; or development purposes, such as model debugging. There is hence a need for analysis tools which support these tasks, particularly general-purpose analysis tools applicable to entire classes of simulation models such as those involving numerous agents.

Multi-agent occupant simulations are becoming prevalent in the domain of architecture and building science [1,3,12,16]. These simulations can produce large datasets that are difficult to analyze and visualize. For example, in case of crowd simulation [19], simulation output is generally shown as an animation of agent movements. In cases where unexpected behavior is somewhat clear, such as emergency evacuation scenarios, this level of detail is sufficient. However in context of other building occupancy models [1,3,13,16] unexpected occupant behavior is likely to emerge, and thus a greater number of exploratory options are needed at the analysis and visualization stage.

To help practitioners find and debug important behavioral patterns produced by multi-agent simulations, we present an Exploratory Sequential Data Analysis (ESDA) tool called UberTagger [6] that displays aggregate data in the context of agents’ positions and other time-varying properties. We demonstrate the system’s usefulness by applying it to a hotel occupant simulation involving thermal comfort and energy and water consumption. With an effective system for finding behavioral patterns and tagging them, one can gain insights about a simulation model that might be missed when viewing animations, profiles, or statistics in isolation.

RELATED WORK
Exploratory Sequential Data Analysis (ESDA)
Data analytics has been called “detective work” by Tukey [22] to support hypothesis generation. To capture the scope of work done by analysts, a set of principles called Exploratory Sequential Data Analysis (ESDA) was proposed by Sanderson and Fisher [10], originally designed for video analysis of human-computer interaction (HCI) tasks. To better categorize the needed features of analysis tools, the ESDA methodology proposes eight fundamental data transformations critical to support scientific inference and hypothesis generation workflows. The transformations are referred to as Chunks, Comments, Codes, Connections, Comparisons, Computations, Conversions, and Constraints.

Chunks (Groups)
Chunks are “segments of adjacent data elements that the analyst perceives as forming a coherent group” [10]. Grouping and segmentation of data is one of the most fundamental analytical operations that allows the analyst to observe differences and similarities between or within subsets of the data. It is also sometimes becomes necessary to support hierarchical grouping, where groups can be further grouped.
Comments
Comments are “unstructured informal or formal notes that the analyst attaches to data elements, to groups, or even to the results of intermediate analyses” [10]. Comments help to document steps taken during the analysis, which leads to richer data provenance information. Also, in the context of group projects, the ability to add comments helps analysts communicate observations to other members of their team. This has been shown to help emergent patterns to be more easily discovered [15].

Codes (Tags)
Codes, or tags, are user-defined names “attached to data elements or chunks designed to capture the meaning of the data while reducing the variability of its vocabulary” [10]. A tag may be just one word, or a phrase, where each word is separated by either a dash or an underscore. The ability to add tags aside from just comments adds rich metadata that helps analysts more consistently and accurately classify evidence and establish common ground [24], as well as adding a useful organizational mechanism that has been shown to improve overall data analysis results [24].

Connections (Links)
Connections are “a means of following threads through their nonlinear paths and identifying the relationship among their elements” [10]. Connections, or links can also express linear, temporal, or implicit relationships in the data, or relationships between different types of data. Support of links in an analysis process have also been shown to help to gather scattered evidence to support a hypothesis generation process [24].

Comparisons
Comparisons “demonstrate the effects of different treatments of the data with one another” [10]. For example, one might compare different runs of the simulation to identify effects of the different input parameters. Or on the occupant level, one may compare behavior of different occupants and try to discover anomalies or gain a greater understanding of space utilization.

Computations (Aggregation Functions)
Computations “reduce the data to summary representations, including simple counts, complex quantitative relationships, or tests of statistical significance” [10]. While visual-analytics offers a rich analytical foundation, coupling it with quantitative statistical analysis lets the analyst be more confident in the statistical significance of their observations. Aggregating data in this manner promotes the use of informal observation in rigorous scientific approaches.

Conversions
Conversions “transform data in order to reveal new patterns” [10]. Often, conversions are visual, such as in cases of using a new visualization, for example plotting a time series data in a line chart. However, conversions can be more numeric or procedural, such as changing units, converting to a new coding scheme, or changing the scale of analysis.

Constraints (Filters)
Constraints are filters applied to data to exclude items or to select specific items. For example, an analyst may want to focus on a certain subset of the data, such as only a particular group of occupants or a specific period of time.

In the context of the overall modeling and simulation cycle [2], ESDA falls within the Analysis phase, where the analyst tries to gain insight from the simulation results (see Figure 1). Traditionally this phase is associated with testing the validity of the model, quantifying uncertainty in the results, verifying the correctness of the simulation code, and improving performance.

Figure 1: Modeling and Simulation Cycle [2]. Arrows represent processes and boxes represent outcomes.

Occupant Simulation
To produce the input dataset for our exploration, we replicate a resource consumption simulation of occupants in a hotel building described in Goldstein et al. [13]. At any given time the hotel may be occupied by a number of employees and guests. The simulation tracks the position of each simulated occupant, their activities such as eating, sleeping, and rates of power and water usage for all activities. It also predicts air temperatures, which varies smoothly over the interior of the hotel and changes gradually over time.

The output of this simulation has been previously visualized in [4], as shown in Figure 2, where occupant paths are animated using streamlines communicating overall space utilization. Such visualizations encompass some of the ESDA Transformations. For example, visualizing the occupant path is an example of a Conversion, while using different colors for hotel guests (yellow) and employees (purple), is an example of Chunks. However, many of the ESDA Transformations are missing, such as Comments and Codes. Similarly, other work in occupant simulation output
analysis [11,17,20,21], may implement some of the ESDA Transformations, but may leave out some important aspects as they may not be as relevant in the particular evaluation. In this paper, we try to present a system that incorporates all of the ESDA Transformations to illustrate the potential use of these techniques in future work on simulated occupant behavior analysis.

![Figure 2: 3D Floor plan of the Hotel Building from [4]. Yellow paths are hotel guest, while purple are hotel employees, green flash indicates a window opening event.](image)

**Visual Analysis in HCI**

To apply ESDA to the domain of occupant simulation, we draw on work done in the field of human-computer interaction (HCI), as that was the original source of the ESDA theory [10]. Developments in the visual analytics field may be applied to many systems for the analysis of complex datasets [5,6,8,14]. Specifically, we observe a similarity between the building visualization in Figure 2 and visualizations that depict user interaction data (mouse movements) as a Heat Map in Figure 3. The user interaction visualization shows the aggregate behavior of many participants of an online survey, providing information about the amount of time spent in a given area of the webpage. This maps well to the building design domain, where space utilization is of great concern.

To perform our data exploration, we use UberTagger [6], an open source ESDA tool that was designed for analyzing user interaction data. In the next section we outline UberTagger’s user interface, and explain how it supports analyses of not only user interaction data but also multi-agent occupant simulation results.

**APPLICATION OF UBERTAGGER**

The user interface of UberTagger is shown in Figure 4 with panels labeled A through I. Here we describe each panel with a focus on its use of building occupant data and its association with the eight fundamental data transforms of ESDA.

![Figure 3: Heatmap of Mouse Movements from [5] showing large interaction patterns, such as the evidence of scrolling in different window sizes (evident by several vertical striped groups of movements in the right side of the image.](image)

**Data Grid Panel**

The Data Grid Panel (see Figure 4A) is a traditional data table widget, similar to the table interface found in general purpose tools such as Microsoft Excel [18]. To map the data into the Data Grid, we take an occupant centric approach, where each row of the table represents a single occupant, and each column represents some variable associated with that occupant. These column-specific variables may be input parameters or aggregations of time series data.

To make the population of the hotel more realistic, a number of demographic parameters are used as input into the hotel model simulation [13], specifically name, age, gender, height, weight, Body Mass Index, and smoking habit. There parameters are generated procedurally using statistical averages from number of sources, such as the CIA World Factbook [9], NationMaster.com [25], the and World Health Organization BMI Database [26]. Two other very important input parameters for each occupant are the role and group membership. The role parameter determines if a given occupant is a guest or an employee, and a group parameter indicates (a) which room they are staying in the case of a guest, or (b) what job they are performing in case of an employee. Each parameter is displayed in a different column of the Data Grid.

The time series data that we take advantage of in this view include the following: the occupant’s position (floor, and x, y coordinates), his/her water and energy consumption, and his/her window opening actions. In order to map time series data into the Data Grid, an aggregation function needs to be defined for each time-series type. For example, for window opening events, we use summation, while for water consumption we perform an integration to find the total number of liters consumed by an individual. When a given
cell is selected, the corresponding source time series can be visualized in other panels (e.g. Line Chart, Figure 4C).

In terms of ESDA support, Chunks are implemented using a flexible selection and tagging mechanism, where any set of rows or columns can be selected as a group, and saved and tagged. Sorting based on column value implements Comparisons, which gives the ability to rank occupants relative to each other. Sorting by similarity allows for ranking based on multiple columns at the same time. See [6] for details related to similarity sorting implemented in UberTagger. The flexible row and column selection is also an example of Constraints. As the analyst selects different rows and columns, this selection can serve as the filtering mechanism and may be tagged to be re-used. On top of that, any selection can also become a filter, and selected rows or columns can be hidden from the view to decrease visual complexity of the grid. If a given cell has a corresponding Comment or a Tag (Codes) it is styled with a blue border.

Heat Map Panel
The Heat Map Panel (Figure 4B) contains a floor plan of the building design with a heat map of occupant movement overlaid. The hotel design used for our exploration consists of a two-story building, each floor shown side by side in Figure 4B. The hotel features 11 guest rooms, private and public bathrooms, a restaurant, a kitchen, an office, hallways, two elevators, and storage spaces. Waypoints (green dots) represent places where people perform actions, for example, guests eat and sleep, and employees prepare food and perform office work [13].

The visualization of occupant locations in a form of a Heat Map is a good example of the Conversions and Connections transforms. Since the occupant’s locations are visualized on top of the building’s floor plan, implicit Connections are revealed between occupant-specific behavior and the special layout of the building. The Conversion is created when an occupant’s location coordinates are converted into a Heat Map plot, where gradient from purple to yellow indicates increased amount of time spent in that space over selected region of time. Note that “heat” in this case refers to the utilization of space, not temperature. The Heat Map Panel also supports Constraints by two mechanisms, first only selected occupants’ paths are visualized, and second, if a time interval is selected, movements that are within the selected interval are colored with a purple to yellow gradient, while movements outside of the time interval are in gray. See Figure 6, for number of example Heat Maps with different occupants and time intervals selected.

Line Chart Panel
The Line Chart Panel (Figure 4C) visualizes time series data that has been selected. Whenever the analyst selects a time series by clicking on a column in the Data Grid or interacting with various menus associated with the Tags and
Comments panels (Figure 4F-I) a line graph corresponding to all the selected time series is plotted. The colors of each time series are defined as an input parameter for each type of time series. For example, as can be seen in Figure 4C and Figure 7, water consumption rate is in green, and power consumption rate is in orange.

Plotting time series data is an example of Conversions, as sequences of time-associated values are arranged on a 2D viewing area. Comparisons are supported by plotting multiple selected rows or columns. All selected time series are overlaid in the line chart on the same x-y axis, with the y axis normalized to a 0 to 1 interval. Additionally, all the individual time series are displayed below, with each line chart having its own properly scaled and labeled y-axis. This allows analyst to compare both, different time series for a particular occupant, and same-type time series for different occupants.

To be able to explore some period of time in detail, an analyst can select a time period in the top line chart, and all the line charts below update to only the selected period. This is an example of Constraints as well as an implementation of a Context + Focus interface [7]. As the selected time interval changes, the Heat Map view of the occupants’ movement paths also updates to highlight the space occupied during this time.

The line chart panel also provides a playback feature in the top left corner, with an option of different playback speeds. As the playback is activated, other views can update in response to change of the current time. For example, the Heat Map is updated to show current positions of all the selected occupants.

**Current Selection Panel**

The Current Selection Panel (Figure 4D) displays currently selected items, and lets the analyst clear out that selection. There is also a button to update the similarity measure of occupants to a given selection, which is an example of Comparison feature. For example, if an analyst selects water and power consumption columns of a particular occupant in the Data Grid, and then clicks the “Similarity” button, the Similarity column (first column of the Data Grid) will update with a distance to the selected item. See [6] for details on how similarity is calculated.

**New Comment Panel**

The New Comment Panel (Figure 4E) is the main annotation input interface. Comments are the only annotation content made by users, however, comments can contain any number of tags (Codes) and any number of selections (Connections).

Tags are simple single-word annotations preceded by a hash sign: “#”. Tags may be appear separately or may be embedded in a comment, for example:

This occupant seems to be #lost in the building.

An “@” symbol is used to specify an address or location in a comment. For example, the comment above could specify the data rows for a specific duration:

>`The occupant @rows=[27]&time=["07:23:07.986", "07:44:20.833"] seems to be #lost in the building.`

Beyond tags and selections, JavaScript code (Computation, Comparisons, Conversions) can also be inside of comments. A simple JavaScript API allows analyst to do custom plotting and perform basic statistical analysis. When the comment is added using the “Save Comment” button, the computation is performed and the output is rendered as part of the comment. For example, analyst can include the computation is performed and the output is rendered as part of the comment. For example, analyst can include the computation is performed and the output is rendered as part of the comment.

```javascript
1 ***
2 var waterConsumption = c0.getChartData("[water_consumption_d"])[0];
3 var energyConsumption = c0.getChartData("[energy_consumption_d"])[0];
4 var correlation = c0.corr(waterConsumption, energyConsumption);
5 c0.print("Correlation between Water and Energy Consumption: " + correlation);
6 ```

```javascript
5789
```

**Comments Panel**

The Comments Panel (Figure 4G) displays the list of existing comments and lets users select comments, edit, and delete them. This view can be filtered (Constraints) by entering text inside of the Search field. Part of the search query can be a selection (e.g. @row=[27]), which will show the comments that link to that selection.

**Tags and Tag Suggestions Panel**

The Tags Panel (Figure 4H) and Suggestions Panel (Figure 4F) contain tags (Codes). The Tags panel contains all the tags previously added to the dataset, which can be filtered (Constraints) in a similar manner to the Comments Panel. A number of operations can be performed relative to a given tag, such as inserting it into a current comment or filtering comments, rows, columns, or relationships associated with a given tag.

The Suggestion Panel also contains tags. However, some of them may not have been added to the system by the analyst yet, and are automatically extracted by performing Natural Language Processing on the dataset and looking at similar items to a current selection. These automatically extracted tags appear in gray color, while tags that already have been added by the analyst in the past are in blue. See [6] for more detailed description of UberTagger's Recommender System, which is an example of Conversion, where dataset
content is converted into tags, in combination with Connections, since by re-using the same tags, implicit connections are created.

**Relationships Panel**
The Relationship Panel (Figure 4I) displays relationships (Connections) between tags, comments, and selections, where these elements form a directed graph. In practice, users can refer back to these connections to help re-use tags and to informally identify tag frequency in a given dataset.

**ANALYSIS OF RESULTS**
To evaluate the usefulness of the ESDA transformations as realized in UberTagger, we explore a dataset produced by a run of the hotel simulation [13], representing 18 hours of simulated time, as previously described in the Occupant Simulation Section.

**Occupant Behavior**
Each activity and action of each simulated occupant is determined randomly according to probabilities influenced by their role, the time of day, and comfort level [4]. Grouping occupants based on their role (guest vs. employees) and visualizing each group’s location paths in a Heat Map view reveals a difference in space utilization based on the role. While guests tend to only stick to their rooms, hallways and the restaurant (see Figure 6A), employees never go to the guest’s rooms (see Figure 6B). A question concerning the lack of cleaning staff in the current hotel model becomes immediately apparent, giving a clear path for future model improvement.

During the exploration of the individual paths in the Heat Map, an unexpected pattern in the model is revealed. Once or twice during the 18 hour period guests would visit rooms they were not staying in, suggesting that a group of friends or colleagues had booked multiple rooms. Strangely, guests would only visit a room directly above or below their own room (See Figure 6C). This turns out to be a known defect in the model where the floor value is not checked. Animations such as the one illustrated in Figure 2 tend to conceal this behavioral pattern, as a viewer cannot easily track the various rooms visited by various occupants. By contrast, the visualizations in UberTagger make the defect obvious. Analysts may tag these suspected issues, and the annotations can help communicate them to other members of the development team. Issues can be marked as #fixed in later versions of the model.

From a Heat Map over some period of time (see Figure 6D), one might hypothesize that occupants from the same room are likely to dine together. However by looking at the line chart of water consumption (orange blocks in Figure 6D), it can be observed that the consumption rates appear uncorrelated, leading one to question the coordinated dining hypothesis. Investigating further, the playback feature of the Line Chart reveals that an occupant who was dining alone switched seats for no apparent reason, leaving the impression that he/she had company. This turns out to be an oversimplification in the model: the agents essentially forget where they had been sitting as soon as they move. As the analyst discovers these behaviors, she adds comments to document the hypotheses generated during her analysis. These comments and tags can be used for future confirmation of any hypothesis, for comparisons, computations, and to build richer connections in the dataset. Later on, she may come back to a dataset, and be able to recount her previous exploration more easily, or communicate her discoveries to her collaborators.

![Figure 6: Floor plan Heat Maps revealing behavior patterns.](image-url)
Resource Consumption

Sorting occupants based on water usage (Figure 7A) reveals that guests are the top consumers of water. Looking at the distribution of the consumption in the Line Chart also suggests increased usage of the water in the morning. Sorting based on energy consumption (Figure 7B), employees consume more than the guests. Looking at the distribution of the consumption, there is slight hint of the dip in consumption during the night. Seeing these interesting patterns, analysts tag the observations to be more closely explored and confirmed later on.

CONCLUSION & FUTURE WORK

In this paper we have presented the use of Exploratory Sequential Data Analysis principles to analyze multi-agent simulation results. By combining analysis and annotation tools outlined by ESDA, UberTagger gives simulation users and developers a rich toolbox of analysis features. All of the ESDA Transforms seem quite useful, especially combining multiple Conversions together as in the case of the Data Grid, Heat Map, and Line Chart panels, and filtering them (Constraints) based on time regions. Each widget’s Comparison capabilities (e.g. overlaying time series in the line charts for multiple occupants, and overlaying multiple occupant paths in the Heat Map) stood out as the key to be able to draw conclusions about the data. Computations appear to be useful in later stages of the analysis when hypothesis confirmation is needed and when one must calculate some aggregate values not performed by the default visualizations. The effectiveness of Comments and tags (Codes) is evident for bug tracking, analysis documentation, and possible collaborative work.

Analyzing the results using ESDA Transforms revealed a number of possible next steps a simulation modeller can take, such as fixing peculiar occupant behaviors or adding cleaning staff to the simulation. Another important avenue to consider is the question of how ESDA exploration can help one distinguish between efficient and wasteful use of water and energy resources.

With respect to UberTagger’s user interface, we identified missing features that would be helpful. For example, adding spatial filtering of the Heat Map Panel would allow analysts to draw connections between spatial and temporal behavior, such as use of a particular room or a door. Also, since UberTagger is a generic data exploration tool, it lacks simulation-specific information, such as the internal details of the simulation models, to help investigate deeper relationships between the simulation model and simulation results. Adding more simulation-specific features that appear in the literature [23] may be beneficial.

While we have informally tried to see if the ESDA process enhances collaborative work on a large display (Figure 8), a formal study is needed to evaluate cooperative analysis for simulation development. We note that annotation features have been shown to be quite useful in such scenarios [24].

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Occupant-Aware Indoor Monitoring for Enhanced Building Analysis

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ABSTRACT
In this paper a novel, cost-effective and robust occupancy monitoring system is presented, which is based on a fuzzy confidence voting algorithm utilizing spatial height histograms. Spatial height histograms are invariant to rotations and translations, providing this way a desirable feature to occupancy measurement systems, and when combined with distance coefficients can fix an occupancy feature vector, which is the main source for the fuzzy confidence voting occupant tracking algorithm. The proposed occupancy extraction system can be efficiently applied to multi-space environments using a privacy preserving multi-camera cloud. Statistics per building, space and occupant can be finally extracted by the system. The experimental results will illustrate its robustness, accuracy and efficiency on occupancy extraction.

Author Keywords
Occupancy extraction; occupant detection; occupant tracking; spatial height histograms; fuzzy confidence voting; privacy-preserving; multi-camera; multi-space.

ACM Classification Keywords
I.4.8 [Image Processing and Computer Vision]: Scene Analysis

INTRODUCTION
Building occupancy is an essential task for building analysis and simulation. Precise building analysis is highly related to the accurate occupancy information in buildings. Building occupancy can be defined using predefined functions without use of any kind of measuring and training. These tools analyze the building occupancy based on stochastic models (e.g. Markov chain or probabilistic distribution), but they are not accurate since the exploited occupant building usage takes into account predefined models that in most cases do not match to the actual operation of the building [17]. Another methodology for defining the building occupancy is based on information manually collected from occupants’ responses to a questionnaire [9]. However, one can wonder about the accuracy of the occupants’ responses and as a consequence to the building’s usage.

The more accurate building occupancy acquisition can be automatically performed by utilizing surveillance sensors. Thus, occupant tracking is an essential and fundamental task in occupancy extraction. During the past decades, numerous and various approaches have been endeavored in order to improve its performance, as a result there is a fruitful literature in occupant tracking algorithms. However, occupant tracking and extraction still remains a challenging problem in tracking the non-stationary appearance of occupants undergoing significant pose, illumination variations and occlusions as well as shape deformation for non-rigid objects.

An object tracking system mainly raises two essential issues: the detection algorithm that should be applied to locate the target and the type of features which should be used to represent the object. For the first issue, there are two main detection algorithms in the literature, which are referred to as particle filtering and mean shift. The particle filter is based on a stochastic motion model in order to obtain an estimation of the posterior object’s configuration distribution (stochastic model-driven methodology) [16, 17]. On the other hand, mean shift method is based on the density gradients in order to find the peak of probability distributions (deterministic methodology) [7].

Modeling objects’ appearance in videos is a problem of extracting features and is of utmost significance in the overall tracking procedure. In general, there is a large number of tracking algorithms in the literature [8, 14, 15, 18], which can be divided into three main categories:

- **Blob-based methods**: Mimik et al. [13] exploit Kalman filtering, which is applied on 3D points obtained by fusing in a least-squares sense the image-to-world projections of points belonging to binary blobs. Similarly, Black et al. [4] utilize a Kalman filter to simultaneously track in 2D and 3D, while object locations are estimated through trajectory prediction during occlusion. Focken and Stiefelhagen [8] compared a best-hypothesis and a multiple-hypotheses approaches to find people tracks from 3D locations obtained from foreground binary blobs extracted from multiple calibrated views.

Otsuka and Mukawa [15] exploit a recursive Bayesian estimation approach to deal with occlusions while tracking multiple people in multi-view. The algorithm tracks objects located in the intersections of 2D visual angles, which
are extracted from silhouettes obtained from different fixed views. When occlusion ambiguities occur, multiple occlusion hypotheses are generated, given predicted object states and previous hypotheses, and tested using a branch-and-merge strategy. The proposed framework is implemented using a customized particle filter to represent the distribution of object states. Furthermore, particle filters and more sophisticated methods have been utilized by other approaches [5, 6] in the literature as well.

- **Color-Based Methods**: Mittal and Davis [14] propose a system that segments, detects and tracks multiple people in a scene using a wide-baseline setup of up to 16 synchronized cameras. Intensity information is directly used to perform single-view pixel classification and match similarly labeled regions across views to derive 3D people locations. Occlusion analysis is performed in two ways. First, during pixel classification, the computation of prior probabilities takes occlusion into account. Second, evidence is gathered across cameras to compute a presence likelihood map on the ground plane that accounts for the visibility of each ground plane point in each view. Ground plane locations are then tracked over time using a Kalman filter.

  Kang et al. [10] introduce a method which tracks occupants both in image planes and in top view. The 2D and 3D positions of each occupant are computed so as to maximize a joint probability, defined as the product of a color-based appearance model, while 2D and 3D motion models are derived from a Kalman filter.

- **Occupancy map methods**: Recent techniques explicitly use a discretized occupancy map where the objects detected in the camera images are back-projected. Beymer [3] relies on a standard detection of stereo disparities which increase counters associated to square areas on the ground. A mixture of Gaussians is fitted to the resulting score map to estimate the likely location of individuals. This estimate is combined with a Kalman filter to model the motion. Yang et al. [18] compute the occupancy map with a standard visual hull procedure. One originality of the approach is to keep an upper and lower bound for each resulting convex component, on the number of objects it can contain. Based on motion consistency, the bounds on the various components are estimated at a certain time frame, based on the bounds of the components at the previous time frame, that spatially intersect with it.

The proposed system takes into account all the afore mentioned problems and extracts occupancy in the monitoring area, while utilizing a network of privacy preserving cameras, taking into account all the privacy preserving and ethical issues. Thus, the proposed method exploits only the depth information, while color information is discarded.

The occupant tracking and extraction approach introduced in this paper, utilizes a novel fuzzy confidence voting algorithm, which is based on spatial height histograms. Spatial height histogram is a tracking feature based on the height of the detected object, since the privacy preserving cameras utilized by the proposed system can provide only 3D spatial information. Color information is missing. Thus, only a part of the object’s shape is available. Spatial height histograms have some desirable characteristics, such as invariance to rotation and translation transformation, which render them to a useful tool for occupant tracking algorithms. Finally, a combination of the spatial height histograms with a convex hull decision-making algorithm, provide consistency, robustness and efficiency to the proposed occupant tracking and extraction system.

The main novelties of the proposed occupancy extraction algorithm can be summarized as follows:

- Spatial height histograms are utilized as an object feature vector. The spatial height histogram are invariant to rotation and translation transformation.
- A novel fuzzy confidence voting algorithm, which takes the tracking decision.

The rest of the paper is organized as follows. The first Section briefly describes the adopted detection methodology, while the second introduces the occupant tracking and extraction algorithm based on spatial height histograms. Experimental results are presented in the corresponding Section and conclusions are drawn in the last Section.

**OCCUPANT DETECTION**

In this Section the adopted detection methodology described briefly for the article to be complete. A multi-camera occupant detection algorithm [12] was utilized allowing to cover multi-space areas. Each camera is calibrated by calculating the transformation matrices that convert/transform the 3D coordinates extracted by the camera (defined at its own coordinate system) at the global/real coordinate system. The real coordinate system is inherited by the planar architectural map of the area under interest.

The detection algorithm utilizes depth information of the cameras offering data anonymity and taking into consideration all legal and ethical issues regarding individual privacy. The occupants detection approach is very fast taking into account partial object occlusions, and in combination with the adaptive background method, it efficiently detects the occupants in the area under interest. The adaptive background algorithm provides flexibility to the presented system, since the “pure” initial background of an area changes dynamically through time.

Finally, the adopted detection algorithm has a number of advantages [12]:

- Direct camera calibration to the architectural map of the area under interest:
  - each camera is independently calibrated;
  - no overlapping area is required;
  - potential calibration error does not propagated to other cameras.
- A dual-band adaptive background methodology, which incorporates to the background moving objects exploiting different bands, depending on the height of the objects.
- Partial occlusion handling utilizing a virtual top camera.
Privacy protection, since only depth information is utilized.

**OCCUPANT TRACKING**

In this Section the proposed occupant tracking algorithm is going to be introduced. The tracking method is based on a fuzzy confidence voting algorithm adapted on feature vectors extracted from spatial height histograms. The spatial height histograms utilized by the proposed algorithm have some interesting properties, such as rotation and translation invariance, which makes them a useful tool for tracking algorithms.

Spatial height histograms are basically exploited in order to extract the desired feature vector for each detected occupant. In the sequence, a fuzzy confidence voting algorithm is applied on the extracted feature vectors, which votes how an already tracked occupant is similar to a newly detected, based on the determined feature vectors.

**Spatial Height Histograms**

In this subsection, the spatial height histograms are going to be introduced. The only available information that could be utilized by the proposed system is the 3D point cloud of the detected objects. Thus, 3D models entails the potential for supporting tracking through structural information about the occupant. In the proposed approach, structural information of an occupant is captured through its 3D shape and relative arrangement of concentric stripes is identified on the model surface. Concentric stripes are loci of surface points characterized by the same value of a function computed with respect to a center point. The highest point of the detected object’s point cloud is identified as the reference point for the computation of the function. The value of the function on a generic point on the model surface is defined as the Euclidean distance of the point to the center point.

The center point \( c = [c.x, c.y, c.z]^{T} \) of the stripes is defined as the highest point of the object’s point cloud \((c.z > p.z \forall p \in P)\), where \( P \) is the detected object’s point cloud. The distances among the center point and all points of the point cloud \( P \) under examination are computed. Once distances are computed for every surface point (point cloud), concentric stripes \( s_1, s_2, \ldots, s_M \) are identified. \( M \) is the number of the utilized concentric stripes and the \( i \)-th stripe corresponds to the set of surface points on which the distance falls within its limits. All stripes are concentric around the center point \( c \) and have equal radius \( r \). The only stripe that violates this rule is the outer stripe \( s_M \), which is concentric with its radius not being equal to the rest ones, but is still large enough to enclose all outer model points. An example of the geometry of the five stripes is shown in Figure 1(a). Figure 1(b) shows a human 3D point cloud, where five stripes are utilized and each point has been coloured with the corresponding stripe color (the color of the stripe that it belongs).

In the sequence, for each stripe \( s_k \), the height histogram of the points falling into it is computed. Height histogram is defined as the histogram of the points according to their height. Thus, the height histogram of stripe \( s_k \) is defined as follows:

\[
H_k = \{h_{k,1}, h_{k,2}, \ldots, h_{k,N}\}, \tag{1}
\]

where \( h_{k,i} \) is the \( i \)-th histogram bin of the height histogram corresponding to stripe \( s_k \) under examination, and \( N \) is the number of histogram bins. More precisely, each histogram bin \( h_{k,i} \) is computed in a normalized manner, defined as:

\[
h_{k,i} = \frac{\sum_{R_k} H(p.z - b(m)) \cdot H(b(m + 1) - p.z)dp}{\sum_{R} H(p.z)dp}, \tag{2}
\]

where \( R_k \) denotes the pixels belonging to stripe \( s_k \), \( R \) denotes the whole stripes’ area, \( p.z \) is the \( z \) value (height) of pixel \( p \) and \( b(m) \) is the \( m \)-th bin value. \( H(\cdot) \) is the Heaviside function defined as:

\[
H(s) = \begin{cases} 
1, & s \geq 0 \\
0, & s < 0 
\end{cases} \tag{3}
\]

**Tracking Feature Vector**

Having computed the normalized height histograms of all stripes, a spatial feature vector \( F^q \) could be formed for each object \( q \) comprised of all height histograms assigned with a weight. Thus, the spatial feature vector can be defined as:

\[
F^q = \{w_1 H^q_1, w_2 H^q_2, \ldots, w_M H^q_M\}, \tag{4}
\]

where \( H^q_k \) is the height histogram of stripe \( s_k \) of occupant \( q \) and \( w_k \) is a weight factor controlling the influence of the height histogram of each stripe \( s_k \) to the feature vector \( F^q \).

The weights \( \{w_1, w_2, \ldots, w_M\} \) could be equal among each other \((w_1 = w_2 = \cdots = w_M = \frac{1}{M})\). In this way, the height histograms of all stripes have the same influence to the feature vector \( F^q \) and, as a consequence, to the tracking procedure described below. On the other hand, assuming that the occupant height histogram could carry some noise (basically incorporated by the movement of hands), a better approach is to define weights with different values. In the proposed algorithm, in order to overcome the above statement, the height histograms corresponding to central stripes (stripes that are closer to the center) are assigned with larger weight. The weight is getting smaller as the height histogram corresponds to a stripe far away from the center. The adopted kernel function for the weight calculation in the proposed tracking algorithm, is a linear monotonically decreasing kernel function assigning smaller weights to the stripes located farther away from the object’s center, since the points located to these stripes are less reliable. The weigh kernel function
adopted by the proposed algorithm can be defined as follows:

$$w_i = \frac{2}{M(M+1)}i,$$

(5)

where $i (i = 1, 2, \ldots, M)$ is the number of stripes under examination and $M$ is the total number of stripes. More complex weight functions, such as non-linear functions, could be also utilized in that step of the tracking algorithm.

The tracking feature vector produced by spatial height histogram utilizing the above described procedure are invariant to rotation and translation transformations. The invariance properties of the tracking feature vector completely rely on the definition of the spatial height histograms. If the object under examination has been translated or rotated, then the center point $c$ of the stripes remains the same and, as a consequence, the extracted spatial height histograms are also the same. Thus, the invariance properties of the introduced tracking feature vector are inherited by the structure of the spatial height histograms.

**Occupant Tracking**

The occupant tracking algorithm introduced here is a twofold methodology. The first part is comprised by the comparison of the tracking feature vector of each occupant under examination among each other, while the second part is a fuzzy confidence voting method taking the final tracking decision.

In order to measure the similarity between two tracking feature vectors $F^q$ and $F^b$ belonging to objects/occupants $q$ and $b$ respectively, a similarity feature vector metric $dH_{i,j}(\cdot)$ is defined as follows:

$$dH_{q,b} = \sum_{k=1}^{M} \left[ w_k \frac{1}{N} \sum_{i=1}^{N} \left( h^q_{k,i} - h^b_{k,i} \right)^2 \right].$$

(6)

This feature vector similarity metric provides a measurement of how similar the feature vector under examination are. The output of this similarity metric is normalized ($dH_{q,b} \in [0, 1]$), since all the values participating at its computation are already normalized.

Moreover, another metric $dD_{q,b}(\cdot)$ is utilized, which expresses the Euclidean distance in 3D space among the feature vectors’ centres, and it is defined as follows:

$$dD_{q,b} = \frac{\sqrt{(c_q.x - c_b.x)^2 + (c_q.y - c_b.y)^2}}{d_n},$$

(7)

where $c_i = [c_i.x, c_i.y, c_i.z]^T$ is the feature vector center of object $i$, and $d_n$ is a normalization factor that forces the distance metric to provide normalized output ($dD_{q,b} \in [0, 1]$).

Furthermore, the final similarity metric $d_{q,b}(\cdot)$ between two tracking feature vectors $F^q$ and $F^b$ belonging to objects $q$ and $b$ respectively, is a linear combination of the above mentioned metrics (6) and (7), and is defined as follows:

$$d_{q,b} = \alpha \cdot dH_{q,b} + (1 - \alpha) \cdot dD_{q,b},$$

(8)

where $\alpha$ is a constant factor that controls the influence of each metric to the final similarity metric. When factor $\alpha$ is getting larger, the influence of the height histogram similarity metric to the final similarity metric is larger against to the Euclidean distance metric of the vectors under examination. On the other hand, as factor $\alpha$ gets lower values, the influence of the height histogram similarity metric to the final metric is also getting lower. If factor $\alpha$ is set equal to zero ($\alpha = 0$), then only the Euclidean distance metric participates in the computation of the final similarity metric among tracking feature vector. If factor $\alpha$ is set equal to one ($\alpha = 1$), then only the height histogram similarity metric participates in the final similarity metric computation.

**Target Localization**

Target localization consists of a fuzzy confidence voting method. In a fuzzy confidence voting method, each already tracked object $i$ (existing from the previous tracking step) is required in order to cast a vote for the newly detected objects $j$ with a confidence $v_{ij}$ exploiting fuzzy logic.

The voting procedure achieves the best vote distribution by minimizing a weighted objective function $J_m$, defined as:

$$J_m = \sum_{j=1}^{N_{tr}} \sum_{i=1}^{N_{det}} v_{ij} \det_i d_{i,j}^2,$$

(9)

where $N_{tr}$ is the number of the already tracked objects, $N_{det}$ the number of the newly detected objects, $v_{ij}$ the confidence of the vote of object $i$ to object $j$, $m$ is the weighting exponent of each vote, and $d_{i,j}$ is the similarity metric (8) based on height histograms among objects $i$ and $j$. Taking the partial derivative of $J_m$ (9) with respect to $v_{ij}$ and setting the result equal to zero, the explicit function of the vote’s confidence $v_{ij}$ can be derived [11], which is finally given by:

$$v_{ij} = \frac{1}{\sum_{k=1}^{N_{det}} \left( \frac{d_{i,k}^2}{\pi_{i,k}} \right) - \frac{1}{m-t}},$$

(10)

where $N_{tr}$ is the number of the already tracked objects and $m$ is a fuzzifier weighting exponent.

The confidence matrix $V$ consists of all votes’ confidence $v_{ij}$ from each already object/occupant $i$ to the newly detected object/occupant:

$$V = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,N_{det}} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,N_{det}} \\ \vdots & \vdots & \ddots & \vdots \\ v_{N_{tr},1} & v_{N_{tr},2} & \cdots & v_{N_{tr},N_{det}} \end{bmatrix}.$$ 

(11)

The voting confidence function $v_{ij}$, and as a consequence the confidence matrix $V$ adopted in the proposed algorithm, have some characteristic attributes:

- All produced confidences based on the proposed fuzzy voting function inherently has values between $v_{ij} \in [0, 1]$.

- The summation of the votes’ confidence produced by a single occupant against all detected occupants should be equal to $\sum_{j=1}^{N_{det}} v_{ij} = 1$. 

88
Exploiting the above defined fuzzy voting confidence function $v_{ij}$, the proposed algorithm can track the detected objects. Thus, a greedy search in the confidence matrix $V$ is looking for matching already tracked objects to detected objects. The confidence $v_{ij}$ of the vote of an already tracked object $i$ to a detected object $j$, is equal to one ($v_{ij} = 1$) for a perfect match. The confidence $v_{ij}$ is getting smaller as the match gets worse, and becomes zero ($v_{ij} = 0$) for a perfect mismatch. Utilizing the confidence matrix $V$, the tracking algorithm can easily identify which already tracked object $i$ corresponds to each newly detected object $j$. The correspondence among tracked and detected objects is accomplished by looking for the maximum entry $v_{ij}$ in each column $j$, which should also be the maximum in the corresponding row $i$ of the confidence matrix $V$. Due to the reduced basis matching, the maximum confidence value is required in both directions (rows and columns) instead of one direction only (either row or column). In other words, a match between the tracked object $i$ and the detected object $j$ can only be valid if $v_{ij}$ is the maximum value for both $i$th row and $j$th column in the confidence matrix $V$. A restriction that should be applied on the reduced basis matching algorithm is that the maximum matching value should be larger than a predefined threshold ($v_{ij} > \text{thr}_{\text{matching}}$).

This matching threshold $\text{thr}_{\text{matching}}$ controls and protects the matching process from undesirable matches. The physical meaning of the threshold $v_{ij}$ of the vote under examination should be high enough against the opponents votes, in order to consider that vote as valid. Exploiting the trial-and-error method, it has been experimentally proven that a good value for the matching threshold is $\text{thr}_{\text{matching}} = 0.5$. This value is physically explained that the object/occupant $i$ votes object/occupant $j$ with more than 50% confidence, since $v_{ij} = 1 - \sum_{k \neq j}^{N_{\text{det}}} v_{ik}$.

Through the above correspondence method on the confidence matrix $V$, the already tracked occupants are corresponded to the new detected occupants. But, some objects remain “orphans” (no available correspondence found) under certain circumstances. The orphan objects can be divided into two major categories, and their behaviour is determined by a number of tracking rules introduced in this paper. Let us examine each category:

- **Tracked “orphan” occupants.** The already tracked occupants that do not correspond to any available newly detected occupant, belong to this category. These “orphan” occupants are considered as gone or estimated occupants, depending on their location:
  - If they are located in the region of camera’s convex hull, then they are considered as occluded and their position is estimated.
  - If they are located at the boundaries of camera’s convex hull, then they are considered as exited and removed from the system.

- **Detected “orphan” occupants.** All the detected occupants that do not correspond to any already tracked occupants, belong to that category.

The combination of the fuzzy confidence voting method and the tracking rules described above, have proved to be efficient and robust, as it is demonstrated in the Experimental Results Section.

A block diagram of the proposed occupant tracking methodology is illustrated in Figure 2.

![Figure 2. The block diagram of the proposed occupant tracking algorithm](image2.png)

**EXPERIMENTAL RESULTS**

To evaluate the introduced occupants’ tracking and extraction system, a large, real experiment has been set up to the medical oncology department of a University Clinic. The utilized depth cameras provide a monochrome depth sensing video stream in VGA resolution ($640 \times 480$ pixels) with 11-bit depth at 2048 levels of sensitivity.

![Figure 3. Depth cameras’ position at the pilot site.](image3.png)
The experiment consists of eleven depth cameras monitoring two meeting rooms, the lift area and the corridor, connecting all these three areas (Figure 3).

The evaluation of the described occupant tracking algorithm has been performed exploiting different accuracy metrics, the Sequence Tracking Detection Accuracy (STDA), the Average Tracking Accuracy (ATA = STDA/N frames) and the Multiple-Object Tracking Precision (MOTP) [1], which are defined as:

$$STDA = \frac{\sum_{i=1}^{N_{frames}} \left[ \frac{G_i^{(t)} \cap D_i^{(t)}}{G_i^{(t)} \cup D_i^{(t)}} \right]}{N(G_i \cup D_i \neq 0)}$$

(12)

$$MOTP = \frac{\sum_{i=1}^{N_{frames}} \sum_{j=1}^{N_i^{mapped}} \left[ \frac{G_i^{(t)} \cap D_i^{(t)}}{G_i^{(t)} \cup D_i^{(t)}} \right] \sum_{j=1}^{N_j^{mapped}}}{N_{frames}}$$

(13)

where $N_{mapped}$ is the number of mapped object sets, $N_{frames}$ is the number of frames under examination, $G_i^{(t)}$ denotes the $i^{th}$ ground truth object in $t^{th}$ frame, $D_i^{(t)}$ denotes the $i^{th}$ detected object in $t^{th}$ frame, $N(G_i \cup D_i \neq 0)$ indicates the total number of frames in which either a ground truth object or a detected object or both are present, $N_G$ denotes the ground truth objects, $N_D$ represents the number of detected objects, and $N_i^{mapped}$ refers to the number of mapped objects in the $i^{th}$ frame.

In all experiments described in this Section, the presented tracking system configured utilizing 3 stripes, 60 bins for each spatial height histogram, factor $\alpha = 0.3$ and fuzzy weighting exponent of each vote $m = 2$. The selected numbers are justified below.

| Table 1. Accuracy of the proposed occupant tracking algorithm |
|------------------|---------|---------|
| **STDA** | **ATA** | **MOTP** |
| 26.1184 | 0.7647 | 0.7898 |

For the proposed occupants’ tracking algorithm’s evaluation, a 5800 frame video stream (for each camera) has been manually annotated. Table 1 shows the accuracy metrics for the tracking algorithm. One can notice that both the tracking accuracy (ATA) and precision (MOTP) are very high.

The proposed occupants’ tracking system basically works with object’s coordinates, thus distance tracking metrics are more suitable for its evaluation. A thorough evaluation of the introduced algorithm has been performed based on the Sequence Tracking Detection Accuracy - Distance (STDA-D), the Average Tracking Accuracy - Distance (ATA-D) and the Multiple-Object Tracking Accuracy (MOTA) [1]:

$$STDA-D = \frac{\sum_{i=1}^{N_{frames}} (1 - d_i^t)}{N_i^{G}}$$

(14)

$$MOTA = \frac{\sum_{i=1}^{N_{frames}} N_i^{G}}{\sum_{i=1}^{N_{frames}} N_i^{G} - \sum_{i=1}^{N_{frames}} N_i^{D}}$$

(15)

where $d_i^t$ represents the distance between the $i^{th}$ mapped pair, $c_m(\cdot)$ and $c_f(\cdot)$ are cost functions for the missed detects and false alarm penalties, $m$ is the number of missed tracks, $fp$ the total number of false alarm tracks, $id_{switches}$ is the total number of ID switches made by the system output for any given reference ID and $N_i^{G}$ denotes the ground truth objects in the $i^{th}$ frame.

Figure 4 illustrates the ATA-D and MOTA metrics for different number of stripes.

Furthermore, in order to determine the parameters utilized by the proposed algorithm, a deterministic optimization algorithm, known as Iterated Conditional Modes (ICM) [2], was exploited. Thus, each parameter was examined separately, while keeping fixed the others. So, the introduced algorithm has been tested with a variety of different number of bins producing different spatial height histogram features. Figure 5 illustrates the ATA-D and MOTA metrics of this kind of experiment. One can easily notice that the best system’s accuracy and performance was acquired by utilizing 60 bins in the spatial height histogram feature vector extraction algorithm.

A similar self-benchmark of the proposed system has been performed for the factor $\alpha$, utilized in (8), which controls
the influence of the spatial height histogram feature and the Euclidean distance feature affect at the final object similarity metric. Figure 6 illustrates the ATA-D and MOTA metrics for different values of $\alpha$ factor varying from zero to one ($\alpha \in [0, 1]$). It is clearly depicted that the best algorithm’s performance and accuracy according to ATA-D and MOTA metrics is acquired by utilizing $\alpha = 0.3$.

There is no a benchmark database with depth images in the literature in order to compare the proposed algorithm with other tracking algorithms. Depth channel produces noisy information, however the proposed algorithm succeeds to achieve and produce very accurate results. Furthermore, a comparison of the proposed approach with existing algorithms on different video sequences with different kind of information (depth and color) will be biased, so it has been avoided.

However, the proposed algorithm has been compared with the approach introduced by Krinidis et al. [12], where the tracking procedure is based only on the Euclidean distance metric.

Table 2 illustrates a comparison with the method presented in [12] using the ATA-D and MOTA metrics. It is clearly depicted that the proposed algorithm surpassed the method presented in [12] producing more accurate tracking results. Furthermore, Table 2 illustrates the quantitative efficiency of the introduced tracking algorithm utilizing only depth information. In general, the combination of the spatial height histogram with the fuzzy confidence voting algorithm and the convex hull tracking rules inserted to the tracking algorithm, proved to be efficient and robust, as it is confirmed by the numerical results presented in Tables 1 and 2.

Finally, another experiment performed for a whole year assisted in (Figure 3) extracting statistics for the monitoring area, for each space, as well as for each person.

The statistics of the overall monitoring area at the pilot site (Figure 3) are shown in Table 3, while those per spaces are illustrated in Table 4. Table 5 shows the statistical results of a randomly selected person (person with ID=787).

The whole experiment was concluded through the year without any particular problem. Furthermore, the algorithm was installed to an area covering over 350 $m^2$, without any particular changes in its performance.

CONCLUSION

In this paper an occupants’ tracking system has been presented. It adopted a simple and fast occupant detection algorithm utilizing depth information of the cameras offering data anonymity. Spatial height histograms, which are invariant to rotation and translation transformation, were utilized by the proposed system and they constitute the main object features, while a fuzzy confidence voting algorithm is exploited in order to perform tracking. The combination of the introduced feature vector with the fuzzy confidence voting method and a convex hull tracking decision-making methodology, has proved to be robust, efficient and reliable.
Moreover, this system could be utilized to improve building performance monitoring, building management systems, facility management systems, building automation systems, etc. In addition, it can be exploited to extract detailed building occupancy information for accurate building analysis and simulation purposes.

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ABSTRACT
This paper presents our work on indoor tracking and demonstrates its capacity as a data collection system for the study of socio-spatial interactions that occur in a collaborative work environment. Deployed at a recent week-long international design workshop, our system was able to track the movements of more than fifty people from various roles, and generate live visualizations. In this paper we will present the data collection system and the system configurations, the complete dataset collected and sample visualization scripts to stimulate further research in the area of people interaction study and its relation to spatial usage.

Author Keywords
Indoor tracking; behavior modeling; data visualization; collaboration; design workshops.

INTRODUCTION
The study of social interactions has many applications including organizational management, post occupancy evaluation and occupant behavior modeling. The widely used ethnographic methods of data collection such as participant observation, interviews and questionnaires are labor intensive and require experience and expertise to properly execute and process into quantifiable datasets. With the rise in digital communications, researchers now have relatively easy access to vast amounts of social data from social network platforms as well as from tracking personal devices [1]. In the physical spaces, especially the indoor environment, there is still an active area of research in sensor systems and applications in developing systems to accurately capture human movements [2]. This paper extends current work in this area [3-6] by presenting the technical specifications of our deployable system that is capable of collecting social data in the built environment in an automated and minimally intrusive manner. We aim to present the system in a format that is easily replicable and adaptable by others that are interested in conducting research on indoor people behavior. The data collected from this system is supported by a set of fixed cameras that collect time-lapse photography of the space.

In this paper we will present an overview of the technical details of the equipment and the data collection setup, demonstrate the functionalities of the system using sample data and visualizations, as well as recommendations on how to implement our setup at other venues and events. The dataset and sample visualization script are included with this paper [7].

EQUIPMENT AND SETUP
The setup used in this project is categorized into two sub-systems: indoor tracking and time lapse photography.

Indoor tracking
The indoor tracking system is composed of an off-the-shelf ZigBee-based indoor location system, a Raspberry Pi-based local database and an automated visualization interface hosted on Amazon Web Services (AWS).

The ZigBee-based indoor location system includes a set of tracking tags, a set of beacons and a data module. The tagged participants attached the tracking tags to their nametag lanyards. The beacons and the data module require external power. The location system modules communicate to each other wirelessly via the ZigBee mesh protocol [8]. The ZigBee protocol supports auto configuration between devices, giving greater system adaptability and flexibility: we could rearrange the beacons and introduce new participants into the system with ease. The ZigBee data module periodically outputs the tag locations via an Ethernet connection using the UDP protocol, targeted to a specified IP address and port number.

The Raspberry Pi-based data collection system (to be referred to as the data collector) is a single board computer running the Raspbian operating system (a Linux distribution optimized for the Raspberry Pi hardware). We set up the system with the required IP settings and connected it to the same local area network (LAN) as the ZigBee data module. It listened on the specified UDP port number to capture the location data as the ZigBee data module transmitted it. The data was then stored on a MySQL database, with the current computer time taken as the data time stamp. This LAN setup allowed us to place the ZigBee data module at an advantageous position inside the wireless mesh network and away from the Raspberry Pi.
which required easy access for maintenance. A time-based script was scheduled on the Raspberry Pi to synchronize the local database with a remote database.

Due to its limited processing power, a Raspberry Pi computer could not reliably handle stream data capturing and advanced data processing on the same device. An AWS EC2 instance running Ubuntu Linux was set up as the cloud computer to handle live data analysis and visualization. A MySQL database was set up and periodically synchronized with the onsite database. We installed R and a collection of R libraries to conduct primary data analysis and generate visualizations. This will be described in detail in the later section of the paper. A t2.micro EC2 instance was found to be sufficient to process and generate the visualizations at scheduled one-minute intervals. The visualizations were publically accessible via a website hosted on the EC2 instance.

**Time-lapse photography**

A set of Raspberry Pi-based IP cameras was configured to capture photographs of the areas of interest. It utilizes the Raspberry Pi camera module, and can be configured to capture an image on command or at preset intervals. Each was installed on the ceilings of the spaces with a view to cover an activity area. This provided us with a good visual record of the activities that occurred in these spaces.

![Figure 1 Floor plan of the main workshop spaces monitored by the tracking system](image)

**Figure 1** Floor plan of the main workshop spaces monitored by the tracking system

<table>
<thead>
<tr>
<th>Tag</th>
<th>Time</th>
<th>Beacon 1</th>
<th>RSSI 1</th>
<th>Beacon 2</th>
<th>RSSI 2</th>
<th>Beacon 3</th>
<th>RSSI 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEX 6</td>
<td>String</td>
<td>HEX</td>
<td>HEX</td>
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<td>HEX</td>
<td>HEX</td>
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</tr>
<tr>
<td>chars</td>
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<td>4 chars</td>
<td>2 chars</td>
<td>4 chars</td>
<td>2 chars</td>
<td>4 chars</td>
<td>2 chars</td>
</tr>
</tbody>
</table>

**Figure 2 Tracking data stored format**

**DATA COLLECTION**

The data collection was conducted at a recent international design workshop. The workshop was held over five days with an exhibition on the evening of the last day. Several projects operated within the workshop. Each project consisted of project leaders, participants and technical supporters. Throughout the five-day event, the workshop occupied the entrance, atrium space and a large proportion of a floor of an educational institution building. The spaces were mostly open, allowing the workshop organizers to vary the amount of the space assigned to individual projects as needs arose.

Thirteen beacons were installed at the beginning of day two and an additional nine beacons were installed on day four, with configurations as shown in Figure 1. We placed the beacons regularly around and above the activity spaces to get good coverage of the activities. This covered the atrium and project areas on the main workshop floor level; these were occupied by the eight workshop projects and the workshop organizers’ desk. Participation in the tracking experiment was voluntary; fifty tags were distributed to the workshop attendees, this included representatives from all of the eight projects that occupied the floor as well as several of the workshop organizers. Additional tags were placed in the tracking zone for evaluation use. The tracking system recorded data from the start of day two to the end of day five. The location system was configured such that when a tag was detected to be within range, it collected the ID and the received signal strength indication (RSSI) from the three strongest beacon signals and output a data entry via the ZigBee data node. A timestamp was added by the data collector. Figure 2 shows the final data format.

The dataset published with this paper includes:

- the raw tracking data recorded from the ZigBee location system;
- a floor plan of the workshop area;
- the coordinates of the beacons in relation to the floor plan;
- a list of the tags, noting the project or activity they were associated to (labeled as ‘group attributes’.)

The IP cameras were installed to cover each of the project activities, in operation from the start of day one to the end of day five. We configured the cameras to take a long exposure image at five-minute intervals. This was to produce a blurred image that captured the dynamics of the activities, and also had the additional advantage of giving privacy to the workshop participants. The photos are not part of the dataset that is published with this paper, but we have produced a set of videos from them which can be viewed from the Author’s website [9].

**SAMPLE DATA AND VISUALIZATIONS**

In this section we will present samples of the tracking data and sets of visualizations to explain aspects of the data.

**Live visualization of the tracking data**

During the data collection period we knew the locations of the beacons but not the group attributes of the tags. From these we produced a set of the live visualizations based on the latest ten minutes of data. The color corresponds with the tags’ group attribute.
• For each tag we plotted the triplet beacon records against time (Figure 3 top insert).

• Referring to the known coordinates of the beacons we could estimate the positions of the tags using weighted mean methods [10], where the weight is the corresponding RSSI. In the rest of this paper we will refer to these coordinates as (tag) position estimates (Figure 3 top main).

• We also produced overview versions of the time and spatial plots by overlaying all tag data onto one plot (Figure 3 bottom).

**Figure 3** Sample live data visualizations produced from ten minutes of data. Top: Time plots and spatial plots for an individual tag, showing individual’s movement path. Bottom: Combined overview of all tags in the space, showing group spatial preference.

**Group behaviors**

We collected information on the activities that the tagged individual were involved in, which allowed us to assign group attributes to tags. By assigning colors to the group attributes we can start to represent and visually identify the group behaviors.

Taking a one hour sample from the dataset, we separated the sample by the data entries tag group attributes and plotted each group onto the floor using the tag position estimates (Figure 4). We could see that in this hour the workshop coordinators (SG) and hosts (CUHK) visited different projects. Between the eight tracked projects (PM, SE, RN, DS, FB, ST, DSE and Block) we could also observe distinct behaviors: PM appeared to be operating from two spaces, FBR was more mobile and Block was absent during that hour.

**Figure 4** Spatial plots of the estimated tag positions from 1 hour of sample data, categorized by the tag group. From these we can see district spatial behavior between the groups.

**DISCUSSION**

As with any project involving humans, it was very important for us to conduct this project in an ethical manner. Specifically we sought ways to protect the participants from harm and encourage participation through engagement:

• Voluntary participation: We selected the ZigBee based system as the tracking tags are self-contained; this allows the participants to easily detach the tag from their person if they do not wish to be tracked for a period of time. We believe this is less intrusive than other tracking systems that rely on personal devices (such as WiFi or Bluetooth based systems)

• Transparency and participant engagement: By producing live data visualization the people were more comfortable with the idea of been tracked. After recruiting the initial set of participants, we had people approach us to be tagged because they have seen or heard from others of the data visualizations. Participants also came to us with unplanned requests such as asking us to help to locate a bag and increase time-lapse photograph frequency to help document their project.

Positive engagement also extends to the workshop organizers and hosts. During the project planning stage the host was actively contributing to the selection of the locations for beacon and camera installation. Communication with the workshop organizers allowed us to more accurately plan the quantity of equipment required. The support from the organizers and host eased the installation and recruitment process.

**Known system limitations**

We estimated the spatial accuracy of the tracking data to be between 1 to 2 meters. This is highly dependent on the spatial context: such as the presence of people, furniture placements, and surface materials; this is a known issue with RSSI-based indoor tracking systems operating at 2.4GHz. We are conducting ongoing research to improve tracking accuracy using data processing methods.

The data collection Raspberry Pi performs database backup and remote synchronization at five-minute intervals, which minimizes data loss. We also noticed issues with data drop: when the data collector lost internet connection the system hangs for approximately 45 seconds at each scheduled
synchronization job. These issues could be resolved with a better system design.

With reference to the time-lapse we observed instances of tags left behind overnight. It is also known that some participants kept the tag in bags. We are currently developing data mining methods to identify the idle tags and remove them from the dataset. This is still a work in progress; from the reference tags placed in the space we have data on the “appearance” of idle tags. In the tag list included in the dataset we have included descriptions of the reference tags, and we welcome external collaboration on this topic.

We are also working on modeling interaction behavior based on (a) personal proximity extracted from the position estimates and (b) people-spatial interaction interpreted from the tag-beacon data entries. We see the methods developed from this research applicable to other tracking setups and contexts. Figure 5 shows some of our preliminary results.

ACKNOWLEDGMENTS
The authors would like to thank the participants of the SmartGeometry2014 Workshop for their support and contribution to the case study reported in this paper; we also thank the SmartGeometry Group and the Chinese University of Hong Kong for giving us the permission to conduct data collection. This research was supported under Australian Research Council’s Integrating architectural, mathematical and computing knowledge to capture the dynamics of air in design funding scheme (project number DP130103228).

REFERENCES
((MODYPLAN)) - Early-Stage Hospital Simulation with Emphasis on Cross-Clinical Treatment Chains

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ABSTRACT
Health trusts are aiming to consolidate the clinical landscape: The provision of medical services, now handled by individual clinics, is to be transformed such that the patient volume can be redirected between different specialized service providers. As implication, hospital planning needs to embrace the subject of cross-clinical development rather than looking at each facility in isolation. In this context, we have been developing ((MODYPLAN)), a cross-clinical simulation for early-stage architectural planning. Our software takes the patient volume as input and redirects it to different facilities, each one having a different spatial layout and treatment capacity. As outputs, we obtain the utilization and occupancy of each service unit on which we can base further analysis concerning bottlenecks. Furthermore, different configurations of the clinical landscape can be compared, facilitating a multi-faceted discussion among stakeholders (clinical providers, their staff and patients). As audience, we target hospital administration, architects and process designers preparing or working on tenders. Such an early application of cross-clinical simulation is, to the best of our knowledge, yet unprecedented.

Author Keywords
Hospital planning; cross-clinical simulation; early-stage planning; service provisioning; resource utilization.

INTRODUCTION
Medical service provision is planned both regionally (strategic planning of a clinical region) as well as locally (hospital planning concerning a single clinic). The goal is to adapt the capacities of medical service units in accordance with the needed future demand. Physically, this may be accomplished through (1.) building, refurbishing or closing clinics and (2.) transferring departments to specialized facilities, leading to strong cooperation in a clinical region. But how to evaluate which of these measures should be taken? In this paper, we seek to answer this question through whole-building simulation based upon the patient schedules and the preliminary building layout. In more detail, we

• give a short overview of the whole-building simulation approach which we use, which is aimed at early-stage planning conducted by architects and organizational planners (see Background),
• define which options exist when developing a clinical region both from a building as well as from an organizational viewpoint (see Options for Clinical Development),
• outline how these options can be represented and quantified in our simulation (see Representing and Simulating Planning Options).

To be fair, we have so far not applied these concepts in an actual planning process: The implementation of our software is just finishing and we are transitioning to a phase where we have first customer shipments of the alpha version. Instead of a case study, we thus give a discussion of our idea (see Discussion) before concluding.

RELATED WORK
We use an Agent-Based Simulation (ABS) model in which each agent visits a sequence of functional units (FUs) – spaces having a finite capacity and defined spatial scale (e.g. examination room, medical department or whole clinic, depending on the type of simulation study). The choice of ABS is motivated by the ease of interacting with the environment (i.e. the spatial program consisting of FUs and circulative system). We have no “behavioral” aspect in our implementation as other authors do [1,2]. Omitting the reference to space, we could also have used DES [3] or even Petri Nets [4], however, we chose not to do so for being able to reason spatially (e.g. also for adjacency planning conducted as extra module of the development of our software [5]).

Within ABS, our approach can be seen as schedule-based simulation where each entry of the schedule is exported from a Hospital Information System (HIS). Other approaches rely on questionnaires for obtaining this information, e.g. Tabak in his Ph.D. thesis “User Simulation of Space Utilisation” [6]. Regardless of whether an automatic or manual surveying technique was used, the gathered data can be used to generate fictional schedules reproducing the same characteristics. Goldstein et al. [7] have called this extrapolative approach “schedule-calibrated”, where a future activity can be based on the past schedule. We have a similar possibility for generation,
Based on often-reoccurring “standard schedules” in which we can leave out certain activities according to probabilities (see Background).

**BACKGROUND**

Our paper builds upon a previously published description of our simulation model [8], which we wish to summarize briefly before returning to the scope of cross-clinical simulation.

**Overview of our Simulation Model**

Our model is based on individual schedules for each patient which are executed within the building layout. More precisely, a schedule in our terms is a sequence of FUs that a patient has to visit. These are spaces (see Figure 1a) - e.g. a single examination room, a department or a whole clinic, depending at the intended resolution of the simulation study. A FU can further be capacity-constrained, i.e. acting as resource of the simulation (e.g. examination room with 2 treatment places in Figure 1a). Exceeding this capacity leads to queue formation. The queuing strategy (e.g. FIFO, priority queuing such as in the form of a Manchester Triage) is specified separately, in the form of a behavior governing the FU.

![Figure 1.](image)

**Figure 1.** (a) FU of capacity 2 means that two agents may enter and all others have to queue. (b) FU consisting of nested sub-units, governed by a single overall behavior.

FUs can be nested to form a spatial hierarchy (FUs within FUs, see Figure 1b). A behavior controlling such a composite unit can be used to guide the passage of patients through its sub-units, allowing to model processes that are standardized (e.g. acting on a preset spatial configuration, e.g. for an operation area).

**Outputs**

Our simulation model measures three types of results,

1. the agent history in the form of FUs utilized and queued for, implicitly, this also gives the passage length of each individual patient (obtained through route computation between each two FUs on the way),
2. utilization of each FU (agents in the FU as well as queues before the FU),
3. occupancy (time spent within the FU, which is different from utilization for FUs that are not capacity-constrained, such as general waiting areas without seats).

Based on these factors measured in each simulation run, we can go on to compare the different options for clinical planning that are presented due course.

**OPTIONS FOR CLINICAL DEVELOPMENT**

Clinics have to be constantly adapted so as to keep track with the expected patient volume, which undergoes changes not only in numbers but as well in its characteristics (medical progress leading to changed treatment, and thus also to different schedules for each patient). An effect of this is that a FU may be over- or underutilized, as given in Figure 2a. More specifically, the capacity of a FU refers to physical entities such as chairs in a waiting area (see Figure 2b), which have a required area. In that example, overutilization would mean that there are not enough seats available in that area, but increasing the capacity of the FU may not be possible due to lack of extra space within the FU. Underutilization would mean that there are always seats free and thus space is wasted.

![Figure 2.](image)

**Figure 2.** (a) Over- and underutilization of a FU. (b) Space requirements of a resource unit of a FU.

The core problem of how to extend or decrease the capacity of a FU, also acting on its space, is the main topic to be addressed by clinical planning. As we will see, measures in that context range from localized to regional options, which will be scrutinized in due course before coming to details of how we handle these cases using our combined simulation/planning tool, ((MODYPLAN)).

**Local options**

The simplest type of intervention is to adapt the capacity of a FU by adding or removing resources, which might entail building activities (changed arrangements of spaces, changed equipment, etc). Such an approach is usually called refurbishment, if the actual building structure is not changed. Another option would be to add a (temporary or permanent) structure to the building, which acts as an extension. One example for the latter are prefabricated surgery modules, which have recently become popular (minimal planning time, fixed costs for building and known running costs). By contrast, a new building requires a lengthy process for planning and building (typically 10 years, as by an own survey by the authors), based on requirements that try to predict the next 10 years after the building goes into operation. Given such an uncertainty in planning, closing a clinic and transferring the departments to the new building might not work as expected, since requirements and patient volumes might have changed in the mean time.
Cross-clinical options
Forming highly-cooperating special clinics in which medical services are concentrated is a long-term trend in provision planning. From a practical standpoint, this means that departments are transferred and patients are redirected. The question of existing patient volume in the target clinic being merged with that of the old department needs to be investigated. The same goes for the coordination between the cooperating clinics. Electronic integration, physical interactions such as pick-up and delivery service and so on are central for ensuring the cooperation between the facilities.

REPRESENTING AND SIMULATING PLANNING OPTIONS
The aforementioned planning options are represented as follows in our tool:

- Refurbishments act as a change in capacity of a functional unit. We store the space requirements of each resource unit (see again Figure 2b) and complain if there is not enough space to accommodate the new capacity. The planner can then change the space of the FU to make that possible.
- Extensions of a clinic are new FUs giving additional capacity. The agents will use the extensions in parallel to pre-existing ones.
- For new buildings, we design a schema with the envisioned functional units but simulate with the given patient volume of the previous building. In that way, we can constrain the building such that it can handle the current patient flow. Changed departmental roles (e.g. a central A&E instead of two individual departments) need to be mapped manually by the planner in the input data.
- We do not explicitly handle the case of a clinic being closed and its departments transferred to a new building. However, one could set the capacities in the old clinic to 0 consecutively, thus simulating a gradual shift between old and new facility.
- For the cross-clinical cooperation between multiple clinics, we lay them out side-by-side and let a connecting functional unit with a specialized “transfer” behavior handle the simulated service integration (e.g. shuttle services, public transport). We do not currently simulate the flow of material (e.g. central kitchen serving to all clinics via cook-and-chill), since the emphasis lies on patients.

Using the schematic drawings gained in the above fashion, we get a tree of functional units in which our simulation steers agents through the clinical buildings (see Figure 3). As result of that computation, we store for each simulated scenario the resulting individual patient histories (paths taken, queues encountered and functional units utilized for an individual), space occupancy and functional unit utilization over time.

Figure 3. Screenshot of simulation during computation
The final step lies in a comparison of results obtained via the simulation, using a comparison as in Figure 4, either side-by-side or stacked, using occupancy or utilization of FUs as input. Analyzing a common functional unit in both scenarios gives a performance measure of both options. For example, transferring the Daycare unit shown in Figure 4a from Clinic A to Clinic C will entail a higher utilization for that unit, but only once exceed its capacity for a short period of time. The stacked occupancies shown in Figure 4b can give a measure of how busy two compared functional units will be in terms of patients being present (e.g. for non capacity-constrained areas). Furthermore, we offer a Gantt Chart showing relative utilization, color-coded to show under- and over-utilized units (Figure 4c). Also, the characteristics of the inhibiting patients can be shown aggregated by their type (e.g. walking/sitting/lying or other categorization dependent on the input data), and characterized further to show the duration of treatment so far, time spent queuing and time utilizing the functional unit (not shown in any Figure).

DISCUSSION
The presented concept for comparing two clinical configurations lacks an assessment of an “overall fitness”. However, we argue that the design of healthcare facilities cannot be summarized easily; the planner has to go through each department and analyze the impact of chosen planning options for the patient before being able to decide for one over the other scenario. In the future, we will add more evaluation options apart from the purely resource-based ones - adjacencies of functional units, usage of the circulation immediately come to mind - so that we can compare also the form of the building and with that the viability of a concept for the staff (short ways, compare the two building types in Figure 5). Another necessary addition to the model is the inclusion of staff schedules to back the capacities of FUs. Such functionality would certainly need to include specialized logic for legal constraints in the respective national context, which we have so far avoided.
Likewise, material supply and disposal logistics forms another area for extension of the model which we will conduct in the future.

CONCLUSIONS
In this paper, we have presented ((MODYPLAN)), a schedule-based simulation model that focuses on comparing different building concepts, especially dealing with cross-clinical development options (medical service provision in cooperating clinics) in addition to the common practice of refurbishments and adaptation of clinics. The context of our approach lies within early planning, i.e. during competitions or as means to quickly build up and compare a number building concepts for later refinement. The early application of simulation within hospital planning makes our approach unique, valuable for architects and organizational planners.

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School of Architecture, Rensselaer Polytechnic Institute; Department of Physics, University of Oregon.

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Holly Samuelson, Apoorv Goyal, Sebastian Claussnitzer, Alejandro Romo-Castillo, Yujiao Chen, Arpan Bakshi
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ABSTRACT
Life Cycle Analysis (LCA) is an environmental assessment and management framework that aims to simplify the decision-making processes of manufacturing and consumption, with regard to their environmental impact. In the built environment, LCA is often used as a comparative tool that helps in choosing one design alternative over another. Most LCA studies compare a limited number of design alternatives due to the complexity of the method.

The main goal of this study is to examine the various Life Cycle aspects of a refurbishment of a case study, and explore the potential of using Multi Objective Genetic Algorithms (MOGA) with Dynamic Thermal Simulation Tool (EnergyPlus) to find optimal refurbishment measures in terms of Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) over an assumed life span of 60 years.

Results show that MOGA successfully identified optimal design solutions, when taking into account both basic design aspects such as window-to-wall ratio or envelope build-ups, but also more detailed ones, such as thermal bridges insulation and the use of different fuel types for energy generation.

Author Keywords

INTRODUCTION
The building industry is responsible for approximately 40% of the global energy consumption, 40% of global raw aggregates, gravel and sand and 25% of wood [1, 2, 3, 4]. In the built environment, energy is used throughout the different phases of a project, starting from material extraction through to building components manufacturing, construction, usage and demolition [5].

LCA (Life Cycle Assessment) is a method that offers a holistic approach for assessing the potential impact of products and process on the environment throughout their lives in what is referred to as a ‘cradle to grave’ approach [6, 7]. The inputs of an LCA study are units of resources and substances, and its outputs are the environmental impacts (called Impact Categories). In the built environment, LCA impact categories are usually converted into a single value – CO₂e (CO₂ Equivalent) – which measures the Global Warming Potential - GWP [8]. This type of analysis is referred to as Life Cycle Carbon Footprint (LCCF).

In order to achieve the maximum carbon emission savings throughout a building’s lifetime, the optimal balance between the Embodied Carbon (carbon that had been invested during construction) and Operational Energy Carbon (carbon emissions associated with in-use burning of fossil fuels) needs to be found.

In acknowledging the value of existing buildings, the demand for refurbishment has increased. Improving the performance of existing buildings, while keeping the additional embodied carbon and cost to a minimum, has become a key challenge in reducing the Life Cycle impact of buildings.

This study examines the impact of the refurbishment of a case study building on its LCCF (Life Cycle Carbon Footprint) and the LCC (Life Cycle Cost). In particular, the study aims to answer the following questions:

- Can computational optimisation methods with Dynamic Thermal Simulation Tools be utilized to find the optimal refurbishment measures, in terms of LCCF and LCC?
- What LCCF and LCC improvement rates can be achieved by using optimisation methods?

BACKGROUND AND LITERATURE REVIEW
Carbon in Buildings
In order to mitigate building carbon emissions from, it is essential to first identify their sources. As carbon emissions are the result of the burning of fossil fuel, an aggregation of energy consumption in the building must be carried out.
The inputs and outputs of LCCF in buildings are therefore a combination of two components [9]:

**Embodied Energy (EE)**
EE is the required energy for the manufacturing of a building product, including the energy associated with the extraction of raw materials, transport to factories and manufacturing (also called “cradle to factory gate”), as well as transport to site (“gate to site”) and energy consumption for construction on-site [5]. Various case studies indicate that EE is responsible for 9-46% of the total Life Cycle energy consumption in low-energy buildings, and for 2-38% in conventional ones. [10, 11].

A common method for calculating Embodied Carbon is using Embodied Carbon Factors from pre-calculated Inventories. In the UK, one of the most popular pre-calculated databases is the Bath Inventory of Carbon and Energy (Bath ICE [5]) developed at Bath University.

**Operational Energy (OE)**
Operational Energy in buildings is the energy that is used for maintaining the thermal and environmental conditions and includes such aspects as heating, cooling, domestic hot water and lighting [12]. OE is usually calculated by using Building Performance Simulation tools. Once OE consumption is calculated, it is multiplied by carbon emissions associated with each fuel type, thus the choice of fuel may have a significant impact on LCA results [13, 14].

**Components of LCA**
ISO 14040:2006 (Environmental Management — Life Cycle Assessment — Principles and Framework) is regarded to be one of the most commonly used LCA frameworks in the LCA industry. It consists of four steps:
1. **Goal and Scope** – Determination of the goals, boundaries, assumption and limitations.
2. **Life Cycle Inventory (LCI)** – Specification of input and output inventories of energy flows of all systems and sub-systems of production.
3. **Life cycle impact assessment (LCIA)** – Evaluation of the different components in the inventory and their impact on the environment.
4. **Interpretation** – The formulation of conclusions and recommendations based on the LCIA.

**Optimisation and Genetic Algorithms (GA)**
Parametric simulation has in recent years been used in built environment research to improve building energy performance. As the basic method involved in parametric simulation is considered to be both time and resource consuming [15], to make the process more efficient, optimisation algorithms have been incorporated within them. Optimisation, in mathematical programming aspects, is the task of finding a solution which is both feasible and when it is the best of all other possible alternatives. [16]. Finding a solution for an optimisation problem might be a complicated task, especially if the given problem has a large number of possible scenarios to cover.

**Genetic Algorithms (GA)**
The principle behind GA is based on the theory of natural selection and evolution. The elements of a basic GA are:
- The generation of a set of possible solutions to a problem. Each solution is a result of a unique set of properties (‘genes’).
- The evaluation of the success of each solution, and comparing it to the other solutions.
- The selection of a set of the best solutions on which mathematical manipulations are applied to the ‘genes’. These are based on principles inspired by evolution (mutating, breeding and crossover) to create a new, fitter, set of solutions to the problem.

**Non-dominated Sorting Genetic Algorithm 2 – NSGA2**
To enable the realization of the two objectives of this study (LCCF and LCC), a Multi-objective GA was used. Previous studies state that NSGA2 is one of the most widely used Multi-objective GAs [17] and is less prone to local optimums than other optimisation algorithms [18].

NSGA2 is based on the concept of Pareto Dominance; where for a given set of solutions for multiple-objective problem, one solution option is considered to be better than another (or, Pareto dominates it). This occurs when all solutions presented for one option are deemed as good as the other option for all objectives, and at least one solution is deemed better [19].

Figure 1 shows a two-dimensional Pareto optimal front, where individual ‘B’ is better than ‘A’ along the x axis and individual ‘A’ is better than ‘B’ along the y axis. They dominate each other for different objectives. Individual ‘2’, however, is better than ‘B’ for both axes. No other individual dominates it on either axis. The goal of NSGA2 is to find a set of solutions which are not dominated by any others [18].

![Figure 1. Pareto front. [19]](image-url)

**Building Performance and LCA Optimisation**
Various studies have used GA to minimise building life-cycle impacts. While studies [20] have shown that a multi criteria GA can be used for the minimisation of the life cycle environmental impact and cost of a 1000 m² case study office building, the methodology used involved the utilisation of a steady-state simulation toolkit for Operational Energy calculations (i.e. a simplified and general calculation method), instead of a more detailed
Dynamic Thermal Simulation (DSM) tool. Another study [21] used optimisation algorithms on the refurbishment of a semi-detached house to optimise refurbishment associated costs, energy consumption and thermal comfort within the building. The study used a simplified optimisation algorithm that only allowed for the alteration of a very limited set of numerical values (e.g. U-Values), rather than physical elements within the building (window-to-wall ratio / shading elements, etc.). It concluded that for more complicated optimisation problems - Evolutionary Multi-Objective Algorithm should be used.

THE CASE STUDY

For this study, a council housing complex in the city of Sheffield in the United Kingdom was used. The complex was built in the late 1950s and was recently refurbished by Hawkins Brown Architects.

The original building was regarded as being poorly-built. The original envelope consisted of un-insulated brick and exposed-concrete structure which was considered to be one of the main architectural features in the original design, but lead to significant thermal bridges which can result in higher energy consumption and the formation of mold in interior spaces. The exposed concrete was also a main feature in the refurbishment and was therefore kept intact, while the facades of the building were re-clad. In doing so, the designers not only kept the original appearance of the building, but were also able to minimise its life cycle environmental impact. However, in keeping the concrete exposed, the risk of creating thermal bridges increased.

The case study building uses waste combustion district heating system for space and water heating, which is considered to be a very efficient supply system.

METHODOLOGY

Research Design and Tools Used in the Study

In order to carry the optimisation process, this study used EnergyPlus as the DSM tool. The study was implemented in the following steps:

1. Model preparation: An initial .idf (Input Data File) file which includes all the required geometric data for a thermal simulation (coordinates of walls, roof, floors, thermal zones etc.) was created in Google Sketchup 8.0.
2. Model specification: The thermal parameters of the model (U-Values, weather file data, HVAC etc) were set in EnergyPlus.
3. Optimisation preparation: The definition of the GA objectives and genes was undertaken in jEPlus (v.1.5). This java-based parametric simulation manager, designed for EnergyPlus, allows batch simulation, and was responsible for generating models following the genes.
4. Run optimisation and results analysis: The jEPlus project was imported to jEPlus+EA – a platform that allows the manipulation of the batch simulation and the performance of a GA optimisation studies. The GA code was run in jEPlus+EA, which was also used to control the population size, number of generations, crossover rate, etc.

Model Construction and specification

The study focused on the optimisation of the building envelope, as this has a major impact on the passive performance of the building. In exploring the thermal qualities of the various components of the envelope, the study specifically focused on U-Values, window-to-wall ratios and thermal bridge insulation. The genes for the GA were therefore defined as:

- Insulation thickness
- Wall build-ups
- Window-to-wall ratio
- Thermal bridge insulation

The shaded surfaces in Figure 2 indicate the materials and building components that could be manipulated by the GA. This led to a total of 55,296 possible combinations (Table 1). A total of 1125 individuals were simulated – a population of 9 individuals during 125 generations. The code had a mutation rate of 0.2 and a cross-over rate of 1.0. Table 2 shows the building component build-ups and GA genes. The CIBSE "UK-ManchesterTRY" weather-file was used for the thermal simulations as it was considered to be the closest and most reliable available weather data.

THE CASE STUDY’S LCA

In adhering to the ISO 14040 framework, the LCA study was implemented as follows:

Goal and Scope

The goal of the study is to examine the use of optimisation methods using Dynamic Thermal Simulation Tools to minimise the LCCF and LCC of a case study building. Furthermore, the study also examines the improvements, generated by the optimised LCCF and LCC. As such, all steps from cradle to grave were taken into account and carbon emissions were calculated through a mixture of calculated and assumed coefficients (Table 3). Based on similar studies [10, 11], a 60 year building life span was defined. In the analysis, the whole building was treated as the system unit, and the functional unit for the analysis was 1 m2 of the building floor area.

![Figure 2: The building elements for the GA optimisation]
**Gene’s name** | **Possible value**
--- | ---
Panel Insulation, Street insulation | 50, 100, 150 [mm]
Exterior Insulation | 50, 100, 150 [mm]
Bricks | 0, 100 [mm]
Thermal bridges Insulation | 0, 50, 100 [mm]
Window South-West Bottom | 25, 50, 75, 100 [%]
Window South-West Middle | 25, 50, 75, 100 [%]
Window South-West Top | 25, 50, 75, 100 [%]
Window North East Bottom | 25, 50, 75, 100 [%]
Window North East Top | 25, 50, 75, 100 [%]
Total Number of combinations | 55,296

*Table 1: Genes and their possible values*

**Panel** | **Exterior Wall** | **Interior Wall** | **Window**
--- | --- | --- | ---
Metal surface | Cement board | Plaster board | Clear glass
Brick | Brick | Rock Wool | 13mm Air gap
Rock wool | Rock wool | wood | Clear glass
Plaster board | Plaster board | Plaster board | 

*Table 2: Build-ups. In gray – GA’s genes*

**Life Cycle Inventory (LCI)**
An inventory of the environmental impacts of building materials used in the refurbishment was established, based on the architectural drawings and specifications. The carbon inventory was based on various assumptions:

- Embodied Energy – Since the GA generates a large number of models, the total area of each building component (walls/floors/windows etc.) in each simulation had to be calculated automatically for each model. The total areas were then multiplied by the relevant carbon factors using Bath ICE [5]. Costs were calculated in a similar way, based on Spons’ Guide for Architects [22].
- Waste rates, carbon due to transport and construction, Recurrent Embodied Energy (for refurbishments) and ‘End of Life’ carbon (demolition) were also taken into account, as shown in Table 3, based on assumptions used in previous studies [13, 23, 24, 25]. The percentages in Table 3 refer to total material EC, which was regarded to be 100%. This is the value that had been calculated automatically for each model in the “Building Material + Waste” section in that table.
- Energy in use – Operational Energy was calculated in EnergyPlus. Energy outputs were then converted to carbon emissions using the National Calculation Methodology’s (NCM) carbon conversion factors [26]. Energy costs were taken from the UK Government Energy Price Statistics [27].
- The district heating system has a very low carbon emission factor value of 0.057 kg CO₂/kWh [14, 29]. In order to examine the life cycle impacts of the refurbishment under a more generic fuel type, two LCA optimizations were undertaken; one in which the primary energy was the waste combustion district heating, and the other in which the primary energy was the more conventional gas boiler, which has a carbon conversion factor of 0.21kgCO₂/kWh [28].
- The cost of heating energy is the same, whether heating is produced by waste or natural [29].

**Life Cycle Impact Assessment (LCIA)**
In order to minimize the LCCF and LCC of the building, the GA code had to calculate both values for each and every model it generated. The calculations were split into two parts. The first summed up the Embodied Carbon and cost, and the second calculated the Operational Energy related carbon and cost.

The LCCF was calculated based on the following equation:

\[ LCCF = \sum_{i} (K_i \times T_i \times D_i \times (1 + M_i) \times (\sum_{j} A_{ij})) + Y [(S + W) \times EH] + (E \times EE) \]  

Where:
- \(i\) = Number of material
- \(K_i\) = Material’s Embodied Carbon (kgCO₂/kg)
- \(T_i\) = Material’s Thickness (m)
- \(D_i\) = Material’s Density (kg/m³)
- \(M_i\) = Material’s additional energy coefficient – includes embodied energy in waste, transport construction and demolition (%).
- \(A_{ij}\) = Material’s Area (m²)
- \(j\) = Number of surfaces of the \(i\)th material
- \(Y\) = Number of years
- \(S\) = Space heating energy (kWh)
- \(W\) = Water heating energy (kWh)
EH = Carbon emissions due to heating fuel (kgCO2/kWh) 
E = Electricity energy (kWh) 
EE = Carbon emissions due to electricity fuel (kWh) 

**Equation 1: LCCF Calculation**

Similarly, LCC was calculated by the equation:

\[
LCC = \sum_{i=1}^{n} C_i \times \left(1 + Li \right) \times \left[ \sum_{j=1}^{n} Ay \right] \times \left( S + W \right) \times \left( CH \right) \times \left( E \times CE \right)
\]

Where:
- \(i\) = Number of material 
- \(C_i\) = Material’s Cost (£/m²) 
- \(Li\) = Material’s additional energy coefficient – includes embodied energy in waste and transport 
- \(A_i\) = Material’s Area (m²) 
- \(j\) = Number of surfaces of the i’th material 
- \(Y\) = Number of years 
- \(S\) = Space heating energy (kWh) 
- \(W\) = Water heating energy (kWh) 
- \(CH\) = Cost of heating energy (£/kWh) 
- \(E\) = Electricity energy (kWh) 
- \(CE\) = Cost of electricity (£/kWh)

**Equation 2: LCC Calculation**

**Results and Interpretation**

Four optimisation projects were simulated, using a cloud simulation service and an i7 Intel processor with 6.0 GB installed memory. Each project had a population size of 9 individuals and tested 125. It took around 6 hours to simulate using the cloud service, and 10 hours using the PC.

**Optimisation Results**

Figure 3 shows the progress of the typical optimisation run in this study.

The graph shows that the code achieved significant improvements in LCCF and LCC after 25 generations, and then reached the optimal solutions after approximately 75 generations. This shows that using NSGA2 for LCA optimisation can work and save many hours of simulation (1,125 models were simulated in each optimisation run, instead of the original 55,296 models).

The use of GA therefore presents the opportunity to examine the performance of numerous buildings and compare their performance. Each dot on the graph below represents a model with different set of genes.

**Embodied / Operational Carbon - Waste Combustion District Heating**

Figure 4 shows the embodied and operational carbon in the waste combustion district heating scenario. The following conclusions can be drawn from it:

- The embodied energy of the refurbishment was between 210-290 kgCO2/m². In the case of a very efficient heating energy source, it has a relatively big impact on the overall LCCF (between 20-30%). Even though the building was only being refurbished (i.e. a large quantity of carbon has already been invested in its initial construction), these results echo previous studies [10, 11].
- The analysis of GA results shows the impact of insulating the thermal bridge and the thickness of the wall insulation on operational-related carbon emissions, as most optimal models had an insulated thermal bridge and the thickest available insulation.
- GA also showed that the majority of optimal individuals had minimal north facing windows. This can be attributed to the fact that northern windows do not have significant solar gains. Effectively, this means that these windows embody more carbon than saved.
- Interestingly, results show that none of the optimal individuals used any brick. This is likely due to the fact that since it has high embodied energy and makes relatively little contribution to building performance, it was therefore not considered beneficial from a life-cycle point of view.

**LCCF + LCC: Waste Combustion District Heating**

Figure 5 shows the multi-criteria optimization process in the scenario of a waste combustion district heating system, where fitness criteria are LCCF and LCC.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>LCA</th>
<th>LCC</th>
<th>Source/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Materials + waste</td>
<td>√</td>
<td>√</td>
<td>Sketchup, Bath ICE</td>
</tr>
<tr>
<td>Transport</td>
<td>√</td>
<td>√</td>
<td>3%</td>
</tr>
<tr>
<td>Construction</td>
<td>√</td>
<td>-</td>
<td>7%</td>
</tr>
<tr>
<td>Energy in use</td>
<td>√</td>
<td>√</td>
<td>Energy Plus</td>
</tr>
<tr>
<td>Demolition</td>
<td>√</td>
<td>-</td>
<td>2%</td>
</tr>
<tr>
<td>Maintenance</td>
<td>√</td>
<td>√</td>
<td>Various values by material</td>
</tr>
</tbody>
</table>

**Table 3: LCA boundary**
Results show that GA successfully found an individual model with the best LCCF and LCC. Four groups of individuals clearly appear on the graph; individuals with and without additional brick wall, and individuals with and without thermal-bridge insulation. Results also show that:

- The optimal individual chose the smallest windows in all facades (minimal embodied carbon).
- Individuals with a brick layer have lower Operational Energy consumption than individuals without it. However, it seems that this layer embodies more carbon than it saves throughout the building’s life.
- GA shows that insulating the thermal bridge reduces LCCF and LCC by around 10-15%.

Embodied / Operational Carbon: Natural Gas Heating

The performance of the building under the natural gas heating fuel scenario is illustrated in Figure 6. This shows that:

- The total embodied carbon of the optimal cases is similar to that of the previous case, however, in this scenario, as the OE related emission values are 2-3 times higher than those of the waste combustion district heating system scenario, the refurbishment embodied carbon is around 10% of the buildings LCCF.
- Similar to the previous scenario, GA results show the impact of insulating the concrete frame (thermal bridge) has on Operational Energy consumption. Almost all optimal individuals had the thickest available insulation and none used the brick.
- The building with the lowest LCCF and LCC values had the smallest north-facing windows and allowed various combinations for the south-facing windows.

LCCF + LCC: Natural Gas Heating

In the natural gas heating fuel scenario, where the fitness criteria are LCCF and LCC, results show that the multi-criteria GA successfully found optimal individuals (Figure 7). Two groups of individuals are clearly shown on the graphs – individuals with and without insulated thermal bridges.

- Even when OE related carbon account for around 90% of the building’s LCCF, the optimal individuals have the smallest available windows in all facades.
- GA shows that the optimal individuals chose the thickest available insulation, as it seems that adding insulation...
saves more carbon than it embodies, and that insulating the concrete structure can bring to a reduction of between 10-20% in the LCCF and LCC in this scenario.

• Using a brick wall is still a more significant investment than what it can save (both in terms of carbon and cost).

Optimised Individuals’ Carbon Payback Times
Carbon payback times were calculated for the optimised individuals for both primary-energy-source scenarios. Table 4 shows that the optimised solutions can be paid back much quicker. In addition, Table 4 shows that the payback time (in terms of whole-life carbon emissions) of a refurbishment of buildings that use waste-combustion district heating is very long, and therefore might not be worth the investment.

The reason for the difference between Figures 5 and 7 is the fact that the two scenarios used different fuel types. While Figure 5 shows the case of using a very efficient (low carbon emitting) district heating system, Figure 7 shows a less efficient (or more carbon-emitting) gas boiler scenario. The Y axis in both graphs shows that whole-life cost of the building, where Operational Energy costs are not affected by the different energy generation technology (district heating / gas boiler) [29].

The X axis, on the other hand, shows the building’s whole-life carbon emissions. When the Operational Energy is very low (i.e., in the district heating case) – the significance of building Embodied Carbon becomes more prominent as compared to its Operational-Energy-Related emissions.

In this case study, the building whole-life cost was substantially affected by the building Embodied Cost. In the case of the district heating, both axes are highly influenced by the Embodied component (Figure 5 suggests a stronger relationship than in Figure 7).

CONCLUSIONS
This study examined the optimisation of the LCCF and LCC of a refurbishment of a large residential complex. The main aim of the study was to examine the use of multi-criteria GA with Dynamic Thermal Simulation Tool as an optimisation method in LCA studies of buildings. The goal of implementing the optimisation code was to find the optimal building envelope properties that minimise the environmental impact of the refurbishment and the cost of its materials.

The study has shown that GA successfully found optimal solutions for the various examined scenarios. The study also examined the carbon emission savings and their payback times. Optimisation results indicate that the optimal models had the smallest available windows, which may be attributed to the fact that window Embodied Carbon is higher than the Operational Energy-related carbon that they save. For the same reason, bricks were not used in any optimal individual. The study also illustrates the impact of insulating thermal bridges on LCA, as well as the potential impact of various primary fuel types and heating systems on building LCA.

Further Studies
Even though the study successfully found optimal refurbishment measures for the case study, it is important to note that different buildings are likely to have different results. To draw a more generic set of conclusions that can be considered to be more widely applicable, a larger range of case studies should be examined.

In addition, while this study illustrated the benefits of using optimisation methods with Dynamic Thermal Simulation Tools for minimising various life-cycle aspects in buildings, the simulation and optimisation process is still a complicated and a time-consuming process. It is still not possible to carry an optimisation study in a single simulation environment. A further examination of the communication between the different tools (3D modeling, thermal simulation and GA optimisation) is therefore required.

<table>
<thead>
<tr>
<th></th>
<th>Optimal design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy savings from original non-refurbished building (kWh/m²/y)</td>
<td>70</td>
</tr>
<tr>
<td>Waste combustion</td>
<td>Operational Carbon savings (kgCO₂/m²/y)</td>
</tr>
<tr>
<td>district heating</td>
<td>payback time (years)</td>
</tr>
<tr>
<td>Natural gas-based heating system</td>
<td>Operational Carbon savings (kgCO₂/m²/y)</td>
</tr>
<tr>
<td></td>
<td>payback time (years)</td>
</tr>
</tbody>
</table>

Table 4: Optimised individuals savings and payback times

ACKNOWLEDGEMENTS
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REFERENCES
Optimization of Passive Cooling Control Thresholds with GenOpt and EnergyPlus

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ABSTRACT
Passive cooling strategies (e.g. shading, natural ventilation, use of thermal mass) can effectively reduce a building’s cooling load during hot summer weather. Such techniques have been well-studied, with the provision that precedent work assumes operable shading devices, windows, and vents are operated according to pre-determined schedules or setpoints. This work, in contrast, investigates numerical optimization of the setpoints themselves.

Among space types most useful for studying passive cooling are unconditioned zones such as sunspaces, because they can easily overheat on sunny days and because heat loss pathways in the forms of wind, cool night air, cold night skies, ground contact, and precipitation can sum to a sizable proportion of the cooling load in temperate climates. At the same time, the transition of a given path between heat gain and loss may be undetectable to an occupant, causing manual controls to be ineffective and mechanical controls to be of interest.

Here, GenOpt was used to manage optimizations of shading and natural ventilation control thresholds, as well as auxiliary optimizations of shading type, material, and position; vent area; and thermal mass quantities, within a field-validated EnergyPlus sunspace model. Results predicted that controls operated according to optimized setpoints should maintain peak indoor temperatures 8-10°C (14-18°F) below outside air temperatures during the hottest August afternoons of the sunspace’s native American Pacific Northwest climate. In addition, optimization data established clear priorities among field configurations to be tested, showing the potential to simplify subsequent field validation greatly.

Author Keywords
passive cooling; controls; sensors; EnergyPlus; GenOpt; optimization; natural ventilation; shading; thermal mass

ACM Classification Keywords

INTRODUCTION
Air conditioning in America has risen from a luxury to a perceived necessity in the past fifty years. Non-residential buildings that once relied on awnings, shades, and operable windows for cooling have been retrofitted to the extent that three-quarters of those built before 1964 now have mechanical cooling, of which half cool 100% of their floorspace [24]; in 2013, only 9% of new homes were built without air conditioning [22]. As a result, space cooling in the U.S. now consumes approximately 6 quadrillion Btu of energy each year, at a cost of approximately $62 billion, and emits over 340 million metric tons of CO₂ [23].

At the same time, the pressure to design buildings with smaller carbon footprints is rising both nationally and internationally [1, 3, 27], coinciding with greater recent interest in passive cooling designs [8, 9, 16]. Diverse strategies, including shading, cross ventilation, stack ventilation, wind catchers, passive cool towers, night-flush cooling of mass, green roofs [15], earth tubes, courtyard designs, and many others, have now been well-studied in numerous climates, building types, and configurations; recent work is reviewed in [5, 14].

Control of operable elements is central to many passive cooling strategies, and several efforts have compared contrasting operational strategies in natural ventilation [e.g. 18], night ventilation of thermal mass [4, 6, 17, 19], shading [10, 21, 28], and both natural ventilation and shading [e.g. 11], revealing that control thresholds can greatly alter cooling effectiveness, particularly when tailored to weather and climate.

Numerical optimizations using Monte Carlo methods, parametric analyses, genetic algorithms, particle swarm algorithms, BOpt, and other approaches have been applied to passive cooling problems, as well, to illuminate design decisions regarding building orientation, glazing type and position, wall composition, overhang depth, ventilation rate, and other parameters; these are reviewed comprehensively in [20]. While several of these efforts have included the presence or absence of operable elements as optimizable parameters [e.g. 11], control thresholds are routinely pre-established. To our knowledge, the direct numerical optimization of threshold values controlling operable elements for passive cooling purposes has not yet been addressed.
The purpose of this work is therefore to investigate a new method for discovering optimal control thresholds for passive cooling systems. EnergyPlus is an open-source building energy simulation tool that carries results of one timestep into the next [25], in contrast to DOE-2 and similar engines that reset zone temperatures to a user-input value at each timestep [7]. As a result, EnergyPlus is one of few contemporary simulation tools capable of accurate passive system simulation, and it is the only one known to have been validated with built passive systems [e.g. 12, 13]. GenOpt, in turn, is a numerical optimization interface designed to manage serial simulations of a given model, such as one in EnergyPlus, in which one or more parameters of interest are varied across specified ranges. Outputs are then evaluated with respect to a user-defined “cost” function. With this information, following a user-selected optimization algorithm, GenOpt searches the design space for combinations of the designated variables that minimize the cost function [29].

METHODS

All simulations used an EnergyPlus model of the Gates residential sunspace in western Oregon, previously validated with actual meteorological year (AMY) data ([12], Table 1), because it represents realistic passive cooling conditions and is available for field testing to evaluate optimization results. Automatic roof vents exist in the built space, controlled by wax actuators that expand above 26.7°C (80°F) to open the vents (Table 1), and were allowed to operate as built in simulations preceding those that addressed ventilation.

Within the EnergyPlus model, shading devices were added to skylights and vertical windows of the model as WindowProperty:ShadingControl objects, referencing WindowMaterial:Shade or WindowMaterial:Blind objects that specified material properties. Deployment and retraction of the devices were controlled by thresholds of incident solar radiation, global horizontal radiation, indoor dry-bulb air temperature, and/or outdoor dry-bulb air temperature as described below.

The cost function minimized was "Overheated Hours", defined here as the number of August afternoon and evening hours (12n-8p) exceeding 27.3°C (81°F) (Eqn. 1).

While this threshold approximates the corresponding limit of the ASHRAE 55 Adaptive Comfort zone [2], it is not a substitute for thermal comfort, which involves radiant temperatures and air velocity. As a space unoccupied by humans during the hottest hours but filled with fruit trees and flowers, the primary goal was to prevent high air temperatures.

\[
F(x) = \min \left\{ C(x) = \sum_{i=1}^{284} \left[ T_i > 27.3 \degree C \right] \right\};
\]

\[
[P] = \begin{cases} 
1 & \text{if } P \text{ is true} \\
0 & \text{if } P \text{ is false} 
\end{cases}
\]

Equation 1.

All simulations were performed in EnergyPlus 8.1.0 [25] using Eugene-Mahlon Sweet Field TMY3 weather data [30], preferred to AMY because it shows more typical conditions. Optimizations were managed by GenOpt v3.1.0 [29] using the Hooke-Jeeves Generalized Pattern Search (H-J GPS) algorithm in optimizations of continuous variables or a hybrid Hooke-Jeeves GPS / Particle Swarm Optimization (H-J PSO) algorithm in optimizations with categorical variables; optimizations each required <10min on a Windows 8.1 computer with a 2.00GHz processor and 8.0Gb of RAM.

RESULTS and DISCUSSION

The optimizations below address August overheating in the Gates sunspace, a glass-enclosed patio with substantial thermal mass in the form of potted plants, a large fish tank, and a floor of concrete and slate (Table 1). Although this space performs well in heating mode [12, 13], it has a tendency to overheat on August afternoons (Fig. 2), despite the operation of manual ground-level vents in conjunction with automatic roof vents that open when the indoor air temperature exceeds 26.7°C (80°F) to allow stack ventilation. Of the 248 August afternoon hours considered, 216 were overheated in the starting configuration, leaving ample room for improvement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>118 sf (11 m²)</td>
</tr>
<tr>
<td>Roof glazing</td>
<td>Single clear, 64 sf (5.9 m²), U = 5.6 W/m²K</td>
</tr>
<tr>
<td>Roof tilt</td>
<td>23°</td>
</tr>
<tr>
<td>Wall glazing</td>
<td>Single clear, 87 sf (8.1 m²), U = 5.0 W/m²K</td>
</tr>
<tr>
<td>Floor assembly</td>
<td>Concrete slab / XPS insulation, 4in. (10 cm) slab; U = 0.6 W/m²K</td>
</tr>
<tr>
<td>Internal mass</td>
<td>Fish tank, pots, soil; 1320 lbs (600 kg)</td>
</tr>
<tr>
<td>Infiltration Effective Leakage Area</td>
<td>37.2 in² (240 cm²)</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Automatic; 0.1m²; setpoint=80°F (27°C)</td>
</tr>
<tr>
<td>Common wall assembly</td>
<td>Stucco / wood stud / batt insulation, 215 sf (20 m²), U = 0.48 W/m²K</td>
</tr>
</tbody>
</table>

Table 1. Gates sunspace parameters.
Shade Type, Position, and Material
Shading devices usually cool a space by blocking direct solar radiation, but other cooling modes may operate as well: if a device has insulating properties, it may slow conduction, and it may also be designed to promote or inhibit convective heat loss from a sun-warmed surface. Since the effectiveness of control thresholds was expected to depend on characteristics of the shade itself, this preliminary optimization addressed shade type, position, and material. Position parameters included interior or exterior location, distance from glazing (D), and open areas at each edge of the shade. The latter are quantified in EnergyPlus in proportion to the area of the shade itself, yielding left or right side opening “multipliers” (TOM, BOM) [26]. Material parameters included thermal conductivity (k) and thickness (T). Initial values were 0.5 cm for D, 1.0 W/mK for k, 0.5 cm for T, and 0.0 for each of the opening multipliers (Table 2). Because shading type was a categorical variable, the H-J/PSO algorithm was used.

Solar transmittance (T_{sol}) was set to 0.1 in this optimization as the lowest value that could realistically be implemented in a retractable exterior fabric shade. Such a low value could overly dim an occupied space, increasing electric light use and the resulting cooling load; however, the sunspace was not occupied during hot afternoons, and a low T_{sol} was deemed acceptable. Shade control was set to respond to solar radiation incident upon the glass surface with an arbitrary threshold of 20 W/m². Making an arbitrary choice was necessary, because attempting to optimize materials and controls simultaneously sometimes prevented GenOpt from finding a global minimum, and this threshold parameter would be revisited in subsequent optimizations (below).

Results strongly favored exterior over interior shades, as expected. Unexpectedly, however, shades were positioned 7.5 cm from skylights and 4.5 cm from windows with appreciable openings at shade edges (Fig. 3). The separation of each shade from its glazing was clearly important, and further investigation confirmed that these configurations not only shaded the glass from solar heat gain, but also facilitated convective heat loss from exterior surfaces: considering only hours that external shading was deployed (~5a-7p), monthly convective heat loss from roof glazing was increased from -18 MJ to +0.4 MJ by the separation; for vertical glazing, the increase was more modest (+9 MJ to +13.5 MJ).

Thermal conductivity and material thickness showed less pronounced impacts, however, and optimizations beginning from different starting points yielded somewhat different results for these variables (+/- 50% of the Fig. 3 values), indicating that they should be revisited in subsequent optimizations. This optimization also illustrated the creation of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range; Ini. Step Size</th>
<th>Initiation Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade type</td>
<td>Interior / Exterior</td>
<td>Interior</td>
<td>Exterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S, W</td>
</tr>
<tr>
<td>Distance from glass D</td>
<td>0.5cm - 10cm; 1.0cm</td>
<td>0.5cm</td>
<td>7.5cm S 4.5cm W</td>
</tr>
<tr>
<td>Thermal conductivity k</td>
<td>0.05-1.0 W/mK; 0.1 W/mK</td>
<td>1.0 W/mK</td>
<td>0.6 S 0.5 W</td>
</tr>
<tr>
<td>Thickness T</td>
<td>0.5cm - 5cm; 1.0cm</td>
<td>0.5cm</td>
<td>3.5cm S 2.5cm W</td>
</tr>
<tr>
<td>Left- and right-side opening multipliers LSOM, RSOM</td>
<td>0.0 - 1.0; 0.1</td>
<td>0.0</td>
<td>0.4 S 0.6 W</td>
</tr>
<tr>
<td>Top and bottom opening multipliers TOM, BOM</td>
<td>0.0 - 1.0; 0.1</td>
<td>0.0</td>
<td>0.4 S 0.5 W</td>
</tr>
</tbody>
</table>

Overheated hours: 82

Table 2. Shade type, position, and material parameters; ranges over which they were allowed to vary and initial step sizes; values at which the optimization was initiated; and optimization results. S = skylight, W = window
implausible combinations. A shading device of 3.5cm with a thermal conductivity of 0.6 W/mK, for example (Table 2), would be roughly equivalent to a thick panel of lightweight concrete or gypsum board, an element that would be at least structurally undesirable as an exterior tilted shading device.

As expected, shading reduced the number of overheated hours considerably, from 216 to 82 (Table 2), with the remainder concentrated in either late-afternoon hours or in the hottest week (Aug 6-12).

Shade Control

With shade type and position priorities established, the next question was the nature of the condition(s) to which shade deployment should respond. Within EnergyPlus, numerous options exist for controlling operable shades; this work considered (a) Always On, (b) On If High Solar On Window, (c) On If High Horizontal Solar, (d) On If High Outdoor Air Temperature, and (e) On If High Zone Air Temperature, as well as their respective thresholds. Preliminary simulations revealed a conflict in varying solar radiation and temperature thresholds simultaneously, however, so optimizations with (a), (b), (c) and with (a), (d), (e) were compared to reveal the most favorable strategy (Table 3).

Results of the solar shading control optimization, addressing the effectiveness of two different solar strategies in comparison with full-time deployment, revealed that the retraction of shades at night was indeed valuable, ultimately favoring both solar radiation-controlled deployments over the “Always On” strategy. Even retracting one of the two sets reduced the number of overheated hours noticeably (Fig. 4), and further investigation found that this resulted from greater nighttime heat losses, through both convection and radiation, from bare compared to shaded glazing: combined monthly nighttime losses increased from ~330 MJ when shades were deployed each night to ~470 MJ when they were retracted.

The solar optimization returned an optimal solar radiation threshold of 25 W/m² (Table 3), resulting in shade deployment beginning between 7a and 10a each day. This illustrates a persistent problem with manual controls: that the necessary time of operation may occur well in advance of the hours of interest, requiring that the occupant be present and anticipate overheating by several hours. While values lower than 25 W/m² would have been equally optimal, the Hooke-Jeeves algorithm selected this value because it searches from the direction of the initial value and returns the final attempt that minimizes the cost function. This property appears to have useful potential, as well, in designing a problem to find a value on the preferred side of the optimal range.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range; Ini. Step Size</th>
<th>Initiation Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shading Control Type (Solar Options)</td>
<td>Always On, On If High Solar On Window, On If High Horizontal Solar</td>
<td>Always On</td>
<td>On If High Solar On Window (S, W)</td>
</tr>
<tr>
<td>Solar Control Threshold</td>
<td>0 - 140 W/m²; 5 W/m²</td>
<td>140 W/m²</td>
<td>25 W/m² (S, W)</td>
</tr>
<tr>
<td>Overheated hours: 81.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shading Control Type (Temp Options)</td>
<td>Always On, On If High Outdoor Air Temperature, On If High Zone Air Temperature</td>
<td>Always On</td>
<td>Always On (S), On If High Zone Air Temp (W)</td>
</tr>
<tr>
<td>Temp Control Threshold</td>
<td>10 - 40°C; 10°C</td>
<td>40°C</td>
<td>40°C (S); 10°C (W)</td>
</tr>
<tr>
<td>Overheated hours: 87.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Shade control optimization parameters.

S = skylight, W = window
Shade control by incident solar radiation on window surfaces offered only a slight improvement over control by global horizontal radiation, suggesting that the expense of sensing radiation on every window would not be warranted. The Fig. 4 plateau from simulations 55 to 150 shows the tradeoffs possible among the solar control parameters and solar radiation threshold values, as well, indicating the extent of comparable options.

Optimization of shading control by outside or zone air temperature thresholds, again in comparison to the “Always On” strategy, converged on “Always On”, either explicitly or by choice of a zone air temperature threshold so low that the shades were deployed continuously (Fig. 4, Table 3), showing that temperature control offered no further improvement. Although this optimization reduced the total number of overheated hours by only one-quarter hour, it did clarify the importance of using a solar rather than temperature threshold, as well as the importance of keeping the solar threshold low.

Natural Ventilation

The sunspace was originally equipped with manual floor vents and a 0.1m² roof vent operated automatically by an expanding-wax actuator: at a sufficiently warm temperature, the wax expanded and the vent opened. This vent was allowed to operate in its original configuration for all previous simulations. However, even excellent shading control could not sufficiently cool approximately 80 hot August afternoon hours (Tables 2, 3), suggesting that further effort was needed.

To optimize the space’s natural ventilation system for cooling, indoor and outdoor temperature thresholds at which the vents opened and closed were allowed to vary, as was the vent area (Table 4). Because these were continuous variables, and because a solution on the smaller side of the vent area options was desired, this optimization returned to the Hooke-Jeeves algorithm.

Results showed, strikingly, that the existing vents had been operating in complete opposition to the optimal mode for August afternoons. Far more effective cooling was achieved when vents opened at low temperatures and closed at high temperatures, whether indoor (22.5°C) or outdoor (25°C), than when they opened at high temperatures and closed at low temperatures, as designed (Fig. 5, Table 4). (The optimal mode for achieving comfort, however, in which air movement plays an important role [2], could indeed have required open vents during hot hours.)

Further inspection of models in which optimal values had been encoded revealed that nighttime cooling lowered morning (8a) thermal mass temperatures by an average, during the course of the month, of approx. 2°C, suggesting that thermal mass design adjustments might further diminish overheated hours.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range; Init. Step Size</th>
<th>Initiation Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent area</td>
<td>0.1 - 1.0 m²; 0.1 m²</td>
<td>0.1 m²</td>
<td>1.0 m²</td>
</tr>
<tr>
<td>Indoor temp. below</td>
<td>0 - 40°C; 5°C</td>
<td>20°C</td>
<td>0°C</td>
</tr>
<tr>
<td>Vent area</td>
<td>0.1 - 1.0 m²; 0.1 m²</td>
<td>0.1 m²</td>
<td>1.0 m²</td>
</tr>
<tr>
<td>Outdoor temp. below</td>
<td>0 - 50°C; 5°C</td>
<td>25°C</td>
<td>0°C</td>
</tr>
<tr>
<td>Vent area</td>
<td>0.1 - 1.0 m²; 0.1 m²</td>
<td>0.1 m²</td>
<td>1.0 m²</td>
</tr>
<tr>
<td>Outdoor temp. below</td>
<td>0 - 50°C; 5°C</td>
<td>25°C</td>
<td>0°C</td>
</tr>
<tr>
<td>Overheated hours:</td>
<td>56.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overheated hours:</td>
<td>56.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Natural ventilation optimization parameters.
Thermal Mass
EnergyPlus quantifies InternalMass objects by surface area, calculating volume by requiring each InternalMass object to reference a material of a given thickness. In the mass optimization, therefore, the surface area of an adjustable type of thermal mass - a sector of a water barrel - was allowed to vary simultaneously with vent area and with the outside air temperature threshold controlling vent opening (Table 5).

Results confirmed the interdependence between natural ventilation and thermal mass in cooling; in this case, greater mass diminished the need for night ventilation, allowing the optimal vent area to drop to 0.8 m² as the internal mass increased from the original value (which included a concrete floor, fish tank, and potted plants) by 3.6 m², corresponding to approx. 3.6 water barrels (Fig. 6, Table 5). The temperature threshold for vent opening remained constant at 25°C. This thermal mass addition and vent adjustment reduced the overheated hours by only about seven hours compared to the previous optimization (Table 5), however, suggesting that the limit of the available strategies was approaching.

Revisitation of Shade Parameters
Results above established the importance of (1) exterior rather than interior shading, including distance from glazing, (2) use of solar radiation rather than temperature thresholds for shading control, including nighttime shade retraction, and (3) opening of vents only during specific, sufficiently cool hours. Other shading parameters (thickness, thermal conductivity) showed less-pronounced effects in previous optimizations. In addition, the value of $T_{sol}$ was previously set to 0.1 as the lowest realistic value for a retractable fabric shade.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range; Ini. Step Size</th>
<th>Initiation Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal mass surface area</td>
<td>0.1 - 4.0 m²; 0.5 m²</td>
<td>0.1 m²</td>
<td>3.6 m²</td>
</tr>
<tr>
<td>Vent area</td>
<td>0.1 - 1.0 m²; 0.1 m²</td>
<td>0.1 m²</td>
<td>0.8 m²</td>
</tr>
<tr>
<td>Outside air temperature above which vents close</td>
<td>5 - 50°C; 5°C</td>
<td>25°C</td>
<td>25°C</td>
</tr>
</tbody>
</table>

Table 5. Thermal mass optimization parameters testing the addition of 208-liter (55-gallon) metal drums of water. One drum possesses approx. 1 m² of surface area.

The final optimization therefore revisited these parameters, exploring the possibility of replacing the exterior fabric shade with an exterior slatted blind of lower minimum $T_{sol}$ and investigating interactions among shading parameters, natural ventilation, and thermal mass that might have arisen, to determine whether further improvement were possible (Table 6). Results indicated a strong preference for the lowest possible $T_{sol}$; in this case, 0.0 was attainable by use of exterior composite blinds with slats fully closed (Fig. 7). While this approach was acceptable for a sunspace unoccupied during hot afternoon hours, it would have diminished visual comfort and increased electric lighting use in work spaces, necessitating restriction to unoccupied hours.
priorities for minimizing overheated hours under the conditions of interest, namely: (1) addition of exterior shading, using (2) a low solar transmittance material (3) positioned well away from the glass to facilitate convective heat loss and (4) controlled by solar radiation rather than temperature, such that it is retracted at night to improve convective and radiative heat loss. Natural ventilation was also shown to be a priority, with (5) vents of increased area that were (6) opened only during sufficiently cool hours; also valuable was (7) internal mass, which could diminish the necessary vent area.

The most intriguing result of these optimizations was the performance of the model that incorporated the final parameters: not only were overheated hours reduced by 80% (from 216 to 41.25), but peak operative temperatures on the hottest afternoons were reduced from 5-8°C (9-14°F) above outside air temperatures in the original (Fig. 2), to 8-10°C (14-18°F) below outside air temperatures in the optimal (Fig. 8), a reduction of up to 14°C (25°F) on some days. Well-controlled passive cooling may have tremendous untapped potential.

Table 6. Revisitation of shade type parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range; Init. Step Size</th>
<th>Initiation Value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade type</td>
<td>Exterior shade / Exterior blind</td>
<td>Exterior shade</td>
<td>Exterior blind</td>
</tr>
<tr>
<td>Solar transmittance T_{sun}</td>
<td>0.0 - 0.1; 0.05</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Thermal conductivity k</td>
<td>0.1-1.0 W/mK; 0.1 W/mK</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Thickness T</td>
<td>0.5 cm - 5 cm; 1 cm</td>
<td>0.5 cm</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Vent area</td>
<td>0.1 - 1.0 m²; 0.1 m²</td>
<td>0.1 m²</td>
<td>0.65 m²</td>
</tr>
<tr>
<td>Mass area</td>
<td>0.1 - 4.0 m²; 0.5 m²</td>
<td>0.1 m²</td>
<td>3.975 m²</td>
</tr>
</tbody>
</table>

Overheated hours: 41.25

Internal mass and vent areas responded to this change by increasing and decreasing in area, respectively, diminishing August overheated hours to a final value of 41.25 (Table 6) from the initial value of 216.

Simulation of the model incorporating all final values revealed the transformation of the space more clearly. Comparing outside air and indoor operative temperatures, as shown for the original model (Fig. 2), revealed that peak afternoon operative temperatures were ultimately maintained 8-10°C (14-18°F) below outside air temperatures, a reduction of up to 14°C (25°F) from the original on the warmest afternoons.

CONCLUSIONS

The purpose of this work was to investigate GenOpt as a tool for discovering optimal control strategies for passive cooling, or by extension, other passive systems that could benefit from mechanical sensing and control. The first part of this effort is now complete, in that GenOpt and EnergyPlus revealed clear

![Figure 7. Revisitation of shade type, including (a) Exterior Blinds and (b) Exterior Shades, mass area, and vent area. Simulations are sorted by number of overheated hours.](image)

Figure 7. Revisitation of shade type, including (a) Exterior Blinds and (b) Exterior Shades, mass area, and vent area. Simulations are sorted by number of overheated hours.

![Figure 8. Passive cooling by the final optimized model, with indoor air and operative temperatures now 6-8°C cooler than outside air (and up to 15°C cooler than the original configuration) on the warmest afternoons, as the result of (i) exterior opaque blinds, deployed (ii) only when incident solar radiation > 25 W/m², accompanied by natural ventilation of (iii) greatly expanded area, (iv) open only when OSAT < 25 °C, and (v) increased thermal mass in the form of four water-filled 55-gallon drums.](image)

Figure 8. Passive cooling by the final optimized model, with indoor air and operative temperatures now 6-8°C cooler than outside air (and up to 15°C cooler than the original configuration) on the warmest afternoons, as the result of (i) exterior opaque blinds, deployed (ii) only when incident solar radiation > 25 W/m², accompanied by natural ventilation of (iii) greatly expanded area, (iv) open only when OSAT < 25 °C, and (v) increased thermal mass in the form of four water-filled 55-gallon drums.
This strategy also predicted some cool mornings. In practice, a client might prefer warm mornings and evenings, or find additional vent area too expensive or water barrels too cumbersome. These preferences could be built into GenOpt, however, by modifying the cost functions accordingly.

To complete this effort, the results must be field tested. Though the base model was field-validated [12, 13], these optimization results cannot be assumed to be fully accurate without verification. The great benefit of this process, nevertheless, lies in its indications of the most influential parameters, narrowing the range of options to be tested in the field and suggesting a level of performance within reach.

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REFERENCES
Toward Pre-Simulated Guidelines for Low-Energy High-Rise Residential Design in Megacities

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ABSTRACT
In order to improve early decision-making for similar projects, the authors used parametric energy simulation with the eventual aim of providing pre-design guidance for multiple teams of architects and policy-makers. The authors investigated high-rise, multi-family residential buildings in three megacities as case studies. They tested the impact of various design parameters on different energy objectives that they anticipate including in their pre-design resource. The research included three parts. (1) The authors identified synergies and trade-offs, in terms of early design decisions, when designing for different energy objectives, including (a) reducing annual energy consumption, (b) shaving peak-energy demand, and (c) increasing passive survivability – i.e., maintaining the safest interior temperatures in an extended power outage. (2) They performed sensitivity analyses to identify the impact of various design parameters – which included building form, window-to-wall ratio, envelope construction, shading design, and others – in the presence of confounding variables such as varying internal loads. (3) The authors investigated the impact of urban context. Since in generalized guidelines the future building site is unknown, the authors tested a method for generating an urban context based on the floor area ratio and maximum building heights of an urban district. These tests support the larger idea of eventually creating a comprehensive, pre-simulated resource for pre-design.

Keywords
Energy Modeling; Parametric Simulation; Urban Context; Passive Survivability; Resiliency; Peak-Load Reduction; Multi-Family Housing

INTRODUCTION
The United Nations expects the world's urban population to nearly double by 2050, increasing from 3.3 billion in 2007 to 6.4 billion in 2050, with much of this growth occurring in developing megacities [1]. Because of this new growth, society cannot afford to simply replicate standard building practices. New buildings must respond to the local climate and urban form, rather than rely on fossil fuels to make up for ill-suited designs. Yet achieving a high-performance design can be challenging.

Today, design teams rely on computerized energy simulation to help achieve energy performance goals, but that is far from a ubiquitous practice. Design teams not pursuing green rating certification, or teams in regions without local simulation requirements, rarely use energy simulation. The American Institute of Architects stated that U.S. firms had little understanding of the potential energy consumption for more than 40% of their projects [2]. The situation is likely worse in cities with rapid development schedules and limited design budgets.

Many design teams lack the budget or skills necessary to use energy simulation. Research shows that teams who do employ this tool habitually apply the analysis too late in the design process to take advantage of important passive design opportunities [3]. The most influential and cost-effective decisions occur earliest in the project's life [4], and experts suggest that building energy simulation would be more valuable much earlier in the design process [5]. Several researchers even recommend using energy simulation as a pre-design tool [6,7]. At that stage, simulation can assist teams in setting energy performance targets [8], evaluating passive energy strategies, identifying the most influential design parameters, and setting preferred ranges for key design parameters [7].

Firms who do start simulation early bear the cost of the entire customized analysis, starting from scratch. These firms then relegate their results to private client reports rather than a shared database [3]. Therefore, one firm’s analysis rarely informs others. The authors propose to create comprehensive design guidelines for high-rise multifamily housing in megacities by utilizing today’s computing power and parametric simulation techniques to pre-simulate numerous potential design combinations. The energy simulation results would be translated into comprehensible design guidelines and easily parsed via a web-based interface to assist design teams as a starting point in the decision-making process. One could test the impact of various inputs, similar to the U.S. Department of Energy’s (DOE) Building Performance Database [9], except populated with simulation results. The authors will expand the investigation beyond custom geometries, unique specifications, and limited ranges of performance parameters, to create a resource that can inform multiple teams of architects and policy-makers.
As a first step, the goal of this research was to help establish criteria that would be included in the pre-simulated resource for architects. The authors used computerized energy simulation to test combinations of design parameters on one floor of a prototype multifamily, high-rise (100m+/ 328ft+) residential building. The research included three parts. First, the authors compared the results of prioritizing different energy objectives. Researchers have shown the importance of architectural design on reducing peak energy demand [10, 11] and improving passive survivability, especially in multi-family residential buildings [12, 13]. Here, the authors strove to identify synergies and trade-offs, in terms of early design decisions, when designing for these different energy objectives.

Second, in the spirit of precedent research [14,15], they performed sensitivity analyses to identify the most influential of the tested design parameters, – including building form, window-to-wall ratio, envelope construction, shading design, and others – in the presence of confounding variables such as varying internal loads.

Finally, researchers have shown that urban context affects simulated energy use [16, 17]. However, with generalized pre-design guidance, context must be generalized because the actual project location within the urban fabric is unknown. In addition, neighborhoods are not static and it is difficult to account for future developments. Therefore, the authors analyzed the impact of urban context on the investigated design parameters, and tested a method for generalizing context when the future building site is unknown.

The authors began with three test cities. Beijing and Shenzhen, China, which have a growing market for tall buildings, are the second- and fourth-fastest growing megacities globally [18], and represent two unique climates, ASHRAE Climate Zones 2 and 4 respectively. The authors included New York City (also Zone 4), because of available urban context data. In this project, researchers from academia and practice collaborated with the goal of informing real-world architecture.

**METHODOLOGY**

**Software**

The authors set up the parametric building and urban context models using Grasshopper, a graphical algorithm editor for the 3D modeling tool Rhinoceros. They used ArchSim, a Grasshopper-based plug-in, to create input files, which were run in the U.S. Department of Energy's simulation engine, EnergyPlus.

**Passive Survivability and Peak Load Objectives**

The authors identified synergies and trade-offs, in terms of early design decisions, when designing for different energy objectives that may be included in the pre-design guidelines. Included in these objectives are the reduction of Energy Use Intensity (EUI), shaving peak-energy demand, and increasing passive survivability. Passive survivability is a measure of resiliency; the goal is to maintain an indoor temperature as close as possible to comfort conditions in a power outage. To test this, the authors ran each simulation for two weeks. The first week followed a normal operation schedule. Then the heating, cooling, mechanical ventilation, and plug-loads switched off (resembling a power outage) and the simulation ran for an additional week. The chosen two-week simulation period centered around the hottest or coldest (dry bulb) day in the weather file. The authors recorded the indoor temperatures in one thermal zone of the building – the hottest zone in summer and the coldest zone in winter. The authors found the design case in each city that keeps this zone the closest to comfort conditions.

To test the designs for peak loads, the authors simulated each design variant and recorded the hourly (8,760 per year) heating and cooling loads for each case. In each city they found the design case that produced the highest and lowest peak loads for both heating and cooling. The authors used typical meteorological year weather files throughout this research in order to test bad, but not unusually extreme, weather conditions.

**Design Parameters**

The authors strove to test realistic design parameters based on precedent projects in the test cities. The parameters tested included various early-design-phase decisions, such as building shapes, window-to-wall ratios, envelope constructions, and shading designs, as listed in Table 1. Here, the baseline architectural parameters met ASHRAE 90.1 2010 standards, except for the maximum 40% WWR limitation (because contemporary architecture frequently exceeds this limitation).

For floor plan shape, the authors chose variants from prevailing housing high-rise footprints found in aerial photographs of the test cities and in several residential high-rise precedents. The authors modeled a sensitivity analysis for floor plan shape, consisting of a 1-to-0.6 ratio rectangle (labeled “square,”) a 1-to-3.5 ratio rectangle, and a T-shape, each with an approximate area of 1200m² (12,917ft²) and a maximum center-to-glass distance of 10m (33ft). Per simulation best practices [19], each plan was divided into thermal zones by core, perimeter (4.6m [15 ft] wide), and solar orientation. See Figure 1.

The authors also tested solar orientation. For Beijing and Shenzhen, cities without a dominant street orientation, they rotated the building either 0° or 90° with respect to north. In New York they used the prevailing Manhattan street grid and thus tested 29° and 119° with respect to north.

The authors tested the design parameters with two levels of plug-loads (energy consumed by occupant appliances): (a) a baseline called "Low Internal Loads" per the U.S.
DOE’s Commercial Prototype Building Models (based on ASHRAE 90.1 2004) and (b) double that value, as a sensitivity analysis [20]. Their diversity schedule is listed in the appendix. Plug-loads are not a design decision per se, because architects have little control over this parameter. However, plug-loads have a high degree of uncertainty and can vary by 100% or more over design estimates [21]. Therefore, the authors tested whether this uncertain variable could influence the selection of other design variables.

The simulations assumed an ideal load system with mechanical ventilation. (For calculating EUI, the authors assumed a heating and cooling coefficients of performance of 1.0.) Testing of natural/mixed-mode ventilation is planned for the next iteration of this research. See the appendix for a list of other simulation assumptions. In order to investigate the importance of each parameter and inform the future pre-simulated resource for architects, the authors simulated every permutation of the design parameters: 1,296 for each city.

**Table 1: Parameters Tested**

<table>
<thead>
<tr>
<th>Input Name</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td>See Figure 1, 1,200 m² Plan Area</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
<td>0°, 90° (61°, 151° in New York) counterclockwise</td>
</tr>
<tr>
<td><strong>WWR</strong></td>
<td>30%, 45%, 75%</td>
</tr>
<tr>
<td><strong>Glazing Type</strong>:</td>
<td>ASHRAE Climate Zone 4, Beijing, New York:</td>
</tr>
<tr>
<td><em>U-Value W/m²K (Btu/h ft² F) &amp; Solar Heat Gain Coefficient (SHGC)</em></td>
<td>&quot;Glass ASHRAE&quot;: U=2.84 (0.50), SHGC = 0.4</td>
</tr>
<tr>
<td></td>
<td>&quot;Lower-U Glass&quot;: U=1.70 (0.30), SHGC = 0.4</td>
</tr>
<tr>
<td></td>
<td>&quot;Lower-SHGC Glass&quot;: U=2.84 (0.50), SHGC = 0.2</td>
</tr>
<tr>
<td><strong>ASHRAE Climate Zone 2, Shenzhen:</strong></td>
<td>&quot;Glass ASHRAE&quot;: U=3.97 (0.70), SHGC = 0.25</td>
</tr>
<tr>
<td></td>
<td>&quot;Lower-U Glass&quot;: U=2.27 (0.40), SHGC = 0.25</td>
</tr>
<tr>
<td></td>
<td>&quot;Lower-SHGC Glass&quot;: U=3.97 (0.70), SHGC = 0.2</td>
</tr>
<tr>
<td><strong>Horizontal Shading</strong></td>
<td>No Shading, Projection Factor: 50%, Projection Factor: 100%</td>
</tr>
<tr>
<td><strong>Wall Insulation</strong>:</td>
<td>&quot;Wall ASHRAE&quot;: Assembly U=0.365 (R=15.6) Layers and thicknesses: concrete-0.12m, extruded polystyrene (XPS)-0.09m, concrete- 0.12m</td>
</tr>
<tr>
<td><em>R-Value (F² F hr/ Btu)</em></td>
<td>&quot;More Insul&quot;: Assembly U=0.22 (R=25.8) Layers and thicknesses: concrete-0.12m, XPS-0.15m, concrete- 0.12m</td>
</tr>
<tr>
<td><strong>Thermal Mass</strong></td>
<td>&quot;Low Thermal Mass&quot;: see exterior wall description above, with 25m (9.8in) thick concrete ceiling and floor</td>
</tr>
<tr>
<td></td>
<td>&quot;High Thermal Mass&quot;: same as above with double thickness concrete in ceiling</td>
</tr>
<tr>
<td><strong>Plug-Loads</strong></td>
<td>&quot;Low Internal Loads&quot;: 5.5 (1.74)</td>
</tr>
<tr>
<td><em>kWh/m² (kBtu/ft²)</em></td>
<td>&quot;High Internal Loads&quot;: 11 (3.49)</td>
</tr>
</tbody>
</table>

*Glass ASHRAE = ASHRAE 90.1 2010 maximum values.  
** Wall ASHRAE = ASHRAE 90.1 2010 Zones 2 and 4 maximum wall assembly U values (same requirements for both zones)  

As a second step, to evaluate the accuracy of the authors’ Grasshopper script used to generalize the context, they chose three different neighborhoods in NYC as test cases: (1) a high-density context with a Floor-Area-Ratio (FAR) of 15 and a maximum building height limit of 180 meters, (2) a medium-density context with an FAR of 6 and a maximum building height limit of 120 meters, and (3) a low-density context with a FAR of 6 and a maximum context analysis. Assuming that context matters, researchers would face a challenge when creating generalized pre-design guidance: one cannot know where in a district a future building may be located. Therefore, the authors developed a script in Grasshopper for generalizing urban context based on randomized building heights that maintains a district’s Floor Area Ratio (FAR) and height limits (see Figure 2).

As a first step, the authors conjectured whether it is critical to model urban context for this pre-simulated design resource. The presence of neighboring buildings would change energy use, but would it also change the preferred design decisions? To test the impact of urban context, the authors first simulated the 1,296 different design combinations (refer to Design Parameters above) without surrounding buildings, then again within an urban context (the “generalized high-density context” described below). They repeated this study for Beijing, NYC, and Shenzhen, and compared the results with and without context. For this parametric analysis, the authors simulated a lower floor (16m [52ft] above ground) of a high-rise, which would be susceptible to shading from neighboring buildings.

As a second step, to evaluate the accuracy of the authors’ Grasshopper script used to generalize the context, they chose three different neighborhoods in NYC as test cases: (1) a high-density context with a Floor-Area-Ratio (FAR) of 15 and a maximum building height limit of 180 meters, (2) a medium-density context with an FAR of 6 and a maximum building height limit of 120 meters, and (3) a low-density context with a FAR of 6 and a maximum...
height limit of 65m. See Figure 3. In the three NYC locations, the authors chose the design case with the lowest EUI, and simulated it without context, with the generalized context, and with the real existing context. Three floor heights were tested: 16m (52ft), 48m (131ft), and 64m (210ft): a lower, middle, and upper floor of a 100m tower.

Throughout the analysis, the authors only considered the shading impact of neighboring buildings. The authors did not perform energy simulations for these buildings. The potential impact of reflective facades was not considered but could be added in future work.

RESULTS

Design Objectives: EUI, Passive Survivability, Reducing Peak Loads

The case studies are intended to clarify which design objectives are important enough to include, or even expand, and which ones to omit or revise, in a future pre-simulated resource for architects. An initial research question was, did the range of parameters tested produce a substantial difference between the design cases according to each objective?

The early design decisions studied here had a significant impact on the building’s EUI in each city. The differences between the best and worst simulated EUI in Beijing, New York, and Shenzhen were 19%, 21%, and 13% respectively. (Unless noted, results include the low plug-load cases only). The authors also found a large difference between the performance of the test cases in terms of peak loads, and a moderate difference in terms of passive survivability. Therefore, one can conclude that within the parameter ranges tested, each of these objectives mattered.

Figures 4 and 5 show example indoor temperature results for the best and worst design cases, while Table 2 shows a summary of the simulation results. One might also wonder whether each objective would lead to different design decisions. The answer is that yes, in each city, the preferred design would indeed change if one designed for peak load reduction, or passive survivability, rather than EUI. Figures 6–8 show the EUI breakdowns for the best cases for different design objectives. The worst case for EUI is also shown for comparison. Table 4 in the appendix highlights which design parameters would change in order to prioritize each objective. For comparison, Table 5 lists the worst case for each objective.

<table>
<thead>
<tr>
<th></th>
<th>Beijing</th>
<th>NYC</th>
<th>Shenzhen</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUI</td>
<td>19%</td>
<td>21%</td>
<td>13%</td>
</tr>
<tr>
<td>Peak Hourly Summer Load</td>
<td>37%</td>
<td>22%</td>
<td>18%</td>
</tr>
<tr>
<td>Peak Hourly Winter Load</td>
<td>40%</td>
<td>39%</td>
<td>NA</td>
</tr>
<tr>
<td>Extreme Indoor Temp.: Summer</td>
<td>3.7K (6.7°F)</td>
<td>2.8K (5.0°F)</td>
<td>1.4K (2.5°F)</td>
</tr>
<tr>
<td>Extreme Indoor Temp.: Winter</td>
<td>3.8K (2.4°F)</td>
<td>3.1K (5.6°F)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Interestingly, the benefit of these specialized designs was minimal in most cases. That is, prioritizing low EUI met the alternate objectives fairly well. Compared to the best cases for these objectives, the EUI-prioritized cases underperformed the peak load reductions by less than 2% and the extreme indoor temperatures by less than 1K (1.8°F). Exceptions are discussed below. At the other extreme, design cases that failed in terms of EUI performed even worse in terms of peak loads. In Beijing, the worst EUI case produced a 34% higher peak heating load and a 20% higher peak cooling load than the best EUI case. (These results were 35% and 18% respectively in New York, and 13% for the peak cooling load in Shenzhen.)

Furthermore, the results indicated that prioritizing alternate objectives had its drawbacks. In Beijing and New York, the best case for passive summer survivability reduced the average indoor temperature only slightly compared to the lowest EUI case, and not without substantially compromising the EUI performance, which increased by 7% and 8% respectively over the lowest EUI case. By prioritizing peak cooling loads in Beijing and NYC, one could reduce this load by 2% and 3% respectively over the lowest EUI case, but in so doing increase the EUI by the same percentage. This is a substantial annual energy penalty for the peak load benefits.
Perhaps these results are not surprising in these mixed heating/cooling climates, but prioritizing peak cooling in cooling-dominant Shenzhen also had drawbacks. Here, the lowest peak-cooling-load case decreased the peak load marginally (~1%) compared to the lowest EUI case. Ironically, though, it increased both the EUI and annual cooling load by 2% over the best EUI case. This result highlights the problem of designing for a certain peak hour (especially when this moment may or may not prove to be the peak condition in future years.)

In summary – even though the design parameters tested could have a large impact on peak loads and a moderate impact on passive survivability – if one does a good job designing for low EUI with these parameters, it is difficult to do much better for peak loads or passive survivability by specifically prioritizing these objectives.

**Sensitivity of EUI to Test Parameters**

To inform the methodology for a future pre-simulated design resource, the authors investigated which design parameters made a substantial impact on EUI. For each category, e.g. WWR, the authors found the median simulated EUI for the design iterations in each bin, e.g., 30%, 45%, and 75% WWR. They then calculated the percentage difference between the median EUI result in the best and worst performing bin. The results are shown in Figure 9 for each city with the generalized high-density urban context (dashed) and without context (solid). Of the parameters tested, EUI was most sensitive to WWR, glass type, building shape, building orientation, amount of wall insulation, and thermal mass, in that order. (The interaction between urban context and parameter impact/selection will be discussed later.)

Changing the levels of thermal mass did not produce a large impact on the simulated results. Two factors likely contributed to this result. First, even the "low mass" option included exposed concrete surfaces, and thus already had high thermal mass relative to the available range of contemporary construction choices. Second, due to the details of the ArchSim export and the EnergyPlus settings, the added thermal mass in the "high mass" option was not exposed to direct sunlight, which limited its simulated effectiveness.

Plug-loads were indeed found to be a confounding variable, in that the use of "high" versus "low" plug-loads did affect the preferred selection of other design parameters (in two of the three cities). In New York, higher plug-loads led to a preference for lower thermal mass, and in Shenzhen, higher plug-loads led to a preference for less wall insulation. However, the energy impact of these design decisions was minimal in an otherwise well-designed case. In the lowest EUI case, subsequently changing between high or low thermal mass in New York, and more or less insulation in Shenzhen, resulted in a difference of less than 1% in the resulting EUI. In the future, the authors will use these results to refine/expand/replace the sets of test parameters. For example, more variants of important parameters such as WWR, glass type, and building shape will be included.

**Impact of Urban Context**

Would urban context affect the early design decisions
studied here? Including the generalized high-density urban context in the simulations increased the heating load by 5% and 6%, while decreasing the cooling load by 6% and 9%, in Beijing and NYC, respectively, compared to iterations with no context. In Shenzhen, the cooling load decreased by 4% with the addition of context. Therefore, the impact of urban context on building loads was substantial. Results for NYC are shown in Figure 10.

Figure 10: Impact of Context on Heating/Cooling in NYC

Importantly, context also affected the preferred design decisions. Figures 11 and 12 show how the energy consumption and preferred design parameters changed in New York and Shenzhen depending on the presence of neighboring buildings. For example, in Shenzhen, with the presence of urban context, the preferred WWR actually increased to 75%. (The preferred Beijing parameters were nearly the same as New York’s, with a slight difference in shading design, as listed in Table 4.)

On the other hand, in each city, some preferred parameters (for example, glass choice) did not change regardless of the presence of urban context, as listed in Table 3. The winning glass selections show that in the cool climates, lowering the U-value was always the more important glass characteristic, whereas in the warmer climate, lowering the SHGC was always paramount.

In summary, including urban context matters. Because several important design decisions changed depending on whether or not context was included, pre-design guidance (and perhaps energy code requirements) should account for the effects of urban context.

The next question is: how much do the details matter? (The following context analysis results are based on tests with the lowest EUI case only. The impact of context details would be even larger in a more vulnerable building design, such as one with 75% WWR.) Nevertheless, floor heights mattered. The difference in heating and cooling loads change between 2% and 4%, in each NYC context, depending on whether one was considering a lower or an upper floor. Urban density (neighboring building height) also mattered. At the 16m floor elevation, when changing from a low-density to a high-density context in NYC, cooling loads decreased and heating loads increased by 3% each. Importantly, these results also impacted early design decisions.

Generalized urban contexts are one method for modeling this important, but unknown, entity in pre-design. How did the generalized contexts perform? As expected, the generalized contexts, based on FAR and maximum building heights, produced slightly different results than the “real” contexts. However, the differences were small. In each of the nine cases, (three urban densities times three floor heights) the differences in the heating and cooling loads between the “real” and generalized context cases were less than 1% (as opposed to a 3% error if no context was included). Therefore, creating a generalized urban context based on neighborhood characteristics produced substantially better results than ignoring urban context altogether.

Figure 11: Lowest EUI Case with/without Context, NYC

Table 3: Preferred Parameters Unchanged by Urban Context

<table>
<thead>
<tr>
<th>City</th>
<th>Preferred Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>Orientation, 30% WWR, Lower-U Glass, Shading, More Insul. Wall</td>
</tr>
<tr>
<td>New York</td>
<td>30% WWR, Lower-U Glass, More Insul. Wall, high internal mass</td>
</tr>
<tr>
<td>Shenzhen</td>
<td>Lower-SHGC Glass, high internal mass</td>
</tr>
</tbody>
</table>

DISCUSSION

Potential for Generalized Pre-Design Guidance

The results here confirm the important impact of early architectural design decisions on building energy performance. When starting design on a low-energy project, it would be helpful for architects to have guidance, such as which design parameters can potentially
make a large impact on energy performance in their climate/city/urban district. Yet many teams lack the budget or skills necessary to use energy simulation in early design phases. With parametric simulation, researchers can test a potentially large enough solution space to provide a pre-simulated, pre-design resource for multiple architecture teams.

This research was the first step toward refining the goals and methodology for creating such a resource. An expansion of this study will link pre-simulated results sets with user selection fields to offer end-users pre-simulated design feedback. Users will be able to select various design choices and see how their changes affect energy performance. Such a web-based, searchable resource will aid design teams who are starting high-rise residential design in certain cities. It will also establish a replicable methodology capable of producing large result sets that can provide value to other designers and researchers.

Here, the authors tried to understand the “design significance” of urban context, design parameters, and differing energy objectives. They defined “design significance” by asking, does this variable change the choice a designer should make, and would that selection then significantly impact the energy results? Consequently, these results will be used to establish which parameters will be included in the design guidelines. For example, varying plug-loads had a very large impact on EUI, and differing levels of plug-loads resulted in differing preferences for other parameters. However, the resulting EUI difference between the preferred design choices based on high or low plug-loads was not significant. Therefore, this variable will not be included.

Other Objectives: Passive Survivability, Reducing Peak Loads

In this study, preferred design decisions changed depending on the energy objective selected, but the performance advantage of designing specifically for peak load or passive survivability – rather than annual energy consumption – was small. In short, designing for low EUI met the other objectives reasonably well.

Here, the authors chose to study these impacts in typical weather years in order to design for high probability conditions. However, as urban growth strains existing infrastructure and the frequency and magnitude of weather emergencies increases, designers may have an ethical imperative to consider extraordinary weather events. Therefore, the authors plan to test these results using extreme and future weather files in their upcoming research. Testing with more extreme weather events would likely widen the disparity between the performance of the lowest EUI case and those cases designed specifically for passive survivability.

The Shenzhen results demonstrated the trade-offs encountered when designing for a certain peak moment, because the design for lowest peak cooling load actually failed to produce the lowest overall cooling load. Therefore, targeting one peak hour may not be the best approach. Moreover, from an environmental perspective, the most important time to reduce demand is during the peak periods experienced at the grid scale, not the building scale, so future research should consider the typical grid-scale peak periods instead.

Urban Context

The results here supported the notion that urban context matters in low-energy design. The presence of the high-density urban context affected the heating and cooling loads by 4% to 9%, and changed the preferred design parameters. Therefore, one needs to consider urban context in generalized design guidelines (and ideally, energy code policy). The approach to estimating urban context presented here – randomizing neighboring building heights based on FAR and maximum height – provided more realistic results than ignoring the context altogether.

In this research, the algorithm produced one context with randomized building heights. In the future the authors will repeat this process numerous times to control for idiosyncrasies. Then they will run all simulation studies with urban context.

China is in the process of planning new cities from the ground up. In situations like this, urban density and form can be design variables, rather than static parameters, and the method of parameterizing urban context presented here can offer testing capabilities to inform design at the urban scale as well.

Future Work

In the future, the authors plan to consider natural and mixed-mode ventilated buildings, which are especially prevalent in residential architecture. They also plan to consider the impact of prevailing HVAC components and efficiencies. Here, the settings portrayed a relatively high occupant density, primarily present in the evening/night, with high illuminance targets. No window blinds have been considered. Due to the EnergyPlus settings, the mechanical systems ran constantly with no set-back temperatures. Future research will investigate the impact of changing each of these parameters and will take into account cultural impacts in each city. For example, different occupant densities may be appropriate in different cities. As noted, here the low-thermal mass and high-thermal mass parameters were relatively similar, and the authors plan to include a lighter-weight construction option in the future. The thermal zoning strategy here was a simplification of reality, which would be broken into more zones. The impact of this simplification, especially on indoor temperatures will be studied and the number of zones expanded if necessary.
The designs for Beijing and New York, with their similar climates, performed very similarly – i.e., the preferred design choices only differed in parameters found to have a minor impact on EUI. Therefore, future research will investigate the feasibility of applying results to different cities within a climate zone.

Future research will also evaluate the feasibility of this pre-design simulation approach by testing against real-world case studies. The researchers will explore the benefits and shortcomings of this approach in lieu of traditional analysis methods, with regard to accuracy, practicality, and cost-effectiveness. The work will be expanded to other climates and possibly later to other building types. The web interface could expand to create a repository of predictive modeling results, so that others could contribute to the resource. Finally, the authors hope to demonstrate that a pre-simulated framework can lead to multiple creative solutions, and that its role is to inspire rather than replace the brain of the designer.

CONCLUSION
Through parametric energy simulation, this research explored energy performance in multi-family housing in New York, Beijing, and Shenzhen as a first step toward creating a comprehensive pre-simulated resource for early-design of residential high-rise architecture in megacities. The authors tested a method to generalize urban context and investigated the impact of methods, design parameters, energy objectives, and confounding variables, providing results which can be used to inform future research.

ACKNOWLEDGMENTS
The authors thank Jason Kirkpatrick for his consultation and gratefully acknowledge grants from the Harvard Graduate School of Design and the Joint Center for Housing Studies.

REFERENCES
10. Selkowitz et al., The impact of fenestration on energy use and peak loads in daylighted commercial buildings, 1984.
APPENDIX
Other Model Assumptions

Weather data:
USA_NY_New.York-Central.Park_TMY3.epw,
CHN_Guangdong.Shenzhen.594930_SHERA.epw,
CHN_Beijing.Beijing.545110_IWEC.epw.
Floor: Adiabatic (The simulated residence is bordered by other
conditioned residences above and below.)
Roof: Adiabatic
Lights:
1. Continuous Dimming
2. Power-Density: 10.76 kWh/m2 (3.41 kBtu/ft²) per ASHRAE
90.1 2010
3. Illuminance Target: 500 lux (46 footcandles)
Occupants Density: 0.2 person/m² (0.019 person/ft²)
Conditioning:
1. Heating Set Point: 20°C (68°F)
2. Cooling Setpoint: 26°C (79°F)
6. Min. Fresh Air per Person: 0.001 m³/s-person (2.12 ft³/min-
person)
7. Min. Fresh Air per Area: 0.001 m³/s-m² (0.197 ft³/min-ft²)
8. Economizer: No
9. Heat Recovery: None
Ventilation:
1. Infiltration: 1 Air Change per Hour (ACH)
2. Scheduled Ventilation: 0.6 ACH
3. Natural Ventilation: No
5. Hybrid Ventilation: No
Schedules:
The following occupancy schedule was used seven days per week,
based on the US DOE’s Prototype Models [20] (Models are based
on ASHRAE 90.1. 2004). All other operating schedules were based
on this schedule. The diversity factor for each hour from 1:00 to
24:00 is as follows: 1, 1, 1, 1, 1, 1, 0.9, 0.7, 0.4, 0.2, 0.2, 0.2,
0.2, 0.2, 0.2, 0.2, 0.2, 0.3, 0.5, 0.9, 0.9, 0.9, 1, 1, 1

Table 4: Parameters of BEST Case for low EUI, and Other
Objectives (Where Different)

<table>
<thead>
<tr>
<th>BEST Case for:</th>
<th>Beijing</th>
<th>New York</th>
<th>Shenzhen</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUI</td>
<td>square, 0°, 30% WWR, lower-U glass, shading 0%, more wall insul., high thermal mass</td>
<td>square, 151°, 30% WWR, lower-U glass, shading 50%, more wall insul., high thermal mass</td>
<td>T-shape, 0°, 30% WWR, lower - SHGC glass, shading 100%, more wall insul., high thermal mass</td>
</tr>
<tr>
<td>Peak Heating*</td>
<td>low thermal mass</td>
<td>shading 0%</td>
<td>NA**</td>
</tr>
<tr>
<td>Peak Cooling*</td>
<td>T-shape, lower-SHGC glass, shading 100%</td>
<td>T-shape, lower-SHGC glass, shading 100%, low thermal mass</td>
<td>lower-U glass</td>
</tr>
<tr>
<td>Passive Survivability Winter*</td>
<td>T-shape, 90°</td>
<td>shading 0%</td>
<td>NA**</td>
</tr>
<tr>
<td>Passive Survivability Summer*</td>
<td>T-shape, 90°, 45% WWR, lower-SHGC glass, shading 100%, less wall insul.</td>
<td>(Same as Peak Cooling Case)</td>
<td>Rectangle, 90°, less wall insulation, low thermal mass</td>
</tr>
</tbody>
</table>

* Only parameters that differ from EUI best case above are listed here.
**Designing for winter passive survivability and reducing peak heating load is unnecessary in this climate.

Table 5: Parameters of WORST Case for low EUI, and Other Objectives (Where Different)

<table>
<thead>
<tr>
<th>WORST Case for:</th>
<th>Beijing</th>
<th>New York</th>
<th>Shenzhen</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUI</td>
<td>Rectangle, 90°, 75% WWR, Glass ASHRAE, shading 100%, less wall insul., high thermal mass</td>
<td>Rectangle, 61°, 75% WWR, Glass ASHRAE, shading 0%, less wall insul., high thermal mass</td>
<td>Rectangle, 90°, 75% WWR, lower U glass, shading 0%, more wall insul., low thermal mass</td>
</tr>
<tr>
<td>Peak Heating*</td>
<td>0°, low SHGC glass</td>
<td>Low SHGC glass, shading 100%</td>
<td>NA**</td>
</tr>
<tr>
<td>Peak Cooling*</td>
<td>0°, shading 0%</td>
<td>Same as worst EUI</td>
<td>glass ASHRAE, less wall insul., high thermal mass</td>
</tr>
<tr>
<td>Passive Survivability Winter*</td>
<td>T-shape,0°, low SHGC glass, low thermal mass</td>
<td>T-Shape, 151°, Low SHGC glass, shading 100%, low internal mass</td>
<td>NA**</td>
</tr>
<tr>
<td>Passive Survivability Summer*</td>
<td>T-shape, 0°, lower-U glass, shading 0%, more wall insul., low thermal mass</td>
<td>T- shape, 151°, Low U –value glass, low thermal mass</td>
<td>T-Shape, high thermal mass</td>
</tr>
</tbody>
</table>

* Only parameters that differ from EUI worst case above are listed here.
**Designing for winter passive survivability and reducing peak heating load is unnecessary in this climate.
Session 6: Fabrication and Architecture

A Digital Design and Fabrication Library
Stylianos Dritsas
Singapore University of Technology and Design.

Aware Design Models
Martin Tamke
CITA: Centre for Information Technology and Architecture.

Curve-Folded Form-Work for Cast, Compressive Skeletons
Shajay Bhooshan, Vishu Bhooshan, Ashwin Shah, Henry Louth, and David Reeves
Zaha Hadid Architects.
A Digital Design and Fabrication Library
Stylianos Dritsas
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ABSTRACT
The goal of our system, for lack of better name at moment named as Alpha, is to offer an integrated approach to digital design and fabrication with capabilities beyond computer aided design and manufacturing. We attempt this to identify new modes of digital design thinking and to address the broader picture, that is, the challenge of translating between design and its production. It is to understand the complexity of design and its implications in production, to enable and perform architectural design analysis, rationalization and design performance optimization. We integrate visual: geometric modeling and simulation components; and non-visual: mathematical modeling and numerical optimization techniques. The intended audience at the current early stage of development is the research community in digital design and fabrication and design education with later goal of expanding to production.

Author Keywords
Design Computation; Digital Design; Digital Fabrication; Parametric Modeling; Robotic Simulation.

ACM Classification Keywords
H.5.m [Information Interfaces and Presentation]: Micellaneous; I.2.9 [Artificial Intelligence]: Robotics; J.5 [Arts and Humanities].

INTRODUCTION
The objective of the research work presented in this paper is twofold in: (a) Digital Design: to investigate alternative paradigms for architectural design computing, relevant to both concept-building as well as problem-solving, beyond associative geometry by introducing advanced methods of scientific computing; (b) Digital Fabrication: to address the broader picture of design and production of architecture beyond digital machinery operations, including embedded rationalization, design complexity management and control; in general the areas adjacent to fabrication such production planning and construction. The intended audience for this work is academic research in digital design and fabrication; design education in architecture and perhaps engineering; and architectural practice.

Background Context
Digital design and fabrication changed the way we think and make architecture. Techniques such as generative and parametric modeling as well as sophisticated equipment of production such as multi-axis machining systems, industrial robotics and 3D printers has captured the imagination of designers, not only within realm of spatial design such as architecture, but also engineering product development as well as non-design trained general audiences.

A comprehensive theoretical framework for thinking about the transformation of design and its production into new modes of computer based praxis is captured by the notion of mass customization [1, 2, 3]. Within this paradigm the new affordance for rapid design to production cycles via digital design and fabrication processes offers opportunities for bespoke design as opposed to uniform products of industrial standardization. To achieve competitive parity with highly optimized industrial processes, contemporary design and production tools and methods for architecture, engineering and construction need to be fundamentally overhauled.

The current challenges are not anymore in the generation of bespoke or parametric design to match client needs or in the machinery operations to achieve for instance complex form. Those are more or less successfully addressed by current design computation systems: parametric design and building information modeling. The core challenges are in the broader picture of overall design-to-production process and control of information complexity. How can we inform the upstream design process of the downstream detail design development, the opportunities and constraints in fabrication and eventual construction; how can we manage large volumes of design information without loss of design quality through various stages of data transformation and rationalization? Those are some critical topics that we have limited understanding and practical methods for addressing computationally.

Design Computation Systems
In the past decades the process of refreshing the traditional computer aided design and manufacturing tool-chain away from design-drafting and towards design-computing gave rise to innovations by adoption of computer programming for designers such as in Processing; visual programming to offer a less steep learning curve into design computing such as Grasshopper; and architectural parametric modeling such
as Generative Components, which introduced a top-down perspective, aligned with architectural design thinking, in contrast to bottom-up part-assembly design [4, 5].

However, interestingly even though there have been at least two decades of research and practice within new generation digital media, our mental paradigm is still heavily drawing-biased and geometry/form orientated. Design computation systems such as the aforementioned offer the means for conceptual design with computation but the primary medium of design is geometry/graphics even though it is operated via computation constructs such as data types, containers and transformations thereof. In addition, systems for easing conventional design-build practice, building information modeling, are also founded on a notion of modeling as an improved version of drawing or post-drafting by lacing geometry with meta-data.

An Alternative Perspective
Those developments are valuable but one may inquire about the next steps in the evolution of architectural computing, for both the sake of advancing the state of the art in design research, which will inevitably finds its way into education, but also for addressing practice challenges.

A pivotal notion identified is that of modeling. But we first need to take a step back. Instead of centering about the idea of design generation or transcription by constructing design intent logical relationships via procedural representations; or automated documentation and production as an improved medium compared to drawing; we may consider the idea of a model in the sense closer to what we find sciences. The key concern is foremost to understand complex phenomena, then to capture and organize their behaviors in functional constructs, only afterwards to exercise control. A model is thus a representation of understanding as well as a medium for experimentation and operations/production.

The logic for this approach is based on the need to expand beyond digital design and fabrication experimentations and address challenges in design to production which requires us to also address the lack of clarity for understanding architectural complexity which is often ambivalent between quantitative and qualitative interpretations. The moment we take steps forward towards the direction of modeling and simulating the broader process of design to production we are immediately confronted with problems that have been studied in the domains of engineering, computer science, mathematics and operational research such as scheduling, routing, packing, clustering and pathing, which are mostly intractable or NP-complete [6, 7, 8]. We thus have some very powerful notions for understanding complexity, modeling design and operational tools for control.

Interim Prototype
What would a design system as such may appear like is a reasonable question. The answer is not clear until a series of thought experiments and their implementations stress test current systems to identify the points of departure. Perhaps there is no need for a radically different approach compared to existing parametric platforms other than integrating an architectural version of document-based modeling systems such as NumPy, MatLab, or Mathematica. In other words, similar to how conventional CAD systems broadened their scope with the inclusion of design-process representations either via modeling hierarchies, tabular data and visual programming graphs, to supersede end product modeling by raw geometric primitives; we may foresee a future version of praxis with capabilities for true design-process modeling, rather than implicit via object models, embedded design optimization rather than external parameter improvement to give rise to a shared version of human-computer design.

SYSTEM ORGANIZATION
The presented system is an application extension library for the Grasshopper parametric modeling system containing new components in the categories of: Numerics, Geometry, Kinematics, Motion Planning, Machining, Transactions and Optimization. Numerics, geometry and optimization are for digital design with advanced modeling techniques while kinematics, motion planning, machining and transactions are closer to process-based modeling of digital fabrication. (Figure 1)

Implementation Logic
The library is organized internally in two layers: (a) Core Algorithms and (b) Presentation Engine (Figure 2: bottom left). The model/view approach is a design paradigm for separating computing logic from graphical user interface
and visualization. However, even though there are no
two-way dependencies there are unavoidable influences in the
design of algorithms to afford interactivity. Embedded
numerical solvers for instance, by driving input parameters
violate the inherent directed acyclic graph logic of models
by introducing feedback relationships. Similar requirements
and constraints are raised in simulating robotic kinematics
as well as network communications where transient events
are integrally modeled rather than externally animated.

Core Algorithms
Data structures and algorithms are comprised of packages
developed by the authors and additionally incorporate open
source libraries for numerical computation, advanced data
structures, computational geometry and portable document
generation. Algorithms are implementations of published
research in computer science, graphics, engineering and
operations research. As the library targets not only research,
there are historically important yet less efficient, methods
exposed for educational purposes. The guiding principle for
algorithm integration is driven by availability of existing
packages, adaptation and integration of current and past
community research work and current research needs.

Presentation Framework
Visual programming is less succinct and certainly relatively
inefficient compared to text-based computer programming,
however it is much more accessible to design audiences.
Eventually the end user’s goal is not to develop production
grade software but rapid design experimentation and idea
prototyping and as such visual programming is an excellent
medium. A major challenge with visual programming is the
perhaps unavoidable clutter produced by creating complex
directed acyclic graphs of numerous nodes and edges that
capture design logic. In developing component libraries for
visual programming this problem is exaggerated with the
potential clutter of the component library with numerous
nodes of similar functionality only with slightly different
input or output parameters.

To maximize functionality in the smallest possible visual
footprint: (a) we developed a visual style for components
such that overall design logic remain accessible at different
graph viewing scales, such that when node/edge saturation
inevitably occurs it is possible to parse high-level logical
relationships; (b) created custom representation components
for such non-visual concepts as bit-fields and data maps; (c)
integrated functional and visual options (enumerated types
and bit flags) within node types as well as multipage nodes
with optional and ignored input/output fields to compress
numerous functions (Figure 2: top and bottom right).

COMPONENT CATEGORIES
Numerics
The aim of providing numerical data extensions is to offer
tools for computational design beyond geometric modeling.
Currently there is a lack of scientific methods in computer
aided design tools and while they are extensively used to
perform for instance various environmental and structural
simulations based on such analyses as the finite elements
and computational fluid dynamics methods, they are seldom
exposed as general purpose tools.

The motivation is not to replace production ready certified
analysis tools but offer programmable interfaces to the first
principles within these packaged methods for the purpose of
research, that is, for rapid prototyping of new computation
methods, and education, that is, teaching exactly those first

![Figure 2: Internal structure of the core algorithm library and properties of the presentation framework.](image-url)
principles.

Numerics contain components for raw/intrinsic data types as well as lists and matrices thereof. Most components are basic in logic and their implementation is patching missing capabilities. In contrast to basic components the matrix component embeds a linear algebra kernel of approximately forty different functions including: matrix generation and construction from data sources, geometric transformations, and algebraic operations, including factorizations, analysis and matrix characterization.

**Geometry**
The current set of geometric extensions is rather limited adding only a few components that are useful for robotics such as construction plane loading and plane interpolation for kinematic model definition and pathing; parallel curve offset, polygonization and clipping for machine pathing; and principal components plane fitting for bounding box alignment in logistical operations such as part packing and point cloud fitting. In a future update we plan to integrate 3D scanning capabilities developed in the past [9] for very large mesh and point cloud visualization and editing.

**Kinematics**
Kinematics tools are for modeling the mathematical and visual representation, and for simulating typical industrial 6-axis robotic systems for digital fabrication. Models are auto-generated by loading visualization geometries, axial configuration data stored as construction planes, and angle limit vectors stored as annotation from a CAD documents. The application examines the axial configuration and builds a characterization code to identify the appropriate forward and inverse kinematics equations. Two kinematic families are currently supported which are for ABB, KUKA, Denso and Universal robots; and perhaps other robots but have not been yet tested. In addition there are tools for defining end-effectors such as generic grippers, welding torches and machining spindles.

**Pathing**
Motion planning captures concepts of machine pathing and overall operation modeling. The current mode of modeling is based on an offline paradigm, where a digital fabrication process is pre-planned, modeled, simulated and executed with target equipment. The abstraction model of this is based on Tasks which contain one or more machine Operations, such as motion or input/output signals. Tasks can be simulated individually and merged into Programs. Advanced task such as pick and place shortcut the process of defining explicitly individual operations.

In prototyping mode currently there are components for online machine interaction. In online mode the model graph contains communication components that exchange live information with the machinery via network ports. The reasoning for this is such that it is possible to use sensors and actuators, external hardware in general, to dynamically program, operate and control machines. The goal for online operation is twofold: (a) to unify robot programming styles instead of using multiple incompatible offline formats, such as Universal Script, Kuka KRL, ABB Rapid, and generic CNC G-Code; and (b) to enable experimentation with non-prescriptive modes of operation using vision systems and bespoke effectors. The challenge with dynamic coding is in the static synchronous or rather strongly state-full logic of parametric models expressed as directed graphs which is conceptually distorted by transient event-driven logic.

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**Figure 3:** Kinematics modeling, simulation, motion control and script generation for common six-axis industrial robots.
Machining

Machining operations provide tools for simplifying motion planning for subtractive material processes. The aim is not to replace functionality found in sophisticated computer aided manufacturing application but to offer programmable tools for connecting design and its fabrication. The motivation is to allow rapid experimental workflows and exploration of the machine capability and aesthetics. Currently only basic functions for cutting and drilling are available but they will be inevitably expanded. Again the core idea is to expose the first principles of machining, which are often geometric, for rapid material experimentations.

An aim for the machining unit is to transparently integrate subtractive operations independent of a target machine and its degrees of freedom but while retaining pathing logic such that target machines can inform the pathing strategy bi-directionally. The first aspect of a common language already exists in CAM systems: generic NC pathing code is generated and post-processed in one or more steps based on end system capabilities. However, the backwards logic of adapting pathing based on machine capability is also critical as it is often that multi-axes systems have multiple solutions for the same motion some of which are not all qualitatively equal. The notion of Motion Protocols explored in the past research [10] is embedded in the current system. Relevant work in this domain include [11-15].

Optimization

As previously noted, optimization offers the opportunity to embed advanced computation methods as first class entities, at the same level of abstraction as with regular components rather than meta-processes. The methods available address common design and fabrication topics organized into: (a) Numerical solvers, univariate and multivariate root-finding and minimization; envisioned integrated in the parametric logic to offer alternatives to problem solving by geometric constructions. Mathematical models accessed via numerics often offer simpler formulations in addressing both linear and non-linear problems. (b) Routing methods, namely basic implementations of the traveling salesman problem useful for machine planning optimization. Perhaps in the future a state of the art algorithm may be incorporated but for the time being current methods are rapid for interactive use cases. (c) Data clustering methods for analysis, such as understanding the range of different parts and dimensional variance in a design and optimizing part typologies and sizes. (d) Graph analysis: contains a very broad range of methods for construction of graphs, analysis of such metrics as various centralities, path finding and tree generation. Graph theory offers advanced set of procedural machinery for such as applications as digital design and fabrication but also urban network analysis studies. (e) Packing methods are extremely relevant to digital fabrication for such notions as material use / waste reduction optimization in subtractive machining processes and even efficient arrangement of rapid prototyping parts into build volumes.

Figure 4: Methods including numerical solvers, bin packing, data clustering, graph and routing operations.
FUTURE DIRECTIONS
There are three areas of interest for future development namely (a) collision detection for robotics simulation and general physics based problem formulation and solving. Currently only kinematic related warnings are emitted when robots reach their motor limits and unfeasible positions. For advanced pick and place operations, large scale 3D printing as well as machining it is paramount to track interference between the machine and materials. Collision detection is also important for such task as static clash detection as in building information modeling, solid and particle spring simulation and in broader terms as means for modeling and problem solving via physics. (b) Online/networked robot control with integration of sensors such as computer vision cameras and peripheral devices such as actuators beyond IO port handling. (c) 3D scanning support for point cloud and massive mesh modeling. Those tools are already developed from previous research and they are pending integration in to the current library.

CONCLUSION
This paper presented a design computation system which aims to discover ideas for digital design and fabrication. The main objective is to integrate scientific computing methods with architectural geometric modeling systems and explore the potential for an advanced version of design modeling but also address issues in the broader area of design to fabrication and construction. The contributions to the field is pending deployment and testing of our methods though the implemented libraries. There are however topics raised for discourse. (a) The notion of a model as not only virtual machinery of design production but closer to a science ideas and methods may potentially enrich the current modes of thinking. (b) The need of first class analysis and optimization methods is certainly a topic that requires broader debate. The argument is that only then we may move away from object modeling, interim process artifacts, and move into direct process definition. We may then model and simulate architectural space and buildings as systems. (c) Embedding advanced methods of analysis and optimization, such as graphs analysis, data clustering, pathing, routing and packing offers some powerful tools for understanding the implications of digital design in its digital fabrication rather more holistically. Our system is currently under development and will be available in alpha state in the first quarter of 2015.

REFERENCES
Aware Design Models

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ABSTRACT
Appearing almost alive, a novel set of computational design models can become an active counterpart for architects in the design process. The ability to loop, sense and query and the integration of near real-time simulation provide these models with a depth and agility that allows for instant and informed feedback. Introducing the term “Aware models”, the paper investigates how computational models become an enabler for a better informed architectural design practice, through the embedding of knowledge about constraints, behaviour and processes of formation and making into generative design models. The inspection of several computational design projects in architectural research highlights three different types of awareness a model can possess and devises strategies to establish and finally design with aware models.

This design practice is collaborative in nature and characterized by a bidirectional flow of information. The concept of the aware model addresses hence the current infrastructures of digital design models and processes, which impede technologically and methodologically feedback between disciplines and processes.

Author Keywords
Model theory; multi scalar modelling; digital fabrication; design systems; informed models;

ACM Classification Keywords
Design; Measurement; Performance;

THE OUTSET OF THE AWARE MODEL
With the arrival of digital tools, the traditional logic of projective geometry is opened up to symbolic calculation. Computer modelling in architectural design enables the description of variable geometries that calculate the values that they embed [1], instigating new practices of algorithmic modelling that actively engage with information, directly calibrating and calculating the impact of a given design decision [2].

Digitization has also impacted the boundaries of the profession. By establishing a shared digital platform, digital design tools allow architects to interface a host of new programmes from parallel design fields providing the basis for more situated and more informed designs [3]. The ability to interface complex analysis tools for the simulation of force and flow, such as Finite Element analysis [FE analysis] that discretise complex problems into finite numbers of interrelated nodes to compute their force-relations, has influenced the thinking of structural design enabling the realisation of buildings with a higher degree of formal freedom and structural complexity [4].

At present the development of digital design tools in architecture is structured around large-scale industry led efforts that have sought to standardise information and develop shared protocols between interdisciplinary partners [5, 6]. However, core efforts such as the Building Information Modelling paradigm (BIM) have difficulties in tackling the high degrees of complexity of current building practice while at the same time not being able to support the needs for flexible, intuitive and communicable design processes [7, 8]. And while recent developments on software level and the general advancement of the industry ease the practice with BIM the underlying prescriptive nature of many implementations remains. A parallel development took therefor place with a series of profession-led research and development efforts creating bespoke methods that liaise different processes in multiple tools to be able to develop individualised solutions [9, 10]. The practice of architects building their own information tools, encoding their models and engaging directly with computer programming is therefore an embedded part of existing practice, both in academia [3, 11] as in industry [10, 12]. This effort is project-led, practice-specific and the information around the underlying models and their setup is rarely shared.

THE ROLE OF MODELS IN DESIGN THAT ACTIVATE MATERIAL PERFORMANCE
In the context of design, the goal of a model is not to obtain the best solution, since this concept makes little sense within this realm [13], but an adequate solution.

Furthermore in the design of structures that activate material performance a system of exchange between the designer and the designed [14] becomes increasingly nuanced. Material, energetic, and external parameters concerning design intention and fabrication can each inform
aspects of a digital model, with a continuous system description made from these partial models. Each aspect has a capacity to act independently, tends towards its own optimisation, and makes an impact upon other models that are linked to it. One can distinguish between three types of model: generative, analytic and decision making [15]. Where this distinction provides roles to sub- or networked models in a design environment, each of the models can hold knowledge about certain aspects of the design and only the conjunction of these provides a sense of awareness on an overarching level.

MODES OF AWARENESS
This paper investigates architectural design models from the practice of the CITA, a practice focused on the interplay of material and making with computational practices in design and fabrication, in order to discuss the different modes of awareness in models and how they are generated.

The models of the Dermoid series (with SIAL 2010-2013), the exhibited demonstrator The Rise (2013) and the interdisciplinary project Sensitive Ceramics (2014) (Fig.1) are generative in nature and cover the process from design to fabrication. All three projects work with a constraint set of materials and utilize the materials behaviour in order to create architectural spaces.

MODES TO ESTABLISH AWARENESS
The aware model needs to be informed. The model can here be front loaded with information or continuously query for updated information. The space of this query can be outside the model or within, as exemplified by the installation The Rise [16]. This demonstrator employed the capabilities of rattan to bend in order to generate a structural system made of bundled rattan rods in the EDF gallery in Paris. The project was an inquiry into models with integrated feedback loops, able to sense and adapt to changes during genesis. The underlying computational growth model queried the space of the gallery for opportunities to create stabilizing connections through branches to walls or floor. The model of the space was established through a 3d laserscan of the space, which was algorithmically transformed into a simplified surface model (Fig.2). While the conception of the environment the model was situated in was in this case static, the use of material behaviour required The Rise to have the capability to query its own bending behaviour constantly during the genesis in the digital model. As the bending behaviour of bundles and three dimensional nodes of rattan (Fig 1) is highly non-linear and has hence many levels of detailed part to part interactions, physical prototypes were used to measure the bending behaviour of larger assemblies under increasing load and calibrate the digital model accordingly.

The Dermoid installation used a similar approach with an even higher degree of rigor in metrology in order to obtain knowledge of the behaviour of the nodes of the structure [17]. This is made entirely from 4mm plywood, inquiring how large structures can be made from small elements, engaging using a single material and hence solely wooden connections from a traditional repertoire, such as tenons and wedges. The elements of the structure are made bespoke to local parameters, such as curvature or required strength. The resulting high geometric variation in the system coupled with unknown mechanical properties of the plywood, along with a tight schedule required a fast and effective way to simulate the complex structure while also making attempts to improve the structural design of the Dermoid. Due to the amount of interaction and unknowns in the structure, the usual approach of discretization, or Finite Element (FE) methods of structural simulation, could not be applied in this case. Instead of understanding the structure through material properties that
cause mechanical behaviour under load, we chose instead to
measure the behaviour directly and calibrate an FE model
accordingly. Here a spring based model in the FM software
Sofistik was used. An appropriate mean to calibrate and
evaluate the simulation were hence a series of mechanical
tests conducted on a custom build test rig. Investigating key
parameters in a controlled way, the rig established a dataset
of the behaviour for each load direction and in the
minimum, maximum and average size of the pod used in
the design of the Dermoid.

A structural analysis undertaken subsequently by means of
an equivalent spring model in order to produce a simplified
and a computationally undemanding representation of the
tripod modules based on relatively simple empirical tests
(Fig.3) instead of simulating in detail the complex material
behaviour and all of the jointing interactions (friction,
slippage, plastification, buckling etc.).

Fig.3 : Diagram of the test rig for Dermoid 3

Additional rotational springs combined with complex
restraints and releases were able to simulate the elements
behaviour accurately (Fig. 4). The time needed for this
simulation prohibited however the establishment of a high
quality awareness of the design model through interactive
feedback.

Fig. 4: Spring simulation of an element of the Dermoid in
Sofistik.

The third mode to establish awareness in a model - besides
the awareness of itself and of the surrounding environment
- is the awareness of its own genesis, as for instance
through processes of assembly or fabrication. This
awareness relates as well to the fact that any element is the
result of its history. On the level of material, properties,
such as ductility, malleability and compressibility are a
direct result of the material processes. While C.S. Smith
focused on his definition of ‘funicity’ [18] - historically
depended properties – on the material level, one can expand
this understanding on any created element.

Sensitive Ceramics explored how generative design
models can become aware of processes that consist of
subsequent and not entirely predictable steps. The making
of three dimensional earthen objects is here only successful,
when the 3d printing of clay and the later process of firing
and glazing are deeply informed by traditional craft
knowledge based on skills and experience.

The observation of the filigree nature of the extruded
ceramic thread inspired us to look at references from Gothic
and Arabic windows, whose filigree patterns fulfil the
functional requirement of the subdivision of a larger wall
opening into batches of available glass sizes – performative
aspects - to provide shadow – and aesthetic purposes -
create local shadow figures.

Sensitive Ceramics employs (similar to the previous
projects) a continuous process of iterations of physical
prototypes, followed by a careful registration of the results
in order to link the behaviour of the ceramic material tightly
to the development of the generative model. The project
addresses simultaneously a lineage of research into digital
fabrication in architecture. Here precedents for design
strategies were created, where the concepts of production
and design become one. Early research in digital fabrication
made used 2d milling toolpaths the ornament of surfaces
[19] or the continuous movement of robot arms the base of
extrusion patterns of acoustically active expanding foam
[20] These synergetic design systems incorporate all
knowledge of the design and genesis process and output
often code that directly steers the production machinery, as
in the movement of the tool.

Fig 5. Testing of the 3d printing steup in Sensitive Ceramics

The process of experimentation in sensitive ceramics
resulted finally in a computational system for designing
wall like compositions based on modules in ceramics that
modulate light. This computational system bridges the
design intent, the 3d clay printing process and the following
steps, such as firing and glazing that further influence the shape and appearance of the product.

**MODES TO IMPLEMENT AWARENESS**

These steps of sensing are essential to establish a base awareness within a design model. They are accompanied by a set of strategies to implement awareness within the model. The **Dermoid project** showcases which considerations have to be taken into account. In this set of demonstrators the multitudes of concurrent parameters that influence the form-finding process of the design prohibit a procedural computational approach [21]. An investigation of the Dermoid’s design displays two types of parameters: key parameters - those that have a high level of reciprocal relations, such as the number of elements, the boundary conditions and the elements geometry, and parameters that only depend on a single (higher level) parameter, such as the detailing or curvature of a beam (Fig. 6). The dependent parameters can usually be abstracted as limiters – here i.e. values for the maximum bending radius of local elements. Following this categorization the overall design system can be devised in design model, which holds the key parameters, and a dependent production model, which takes the previously generated data and creates detailed fabrication information. The workflow integrates the parameters from construction and materials within a solely geometry based design environment. Avoiding heavy simulation a design environment can be lightweight, while being aware of the crucial material and construction parameters in the design stage. This allowed here for the exploration of the constructions potential and the creation of complex surface topologies.

![Fig 6.: The Dermoid consist of a network of interrelated tripods, made entirely from 4mm plywood](image)

**Dermoid**

Abstracting complex material relations into geometric dependencies is a common practice [20] and as in the Dermoid, driven by considerations of balancing and weighting the different constraints, which emerge during the process. The act of design is here the negotiation of conflicting interests and the determination of the importance of parameters. In the case of the Dermoid, parameters determined by the material and structural behaviour, as the exact representation of the deflection, were of less importance in the design process, than the ability to guarantee later constructability and control of the designed structure. This approach was assured through prototyping, downstream simulations and design guidelines that assured continuous surfaces curvature in order to achieve a shell like overall shape of the structure – resulting into mainly compressive forces [17].

The remit of the aware model is here again to ensure that the local consequences of overall design decision comply with local constraints, while the overall design is following sound design principles.

The application of formulas, which work on pure geometrical level, can however provide the model with an awareness of physical forces. Rules of thumb provide for instance instant feedback, whether the bending of rods results in local forces exceeding a tolerable maximum [23].

**The Rise**

How a model can be aware of its later structural behaviour to a level that is precise enough to drive construction was investigated in the installation **The Rise** [24]. This uses natural plant growth as a conceptual framework to generate a 5x5x5m structure made of branching bundles of rattan. The morphogenesis and simulation of design and material behaviour becomes here an interdependent whole, where every step of the designs generation is accompanied by multiple steps of evaluation. This concerns the environment, but especially its own behaviour. A lightweight approach to simulation was needed that would also be able to exhibit bending and torsional rotation during growth (Fig. 7).

A custom-written particle-based spring and gravity simulation system allowed these goals to be achieved. The model exhibits herein its growth through the accretion of minimal triangulated truss-like modules which are managed in a mesh whose point, edge and face topology is registered and deployed in the particle spring simulation. By modelling the bundled system in such a way, both the bending and torsional behaviours as observed in the physical prototypes are approximated. In fact the simulation of bending forces is altogether eliminated in favour of collections of springs embedded in these accumulated tubular elements, speeding up the particle system. The parameterisation of spring stiffness, particle mass, strength of gravity, and the radius and length of each growth module is informed through empirical observations of both the digital and physical. A feedback loop is initiated between both of these environments for the purposes of calibrating the overall system.
The execution of the generative algorithm as informed by the observed material behaviours and managed through the topological system outlined above results in a model that captures the active bending behaviour of bundled rattan, incrementally grown into place under continuous transformations resulting from the simulation of self-weight. Ultimately, based on the intentions and constraints of this project, questions regarding specific material descriptors and structural performances – such as flexural modulus and longitudinal stiffness – are disregarded in favour of modelling for direct adherence to empirical observations based on the testing of prototype performances and behaviours. Additionally, the measurement of each spring’s deformation as it reacts to further module accretion generates data regarding both tension and compression (Figs.8) that proves crucial to the sizing and distribution of rattan members during detailing and fabrication.

MEANS TO ADDRESS THE DESIGN SPACE OF THE AWARE MODEL

The Rise demonstrates how a model is able to sense and evaluate and is finally able to feedback to itself and the environment it is situated in. This includes in the context of design, most importantly the designer. The role of the designer in the Rise is that of an observer. Though he is the creator of the model he has only limited abilities to engage during the process of the design generation. Parameters and conditions inside and for the designed object can be changed, an interaction with the object under genesis is however immediate. The awareness of the model does not include the designer.

Within the Dermoid project the formfinding process of the design (Fig 9) is initiated by the designer modelling a two-dimensional mesh, which is then used, as input geometry in an interactive real-time formfinding system - in the current design tool the Kangaroo physics engine.

For the formfinding process the manifold mesh is discretized as particles and springs and a multi-layered system of dynamic constraints and forces is generated within the particle spring system of Dermoid physical forces are abstracted into a set of relational vectors. This allows to accompany this set of force based vectors with other ones that represent geometrical design goals. All of these can be changed during the design generation, while the effect and the immediate result differ. The set of used vectors can be grouped into four overall categories:

Surface Properties

Vectors which determine the intrinsic and local behaviour of the mesh manifold include the springs keeping the mesh together. These are defined be their stiffness and rest length. Additionally a force is applied which operates on the mesh triangles and attempts to keep these equilateral, in turn resulting in relatively equiangular hexagonal cells. This is not only desirable aesthetically but also ensures fairly consistent beam connection angles. Finally a Laplacian smoothing force is added on top of this, taking out any mesh extremes and ensuring an even mesh.

Shell Forming Forces

There are two forces, which induce curvature onto the mesh manifold. The two forces applied to the vertex particles are: 1) A gravitational force applied along the Z-axis of the world space, simulating the catenary principle of the
inverted hanging chain made famous by Antoni Gaudi. 2) An inflation force applied along the vertex normals of the mesh, simulating internal pressure analogous to the inflation of a balloon. The first force results in a mesh which tends to inherit mainly compressive forces while the second tend to result in more aesthetically pleasing curvature. During simulation the user is free to mix the two forces.

![Fig. 9: Formfinding Sequence of the Dermoid III as sequence of operating forces.](image)

**Geometric Constraints**
Constraints are defined by the simulation input geometry. The naked vertices/particles along the perimeter of the mesh are subjected to a vector “pulling” them to a final position (RailsEndCurves), given by the designer. Additionally the rail curve endpoints are treated like anchors, meaning that any vertex/particle which is coincident with a curve endpoint will be completely fixed to this position in space while the remaining perimeter particles are free to move along the rail curves. These can be changed at any time during the form finding process.

**Attractors**
Attractors are forces which operate using attraction or repulsion principles as a function of distance. A force is applied to the vertices/particles sitting on the naked mesh perimeter. Here a power law is applied which forces the particles to repel each other if they get within a certain distance. This results in an even distribution of beams along the manifold boundary. This force allows designers further more to enforce certain design goals in local areas of the mesh, such as, for instance, density or structural height of beams.

The bidirectional approach with a manual interaction with a hex-based geometry and an instant display of the resulting design constraint by multiple concurrent requirements, is fast and intuitive and does not limit the design space through the determinism that the choice of a certain generative algorithm would imply.

**CONCLUSION**
To possess design agency is crucial for the aware model. It has to have the ability to sense as well as to adapt and generate. Generative capabilities are important, as it provides the model with the ability to demonstrate the consequences of the interplay of internal and external constraints, as the designer’s actions. The role and means of feedback is hence a central question for the aware model.

The emergence of aware models can be understood as an indicator for the transformation of the existing intuitive practice in architectural design, which is based on knowledge embedded in the practice of architects and designers [26], into a practice, where knowledge is seemingly formalized and embedded in models. This can be ad hoc for short design probes or as a strategic method for an enterprise. These models are based on captured knowledge. The areas of knowledge to embed into design models exceed here easily the field of fixed boundaries captured in limiting numeric values. Aware models engage instead with linear or non-linear behaviour of i.e. materials and time-based processes of assembly. The models venture finally into areas that describe ways a structure is operated and interacted with. Models become a persistent part in all parts of the lifecycle of a building [27]. A shift in focus takes place from the static to the dynamic and temporal.

In contrast to the all-embracing notion of the Persistent model [27] an aware model is decision oriented and the knowledge to embed is specific to project-, process and point in time. While the constitutional elements for the models might consist of generic parts and techniques, they are in the further process transformed and adapted. This follows the logic of the architectural discipline, where each project is at least site and program specific. It seems however, that the current architectural practice is not akin to this mode of working with models. It is rather tool centric and uses the same underlying model for many projects, while the steps and combination of tools operating on the model differ vastly between the projects.

As the aware model has an analytical component it inherits the dilemma of any simulation, where depth and precision are challenged by the urge to be fast and cheap. This raises the question of the position of an aware model in the design process. As the aware model holds the ability to transform from simple equation based approaches of simulation to more sophisticated and computational heavy ones it can be initialized in the highly speculative and explorative phase of the initial design phase, where concept and constituents are floating and mature in subsequent phases. Current model conventions might however limit this transgression on a practical level.
CHALLENGES FOR THE AWARE MODEL

Today several challenges have to be overcome in order to create aware models: scalar dependencies, the interaction of different model representations, the question of feedback, the incompleteness and inaccuracy of models and the differences in time needed to compute. It seems that the models have a tendency to become increasingly autistic towards user interaction, the more complex their task is.

The interaction with the user and the process into which a model is embedded, has to be taken into account. An understanding that underlines the insights gained by the cybernetic community [14], which stresses the importance of the environment of the model – this environment includes the designer and the feedback to him.

This feedback is becoming to an increasing amount the base for design decisions. Where projects get more complex and more specific design requirements, they have less precedence in existing projects. Simulation tools and interdisciplinary collaborations provide here the much needed evidence [28]. This evidence is especially needed for the early stages of design, where the most important decisions for a project are taken and the least knowledge is actually available [29]. The aware model is able to integrate the increasing knowledge of a project and exchange initial rough estimates with more refined methods of prediction at a later stage.

The key constraints that limit the potential impact of design feedback in the aware model can be summarised as:

- **The ideal of the integrated model**: The ambition to integrate all design phases and practices has proven difficult as different practices use different kinds of tools to analyse and represent knowledge. A tendency to monopolize the model in the hand of one discipline or even individual could be observed in all cases of this paper. Instead of integrating information into one contained model the design process has to be understood as a network of relations in which smaller dedicated models distribute defined tasks while retaining the ability to interface and communicate.

- **A persistence of hierarchy**: Building practice has traditionally been organised hierarchically as a sequenced set of subsystems each with their own scale of engagement and team of specialised professions. This understanding of design as a progression through the scales limits the potential for design innovation, as it excludes our ability to understand how the small scales - material or detail - can affect large scales – environment or structure. To support a real implementation of feedback mechanisms, models have to be developed for multi-phased and multi-scalar feedback in which cyclical interdependencies can be investigated and assessed.

- **The implicit reduction of design parameters**: To preserve design control current models necessarily implement a reduced number of explicit parameters thereby prioritising particular design criteria over others. In order to support a congruence of design, material and process logic tools need to be developed, by which models can self-parameterise and adapt to continual feedback in a complex multi-dimensional solution space.

ACKNOWLEDGMENTS


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Curve-Folded Form-Work for Cast, Compressive Skeletons

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Figure 1: Showing Precedent (Larsen, et.al, 2013), Artist Impression & Built prototype

ABSTRACT
The research described in this paper explores the synergy between the methods of form-finding (for funicular loads) with curved-crease folding (CCF). The paper will propose a two-step process that combines a form-finding method that finds the form under vertical loading and with a mesh-perturbation method that solves for planarity and developability constraints. The resulting geometry will be shown to be amenable to construct curve-crease folded moulds for concrete casting. The paper will also describe the design of a demonstrative prototype - a self-supporting structure composed of bar-elements that are formed by casting concrete into molds that are curve-folded from sheet material.

AUTHOR KEYWORDS
Curved Crease Folding, Interactive Simulation, Design Workflows & Digital Tools, Form-finding, Dynamic relaxation, Multi-Objective Solvers & Feedback.

INTRODUCTION
Physical form-finding using hanging chains and associated architectural design methods is common knowledge among architects. There are several digital methods to find the equilibrium shape of Shell structures including TNA-Thrust Network Analysis (Block and Ochsendorf, 2007), Mass-spring methods (Fraschini, Prete and Laurino 2009), Dynamic relaxation (Barnes, 1999), Force Density Method (Schek,1974) etc. For a comparative analysis of the methods we refer the reader to (Veenendaal and Block, 2012). We chose to use the Force Density Method for ease of implementation and amenability to interactive design manipulation methods. We describe this in the section regarding ‘Form-finding using the Force-density method’.

The construction of such geometries with concrete requires the use of false-work or form-work, into which concrete is poured. Traditional form-work is often straight and difficult to form curved surfaces that are an essential feature of Shell structures. (Figure 2)

These difficulties extend to the construction of curved skeletal geometries. In this context the proposed use CCF moulds is relevant, in that we can economically and efficiently form curved-molds from sheet material. We describe this in the section regarding ‘Curve Crease Folded Mesh’. It is important to note that the proposed CCF technique is most amenable in cases where the underlying graph (of the skeleton) is embedded on a surface with consistently signed (positive or negative) mean-curvature. i.e. CCF cannot be used when the surface is anti-clastic or when the two principal curvature directions are oppositely signed. CCF produces ruled-surfaces, implying one of the principal directions is always zero and thus the sign of the mean curvature can only be consistently signed as dictated by the other principal direction. Hence, there is compatibility between compressive skeletal structures and CCF moulds. (Figure 3)

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We designed and built a proof-of-concept prototype using the proposed methods to identify construction related constraints and problems. We describe this in section regarding ‘Fabrication’. A precedent project to note is (Pedersen, et.al,2013) for their use of straight folded plastic as form-work for a skeletal shell computed using TNA, as noted in Figure 1.

DESIGN PIPELINE
The design pipeline consists of three main steps, each described in subsequent sections. Such a multi-step process was devised to prioritize speedy, parallel and multiple design iterations.

1. Generating compressive shell geometry (Form-finding using the Force-density method).
2. Deriving geometries for curve-foldable moulds from 1. (Curve Crease Folded Mesh).

FORM-FINDING USING THE FORCE-DENSITY METHOD
This step in the design pipeline consisted of two sub-steps.

1. Definition of a low-resolution mesh.
   Initially a low-resolution mesh (low-poly-mesh), with desired topology, is specified. This is typically planar. Such a low-poly mesh lends itself to ease of shaping the geometry based on design and contextual parameters (Figure 4). For the built prototype, we ensured that all the internal vertices of low-poly-mesh were tri-valent. This was to constrain the construction of the prototype to the use of only Y-shaped nodes, and thus reducing complexity in on-site production. Further, the chosen mesh (Figure 4 - Iteration 03) had a reasonable number of Y-nodes and a good aspect ratio of faces i.e. avoiding acute faces.

2. Finding the Equilibrium solution.
   Next, we solve for the equilibrium positions of the vertices of such a mesh, using the Force Density Method (FDM (Schek, 1974). Typically, the loads considered are vertical and the Force densities – the amount of force in an edge - are also user specified. We used mesh-paint tools in Autodesk Maya to specify these weights. Once the equilibrium positions are found, we update the low-poly-mesh with these locations (Form-found-Mesh). The FDM algorithm is quite robust in that it admits a wide range of user-defined edge-densities whilst still producing a feasible solution. Further, FDM being a linearized, closed-form solution, is highly amenable for use in real-time, interactive shape modelling. As such the choice of the specific edge densities in the final configuration was an interactive exercise between painting the densities and visually inspecting the resultant equilibrium shape. Future work in this regard is noted in the discussion section. (Figure 5)
DISCRETE REPRESENTATION FOR CURVE CREASE FOLDED MESH

There are several discrete representations - exact and inexact - of curve-crease folded geometries. We chose to use a representation based on planar-quad meshes (PQ mesh) that additionally incorporate developability constraints (Figure 6). For a comprehensive list of representations, we refer to (Solomon et al., 2012).

\[ G = k_1 \cdot k_2 = 0 \text{ OR } \sum \phi = 0 \]

AND

\[ S_1 \& S_2 = PQ \text{ strips} \]

Figure 6: Shows essential requirements of a discrete representation.

Given the representation, we used various mesh operations to derive a predominantly quad-faced mesh from the Form-found-mesh (Figure 7).

1. Extrusion of boundary edges of the mesh, so that all the original edges become internal edges.
3. Deleting the original mesh faces.
4. Conversions into a higher resolution mesh using the modified Catmull-Clark subdivision scheme in-built into Autodesk Maya [Stam, J., 1998].
5. Re-topologise based on the heuristics that rulings don’t intersect, except at conical parts. This produces a predominantly quad mesh, with each ruling connecting only to boundary vertices.
6. Extrude and crease the boundary edges of the re-topologised mesh.

PERTURBATION OF A INPUT MESH TOWARDS CURVE-FOLDABLE SOLUTION

For a given mesh to be foldable from a single sheet, it must meet the following geometric criteria: it must be 2-manifold, its faces must be predominantly four sided (some triangular singularities are allowed), its faces must be planar, and it must have uniform zero Gaussian curvature (Kilian et al. 2008). The input mesh (generated in the previous section) only meets the first two conditions, leaving the third and fourth unsatisfied by default (Figure 8).

Satisfying the remaining geometric criteria does not have a closed form solution. We adopt a iterative approach based on principles of dynamic relaxation (Barnes, 1999) where vertices of the input mesh are treated as point masses which are perturbed by virtual forces. While such systems are widely used due to their relative ease of implementation, the challenge of this particular application lay in constructing a set of relevant and compatible virtual forces which quickly yield foldable results without compromising the compression network of the input mesh.

Two virtual forces were developed - one enforcing planarity of faces and the other enforcing developability of vertices. Each one is formulated as the gradient of an energy function, where energy represents the deviation from their respective geometric conditions at a particular vertex. These gradients collectively define the force vector applied to the vertex - perturbing it in such a way that locally minimizes the two energy functions. This method suggests that the vertices of the mesh are simply descending a pair of gradients towards a foldable configuration.
Planarity Force
For a given quadrilateral face, we define the planarity energy function as the volume of the tetrahedron created by its four vertices (Gotsman et al. 2013). The gradient of this function $\mathbf{g}_i$ is calculated analytically as the shortest vector between the face diagonals (Figure 9). This provides both the direction and magnitude of the planarity force $\mathbf{f}_{pln}$ which is applied to each pair of vertices in opposite directions.

Planarity forces are minimal in their perturbation as the input mesh has near planar faces. They can therefore be applied to all faces without compromising the compression network.

Developability Force
For a given interior vertex $v_i$, we use the discrete approximation of Gaussian curvature proposed by (Desbrun et al. 2002) to define the developability energy function. This amounts to calculating the angle defect about $v_i$ (Figure 10). While allowing $v_i$ to descend the gradient of this function is the most direct means of minimizing local Gaussian curvature, doing so causes significant deviation from the compression network. This is compounded by the fact that the energy function is ill defined for boundary vertices - focusing perturbation on the interior “crease” vertices which define the load paths.

Therefore, we formulate a modified scheme which perturbs the adjacent boundary vertex $v_j$ to minimize Gaussian curvature at $v_i$. Here, the magnitude of the applied force is still calculated as the angle defect about $v_i$. The direction, however, is calculated as the sum of the gradients of $\Theta_1$ and $\Theta_2$ with respect to $v_j$ (both of which are perpendicular to the edge between $v_i$ and $v_j$). Because the location of $v_j$ has no effect on the other angles around $v_i$, they can be ignored.

The resulting force vector is then applied to $v_j$ causing it to pivot around the adjacent crease edge - effectively descending the gradient of Gaussian curvature at $v_i$. Because perturbation is now focused exclusively on boundary vertices, the compression network is preserved during the relaxation process.
Boundary Conditions
In cases where the initial low-poly mesh is not closed, the input mesh has special case boundary vertices (Figure 11), which we refer to as “end” vertices. An end vertex is a boundary vertex which is located on an edge loop spanning across any number of fold creases. These are omitted from developability forces since, unlike standard boundary vertices, their adjacent edge loop does not define a fold crease.

Input Assumptions
We make several assumptions regarding the input mesh which allow the relaxation process to successfully converge on a foldable geometry. Firstly, we assume it is topologically suitable i.e. its faces are predominantly four sided and every crease vertex is adjacent to at least 1 boundary vertex. Secondly we assume that the input mesh is a reasonably close approximation of a curved crease foldable geometry. A poor approximation results in numerical instability or, in cases where it does converge, excessive deviation from the compression network.

FABRICATION
Planar development / unfold.
The 3D low resolution mesh which is now developable is an approximation of the actual curve folded panel. These 3D low resolution meshes are first unrolled into 2D low resolution meshes before extracting the boundary curves for laser-cutting. This ensures minimum deviation during the unfold process.

Boundary curve generation
Consistent topology across panels enabled us to easily extract the required information for generating the curves. Three techniques were used to construct the curves, from the edge conditions and ordered vertex lists that were extracted from the low resolution unrolled mesh.

Interpolation curve method
An interpolated curve was constructed through the vertices of the low resolution mesh (Figure 12). This provides the closest approximation of the curve to the fold line, and works well when the number of subdivisions per panel is low. It however fails when they increase, with the curve becoming highly rippled due to increased number of constraints. A rippled curve makes it difficult to fold properly. It also indicates higher deviation to the required curve-fold.

Control-Point curve method
This method used the vertices as the control points to generate curve denoting the fold (Figure 12). The technique helps averaging out any anomalies in the relaxation process which become more evident in higher subdivision models. This method gives better results in terms of smoothness than the interpolated curve, but still fails in extreme singularities.

Modified Control-Point curve method
The control points of the curve generated in the previous method were manually modified to compensate for the extreme situations (Figure 12). This created a smooth curve that akin to a best fit curve which gave the closest approximation of the curve fold and was ultimately used to create the final drawings for fabrication.

Foundation details
Problems in foundation design included termination of shell anchors legs to ground from elevated positions, spread of the shell itself, non-orthogonal mould ends, a hanging installation procedure for moulds, and allowances for field adjustment of compression elements. To solve these issues, the foundation design consists of 3 components, a tensile raft foundation, three pairs of abutments, and an equal number of custom anchor plates to receive the shell anchor legs. All pieces were fabricated on site using mild steel plate 4mm for the raft and 2mm for the remainder of the foundation with geometry simplified to planar elements for fabrication constraints.

The elevated position of the shell was transferred to ground via pyramidal abutments. A tensile raft foundation, a lattice
of 4mm open bottom plate steel strips reflecting the low resolution form of the shell elements was devised to counteract shell spreading between abutments. The raft also acts against rotation of the abutments during installation. Anchor plate design consisted of extrusion of the mould leg end face, and total threaded extension from the plate adjustable to +150mm.

**Assembly Process**

**Edge Beam Detailing**

Two essential problems in detailing the prototype involved the inherent thinness of the geometry (38-40mm), and the shallowness of the total shell curvature ranging between 2.75-8.25m radius at the apex and the supports. The boundary edges were thickened, in order to counter the collection of loads due to the abrupt change in angular direction of mould arms at these edges. Thickening and rigidity of the boundary edge was achieved through pleating technique used and developed by (Sweeney, 2014), (Huffmann, 1976) and (Demaine, 2010). By-products of edge beam development included an integrated pour stop detail for casting, and an edge termination differentiating its requirements from the interior edges. A single pleat was used for workability at scale. (Figure 13)

![Figure 13: Edge Beam Pleating](image)

![Figure 14: Pleating Concepts & Application](image)

It must be noted that, we generated the pleat curve as interpolation between the boundary and fold-curves (Figure 14). This assumed that, over the length of the shallow curvature, discrepancies between a developable curve and a non-developable were negligible. Additionally, pleating allowed us to maintain a geometrically similar edge curvature resulting after successive folding operations.

**Mould End-to-End Joinery**

As the geometry was discretized into (Y-shaped) components, a method of joining moulds was required. The essential problems of joining pre-cast components were non-orthogonal edges shared between panels, the thinness of the concrete cast, and the orientation of the concrete upside down in the installation in relation to their cast direction. The end edge, a remnant of the mesh simulation, made end-bearing between moulds impossible without additional registration hardware between moulds.

Panel joining details were developed and evaluated based upon registration, hardware availability, ease of assembly, etc. We developed details which could be standardized, serially manufactured, and provided ease of installation. (Figure 15)

We utilized a friction fit rebar detail in a PVC sleeve, where each mould arm contained both a male and female fitting. This solved assembly issues of tracking locations of male or female assemblies in addition to registering the centering alignment of the sleeves for different panel profiles.

![Figure 15: Hardware Configurations](image)
DISCUSSION AND FURTHER WORK
The objective of a proof-of-concept for constructing a predominantly compression structure using curve-folded panels as a casting mould (lost form work) was successful. However, issues raised during design iterations and construction of the prototype suggest future research trajectories.

Penalty Functions in the relaxation solver
Additional penalty functions to reduce deviation from the input mesh were not necessary in this case due to the modifications made to the energy function of the developability force. This was also aided by the relatively good approximation of curve-foldable geometry provided by the input mesh.

For the sake of generalization, however, penalty functions could be added to the system as an additional force to minimize deviation from input mesh, as several other authors do (Killian et al., 2012), (Gotsman et al., 2013).

Interactive FDM and CCF constraints
As noted in introduction, there is a general compatibility between compressive structures and CCF moulds. However, there is also an inherent negotiation between the local curvatures of the equilibrium shape and the cross-sectional depth of the mould so formed. The incorporation of such constraints within FDM process is part of intended future work.

Boundary curve generation
In the current exercise, we made use of easily available curve approximation methods based mostly on time constraints of executing the physical prototype. However, we recognise that this is an avenue for future work, especially given the manual intervention currently needed. The essential constraints of such future work would be to develop custom curve approximation methods that minimize the deviation from the unfolded mesh vertices, whilst maintaining smooth and consistent curvatures. Further, the evaluation criteria for the success of the method would be the deviation of a re-folded mesh from the solved 3d mesh.

Mould Curvature vs Fold direction
The direction in which the panel flanges are folded produces positive mean curvature in the panel. As a result, concrete “hangs” from the mould, requiring additional hardware assemblies such as the anchor bolts on face centers to resist a tendency to fall out of open face moulds during installation. Future research could investigate folding techniques to control the curvature of the panel independent of global curvature. This could allow for a panel to be negatively curved while the global form remains positively curved. The aluminium mould could then be more than a lost formwork, additionally providing tensile reinforcing.

Crease Scale, Pattern & Angle
Pleating 1mm thick aluminum sheet and only 18mm wide between folds, by hand proved cumbersome in practice. Paper test-models were pleated with acute fold angles which led to snapping, when used with aluminum at real-scale. Therefore, we did not exceed 90 degree pleated folds which led to some straightening of the edge moulds. Additionally, localized deformations and curvatures occurred due to the manual process. Further investigation into acute angle folds and patterning of creases is ongoing.

Curvature vs Thickness
A higher fold angle corresponds to increased curvature of the panel subsequently increasing depth. In the demonstrative prototype, the mould thickness averaged 3cm due to the shallow curvature of the form found geometry. Thinness is adverse in a predominantly compression structure as there is limited cross-sectional area for the transfer of load from one component to another. Future
work could use details similar to the edge beam (repetitive folding) to increase the depth of the panels.

**Tolerance Allowance**
During installation, two portions of the raft foundation were un-welded and detached approximately a meter such that panels could be fitted, and then the abutments reattached to the raft foundation after installation. Detailing for field adjustment should be extended to foundation elements in addition to anchor legs.

**Panel Connectivity**
During assembly every rebar extension was cut and sleeve fitting abandoned for an external weld plate and reinforcing plate steel collar. Orthogonal mould ends in future work can assist in compression load transfer as well as a standardized cast-in-place weld plates on each arm for flush concrete to concrete connections.

**Registration & Panel Spring-back**
The curve-folded panel should have an embedded design features to enable accurate folding and registration when manually folded and assembled. The decision not to geometrically fasten the flanges in any way to one another via a folded key, or backer plate, caused a number of registration issues between moulds. After managing to get the accurate curvature of the panels, another complication is maintaining the curvature during the casting process, which in this case was the pouring of a cement and sand mix. The weight of the material tends to unfold the panels, disturbing the original setup. This causes issues during assembly as the panels do not have the computed curvature. In future work redundant registrations should be avoided by some physical connective geometry as the current method resulted in time expenditure, tolerance losses, and general lack of a working benchmark between panels.

**CONCLUSION**
In summary, the paper described a combination of known form-finding methods for compression structures with a novel procedural solution to produce curve-foldable casting-moulds in an economical and efficient way. We also described the construction process of a proof-of-concept prototype and the key learnings thereof. We thus believe that our contributions lie in both the simple to implement digital methods of simulation and also the documentation of a construction process that opens up several trajectories for further investigation. We hope both would be valuable for other researchers embarking on exploring this novel and practical method to construct compressive skeletons with curved edges.

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**IMAGE REFERENCES**
A Physical and Numerical Simulation Strategy to Understand the Impact of the Dynamics in Air for the Design of Porous Screens
Mani Williams, Rafael Moya, Daniel Prohasky, Mehrnoush Latifi Khorasgani, Simon Watkins, Mark Burry, Jane Burry and Philip Belesky
RMIT University; University of Melbourne.

Assessing the Energy and IAQ Potential of Dynamic Minimum Ventilation Rate Strategies in Offices
César Porras-Amores and Spencer Dutton
Technical University of Madrid; Lawrence Berkeley National Laboratory.

A Comparative Study of Mixed Mode Simulation Methods: Approaches in Research and Practice
Priya Gandhi, Gail Brager, and Spencer Dutton
Center for the Built Environment, UC Berkeley; Lawrence Berkeley National Laboratory.
ABSTRACT
This paper describes a virtual and physical design and prototyping strategy intended to aid designers to understand the relational dynamic between airflow and porous screens for building facades at the conceptual design stage. The strategy consists of three main components: 1) A prototyping phase involving a combination of computer aided modeling (CAM), physical additive and subtractive fabrication; 2) A virtual simulation phase using computational fluid dynamics (CFD) software; 3) A physical simulation phase of experimental fluid dynamics (EFD) using a miniature wind tunnel (MWT) and microelectronic measurement systems (MEMS) that measure: wind speed, air temperature and relative humidity. The design strategy supports the designer to make design decisions based on relevant feedback from both CFD and EFD methods – covering a vast design solution space. The tools utilized within this design strategy are presented as a kit containing parts that are relatively inexpensive, easy to assemble, and have been successfully user-tested at an international design workshop. The paper includes the description of the application of the strategy combining CFD, MWT, MEMs and real time visualization to the design and study of various porous screens produced during the design workshop.

Author Keywords
Physical prototyping; aerodynamics; façade design; computational fluid dynamics (CFD); experimental fluid dynamics (EFD).

INTRODUCTION
Wind flow in the built environment produces aerodynamic phenomena that affect comfort of building inhabitants and people in public spaces. For this reason, the study of the interaction between aerodynamic phenomena and architectural phenomena has become very important in many fields such as sustainability, environmental design and the area of human comfort [1]. To address the effects of interaction between wind dynamics and architectural forms, designers have started to incorporate wind analysis as an input within the design process by incorporating performance simulations developed with wind experts [2]. Wind engineers consider wind tunnels a reliable technology for wind analysis, but because of the expensive facilities required, this technology has not been fully incorporated into the design process or the education of architecture students [3]. Moreover, technologies such as CFD have facilitated the analysis and quantification of wind pressures and approximations of average wind velocities and turbulence intensities for wind engineering and structural engineering applications. The expertise required to operate advanced CFD tools such as ANSYS is rarely accessible to architects for such architectural design tasks as the design of porous screens for wind mitigation and filtration into the interior environment.

Our proposed technical platform is a miniature wind tunnel (MWT) incorporating microelectronic sensors and real time sensor data visualization for testing physical prototypes. Low fidelity CFD simulation with the digital models used to build the prototypes is considered in parallel. It integrates the capabilities of both physical and virtual simulations of wind flow. It is targeted for use in the early design stages, as a preliminary design exploration suite for small-scale models or architectural details. The relative short feedback time between simulations allows designer to explore multiple conceptual ideas in quick succession. The aim of the simulation tests is less on the performance validation, but to offer opportunities for the designers to grasp the general behavior of wind in the context of their architectural design, assist designers in ranking the aerodynamic performance of designs, and understand how, in general to alter design parameters to improve the wind performance.

This paper includes the details of the wind simulation and sensing systems (both virtual and physical) chosen to support early stage conceptual design. We conclude this paper with a set of porous screen designs to illustrate how
our proposed simulation platform contributed to design decisions that were developed during an intensive design workshop.

**CFD METHODS FOR DESIGN STRATEGIES**

Simulations using CFD principles have been incorporated progressively into the architectural design process for Building Performance Simulations (BPS) [4]. The BPS simulates hypothetical environmental scenarios for building design and makes it possible to visualize the results. In the past few years a large set of computer applications for simulating wind speed and turbulence around buildings have been developed for architects. These range from simple smooth flow CFD programs to more specialize and involved simulation, which, whilst very computationally expensive, have been validated against benchmark flows [5]. However in general the CFD tools for architects are somewhat incomplete and require further development [6].

The incorporation of CFD wind visualization into the architects' design process has presented difficulties because CFD based tools require specialist knowledge for both modeling and the interpretation of results [3]. Moreover, high fidelity simulations are very time consuming and need very fine mesh spacing and are therefore rarely integrated into the workflows of most practicing architects. Also, CFD modeling is challenged to provide a sufficiently accurate solution due to the complex nature of the turbulent atmospheric boundary layer. Thus, in the architectural design process, CFD tools have been used to evaluate the effects of wind on the final building form rather than as a tool used to inform early design decisions [3]. To deal with these difficulties, new versions of CFD programs have been developed to be used by architects from the early design stage. This new generation of programs such as: Autodesk Vasari or Flow Design facilitates the setup of simulation, visualization and analysis by architects without a strong theoretical background in fluid dynamics. However, these programs focus mainly on providing graphical representations for the qualitative analysis of wind flow, a user-friendly interface and the integration with other architectural CAM programs such as Autodesk Revit. Thus, one aim of this research was to understand the limits of the performance of these programs for visualizing and feeding back wind effects in various architectural design contexts for particular design typological problems (see Figure 1). To this end they were used in parallel with testing physical models using electronic sensing to gather data for analysis. The models tested both in the CFD and Miniature Wind Tunnel and sensing environments were of complex porous screens for microclimatic control of an indoor environment in an apartment building.

<table>
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<th>Pros</th>
<th>Cons</th>
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<td>More accessible than traditional CFD software or wind tunnel facilities; suitable for users without a strong theoretical background in fluid dynamics; rapid visualization and feedback; relatively easy to setup and operate; integrated workflow between 3D model, CFD simulation and visualization; useful for the early design stage for low resolution designs.</td>
<td>Mainly for simulation of outdoor wind flow; low level of accuracy in results; cannot simulate/measure temperature or humidity; Methods of visualization with 2D and 3D flow produce different air flow movement patterns which can be confusing; not reliable for detailed analysis of final design</td>
</tr>
<tr>
<td>Portable structure more accessible than a real wind tunnel; relatively cheap; D.I.Y construction; focused on the early design stage; flexible to incorporate platform of multiple sensors</td>
<td>Provides a continuous and relatively homogeneous airflow across the test domain section, not necessarily a replication of real wind conditions</td>
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**Table 1: Summary of the technology used**

**Figure 1. Example CFD visualizations from Vasari**

**WIND TUNNELS AND VISUALIZATION TECHNIQUES**

Wind tunnel tests have existed since 1871 [7] and wind tunnel tests have been conducted for architectural purposes since the early 1890s [8]. Yet simulating the wind for
architectural design is challenging - the dynamics in wind around buildings involves the turbulent nature of the atmospheric boundary layer [9]. The first wind tunnel studies focused on reproducing real wind flows in 12m long tunnels. Subsequent wind tunnels were designed to reproduce the atmospheric boundary layer with a section 2.4m wide, 2.15m height and 33m long [10]. Industrial scale wind tunnels are large and expensive facilities, may require advanced data acquisition systems and processing systems that require specialist training to operate [11-13].

Techniques of visualization used in wind tunnels include tracer methods of the airflow such as fog/smoke emission, the use of floating particles or gas bubbles. Other methods trace air movement patterns on model surfaces using dye or oils to draw wind patterns [14] i.e. the erosion technique [15]. In general they provide a qualitative approach to visualizing the pattern of wind vortices, separation flows, turbulence and changes of wind direction. Quantitative techniques typically involve the analysis of results after the experiment has taken place. Hot-wire anemometry, pressure transduced anemometry (such as a pitot static tube) or tracer methods (such as the particle image velocimetry (PIV) technique) require post analysis for the evaluation of the physical design [16]. It is feasible to note that these techniques could be used to provide near real-time visualizations of the wind. The physical wind sensing system using a MWT and MEMS provides near real-time digital visualizations of the wind, using transduced signals from hot-element anemometers [17,18].

Digital visualizations of scientific data can augment the real world with ‘real-time’ qualitative representations that enhance communication within groups. For example, animations that depict wind flows around physical models of architectural form can help communicate the behaviors of complex wind phenomena across design teams where not all members have an extensive knowledge of wind dynamics. This holds true even when the representations are not as accurate as traditional methods of simulating wind flows, as demonstrated in the Tangible Teamwork Table (TTTHub) project [19]. Digital and physical representations were combined to communicate the complexity of wind flow dynamics for a team undertaking an exercise in urban planning [19]. In a similar manner, the augmentation of physical wind through the quantification of wind at strategic points in space around physical building models or building details can provoke productive design discussions.

**EFD: The Miniature Wind Tunnel**

The use of physical models to test wind dynamics allows architects to experiment with complex designs and environmental patterns without needing to use advanced numerical simulation tools to verify their experiments. The use of miniature wind tunnels can allow designers to observe how the wind may interact with a complex screen configuration. The use of a MWT can inform the designer through various visualization techniques to aid the design process towards more desirable interior microclimatic conditions. The particular wind tunnel used in this study incorporated a microelectronic wind sensing system which allowed the users to observe how the screen may affect environmental parameters such as: the dynamics in air movement, temperature and relative humidity that may be produced by the simulation of rain. These kinds of experiments are much more feasible to conduct using physical means, such as the MWT, even if the simulated airflow does not match the full scale in situ conditions. That idea is to conduct these experiments with a platform of low cost technology that can gather digitally airflow data and visualize it with a graphical interface to provide real-time feedback for architects. The design and improvement of the MWT is a work-in-progress, experiments are being conducted to evaluate the performance of the MWT to an industrial scale wind tunnel.

**The Portable Miniature Wind Tunnel**

The MWT is designed to be portable and is constructed by hand (see Figure 2). All of its components are provided as templates that can be cut using a laser cutter and quickly assembled without the need for any tools. It consists of a test chamber containing four modules. Each module has a dimension of 0.9m wide, 0.9m high and 0.6m long. The wind tunnel walls consist of 8 sheets of 0.6m x 0.9m x 6mm MDF, 8 sheets of 0.6m x 0.9m x 3mm Acrylic. Laser cut 6mm MDF sheets were used for the structural frame. The vertical bracings were designed with two sections, which are then replicated — one corner section and one spanning section (8 of each are required per module). The lateral bracing requires one section type (16 are required per module). Connectors for the frame elements and between the modules are also required.

In addition, four fans are installed in the inlet zone to produce a continuous airflow of approximately 4m/s. In general, the wind tunnel is not designed to reproduce full-scale wind flow conditions such as atmospheric boundary layer or turbulence intensity profiles. However, it presents a controlled and stable wind flow environment for reasonable observations of the dynamics in environmental parameters that, in situ, exist in a similar manner.

**The Physical Test Domain for Porous Screens**

The test domain and sensor configuration utilized for observing the effects of porous screens within the miniature wind tunnel had the following attributes (Figure 3):

- 0.3m wide, 0.3m high and 0.6m long Acrylic square sectioned tube
- Centrally suspended within the MWT test section
- 0.3m wide by 0.3m high prototype screen to be placed at inlet
- Outlet configured for three scenarios: open, closed and doorway-sized opening to simulate variations in cross ventilation
- Test domain is an abstract representation of an apartment not dissimilar to one that may be located in Hong Kong
- 9 sensor positions within the test chamber arranged in a 3 x 3 grid with 10cm spacing

The environmental sensing system and visual interface that is presented here is an integrated low cost system relative to traditional systems that allows the user to measure and observe fluctuations in wind, relative humidity and air temperature, see Figure 5. The system can be repurposed for use in industrial scale wind tunnels [17,18], in-situ en-mass measurement of atmospheric boundary layers or post occupancy evaluation of buildings for thermal comfort. This particular application is specified for use in the MWT for architectural based assessments of porous screens.

The microelectronic wind-sensing platform (Figure 6, Figure 7) uses multiple electronic wind, temperature and humidity sensors to quantify the relative environmental parameters within the MWT. It is integrated with two microprocessors (i.e. Teensy 3.1 and an Arduino Uno) (Figure 6) using 18 x 13 bit A/D channels reading from 9 revP wind sensors [20] and 9 digital pins reading 9 x RHT03 relative humidity and air temperature sensors.

Two separate serial communication ports were used to transfer data from the microprocessors. The high-speed connection (a direct USB serial connection) was used to collect relatively high frequency data (300Hz) for detailed post analysis. A pair of XBee modules was used to collect data at a relatively slower rate (20Hz) required for near real-time visualization.
Visual Interface
The acquired data can be visualized in many conceivable forms within the constraints of the software used (Grasshopper3D, Firefly and Rhino3D) (see Figure 5). In this case a virtual geometric representation of the physical apparatus was preferable with a mesh enabled to morph colors and magnitude of peaks which represented the relative values of temperature and relative humidity. A 3 by 3 grid of spheres represented the magnitude of wind speed. The calibrated numerical outputs in relative units were overlaid with the graphical display to allow the users to compare with other simulations (see Figure 8).

The ability to visualize and discuss the sensor data during physical simulations creates opportunities to adapt during experimentation. This is a constructive environment for designers that are creating conceptual designs. The rapid feedback offers designers a tangible grasp of the performance of designs, complementing and enhancing design workflows that may rely solely on commercially available digital simulation packages. However, to actually evaluate the performance of the porous screen designs the post-analysis of gathered environmental data (e.g. average interior wind speeds, dynamic interior wind patterns or wind pressure on the façade) is also necessary. An example of the data output for post-analysis is shown (Figure 11), however the detailed analysis of results is not within the scope of this paper.
CASE STUDIES: POROUS FAÇADE DESIGN

There is a long tradition of moderating the breeze and bringing it into internal or semi enclosed spaces without mechanical aid, just through the design and placement of perforated or porous screens. The initial stages of the design process were performed using porous screen designs from the collaborators involved in a recent design workshop. The porous screens were designed to be tested in either the virtual or physical wind analysis platforms and, in some cases, within both. This generated reasonable results from the two methods of wind analysis.

The aim of this case study was twofold: 1. Testing the system to demonstrate its feasibility for early stages in the design process of porous screens to facilitate informed decision-making; 2. Discussing the interactions of the workshop collaborators with respect to three main topics including: form discovery; fabrication and analyses. This approach allowed the designer to receive prompt information about the environmental parameters, which is an integral part of this design process. We explored multiple forms of porosity, the initial design began with exploring a venturi-based design. The architectural interventions were designed to accelerate and decelerate wind flows.

A series of porous screen prototypes (Figure 13) have been designed using the proposed design strategy and tested with the wind simulation tools i.e. CFD and the MWT. One set of simulation results can be seen in Figure 9 to Figure 12. Various fabrication techniques including: computer numerical control (CNC) milling, 3D printing and laser cutting were used to fabricate numerous porous forms for wind filtration within the wind tunnel. The observable effects measured by the wind, temperature and humidity sensors were discussed within the team. Parametric patterns were changed to influence the surface characteristics that associate different dynamics in the wind, which could then be observed in near real-time. Recurring patterns within the porous screen designs created the opportunity to further understand how the basic elements or cells change the air movement or air patterns. This was the necessary link for observations of the dynamics within the wind to the geometric characteristics of the physical prototypes. Multiple configurations were defined by varying parameters such as surface roughness, size of apertures, density of porosity and shape of the inlet and outlet openings on the screens.

We observed that virtual prototypes, digitally modeled using parametric software packages such as Autodesk Dynamo and Rhino Grasshopper, were best suited to explore the full functionality of our system. When software packages are compatible, the CFD simulation can be directly applied to the parametric models, allowing more direct feedback between the model parameters and the simulation results. In other cases the parametric model had to be exported into a generics static 3D digital model to prepare it for digital simulation. Without the interactivity, this still allowed relative quick design iterations to occur. For physical simulations, physical models can be constructed using a combination of laser cutting, 3D printing and CNC milling. These rapid automated physical fabrication techniques allowed designers to have precise control over the physical models, implementing design updates to be available for the next iteration of EFD simulation with relative little delay.
DISCUSSION
The mini airflow tunnel is a tool to facilitate the exploration and learning process aerodynamic phenomena interacting with designs. And it is an empirical ‘hands-on’ experience, where users can have a better and closer feeling with the airflow. This tool works as a first step prior to applying CFD techniques that appear more “abstract” to designers without a strong theoretical background.

We are working on the evaluation of a rapid and flexible visualization interface for the proposed EFD. We acknowledge the limitations of this MWT EFD for simulating real wind environments (technical and theoretical), although a precise and accurate quantitative wind simulation is not the intention of this experiment. In a previous study the revP wind sensors were found to be capable of measuring average wind velocities where the direction of wind flow is reasonably well known (to within ±0.5ms-1 accuracy). the sensors The accuracy of the MWT, as well as the comparison between the recommended CFD tools and our EFD system will be addressed in further research currently being conducted. In this paper, the atmospheric boundary layer effect, turbulence intensity, and calibration with Reynolds number (Re) were not considered.

Some CDF programs used by architects for rapid feedback (such as Vasari) are also limited because they are focused on visualization of outdoor airflow with limited control of the grid domain dimensions and density which does not allow the visualization of small details and airflow phenomena. In addition, other data (temperature, humidity, sound) are not possible to incorporate in the analysis with those programs.

CONCLUSION
This paper presented a design simulation and prototyping strategy to aid designers to understand the relational dynamics between airflow and porous screens within conceptual design processes for building facades. The platform allowed designer users to make design decisions based on relevant feedback from both CFD and EFD simulations, covering a vast design solution space. Near real-time observations of numerical and qualitative environmental data provoked productive design discussions supported by both CFD and EFD visualizations.

The CFD software used was found to be very effective in achieving fast simulation results for multiple virtual design iterations; however limitations on obtaining satisfactory results were discovered for the finer resolution porous screens. The EFD method of wind flow measurement was not restricted by resolution or flexibilities in material.

The rigorous evaluation of effects of variable environmental parameters is still under investigation. However, the tests presented here demonstrate the potential and limitations of combining CFD and EFD wind simulations for the virtual and physical construction of prototypes relevant to the conceptual design process of architects.

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Assessing the Energy and IAQ Potential of Dynamic Minimum Ventilation Rate Strategies in Offices

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ABSTRACT
The energy and Indoor Air Quality (IAQ) implications of varying monthly minimum ventilation rates (VRs) in California offices were assessed using EnergyPlus and its integrated multi-zone contaminant modeling feature to predict HVAC energy use and average indoor concentrations of formaldehyde. Minimum mechanical ventilation rates were varied monthly: rates were lowered below Title 24 prescribed values for months when the energy penalty of providing ventilation air was highest; rates were raised during temperate months. For each of California’s sixteen climate zones numerical methods identified the optimal combination of monthly ventilation rates that both lowered annual HVAC energy use and maintained average annual formaldehyde exposure below specified levels. Reference models used the fixed minimum ventilation rates prescribed in California’s Title 24 Standard.

In buildings without economizers, optimal monthly strategies reduced total HVAC energy consumption up to 21.7% and reduced indoor formaldehyde concentrations up to 44%. The benefits in buildings with economizers were much smaller with a maximum energy savings 0.3%. In temperate climates, in buildings without economizers, increasing ventilation rates all year round reduced annual contaminant exposures and lowered annual HVAC energy. A secondary benefit of the optimal variable ventilation strategy was a reduction of peak cooling electricity up to 17% in hotter climates.

Author Keywords

INTRODUCTION
California office buildings consume over 16000 GWh of electricity and 5400 GWh of gas per year. Of this, 6179 GWh of the electricity use and 4350 GWh of the gas use are used to provide heating, ventilation, or air conditioning (HVAC), [6]. A significant proportion of this HVAC related energy is used to condition outdoor ventilation air [5], flushing out indoor-generated air contaminants that would otherwise build up to unhealthy concentrations. This ventilation air impacts energy use because outdoor air must often be either heated and possibly humidified, or cooled and possibly dehumidified, before being supplied to the space. This energy use varies significantly with outdoor conditions; for example, during winter mornings (or summer afternoons), the large indoor-outdoor temperature difference between makes ventilation air more energy intensive, and therefore expensive to condition.

Minimum VRs specified in standards such as California's Title 24 building efficiency standards aim to strike a balance between the energy use associated with providing ventilation and the IAQ improvements that ventilation provides. Current ventilation standards, including California’s Title 24 [7] and ASHRAE Standard 62.1 [2] do not allow for dynamic VR strategies that, at times, reduce minimum VRs below the prescribed minimum VR. These standards do allow minimum VRs to vary with occupancy in a procedure called demand controlled ventilation.

Several prior studies have applied time-varying VRs to lower the energy penalty associated with ventilation, and the approaches taken vary significantly. Sherman et al [14, 15, 16] used ventilation rate changes within a single day to reduce ventilation energy costs and peak energy demand in homes, while maintaining equivalent time-average IAQ to that expected when applying ASHRAE Standard 62.2 [3], with projected ventilation-related energy savings of at least 40% [17]. Apte [1] considered the impact on IAQ and energy use of ventilation strategies that vary minimum VRs throughout the year in a large retail store, taking climate and season into account. Their results found that minimum VR strategies, tailored to specific climates that varied VRs throughout the season provided greater energy cost savings and improved time-average IAQ, compared with strategies that employed fixed minimum VRs.

No prior studies have been identified that provide California-specific estimates of the energy savings potential of dynamic minimum ventilation strategies in commercial buildings, besides the very limited modeling by Apte [1]. A study by Dutton et al [11] estimated the energy cost of changing the prescribed fixed minimum VR in California for offices both with and without economizers. Economizers are widely used in offices; a 2003 survey of U.S. offices [8] found that 50% of the floor stock employed economizers, specifically in California offices, as of 2003-2004, 55% of the floor stock used economizers [6]. The

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results of the Dutton study found that the energy use of providing ventilation air is highly dependent on climate. For California as a whole, the provision of mechanical ventilation at the Title 24 - prescribed minimum rate consumed 6% of the total HVAC energy. That study analyzed energy use at different VRs with 100% and 0% of offices having economizers and projected a statewide 1000 GWh energy savings, 20% of HVAC energy, when economizers are used.

Our study tests the hypothesis that by providing more ventilation when the associated energy demands are low and less ventilation when energy demands are high, it is possible to provide time-average indoor air quality (IAQ) equivalent to or better than the current Title 24 Standard while reducing energy costs. An anticipated secondary benefit was a shift in electricity demand away from peak times. With appropriate control inputs, the time-average indoor-air concentrations of indoor-generated pollutants are expected to be reduced compared to the reference case, however, short term peak indoor air concentrations of indoor-generated pollutants would be expected to increase.

METHODS
We started with simulated monthly energy use and IAQ data for California offices at five different fixed-minimum VRs using published data from a study by Dutton et al [11]. The building models represented California offices built to Title 24 2008 standards [7], and were validated using measured energy use data from the California Energy Use Survey (CEUS) [6]. The minimum VRs were 70%, 100%, 130%, 150%, 200% of the minimum VR prescribed in Title 24. We considered reductions in VRs below 70% of the Title-24 rate likely to increase peak contaminant concentrations unacceptably. Using the monthly HVAC energy costs and time-average contaminant exposures for each minimum VR, monthly schedules of minimum VRs were developed for each climate zone. These schedules, or dynamic minimum VR strategies, were identified with an algorithm designed to minimize annual energy consumption, and fractionally reduce annual-average contaminant exposure.

The algorithm evaluated all combinations of monthly energy use and IAQ to identify the optimal monthly VR schedules for each climate zone. The 5 potential ventilation rates, for each of the 12 months, resulted in 244 million combinations for each climate zone. We considered an optimization algorithm to reduce the calculation time, but found this to be unnecessary. The final predicted annual energy use costs and IAQ for the dynamic strategy was the annual composite of the monthly energy and IAQ values.

Formaldehyde was chosen to represent an indoor-generated contaminant with low outdoor concentrations. The simulated time-average indoor concentration of formaldehyde was used as an indicator of the risk of serious health effects, such as cancer, from exposures to indoor VOCs [13]. The risks of cancer are typically assumed to depend on long-term-average pollutant exposures; consequently, overall risks will decrease if average indoor concentrations decrease even with higher peak indoor-air concentrations.

Building model development
We modeled energy use and indoor contaminant concentrations using the EnergyPlus building simulation software [9]; using EnergyPlus’s integrated multi-zone contaminant model. Appendix Figure A 1 gives a map of the 16 Title 24 climate zones, and provides cooling and heating degree data for each climate zone, indicating that CZ07 through CZ15 are typically cooling dominated, CZ1, CZ2, CZ3, CZ5 and CZ16 are heating dominated, with the remnant being in between.

The building model, representing a three-story medium-sized (4,982-m$^2$) office, was heavily informed by the U.S. Department of Energy (U.S. DOE) reference medium office model [12] and studies by Brunswick et al. [4]. The building has three multi-zone, variable-air-volume, packaged HVAC units, and three gas boilers for heat, but also includes electric reheat coils for each of the 15 zones. The simulations used representative weather files, from each of the 16 Title-24 climate zones published by the U.S. DOE [10].

Simulations were performed assuming the HVAC systems had, or lacked, economizers. Economizers provide free ventilation cooling when the outdoor conditions are suitable. When the outside temperature is cold and heating is required or hot and mechanical cooling is required, the economizer restricts outside air VR to the minimum required outside air VR. The economizer activated when outdoor dry-bulb temperature was less than return air dry-bulb temperature but de-activated at a maximum outdoor air temperature threshold of 28 °C.

Monthly dynamic ventilation strategy
The prior annual simulations, published by Dutton et al [11], produced for each climate location, 12 month by 5 VR matrices summarizing the total energy cost by month and average work-time formaldehyde concentration. The algorithm first identified VR schedules that lowered the annual-average formaldehyde concentrations below the annual-average concentrations predicted with a fixed Title 24-based minimum VR. Strategies that pass the IAQ criterion were then examined to identify the strategy with the lowest energy cost. The resultant optimal strategies therefore lower both total annual energy consumption costs and total annual work-time formaldehyde concentrations. No additional credit was given to strategies with larger reductions in the annual-average formaldehyde concentration.

Economic analysis
We compared ventilation energy costs based on the California models’ predicted gas and electricity use. The average 2012 gas price paid by U.S. commercial companies
[18] was the basis for the unit energy costs of gas: 0.028 $/kilowatt-hour (kWh) ($8.13 per thousand cubic feet). Unit electricity prices of 12.09 cents per kWh are based on the February 2013 year-to-date average price paid by commercial customers in California [19].

RESULTS AND DISCUSSION

Time varying energy use
Monthly HVAC energy use for climate zone 1 with the Title 24 fixed minimum VR, assuming 100% economizer use (Figure 1) and no economizer use (Figure 2).

Of the 16 climate zones modeled, buildings in CZ1 represent an extreme with regard to heating demand (CZ16 has the highest cooling but with a significantly lower population density and so was not selected); CZ15 is the climate with the highest cooling demand.

Results show that HVAC energy use varied seasonally for buildings with and without economizers. The economizer lowers cooling energy use, most significantly in the winter because of the availability of free ventilation cooling. In climate zone 1, economizer use provided an annual cooling energy savings of 58%. Heating energy use was not significantly impacted by the use of economizers. Average monthly total HVAC energy use was 2.83 ±0.31 kW/m² for scenarios without economizers and 1.75 ±0.36 kW/m² with economizers.

Figure 3 and Figure 4 give monthly HVAC energy use in climate zone 15 with the Title 24 fixed minimum VR. Climate zone 15 is representative of a climate with relatively high cooling demand.

The observed variation in monthly average energy use throughout the year, was more significant in climate zone 15, than in the cooler climates (CZ1, CZ2, CZ3, CZ5, CZ16), with average consumption of 5.39 ±2.96 kW/m² and 5.77 ±2.58 kW/m² for the scenarios with and without economizers respectively. The majority of the variation in monthly energy consumption was the result of increased cooling energy use during the summer. In this climate zone, economizer use reduced annual cooling energy by only 0.1% and there was a predicted heating energy savings of 0.06% which may be an indication of modeling uncertainties since economizers theoretically do not reduce heating energy. Energy savings were significantly less in
the hotter climate zones, because during the peak cooling season economizers were deactivated because of the high outdoor temperatures.

Figure 5 and Figure 6 show monthly economizer use for climate zone 1 and 15, where the modeled minimum VR provided when the economizer is deactivated (off) is the VR prescribed by Title 24. The economizer is activated at nearly all times in climate zone 1, but only about 45% of the time in climate zone 15.

Figure 5. Monthly economizer use climate zone 1, with a fixed minimum VR from Title 24

Figure 6. Monthly economizer use climate zone 15, with a fixed minimum VR from Title 24

The percentage occupied time that economizers were activated varied according to the weather conditions in the weather files that represented each climate zone. Typically, during periods of hot weather when the outdoor air temperature exceeded 28 degrees, as found in summer months in climate zone 15, the economizer was deactivated and VRs were restricted to the minimum outside air prescribed by Title 24. Conversely, during moderately warm weather found in the winter months in climate zone 15, and throughout the year in climate zone 1, the economizer delivers increased VRs.

Monthly dynamic strategies
The optimal dynamic ventilation strategies identified as using the lowest HVAC energy, while maintaining IAQ for the 16 climatic zones of California State are shown in Appendix Table A 1. Results show a monthly variation of minimum VRs throughout the year in the more temperate climates (e.g., CZ01, CZ02, CZ16), increasing minimum VRs (200% Title24) during summer season to provide free ventilation, and maintaining minimum VR’s either at Title 24 rates or moderately higher (130% Title 24) the rest of the year. In all climates, the dynamic strategy for models without economizers provided increased annual average VR’s, compared to the fixed Title 24 based strategy.

In the scenarios with economizers, the dynamic strategies successfully optimized for energy use based on the climatic conditions and associated economizer usage. No strategy increased minimum VRs to the maximum VR (200% Title 24). The number of hours of economizer operation varies by climate and month resulting in strategies that adjusted the monthly VR more frequently than the scenarios without economizers.

Energy use and IAQ
Figure 7 and Figure 8 compare the annual HVAC energy cost for the dynamic ventilation strategies and Title 24 fixed VRs strategies. Results are given for each of the 16 climate zones, for scenarios assuming 100% economizer use and without economizers.

Figure 7. Annual HVAC energy cost with economizer by climate zone. Dynamic ventilation strategy versus Title 24 ventilation rate

Figure 8. Annual HVAC energy cost without economizer by climate zone. Dynamic ventilation strategy versus Title 24 ventilation rate
In buildings with economizers, the maximum reduction in HVAC energy cost of 0.3% was achieved in climate zone 16, while in buildings without economizers a maximum improvement of 21.7% was obtained for simulations in climatic zone 1. Figure 9 and Figure 10 show monthly HVAC energy costs per unit floor area for the scenario with economizer use and without economizer use, for California as a whole, weighted by office floor area, applying a weighting method described in Dutton et al [11].

In buildings without economizers, dynamic strategies reduce monthly HVAC energy costs, with the largest savings being found in the cooler months of November through April. The dynamic strategy delivered the highest savings of 17.5% in March. During these periods increased VRs provided free ventilation cooling reducing cooling loads. During the summer period, the dynamic strategy reduced costs by approximately 4%, with the majority of savings due to cooling energy savings. Estimates of total state wide energy costs under the Title 24 scenario were $534 million, compared to total costs of $482 million applying the dynamic strategy, resulting in savings of $52 million (10%). State wide estimates assume that the current floor area of office space remains constant and all offices eventually comply with Title 24 2008 standards. However, the majority of these savings would likely have been realized without implementation of a dynamic ventilation strategy if economizers were installed.

In buildings with economizers, HVAC energy savings from applying monthly dynamic minimum VR strategies were significantly smaller than for the scenario without economizers. In July, the maximum monthly savings was 1.52%. Estimated total HVAC energy use was $439 million under the Title 24 scenario and $439 million applying the dynamic strategy, resulting in state wide savings of $380,000 (0.1%). Using the published data on state wide HVAC energy use, we estimated the total HVAC electricity cost for the current stock of office buildings to be $747 million. This compares to our estimated energy cost for new construction of $439 million. This disparity is a result of the lower energy use intensity (EUI) of the office model compared to the average EUI of existing stock. In buildings with economizers, the energy savings obtained by applying dynamic ventilation strategies were very small. Our analysis found that reducing VRs by 30% for the whole year resulted in reductions in total HVAC energy use of 2.4%. The dynamic strategies increased VRs when the energy cost of providing ventilation were low, to compensate for the reduced VR during months when ventilation energy costs were high. On average, increased minimum VRs lead to increased HVAC energy use, therefore the potential energy savings from the monthly dynamic ventilation strategy are limited to savings of significantly less than 2.4%. The dynamic ventilation strategy limited the number of months when the VR are at their lowest (70%) to maintain average annual formaldehyde concentrations below those predicted for the Title 24 scenario, further constraining any potential energy savings. In the hottest climates, where potential energy savings are greatest, the numbers of hours of economizer operation are lowest during the summer, as found in climate zone 15 and shown in Figure 6. In theory this provides opportunity for changes in the minimum VR to make their most significant impact. However, due to the constraint on indoor formaldehyde concentrations, this high number of hours at reduced minimum VR must be made up by approximately equal numbers of hours of increased VR, in the more temperate months when economizer use is higher. This is demonstrated in the optimal strategy for climate zone 15 shown in Table A 1 (appendix), the dynamic strategy results in five months of VR above the 100% Title 24 reference.

Figure 9 and Figure 10 compare the average formaldehyde concentration during occupancy for the dynamic ventilation strategies and Title 24 fixed VRs strategies. Results are given for each of the 16 climate zones, under the scenarios assuming 100% economizer use and without economizers.
In buildings with economizers, formaldehyde concentrations were little affected by dynamic VR strategies with a peak difference of 0.04% in climate zone 9. This result is consistent with the optimization method that identifies the strategy that at least meets the IAQ criteria, and then identifies the lowest energy use, monthly scenario. In buildings without economizers, increased VRs in dynamic VR scenarios led to reduced energy use and also to significantly reduced time-average formaldehyde concentrations, with a maximum reduction in average indoor formaldehyde concentrations in climatic zone 5 (44%). Average formaldehyde concentrations in California throughout the year were 13.7 ±2.4 ppb and 16.4 ±0.2 ppb for the dynamic ventilation and Title 24 VR strategies respectively. The geographic variation in average formaldehyde concentrations was more significant with the dynamic strategies. Reductions in indoor formaldehyde concentrations were greatest in cooler climates where increased minimum VR throughout the year lowered average formaldehyde concentrations. Figure 13 and Figure 14 compare the monthly formaldehyde concentration in California offices with the data from individually climate zones weighted by floor area, comparing dynamic ventilation strategies versus Title 24 fixed VRs strategies.

In buildings without economizers, applying the dynamic ventilation strategy resulted in significant variations in state-wide monthly average formaldehyde concentrations, with peak reductions in formaldehyde concentrations found in March (43%) and a peak increase in formaldehyde concentrations of 18% in July. Average formaldehyde concentrations were reduced from 16.4 ppb to 12.6 ppb, a 23.3% reduction. In buildings with economizers, a similar pattern of monthly variations was observed, though with much smaller differences in formaldehyde concentrations. Annual average formaldehyde concentrations of 9.3 ppb using the Title 24 based VR strategy, were unaffected by the application of the dynamic strategy.

Appendix Figure A 2 and Figure A 3 show the peak hourly cooling electricity use assuming Title 24-prescribed minimum VRs are applied, and the corresponding cooling
electricity use for the same period, assuming the optimal monthly dynamic strategy had been used. Results are presented for buildings with and without economizers.

In buildings without economizers, the monthly dynamic ventilation strategy reduced peak cooling electricity in warmer climate zones (CZ07–CZ15), by up to 8%, due to the reduction of the minimum VRs. By contrast, when the dynamic ventilation strategy is applied in more temperature climates (CZ01, CZ02, CZ03, CZ05, CZ06 CZ16), peak cooling electricity use is increased (by up to 17% in CZ03), with increased VRs. The dynamic strategy optimized total HVAC energy including both gas and electricity, which during colder climates often resulted in increased peak summer cooling loads. Similarly, in buildings with economizers, the dynamic ventilation strategies tended to reduce the peak cooling electricity in hot climate zones. In climate zones 1-6 and 12, the dynamic ventilation strategy did not affect peak cooling electricity, because the dynamic strategy selected the Title 24 VRs for the peak cooling hour. A peak reduction of up to 8% was found in both climate zones 7 and 11. Peak electricity increased in zone 16 due to increased minimum ventilation rate during the cooling season.

CONCLUSIONS
If applied to California office buildings, strategies that vary the minimum VR by month would reduce total energy consumption and reduce indoor formaldehyde concentrations; however these benefits pertain almost entirely to buildings without economizers. Assuming no economizer use, these strategies could potentially deliver state-wide energy cost savings of $52 million (10% of HVAC energy), with reductions in annual average indoor formaldehyde concentration of 3.8 ppb (23%). These energy saving would in most cases be exceeded by the savings obtained by adding an economizer. Dynamic strategies also decreased peak cooling electricity by as much as 17% in hotter climates zones of California State. In buildings without economizers it is unclear whether seasonally varying minimum VRs could practically be implemented without the mechanical control of VRs that economizers provide. In the majority of climates however most of the energy savings and reductions in contaminant exposure could be obtained with a biannual manual adjustment to the outside air damper position. For the temperate climates zones CZ01, CZ02, CZ03 and CZ05, for buildings without economizers, fixing minimum VR throughout the year at 200% of Title 24 prescribed rates was found to reduce HVAC energy consumption and lower occupant exposure to formaldehyde.

Modeling buildings with economizers, the dynamic strategies had a minimal impact on overall energy use with statewide energy cost saving of $380,000 (0.1%), and average indoor formaldehyde concentrations were not significantly impacted. However, peak energy savings were found in climate zones 7, 10 and 11, with a peak reduction of 8%.

Assuming 55% economizer use in California offices as a whole [6], seasonally varying minimum VRs in offices is expected to reduce in total HVAC energy costs by a modest $24 million.

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Figure A 1. Heating degree days (HDD) and cooling degree days (CDD) of the modeled Title 24 Climate Zones [7]

Figure A 2. Hourly peak cooling electricity with economizer by climate zone

Figure A 3. Hourly peak cooling electricity without economizer by climate zone
Table A1. Dynamic ventilation strategies

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Economizer / No Economizer / Both
A Comparative Study of Mixed Mode Simulation Methods: Approaches in Research and Practice

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ABSTRACT
This project explores how both researchers and practitioners use simulation methods for naturally-ventilated and mixed mode buildings. A focused literature review was conducted to outline the modeling tools and methods used by researchers, including appropriate tools and the importance of site-specific wind data and accurate wind pressure coefficients. The literature review also summarized research on window opening behavior, noting that there is little practical guidance for practitioners interested in related stochastic modeling techniques. The second phase of the project involved conducting interviews with practitioners who model naturally-ventilated and mixed mode buildings. Practitioners reported that they would like to see more integrated tools, tools with improved result visualizations, and early-phase design tools.

Author Keywords
Natural ventilation, mixed mode ventilation, natural ventilation simulation

INTRODUCTION
There is no definitive guide in the research or professional communities for how to model naturally-ventilated (NV) and mixed-mode (MM) buildings (i.e., buildings that combine operable windows and mechanical cooling). The methods described by researchers in published literature vary greatly, while the methods employed by energy modelers in practice differ from firm-to-firm and person-to-person even within a firm, as time, budget, analyst experience, and client needs change from project to project.

This paper provides insight into the variety of methods used to simulate NV and MM buildings. It is not intended to be a comprehensive review of software tools and their technical capabilities or an explicit guide on how to model these building types. Instead, it is intended to facilitate communication between researchers and practitioners about which tools are currently being used by practitioners, the assumptions and inputs they use, and what new functionality is most critical for future tool development. The length restrictions allow only a high level summary of our findings, and a more comprehensive description and list of references can be found in Gandhi et al. [1].

METHODS
This project began with a literature review focused on simulation methods used by researchers. The goal was to create a framework to later compare the methods used by researchers vs. practitioners, and to highlight areas where practitioners may benefit from the approaches used by researchers. The focus was on software tools and critical modeling inputs such as weather data and window opening behavior.

The subsequent investigation of practitioners involved two phases: a pilot survey and interviews. An initial pilot survey of Center for the Built Environment (CBE) industry partners was conducted to identify the variety of tools practitioners were using and how they differed from one another. The results of this provided an early indication of prominent trends in the profession.

The literature review and survey responses then helped inform the development of an interview guide for the main portion of the study. Practitioners targeted to be interviewed included those who directly used energy modeling, with particular experience modeling NV and MM buildings. National awards lists (e.g. past AIA COTE Top Ten winners) were consulted to identify other firms who had worked on NV and MM projects, especially those located outside of California and the U.S. West Coast. As part of the interview process, early respondents were asked for recommendations of other firms and practitioners with the required experience.

During the interviews, respondents were asked to answer questions only in reference to their NV and MM projects. Starting with questions about project locations and simulation goals, practitioners were then asked to discuss the software tools they used, if these tools differed depending on the phase of design, and how they made their tool selection. Next came a discussion of the strengths and limitations of their tools and what further developments would be beneficial in the future, which will hopefully provide insights to tool developers and researchers to prioritize their future work. The interviews ended with open-ended questions about their work to learn about
specific success stories and lessons learned. Using content analysis, responses to each question were coded separately by theme, and then organized to identify trends, similarities and differences, and to draw conclusions and insights from the aggregated responses.

LITERATURE REVIEW
The literature review findings reported here represent a selective overview of the tools and approaches used by researchers when modeling NV and MM buildings; a more extensive review can be found in Gandhi et al. [1]. This section is intended to be a resource for practitioners interested in exploring techniques and methods used in research, but currently lacking the resources for conducting such a literature review. Towards this end, this section focuses on the variety of tools described in the literature, sources for inputs that are especially influential to the results (weather data, wind pressure coefficients, window discharge coefficients, and window opening behavior) and early phase simulation tools.

Overview of modeling tools and methods
Types of tools
The modeling methods for NV and MM buildings are diverse. The three general categories of methods researchers are using include standalone airflow network tools (e.g., CONTAMW), airflow network models coupled with thermal modeling tools (e.g., COMIS and TRNSYS, or the airflow network model within EnergyPlus), and computational fluid dynamics (CFD) tools (e.g., Airpak).

In comparing different categories of tools, bulk airflow modeling tools were cited in the literature as reasonably accurate and preferable to CFD because they were less time-consuming to use and required less detail for inputs such as precise boundary conditions. However, it was also noted that the most difficult part of using bulk airflow tools was providing sufficiently accurate inputs to the tool (e.g. wind pressure coefficients).

Crawley et al. [2] published a comparison of twenty building energy simulation programs, including EnergyPlus, IES VE, TAS, and TRNSYS. Among other topics, this study compared the capability of the tools to calculate wind pressure coefficients, model NV and MM buildings, and to control window openings based on internal or external conditions. At the time of this writing, an update to this report was underway and was anticipated to be completed in 2015.

Thermal comfort
Modeling the performance of buildings ultimately must include an assessment of whether the indoor conditions are thermally comfortable. The two methods cited in the literature for evaluating thermal comfort include the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) model, or the adaptive comfort model, both of which are outlined in ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy [3]. The adaptive comfort model is defined in the standard with specific limits on its applicability to buildings without mechanical cooling systems, where occupants control the operable window. Despite these defined limitations, there seems to be much anecdotal evidence that the adaptive comfort model is being used by practitioners in MM buildings anyway, but only one instance was found in the literature where researchers used it in MM buildings [4].

A recent addition to the ASHRAE 55 standard that is particularly relevant for NV and MM buildings are new guidelines for allowing higher acceptable ranges of operative temperatures at elevated air speeds between 0.15 m/s (30 fpm) and 1.2 m/s (236 fpm) [3]. This added provision expands the abilities of designers to utilize NV. Using the online CBE Thermal Comfort Tool, which is compliant with ASHRAE 55-2010, users can evaluate the output of their building simulation models to determine how far the comfort range can be extended at different air speeds [5].

Source of inputs for models
Several key inputs have been identified in the literature as being critical components for accurate simulation. For wind-driven ventilation, these include wind speed, direction, and pressure coefficients. For both wind- and buoyancy-driven ventilation in buildings with occupant-controlled window openings, occupant window opening behavior is another influential input.

Weather data
Weather data is an important input in NV simulations, especially when modeling wind-driven scenarios. No literature was identified that studied the relevance of airport wind speed and direction data to site-specific circumstances, or the accuracy of extrapolating wind speed or direction data in order to obtain site-specific conditions. However, there were a few studies that looked at the sensitivity of simulations to the wind information in order to understand the importance of site-specific data. In contrast, there were multiple studies that tried to do the same for other parameters such as dry bulb temperature and solar radiation.

Stavrakakis et al. [6] studied the influence of wind data in a sensitivity analysis for a study on cross-ventilation, comparing the effect of various input values for terrain roughness, wind speed, and wind angle of incidence. They concluded that there was no significant difference in the results of their analyses (i.e., the indoor environmental conditions) for flat vs. rural terrain roughness, a variation of +/-10% in wind speed, or a difference of +/-15% in wind angle of incidence. Accurate wind data was stressed by Belleri et al. [7], who found that the wind speed profile was the most influential parameter in an EnergyPlus airflow network model after occupant behavior.

As wind speed and direction can vary greatly from local weather station values due to local terrain and
microclimates, it is recommended to use on-site measured temperature, wind, and solar conditions for more accurate modeling results. However, how to generate site-specific weather data as inputs to simulation models is an area that warrants further investigation.

Wind pressure coefficients

Wind pressure coefficients are a significant source of uncertainty in building energy simulations and airflow network models. In a study of a school in Sweden, Blomsterberg & Johansson [8] found that a CONTAMW-based study was particularly sensitive to wind pressure coefficients they used, which were derived from wind tunnel tests.

Wind tunnel testing is a primary source of wind pressure coefficients along with full-scale modeling and CFD analysis. Secondary sources include published databases and analytical models. Primary sources are typically limited to use by researchers rather than practitioners, due to the time-consuming methods and level of skill required. Although these three types of primary sources are considered more accurate than secondary sources, resultant data is still not always entirely reproducible because differences in the calibration of models, and skill levels of operators and researchers can affect the results.

Under secondary sources, the two main databases in use are those provided by the Air Infiltration and Ventilation Center (AIVC) [9] and the ASHRAE Handbook of Fundamentals [10]. The AIVC tables include wind pressure coefficients for open, semi-exposed and sheltered low-rise buildings based on multiple wind tunnel studies, while their high-rise building data are based on a single source. In the 2013 version of ASHRAE Fundamentals, Chapter 24: Airflow Around Buildings provides guidance for pressure coefficients for low- and high-rise buildings, but does not consider sheltered buildings.

The three main analytical models found for wind pressure coefficients include one developed by Swami and Chandra [11], CpCalc+ which was developed within COMIS [12], and CpGenerator [13]. At the time of this writing, CpGenerator was the only analytical model with a current website and technical support.

A study by Belleri et al. [7] compared wind pressure coefficients from multiple sources and found that for rectangular buildings with regular surroundings, databases provide sufficient accuracy. However, for buildings with irregular surroundings, the coefficients estimated by CpGenerator were closer to those measured in wind tunnels than the database-sourced values because CpGenerator models include the surrounding buildings. This is particularly important for practitioners because real buildings always have to contend with the site conditions and local terrain, whereas in research these are not always considered. However, the use of this tool was not reported by any of the interviewed practitioners.

Window discharge coefficients

The discharge coefficient of a window or opening is a key input parameter used to calculate ventilation flow rates. Some window manufacturers provide limited data on the still-air discharge coefficients for their products, however these values may not be appropriate when the ventilation is due to wind [14]. Several studies have attempted to provide insight into window discharge coefficients [15, 16], but no reviews were identified that collate these disparate studies to provide clear guidance, and there is no published, comprehensive database to date of typical discharge coefficients for the variety of different window types available in the market. This should be a focus of future research efforts.

Window opening behavior

The ways in which occupants manually open and close windows can have a significant impact on the performance of NV and MM buildings, but such behavior is not easy to predict. There has been a large amount of research studying occupant behavior in existing buildings and correlating their window operation patterns with different variables. Extensive summaries of the literature in this area can be found in Gunay [17] and Ackerly et al. [18]. But there is limited guidance directed towards practitioners about implementing improved algorithms in software based on these results.

The literature on occupants’ window operation behavior primarily includes studies linking behavior to obvious variables such as indoor temperature, outdoor temperature, indoor air quality, and the need for “fresh air.” Other studies looked at the relationship between window opening behavior and wind, rain, and season, as well as less obvious potential influences such as the façade orientation, type of window, and number of occupants with access to the same window. The overall conclusion drawn from these studies is that occupant behavior is stochastic, i.e., there is an element of probability involved because behavior cannot be predicted in a repeatable manner.

A number of studies have identified a connection between window behavior and indoor temperature, while other studies demonstrated a link between behavior and outdoor variables (particularly for window closing). In addition to these physical variables, social influences and habits, and other non-physical parameters (i.e., those that do not relate to thermal comfort) may also play a role in how windows are operated. For example, Haldi and Robinson [19] found that the number of occupants responsible for a window affected that window’s operation, and that behavior could be attributed to the most active occupant, rather than a combination of actions among all occupants. Several other studies have found that window operation was correlated to arrival and departure times of occupants, or to a desire for a connection to the outdoors.

The percentage of open windows has also been linked to façade orientation and the type of window, including its
ability to offer more protection from wind or rain, or allow more control over effective opening size. While it is expected that seasons would have an effect on window operation, several studies have shown that occupants open windows even during the heating season for ventilation purposes [20].

With so many variables affecting how occupants operate windows, multiple studies have concluded a stochastic model is the best representation of occupant behavior [17, 18, 21]. Based on this conclusion, Rijal et al. [22] developed an adaptive window algorithm to predict occupant behavior based on outdoor temperature, comfort temperatures, indoor temperatures, probability functions, and the observed assumption that occupants operate windows in order to reduce their own discomfort. Haldi and Robinson [19] outlined another algorithm using a flow chart to predict window operation behavior based on occupancy, current window status, arrival and departure times of occupants, outdoor temperature, and presence of rain. Further developments of stochastic algorithms that can be conveniently implemented by practitioners in existing software are needed.

Early phase simulation tools
Tools that can be used early in the design process can help users assess NV feasibility and determine which particular strategies should be investigated in more detail in later stages of design.

The National Institute of Standards and Technology (NIST) has produced two tools that may be used during early design, the Climate Suitability Tool and LoopDA [23]. The Climate Suitability Tool was developed to provide preliminary guidance to designers on ventilation levels required for daytime and nighttime cooling strategies [24]. The user provides the tool with inputs such as weather file, internal heat gains, minimum ventilation rate, ceiling height, NV parameters, and cooling and heating setpoints. Using a single-zone thermal model and hourly weather data, the tool calculates the ventilative direct cooling and the night cooling potential, as well as the predicted thermal comfort, based on the setpoints provided by the user and the adaptive comfort model [25].

LoopDA is based on the Loop Equation Design Method and runs on CONTAM's simulation engine. It is the only tool found that calculates required opening area based on a specified desired airflow rate, rather than the other way around. Within the interface, users create a line drawing of the zones of the building in elevation. Each zone is defined with a minimum required ventilation rate and thermal characteristics. Airflow paths (e.g. ducts) are drawn in to connect zones to each other. A calculation is performed to determine the minimum opening area required based on the desired air flow rates entered [26].

MIT's CoolVent tool allows designers to analyze different NV schemes over a 24-hour period or at a specific instance in time. It can model single-sided, cross, central atrium, and side atrium ventilation. Users input internal gains, information about the building dimensions, opening dimensions and locations, and ventilation strategies such as thermal mass, night cooling and different types of window control. The tool provides a visualization of the temperatures and flow rates in the space over the course of the day, a plot of the daily temperature variation, air stratification, and thermal comfort results based on ASHRAE or user-defined ranges. The tool can also model fan-assisted NV and will provide fan energy use as a result. The tool has been analyzed as an early design tool, and has been updated with new capabilities, such as implementing thermal stratification profiles [27].

MIT has another early phase design tool intended to help architects quickly determine which design parameters can save the most energy while still preserving occupant comfort. The online tool, Design Advisor, analyzes energy use, comfort, and daylighting potential in addition to NV. Validation of the tool has been conducted, comparing annual and monthly load calculations against EnergyPlus models, demonstrating that Design Advisor can produce reasonable results in agreement with results from EnergyPlus [28].

INTERVIEW RESULTS
Interviewed practitioners
In total, seventeen practitioners and two tool developers were interviewed for this study. All had experience modeling NV and/or MM buildings. Each interview typically took one hour and was conducted in person or via teleconferencing. Of the practitioners, fifteen currently work or previously worked on the U.S. and Canadian West Coast, while two were based in other U.S. locations. Four currently or previously worked in Europe, including England, Wales and Germany. Two of the interviewed practitioners work for architecture or design firms, while the rest work for self-described engineering or building performance consulting firms.

Eight practitioners reported working on projects in the San Francisco Bay Area, while fourteen worked on projects elsewhere on the U.S. West Coast. Also represented were projects across the United States in Hawaii, the Rocky Mountains, the Midwest, and East Coast. Internationally, practitioners reported working on projects in Canada, Australia, China, India, Wales, England, Germany, and Syria, as well.

The most common building types reported were offices (13 practitioners), university or higher education buildings (12 practitioners), and K-12 schools (nine practitioners). At least four practitioners reported analyzing NV or MM systems for high-rise residential projects, sports facilities, and government and civic buildings. Also represented were auditoriums, hospitals, libraries, retail, laboratories, and convention centers.
Findings: general approaches to simulation
The practitioners interviewed gave multiple reasons for when and why they used simulation tools for their NV and MM analysis work. Interestingly, practitioners reported that they did not always consider modeling as an essential step in the design process because the NV strategy was not always critical to achieving thermal comfort (e.g., a backup mechanical system was in place) or was not considered a significant contributor to the performance goals of the project (e.g., it was too difficult to demonstrate the contribution to energy savings for LEED certification). One practitioner reported that he did not typically model NV for small spaces, stating that sufficient airflow is typically not difficult to achieve even with small openings. When modeling was done, practitioners were most often interested in evaluating the feasibility of maintaining thermal comfort for occupants, rather than demonstrating potential energy savings.

Findings: tool selection
Practitioners reported both technical and non-technical reasons for why they selected a particular simulation tool. Unsurprisingly, the most often cited reason was that they felt the software was simply the right tool for the job, which depended on what their particular goal was to begin with (e.g., it might be selected because it was the best bulk air flow analysis software tool available).

The other most common reasons cited were all non-technical, such as ease of use (both being able to quickly learn how to use the tool, and using tools that team members were already familiar with), and circumstances unique to the job. For example, two practitioners stated that they had an opportunity to first try out a new tool on a specific project due simply to availability, and they kept using it afterward because of its success. Another practitioner said that the tools they used were region-specific based on local code compliance regulations. Practitioners also cited budget as a non-technical reason for selecting particular tools. Tools that were more time-consuming to use were limited to projects with larger resources.

The remaining reasons cited were technical and only reported by three practitioners: compatibility with other software tools used (e.g. whole building energy modeling or CAD tool), reliability of software based on access (open source vs. proprietary tools), and availability of technical support by the tool developer.

Findings: tool-specific feedback
Practitioners were asked which simulation tools they used and in which manner, and they discussed their use of specific bulk airflow modeling tools and CFD software. In all, more than 15 different tools were cited, including EnergyPlus, IES Virtual Environment, TAS, eQUEST, CONTAM, TRNSYS, and numerous CFD tools.

Bulk airflow modeling tools
Bulk airflow modeling tools were the most often cited as being regularly used, and included: EnergyPlus’ Airflow Network, IES’ Macroflo module, TAS, TRNFLOW (COMIS integrated with TRNSYS), and CONTAM. Practitioners reported success with bulk airflow tools, and in multiple cases were able to verify the accuracy of their model with post-construction monitoring. As an example, one practitioner reported that the airflow rates provided by a passive downdraft tower were found to be accurately predicted in their TAS model, when compared to measurements with airflow sensors post-construction. In another case, the use of bulk airflow modeling allowed a higher education building in California to gain an exemption from the Title 24 NV requirement of a minimum 4% glazing to floor area ratio. Using the modeling tool, the team was able to prove that a ratio of 2% would be sufficient to meet the ventilation requirements. One practitioner even reported convincing the owner to completely remove the backup mechanical cooling system for a school in southern California, after demonstrating with a bulk airflow model the minimal number of hours per year that the building’s internal temperature would fall above the comfort range with only NV.

IES Virtual Environment (VE) was one of the most cited tools among the practitioners interviewed. Of the nine who reported using it, seven used the Macroflo module (bulk airflow-based) and three used the Microflo module (CFD-based). Practitioners used IES VE primarily to evaluate design alternatives and calculate the annual percentage of hours that NV is possible. Two practitioners reported using IES VE for their whole building energy model and said being able to use one tool for both purposes was an important benefit. In an IES model for a net-zero energy visitor center with a solar chimney, one practitioner found that the backup cooling was running for only a minimal number of hours. Using the model his team adjusted the orientation in order to remove the need for the cooling system altogether. Although the cooling system was included in the final design, in the more than two years since the opening of the building, the practitioner reported that the backup system had yet to be used.

In general, practitioners reported positively about IES VE’s user interface, accuracy of airside calculations, and level of detail and options offered. The proprietary nature of the algorithms used by the software was a point of concern for four practitioners, while others specifically stated that the documentation was clear and transparent. On this point, it is likely to be personal preference (i.e., to what degree do practitioners want to access the software code and make changes) and not necessarily a question of accuracy of methodology and coding.

Four practitioners reported using EnergyPlus to simulate NV, while three others cited the lack of an accessible interface and extensive run times as reasons why they did
not use it in their work. For those that did, these same issues seemed to be barriers as well, leading them to generally use it only for limited, initial, low-detail studies of one or two zones. One practitioner who used EnergyPlus more extensively described its use for a renovated university building where thermal comfort was a significant goal of the NV scheme, and the model demonstrated that NV would be able to maintain thermal comfort in the space. After the building was occupied, his team found that the simulation tool was, in fact, overestimating the temperatures in the space when in NV mode, and they concluded that interior thermal mass (e.g., of less-massive objects such as furniture) was playing a larger role than the model accounted for. Overall, practitioners reported high confidence in EnergyPlus’ research-grade abilities and quality of results but that, on most projects, these were outweighed by time and budget constraints.

Other bulk airflow-capable tools reported by practitioners included CONTAM, TRNSYS, and TAS. Two practitioners referenced CONTAM, stating that it was a good numeric tool. The use of TAS was reported by two practitioners, who cited it as a good bulk airflow modeling tool that allowed for detailed control of apertures and a versatile results viewer. One practitioner cited TRNSYS’ ability to accept custom code as a specific benefit. The lack of ability to do parametric runs or access the input or results as text files for scripting purposes were cited as two main limitations of the software.

CFD tools
CFD was cited by eleven practitioners as being used in some way during their simulation work. In total, practitioners listed ten different CFD software tools that they currently used or had used in the past, including: ANSYS CFX, ANSYS Fluent, Autodesk Simulation CFD (formerly CFDesign), Autodesk Vasari, FloVENT, Flowdesigner, the IES VE Microflo module, PHOENICS, Star-CD, and STAR-CCM+.

CFD was most often used to investigate details of the design (e.g., sizing and locating openings), identify dead spots and conditions under extreme cases, investigate thermal comfort and areas of potential discomfort due to draft risk, and to verify the design in later design stages. The practitioners also used CFD to model innovative or atypical NV schemes. For the California Academy of Sciences, CFD was used to allow the project to claim an exemption to the Title 24 requirement that occupants be within 20 feet of an operable window to consider the space properly NV. A CFD model of the project showed that a much greater distance between the openings and occupied area would still satisfy the ventilation need. CFD was also successfully used to model a passive downdraft system, where post-construction monitoring verified that the flow rates and temperatures predicted by the model were accurate.

As expected, CFD was indeed highly regarded by most practitioners as comprehensive and accurate. Limitations cited had more to do with the user-software interface and included the lengthy run times of CFD models, steep learning curves of the software, and quality of technical support from software developers.

Other Tools
Many practitioners reported using in-house tools and spreadsheets to investigate the potential for NV. Practitioners at the larger multinational firms referenced more advanced in-house tools developed by their firm to do initial thermal and air-side analyses on single or limited zone models. Practitioners at smaller firms reported creating simpler excel-based spreadsheets to post-process results from their simulation tools and to investigate details of buoyancy-driven flow to determine the annual number of hours NV would be possible. These practitioners stated that this extra step of post-processing outside of conventional simulation tools was necessary, but not optimal.

Findings: sources for key inputs
Practitioners were asked about their sources for common inputs such as boundary conditions, wind and weather data, and occupant-controlled window opening schedules.

Most practitioners reported using typical weather files when conducting their analyses (e.g. TMY for the U.S. and CWEC for Canada). Seven practitioners reported that they designed their NV systems to operate under still conditions only and disregard wind speed and direction. Five reported that they would only run an analysis with wind to check for flow reversal, areas of discomfort, or unexpected issues, such as pressure changes. Three stated that they have used site-specific data in the past when it was available.

Schedules describing when windows would be open or closed are often a critical influence in modeling NV systems, but there was no consensus of approach. Eleven practitioners used schedules based on an ideal user, i.e., assuming that windows would be opened when indoor temperatures were above the comfort range (in the cooling season). Four of these practitioners said this was because their systems were always automated for security, comfort, or ventilation. Of the remaining seven who modeled manually-operated windows, two reported scaling the open area based on indoor temperature.

Just two practitioners reported applying a probability distribution to their ideal user schedule to account for variations in actual use, but others expressed interest in applying stochastic modeling principles to their schedules in the future. Three practitioners reported running multiple schedules to understand thermal comfort implications if the windows were operated in a non-ideal manner.

Findings: future direction
Looking forward, practitioners reported what types of improvements and capabilities they would like to see in
their simulation tools. While there was no overwhelming consensus, several suggestions were most prominent.

Integrated tool or data entry interface
It would be helpful to have a NV tool that was better integrated with the whole building modeling tool, but the details of how this might be achieved differed. Half stated they wanted a combined tool, while half stated that a modular tool with a common geometry input interface would suffice. Most importantly, practitioners stated that they wanted to reduce the time and chance for errors created by repetitively entering the same information into multiple simulation tools.

Improved result visualizations
Practitioners also reported wanting to be able to better convey results to architects and clients. Some wanted the tool to be able to generate better visualizations depicting accurate airflow paths through the space, and annual time and temperature distributions. Others just wanted a tool to provide text-based results that could be exported for script-based graphical post-processing.

Early phase design tools
Lastly, practitioners reported that quick tools meant for early design testing would be valuable, stating that many existing tools were designed for compliance or performance modeling and were more difficult to use as iterative design tools. One practitioner cited CBE’s UFAD Cooling Load Design Tool as potential inspiration for a future early design tool for NV. Such a tool could help designers decide whether NV was a viable option for their building based on basic layout and local climate data, and which type of NV scheme might be best suited for their project.

DISCUSSION
In comparing the literature review with the responses from practitioner interviews, it is clear that there is useful research information that practitioners can apply to their current work. It is also clear that there is a limited connection between the needs of practitioners and the work of researchers, and the interviews may serve to clarify which areas warrant further study.

The development of the elevated air speed thermal comfort model and its incorporation into an ASHRAE standard allows the research to directly benefit the practicing community. With respect to the adaptive comfort model, practitioners are using it in MM buildings in spite of this being outside the limits of applicability stated in the standard. It would be valuable if researchers would study the potential wider application of this model.

Providing further guidance to practitioners on the sensitivity of flow rates and thermal comfort on wind speed and direction data, and tools for generating site-specific wind data, would be valuable. The use of analytical tools to predict wind pressure coefficients were found to be common in the research environments but underutilized in practice. Improved analytical tools that reduce the need to perform more time consuming CFD would be beneficial.

Another area that would benefit from more targeted research is window-opening behavior. While a significant number of studies have been devoted to determining influential factors, little practical guidance has been provided for practitioners to use. With this large body of work and the clear interest of practitioners, creating a guideline for implementing stochastic window opening behavior schedules would fulfill an important need.

Lastly, some practitioners reported examples when they were able to compare simulation output with post-occupancy data, but most said they did not have the access or resources to conduct this validation exercise. To improve confidence in modeling tools, research validating tool output with post-occupancy data would be valuable.

CONCLUSIONS
It is clear that practitioners want guidelines and direction from researchers to improve the reliability of their MM models in the following select areas:

- Additional research on the sensitivity of NV models to wind speed and direction data is needed to understand the critical differences between weather station and site-specific wind data.
- Clearer guidance is needed from the research community on what discharge coefficients values should be used to model windows in wind-driven ventilation scenarios.
- Guidelines for implementing stochastic window opening behavior schedules are currently lacking and are in demand by practitioners.
- Integrated simulation tools were regarded highly by most practitioners as ways to reduce user error and reduce time spent building models, but limited options are currently available.
- Practitioners are interested in understanding what their peers are doing in terms of modeling NV.
- Practitioners want to be able to improve the post-processing of their results to better communicate, visually, with clients and architects.

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REFERENCES


Session 8: Solar Shading

A New Approach to Modeling Frit Patterns for Daylight Simulation 183
Mostapha Sadeghipour Roudsari and Anne Waelkens
Thornton Tomasetti | CORE Studio.

Remote Solving: A Methodological Shift in Collaborative Building Design and Analysis 189
Matthew R. Naugle and Mostapha Roudsari
Thornton Tomasetti | CORE Studio.

ComfortCover: A Novel Method for the Design of Outdoor Shades 197
Christopher Mackey, Mostapha Sadeghipour Roudsari, and Panagiotis Samaras
Massachusetts Institute of Technology; University of Pennsylvania; University College London.
A New Approach to Modeling Frit Patterns for Daylight Simulation

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ABSTRACT
With recent progress in the development of affordable and faster digital design techniques and production methods, as well as the rising demand for buildings with better thermal and visual comfort, the use of frit patterns is becoming more common. There is a great diversity of fritted materials, but there are limited highly technical solutions for evaluating the effects of using these materials. This paper introduces a custom workflow for modeling frit patterns for daylight simulation on buildings, which streamlines quantitative and qualitative daylight analysis by using parametric modeling tools such as Grasshopper3D, in association with validated lighting rendering engine Radiance. The presented method was applied to a real-world project with custom ETFE facade elements and complex geometries to explain the capabilities of the workflow.

Author Keywords
Frit, ETFE, daylight analysis, Radiance, Honeybee, performance-based design.

INTRODUCTION
As the technology of producing fritted materials has progressed over the last decade, there has been increasing desire to model the effects of using this technology in buildings. Using fritted materials changes the aesthetics of a building (qualitative aspect), as well as its thermal and daylighting performance (quantitative aspect). Generally, different solutions are used separately to evaluate qualitative and quantitative effects of using ETFE. Designers use photo-realistic rendering engines to visualize the space with fritted materials mapped on surfaces, and engineers use physically accurate rendering engines to model quantitative effects of using fritted material. The two teams therefore end up with different solutions to an identical problem. Moreover, each approach has its own way of preparing models and assigning inputs, which makes it difficult, if not impossible, to create an identical model for both platforms. This paper introduces a custom workflow developed in the 3D parametric modeling environment of Grasshopper3D with Radiance [10] as the rendering engine. The method uses a single model for design and analysis, and Radiance for both qualitative and quantitative analysis.

The workflow is used to study the effects of frit patterns on exterior ETFE pillows of the Culture Shed, a performance and exhibition space in the new Hudson Yards development in Manhattan. The building designer, Diller Scofidio + Renfro [5], included fritted pillows to mitigate excessive solar gain, potential visual discomfort as well as excessive illuminance, while keeping visual continuity between inside and outside spaces.

EXISTING METHODS
Modelling frit patterns accurately consists of two steps. First, the pattern is applied to a defined geometry and the properties of frit and base material are assigned. Second, a physically accurate engine is used to calculate light distribution in the scene. There are a number of photo-realistic rendering packages that allow users to apply image-based patterns for visualization, with simplified methods for defining the materials. These rendering packages do not use physically accurate engines. On the other hand, available interfaces for physically accurate rendering engines, such as Radiance, don’t provide user-friendly solutions for image mapping, which limits their use to more technically inclined users. Currently, there are three common methods to model frit patterns by Radiance.

The first method uses a Radiance function called Perforate.cal to generate an evenly distributed dot frit pattern. Standard Radiance materials can be used for base and hole materials and the Perforate.cal calculates the position of each material on the surface based on diameter of dots and an input scale. The example below shows how the function can be used to generate a green frit pattern on a vertical surface in the XY plane:

void glass VE8-40_glass
0
0
3 .667 .667 .667

void trans greenfrit
0
0
7 0.370 0.502 0.304 0.010 0.15 0.222 0.000

SimAUD 2015, April 12 - 15, 2015, Alexandria, VA, USA
© 2015 Society for Modeling & Simulation International (SCS)
void mixfunc frit-g40
6 VE8-40_glass greenfrit z_hole perforate.cal -s .5
0
1 .357

This method is usually used for planar geometries in standard planes (XY, XZ, YZ). It can be modified to generate a similar pattern in 3D and on non-planar surfaces, but the user will have limited control of UV distribution and the pattern won’t be as expected on complex geometries. Moreover, the function is limited to just generating evenly distributed dot patterns and can’t generate other custom patterns.

The second method used outputs of Optics [7] and glaze script [4]. Optics was developed at LBNL and was designed to evaluate properties of complex glazing units. Radiance’s outputs of Optics can be processed by Optic2glazeddb to generate a format that can be used by Radiance. The results can then be used to generate Radiance renderings. Similar to the previous method, this method doesn’t provide support for generating custom frit patterns.

The third method uses Bidirectional Scattering Distribution Function (BSDF) measurements for frit patterns from available resources such as LBNL Window package [8]. Window is also developed at LBNL, and is used for modeling complex glazing systems. Window has libraries for different window system components, venetian blinds and roller shades. Window can be used to generate BSDF files, including systems with frit patterns. Radiance also has a genBSDF module that can be used to generate BSDF data from a Radiance model. The main constraint of using BSDF files for this study is the limitations for visualizing the geometry, which means they can’t be used for qualitative analysis [1].

THE NEW METHOD

The new method uses Rhino/Grasshopper to map images, frit patterns in the case of this paper, on test geometries and export them to Radiance for daylight analysis. The workflow is developed in Grasshopper3D, the visual programming plugin for Rhinoceros. The visual programming platform provides easy access to different stages of the analysis, from geometry generation through material and frit pattern assignment, to analysis of specific settings, such as weather file and analysis type. Patterns are visualized in Rhino and the user can modify them before running the simulation.

A number of Grasshopper plugins are used in this workflow. The Human plugin [6], developed by Andrew Heumann, is used to map images on geometries and visualize them in Grasshopper. It extends Grasshopper’s ability to create and reference geometries and carries some Rhino functionality, such as image mapping, to Grasshopper. Honeybee is used to export Grasshopper geometries and their assigned materials to Radiance. Honeybee is part of Ladybug, an environmental plugin for Grasshopper 3D that connects Grasshopper 3D to validated simulation engines for daylighting and energy simulation [9]. It currently supports integration with Radiance, Daysim, EnergyPlus and OpenStudio. Finally, a set of new components is developed as an extension for Honeybee to export image patterns from Grasshopper to Radiance.
This workflow was initially developed to study the effects of frit patterns in the Culture Shed retractable structure, which is covered with curved ETFE pillows (Figure 2). In this paper, Culture Shed is used to explain the workflow; however, this workflow can be applied to any building.

The main challenge of the project was to apply several types of frit patterns to ETFE pillows with complex geometries. Each pillow is supported by steel structure. The design team was interested in studying how different frit patterns on ETFE pillows would affect daylight distribution inside the shed. The pillows have a double curvature and are defined based on the results of structural analysis. The following section describes each step of modeling the shed in more detail.

**Preparing Geometry**

This workflow accepts Rhino/Grasshopper’s meshes and surfaces. The resulting design model can be used directly for analysis. The Human plugin, however, supports only image mapping for mesh geometries. Where image mapping is required for a surface, it should be first converted to mesh before applying the map.

**Image Mapping in Grasshopper**

Image mapping is already supported by Radiance, but applying accurate image mapping to multiple surfaces with different shapes and sizes needs a considerable amount of expertise and effort [2]. It is also impossible to check the mapping without running the simulations. Using Rhino and Grasshopper eases the process of image mapping and provides a real-time visualization of image mapping before running the analysis. In this workflow, Human plugin is used to apply the image mapping. This component accepts an input mesh and uses Rhino’s algorithms to generate a modified mesh. Supported image mappings are shown in Figure 4.

A user can control the size of the pattern and other mapping parameters using Grasshopper sliders. Figure 3 shows how two different sizes of dot patterns are applied to multiple pillows with double curvature.
A custom Grasshopper component is developed to export mesh and image patterns to Radiance. The component inputs a mesh from Human component, base Radiance material, and an HDR file of the image, and generates Radiance readable files (Figure 5).

In the first step, Rhino/Grasshopper meshes are exported as an .obj file. Obj is a geometry definition file first developed by Wavefront technologies. It is a simple data-format that represents the data geometry for each vertex, vertex normal, UV positions of each texture coordinate vertex and faces. In the second step, colorpict pattern is used as the modifier to create the material based on HDR image that can be applied to the surfaces [3].

Finally, a Radiance mesh file is generated using the material and the Obj file. This mesh can be added to the Radiance scene using Radiance’s mesh painting and will carry all the geometrical and material data. The following lines is an example of the Radiance file:

```
void colorpict dots_image_pattern
  7 red green blue ./pattern/dots.hdr . (2.11*(Lu-floor(Lu)))
  (Lv-floor(Lv))
  0
  1 1
dots_image_pattern glass dots
  0
  0
  4 0.980 0.980 0.980 1.400

void mesh painting
  1 InteriorPillow.msh
  0
  0
```

Preparing Radiance’s Scene and Run Analysis

Up to this step, surfaces with mapped patterns are exported in a Radiance-compatible format. For the rest of the scene, Honeybee standard components can be used. Honeybee supports creating Radiance materials in Grasshopper and the user can assign them to surfaces or meshes as desired. These geometries can be exported to Radiance next to the files that are prepared in step 3. Figure 5 shows the process of putting the study together in Grasshopper. The component-based organization of different actions and the possibility of grouping related components together and tagging them makes the workflow clear and easy to understand.

In this case study, except for ETFE pillows, generic materials are assigned to the rest of the surfaces in the model.

![Figure 5. Export mesh and mapping from Grasshopper to Radiance. Generated files from this component will be added to Radiance scene.](image)

![Figure 6. Putting the scene together to generate an image-based analysis using Honeybee. The generated files in step 2 are added to the scene as additional Radiance files (additionalRadFiles_).](image)
Once analysis is completed, the results will be saved in a local folder. Based on the type of analysis, the results will be available as rendered images or imported back to Grasshopper using different Honeybee components. It can then be visualized as colored geometries. Several parametric studies have been done for the project to study different densities and radius for the frit patterns for interior and exterior spaces for two different placements of the shed. Since exploring the results of the study is out of the scope of this paper, a selection of the results is presented in the following.

Figure 7 shows illuminance levels inside the gallery in the second floor for two different combinations of frits on the pillows once the shed is retracted over the building.
Figure 8 shows a rendering from inside the plaza area when the shed is deployed. Figures 9 shows illuminance levels inside the gallery for different configurations of the shed.

CONCLUSION

The paper presents a workflow that marries parametric modeling and physically accurate rendering engines that provide an integrated, flexible approach to streamlining modeling and analyzing frit patterns qualitatively and quantitatively.

The workflow allowed the team to explore a wide range of solutions in a short time, and provides the desired results to the design team in a timely manner to help with making design decisions based on daylighting analyses. This method makes the process of studying frit patterns accessible to designers and allows the findings to be integrated early in the design. By doing so it helps designers and engineers achieve a high-quality, high-performance design.

The parametric modeling environment of Grasshopper3D provides flexibility and control of input parameters. It also helps automate the process so multiple studies can be run after setting up the model. Radiance serves as a single platform rendering engine that can achieve accurate results for both qualitative and quantitative analysis.

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Remote Solving: A Methodological Shift in Collaborative Building Design and Analysis

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ABSTRACT
This paper presents a cross-disciplinary design workflow utilizing automated computation as a means for enabling rapid design and engineering collaboration between architecture engineering and construction (AEC) project teams. The workflow, known as Remote Solving, connects digital design models to remotely hosted bespoke engineering analysis engines to provide near real-time engineering feedback. This workflow fundamentally changes the way design and engineering practices may communicate information, resulting in design solutions that embody a fully integrated approach to design and engineering in digital practice. The paper provides an understanding of the fundamental technologies and methodologies that constitute a Remote Solving workflow alongside a case study demonstrating a prototype project designed to leverage this method of collaboration.

Author Keywords
Multi-disciplinary Design; Remote Solving; Parametric Modeling; Embedded Analysis; Automation

INTRODUCTION
Workflows for collaborating and sharing of 3-D models and project data between disciplines have not yet progressed to the level of the advanced digital capabilities housed within the individual disciplines working on a project. Software and hardware advances have exponentially increased the amount and types of data that are able to be produced in a fraction of the time that was previously possible. Traditional methods of communication between team members, ranging from on-site meetings, emails, phone and web calls, file sharing on ftp or cloud platforms, and hand-delivered sets of drawings, fail to provide a means of sharing project information that keep up with how quickly new design iterations may be created with digital design processes provided by parametric and generative design software.

These traditional methods of communication create a correspondence process that typically represents the project at a finite state in the design’s evolution. As soon as the information is sent from one party to the next, the received information is on its way to becoming antiquated as the project continues to progress. The speed at which information is shared has an immediate and subsequential effect on the development of the design. Without new processes for disseminating the continual growth and development of a project, the success of a fully integrated design approach is directly linked to the responsiveness of the various team members. This is a major hurdle in realizing the potential gains that parametric modeling, generative design, automation, and embedded analysis offer to the final delivery of a project. A Remote Solving workflow begins to address this issue by linking design and engineering models together to provide an automated means of analyzing design iterations and returning feedback without relying on traditional communication methods.

Remote Solving connects design and engineering software to provide an automated means of transmitting design and analysis data between teams at a speed which parallels how fast new design options may be generated. As a design develops, the Remote Solving framework enables on-demand transfers of project information to trigger remotely hosted engineering analysis to take place. Upon the completion of each analysis, feedback is automatically
returned to the design team detailing the performance of that particular state of the design.

Figure 2. Diagram depicting a parallel process workflow between architects and engineers where design and engineering occur at the same time, thus allowing more options to be studied.

The communication of a design iteration’s performance for any type of engineering analysis occurs at computer speed (milliseconds to seconds) instead of human speed (minutes to days). When working with feedback loops at this time scale, the ability to not only iterate through tens, hundreds, or thousands of design configurations, but also understanding each instance’s relative engineering performance, is now possible (see figure 2). As a parallel process of design and engineering in lieu of a process indicative of design then engineering, AEC teams are able to explore a greater design space while ensuring that engineering feedback can positively influence the course of a design.

EXISTING METHODS
Currently there are services available that address the need for embedded analysis and collaborative design processes between AEC teams. Among those available options, this paper discusses Green Building Studio (GBS) [6] and Autodesk A360 [1] as examples that are similar in nature to what Remote Solving may offer a workflow. Both software platforms address means and methods of allowing multi-disciplinary project teams to embed analysis into the design process and work collaboratively by sharing digital models and media related to the project.

Green Building Studio is a cloud-based service for building performance simulation. GBS can be used as a standalone web service or from within Autodesk Revit [2] and Autodesk Vasari [3]. A user can send the design model to GBS and receive the results of the analysis with minimum modification to their design model [see figure 3].

Figure 3. Autodesk’s Building Energy Analysis Diagram

This process ensures that designers can evaluate their design options at any stage of the design with minimal effort and without requiring an expert professional. This workflow relies on the premise that the designer’s BIM has been created with enough information and specificity to run as an energy model once loaded into GBS. When inadequate data exists in the BIM, GBS uses default data culled from the model’s high-level inputs or uses other databases to be able to run the analysis. This step helps to ensure that even models with limited information may be analyzed. GBS also takes steps toward running multiple parametric analysis options to create a larger range of data in the feedback results. This enables a project team to evaluate different options as they move forward.

Autodesk A360 is a software platform that utilizes a shared cloud platform for sharing and viewing 3-D models, digital media, and maintaining team coordination. Currently, this platform unlike GBS does not offer any native analysis functionality, but creates a platform for teams to communicate through the evolution of a design. A360 has been designed to work with desktop and mobile devices, imports over 50 2D and 3D model formats along with over 50 media and office file formats [9]. The 3D interface allows for advanced searches of complex models to view parts and properties of objects. Team coordination and communication is possible through shared communications in team calendars and commenting directly on design files.

Both of these packages present means for collaboration and early stage analysis for architectural projects. A Remote Solving workflow differentiates itself from these and other similar available software products by merging both aspects of embedded analysis and communication methods with project-specific customization and implementation. Each Remote Solving workflow is created specifically by the criteria set out by a project team and therefore does not have to meet the rigors and extensibility that is required for
commercial software packages that must cater to a wide audience of users.

The other significant difference between a Remote Solving workflow and how a team may use any available software applications to provide similar services is the means by which questions and changes in process are handled. If a design team does not understand the results while using remote solving during the design process, they have a conversation with the engineering team that is intimately involved in the details of the project. If the means of communication need to be altered, the framework can be manipulated to do so. In this workflow, sharing expert knowledge between the teams is a critical part of using an integrated design-analysis platform to ensure the validity of the analysis and results. In comparison, available software platforms offer limited project-specific support or ability for implementing changes and adjustments to functionality for specific users.

METHODOLOGY
The Remote Solving framework is designed as a set of abstract principles and protocols, not as a specific software platform itself to ensure the workflow may accommodate a wide range of design criteria, software platforms, and design and engineering communication methods. The constraints and goals of each project enabled by a Remote Solving workflow will dictate the implementation and user experience for that particular project team. Deployment will vary from project to project, however, Remote Solving as a framework can be defined as a process reliant on data extraction and remotely automated analysis that is processed through three key components: A set of graphical interfaces for each team to monitor input and output data, a remotely hosted bespoke engineering engine to process design options and run engineering analysis, and storage for the data that is passed between teams to communicate design iterations and feedback (see figure 4).

The interface that project teams interact with may be a graphical user interface (GUI) embedded directly into a team’s preferred software package as a custom developed plugin or a web page divorced from the software platform for inputting design data and reviewing results. In either configuration, these graphical interfaces are the portals for communication between teams. In between the team members’ graphical interface is the engineering engine that runs the analysis and a database or storage system for maintaining the various design iterations and results. The engineering engine is a bespoke solution created specifically for the goals of a particular Remote Solving instance. This engine may be a custom developed set of algorithms that directly perform analysis and record results and/or it may be a series of interoperability scripts to automate triggering and recording analysis through commercially available software packages. The engine is hosted remotely, either on a virtual machine or dedicated networked computer to automatically run the desired analysis upon receiving inputs from the graphical interface. Upon completion of an analysis run, the engine produces feedback in a format predetermined by the team, and returns that information back directly to the design team’s modeling environment or graphical interface for review. All design and analysis data, along with feedback reports, are stored centrally in databases and cloud storage systems enabling the history, evolution, and states of a project to be evaluated at any time.

The key factor that allows a Remote Solving workflow to provide analysis feedback at a similar pace to how quickly designs are generated by these emerging advanced digital design processes is by extracting lightweight data to be shared between the teams. When developing a Remote Solving workflow, the team must decide on the expanses of the design space, goals and constraints to be investigated, and the type of desired feedback that will help move the design along a positive trajectory. Once the workflow planning is in place, the various components of Remote Solving are developed in a manner that transfers as little information between architect and engineer as possible. This is achieved by sharing what is necessary, and nothing more, to perform the desired analysis and is an integral discussion had between the team while defining a Remote Solving workflow. This data is often the parameters that drive design iterations in a parametric model, the shell of a building model without fully detailed and modeled complexities often found in full Building Information Models, or simply layout geometry such as levels, grids, and centerlines. This data is extracted from the design model through the graphical interface placing the design data into a live queue as a new entry to solve in the analysis engine. In order to maintain fast solve times, the extracted design is often represented as xml, tabulated data, or any other means that allows for a lightweight and quick transfer of information (see figure 5).

Figure 4. A typical Remote Solving workflow utilizes a database and analysis engine in between two graphical user interfaces.
With these inputs, the engineering analysis engine automates the adjustment of an analysis-specific digital model constructed by the engineering team during the planning and development phase of creating a project’s Remote Solving setup. This model is created based upon the criteria set out by the team with the ability to adapt and respond to an understood range of design parameters. The same principle of lightweight data sharing is used when returning engineering results back to the architectural team. Engineering feedback is kept lightweight and provided in a platform that most easily helps the design team ascertain the implications of their design. This may be by inserting geometric form into the original design model, 2-D or 3-D visualizations, tabulated reports, or lightweight web-hosted model and design dashboards (see figures 5 & 6).

By abstracting the representation of a project into extractable lightweight data shared between teams, automating analysis to run upon the receipt of new input data, and directly returning feedback into the design team’s in-house digital workflow, Remote Solving begins to remove the hurdle of not having adequate time to investigate all design options produced early in a project’s conception. The lightweight data exchange allows design iterations and analysis to run in parallel without unnecessary models and files to filter through. Since Remote Solving is a framework and software agnostic, the ability to customize any particular part of a specific workflow allows for enhancements and adjustments to be made as the project evolves. Utilizing cloud-hosted virtual machines, processing power can be ramped up or down.
Parsing Input Image

The Grasshopper script hosted on the virtual machine listens for updated images in the shared Dropbox folder. Once a new set of images have been uploaded, the Grasshopper script parses the first set of images in the queue to produce a matrix of percentages that describe the frit pattern for each glass panel. If multiple inputs are received from the design team before a prior analysis run is complete, a queue is formed and each option is processed and returned in order.

Create Radiance’s Materials Based on Frit Density

To model the frits on the glazing surfaces for a Radiance analysis, a custom Grasshopper component was developed to calculate the size of frit dots and distance between neighboring dots for each glass panel based on image analysis initially performed in the script. The method used creates a Radiance material string that approximates the actual geometry from the image pattern provided by the design team. The result is a material described by a normalized distribution of dots that has similar light transmittance to a panel based specifically on the image supplied by the design team.

Create Daylight Analysis Scene

The Grasshopper script uses Honeybee to prepare the analysis scene and run the analysis. Honeybee [10] is an open-source plugin for Grasshopper3D that connects Grasshopper to different validated analysis engines including Daysim [4], which was used as the analysis engine to run the daylight studies. Honeybee has a set of components that allow users to create Radiance materials, apply them to surfaces and execute the analysis from Grasshopper’s environment. Having access to the parameters provided the engineering team the ability to adjust the parameters of the analysis during the process to balance the workflow for accuracy of the results versus speed of analysis.

Prepare Analysis Report

Honeybee supports importing Daysim result files directly into Grasshopper3D to visualize the results overlaid on modeled building geometry. The script overlays the result files and exports bitmap images of each floor plan visualizing the analysis grid in a color gradient based on Illuminance values. Using TT Toolbox, another plugin for Grasshopper3D developed by Thornton Tomasetti’s CORE studio [11], the full analysis grid was exported as numeric results to Microsoft Excel in a spreadsheet with the cell layout matching the building floor plan geometry. The design team could then review the results of a given design iteration as a rendered image file of the building geometry with overlaid Illuminance visualization or as tabulated data in Excel directly back in the Dropbox folder with naming conventions for cataloging and reviewing of results (see figure 7 and figure 8).
LIMITATIONS
Remote Solving as a workflow is a step toward finding ways to make the communication, collaboration, and integration of design and engineering a more fluid process in the rise of computationally heavy design processes. The research and prototyping of this framework have shown that a potential exists to solve issues of latency in sharing of design intent between disciplines when rapid iteration is a prevent part of the project’s development. Yet a number of known barriers exist in making this workflow a viable solution for multidisciplinary project collaboration.

A sound understanding of the technology for not only using parametric design, automation, and embedded analysis, but also for using Remote Solving within the context of a project’s development is needed within all teams. As a new method of sharing design and engineering feedback, a learning curve is expected on how and when teams effectively engage with the process. To address this issue, refinements to the user experience will be critical in making the process easier to integrate into existing processes. The amount of time to develop a Remote Solving workflow for a particular project also varies drastically. While each workflow utilizes a similar framework of components, the ability to reuse and re-purpose different components varies depending on the complexity of the analysis and design criteria for a given project. This ultimately limits the ability of this workflow if adequate time cannot be afforded up front to put a carefully design system into place. To address this, the development to date has been working toward modularizing the code and creating standardized functionally to more quickly put a Remote Solving workflow into practice.

Beyond the experience of using Remote Solving and technical requirements in order to develop this workflow for project teams, it presents the teams involved new contractual liability concerns regarding the data being shared through automated means. Depending on the software and services being used, there may prove to be limitations on licensing, interoperability functionality, speed of simulation, and how the verification of results will occur. With these and other limitations at hand, each Remote Solving workflow will require diligent preparation to ensure the implementation provides meaningful feedback for the integrated design approach which it aims to assist.

CONCLUSION
Remote Solving offers a process that changes the way architects and engineers may work together. It addresses not only the need to find more efficient means of sharing information and design schemes in an era where digital
methods are producing more and more in a fraction of the time, it also bridges practices barriers between both parties. With a Remote Solving workflow in place, it forces all members of the project team to communicate design intent and consulting feedback in highly prescriptive manners. The process helps to mitigate the ‘lost in translation’ conversations – as the teams are effectively developing parallel models that must exchange data upon predetermined rules. As the design evolves, the Remote Solving process may evolve too, adjusting to changing design criteria at any given phase of the project.

The future of Remote Solving as a means of real-time collaboration between multi-disciplinary teams is in its infancy. With a small sample set of use cases and prototypes, the ability to push a design forward in a truly integrated way has shown to have enormous potential. The platform lowers the bar for entry into complex relational design and analysis models that may not be accessible by all parties in the industry, while also addressing major hurdles in how we utilize the emerging technologies of parametric and generative design within the practical application of fully integrated, collaborative, design process.

REFERENCES
ComfortCover: A Novel Method for the Design of Outdoor Shades

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ABSTRACT
Over the past few decades, several methods for designing shades to reduce energy loads of buildings have emerged. However, to date there are virtually no agreed upon methods available to assist in the design of outdoor shades to keep people comfortable. Here we present a novel method named ComfortCover to assist in the design of static shades in outdoor conditions using a 3-step methodology adapted from the current state-of-the-art process for the design of building shades.

The first step is an assessment of radiation falling on a person and the calculation of a corresponding solar-adjusted radiant temperature for every hour of the year. Second, this temperature is fed into an hourly calculation of Universal Thermal Climate Index (UTCI). Lastly, this UTCI is fed into an algorithm that projects sun vectors for every hour of the year from the location of a person through a surface where shade design is being considered. Each of the vectors is associated with a UTCI and a temperature difference from a ‘comfort temperature’ that is summed up for every subdivision of the test shade to color it with shade helpfulness (blue), shade harmfulness (red) and no major effect of shade (white).

Author Keywords
Outdoor; Comfort; Shade; Design; ComfortCover; UTCI

Existing Methods
At present, if a designer were faced with such a task, they would likely resort to an altered version of the original method developed by Olgyay and Olgyay [8] to size brise soleils for window glazing. Perhaps the first of its kind, this method uses heating and cooling degree days around a balance temperature to select “cut-off dates” with corresponding sun altitude angles that effectively trim the boundary of a rectangular shading plane. In theory, designers could use this method in the design of shades for outdoor comfort by selecting a balance temperature that is indicative of an individual person’s energy balance rather than the energy balance of a building. However, because such a human energy balance temperature has never been standardized and the Olgyay method has since been replaced by more precise methods, such an outdoor application would fall far short of the potential accuracy that could be achieved with present technology.
Since the time of Olgyay, there have been large advances in shading design methods for buildings that have factored in criteria such as the azimuth of sun vectors, the thermal lag of buildings, the occupancy schedule of buildings, the buildings’ insulation, and much more. Notable among these methods are the Thermal method, the Eco Degree Day method, the Eco Thermal method, and the cellular Shaderade method [9]. In 2011, Sargent et al. demonstrated that the Shaderade method could suggest a shade with the greatest building energy savings of all these methods. The method’s success is owed in large part to an underlying EnergyPlus simulation and combines the heating, cooling, and solar beam gains of this simulation with hourly sun vector geometry in order to color a shade’s cells with shade helpfulness and harmfulness. With this major advance in building shading, this paper seeks to adapt this current state-of-the-art cellular Shaderade method to create an agreed-upon standard for the design of outdoor shading for comfort.

Proposal for a new Method

Figure 1 illustrates how such a Shaderade adaptation to outdoor shading would progress from the initial selection of a seating area and a surface where shade is being considered to the coloration of the shade surface with shade desirability (blue) or shade harm (red), and finally to the selection of the best part of the shade as a start for design. From here through the rest of the paper, this adaptation of the Shaderade method to the case of outdoor comfort will be referred to as the ComfortCover method.

Much like the adaptation of the Olgyay method, the key feature that must be changed in order to use Shaderade for outdoor comfort is to replace the building energy simulation with an outdoor comfort assessment. The last decade has produced a wealth of validated methods for assessing outdoor comfort and corresponding comfort metrics expressed as a temperature of what the outdoors ‘feels like.’ One particular temperature metric that has proven to have a good correlation to outdoor comfort surveys is Universal Thermal Climate Index (UTCI) [10, 4]. In the design of outdoor shades, UTCI is particularly helpful as it was published with ranges defining conditions of ‘no thermal stress’, ‘heat stress’, and ‘cold stress,’ which can be used to identify whether a given set of conditions should contribute positively, negatively, or not at all to shade benefit [11]. The usefulness of UTCI is further enhanced by the fact that it is calculated independent of clothing level and metabolic rate, assuming a natural adaptation of these variables as outdoor climate conditions change. The only required inputs for UTCI calculation are air temperature, mean radiant temperature (MRT), relative humidity, and wind speed, thus making it easy to calculate from publicly available TMY weather data. Because of UTCI’s validated accuracy, its incorporation of ranges that define thermal stress, and its simple inputs, UTCI was selected as the underlying comfort value with which to derive shade desirability or harm.

In order to adapt the original Shaderade method for UTCI, it is first necessary to state the underlying formula that Shaderade uses in order to determine whether a given hour and its corresponding sun vector contributes positively or negatively to shade benefit. This formula is as follows:

\[
E_{\text{unwanted}} = \begin{cases} 
E_{\text{beam}}, & E_{\text{cooling}} \leq 0 \\
E_{\text{cooling}} - E_{\text{beam}}, & 0 < E_{\text{cooling}} < E_{\text{beam}} \\
E_{\text{beam}}, & E_{\text{cooling}} \geq E_{\text{beam}}
\end{cases}
\]

Where \(E_{\text{unwanted}}\) is the fraction of the sun’s beam gain that is increasing the building cooling load (or the shade helpfulness for that hour), \(E_{\text{beam}}\) is the solar beam gain through the window at the given hour, and \(E_{\text{cooling}}\) is the difference between the cooling load and heating load at the given hour (or cooling load - heating load). Note that \(E_{\text{desired}}\) can be either positive (contributing to shade helpfulness) or negative (contributing to shade harmfulness) depending upon the given conditions. In order to adapt UTCI to this method, a similar approach is taken but the heating, cooling and beam gain are replaced with a temperature difference around a balance temperature. This formula can be written as follows:

Figure 1. The inputs and outputs of the ComfortCover method.
\[
T_{\text{unwanted}} = \begin{cases} 
T_{\text{hour}} - (T_{\text{bal}} - T_{\text{offset}}), & T_{\text{hour}} \leq (T_{\text{bal}} - T_{\text{offset}}) \\
0 , & (T_{\text{bal}} - T_{\text{offset}}) < T_{\text{hour}} < (T_{\text{bal}} + T_{\text{offset}}) \\
T_{\text{hour}} - (T_{\text{bal}} + T_{\text{offset}}), & T_{\text{hour}} \geq (T_{\text{bal}} + T_{\text{offset}})
\end{cases}
\]

Where \( T_{\text{unwanted}} \) is the number of degree-hours for which the additional temperature delta from the sun is unwanted (or the shade helpfulness for that hour). \( T_{\text{bal}} \) is the median outdoor temperature that people find comfortable, \( T_{\text{offset}} \) is the number of degrees away from \( T_{\text{bal}} \) that people will feel no thermal stress, and \( T_{\text{hour}} \) is the UTCI at the given hour. Again, note that \( T_{\text{unwanted}} \) can be either positive (contributing to shade helpfulness) or negative (contributing to shade harmfulness) depending upon the given conditions. Since UTCI was published with a range of ‘no thermal stress’ defined from 9 °C to 26 °C, \( T_{\text{bal}} \) and \( T_{\text{offset}} \) will be defined as 17.5 °C and 8.5 °C respectively for the remainder of this paper in order to ensure alignment with these standardized values.

Following the Shaderade method, the ComfortCover method will project hundreds of solar vectors from an array of test points over the area where a person is seated and are intersect these vectors with a test shade that has been subdivided into cells. The degree-hours of \( T_{\text{unwanted}} \) are summed up for each cell of the test shade in order to give a net shade desirability, shade harm, or net minimal shade effect.

In order to ensure that UTCI values for \( T_{\text{hour}} \) are correctly calibrated for the suggestion of shade desirability, it is necessary to account for the effect of solar radiation falling directly on people by plugging in a solar adjusted MRT into the UTCI calculation. Traditionally, in order to determine this solar adjusted MRT, a radiation study of human geometry is performed and this is then used to produce an Effective Radiant Field (ERF) through the following formula:

\[
\alpha_{\text{LW}} \text{ERF}_{\text{Solar}} = \alpha_{\text{SW}} \text{E}_{\text{Solar}}
\]

Where \( E_{\text{Solar}} \) is the short wave solar radiant flux on the body surface (W/m²), \( \alpha_{\text{SW}} \) is short-wave absorptivity, and \( \alpha_{\text{LW}} \) is the long-wave absorptivity (typically around 0.95). The ERF can then be related to an MRT through the following formula:

\[
\text{ERF} = f_{\text{eff}} \ h_r \ (\text{MRT} - T_a)
\]

Where \( f_{\text{eff}} \) is the fraction of the body surface exposed to radiation from the environment (=0.696 for a seated person and 0.725 for standing) [12]; \( h_r \) is the radiation heat transfer coefficient (W/m² K); and \( T_a \) is the air temperature (°C). To the disadvantage of the design process, this traditional method of performing a radiation study over human geometry is often very time consuming if one is attempting to determine solar-adjusted MRT for every hour of the year. Accordingly, a faster method developed by Arens et al. [13] called SolarCal will be used in this study [14]. SolarCal substitutes this lengthy radiation study with use of weather file radiation values and a few coefficients to account for the geometry of the human body. Specifically, SolarCal works through computing the ERF with the following formula:

\[
\text{ERF}_{\text{Solar}} = (0.5 \ f_{\text{svv}} \ (I_{\text{diff}} + I_{\text{TH}} \ R_{\text{Floor}}) + A_p \ f_{\text{bes}} \ I_{\text{dir}} / A_D) \ (\alpha_{\text{SW}} / \alpha_{\text{LW}})
\]

Where \( I_{\text{dir}}, I_{\text{diff}}, \) and \( I_{\text{TH}} \) are direct normal radiation, diffuse horizontal radiation, and total horizontal radiation respectively, all of which can be obtained from publicly available TMY weather data. \( A_p \) and \( A_D \) are geometry coefficients of the human body, which are computed based on sun altitude and azimuth and are described fully in the paper by Arens et al. [13]. \( R_{\text{Floor}} \) is the reflectivity of the ground, which is assumed to be 0.25 by default in this study. Finally, \( f_{\text{svv}} \) and \( f_{\text{bes}} \) are the sky view factor and the fraction of the body visible to direct radiation respectively. In this study, these two values are computed by ray tracing from the spot of the seated person and noting intersections with surrounding context geometry. Sky view factor is computed once for the whole year by tracing rays from the location of the person to each of the 145 Tregenza sky patches and dividing the non-intersected rays by the total number. \( f_{\text{bes}} \) is calculated individually for each hour of the year by tracing the hourly sun vector from each of 9 vertically-arranged points at the location of the person and noting the fraction of these that do not intersect context geometry. As such, the time-consuming radiation study of human geometry is replaced with a much faster calculation that assumes that the body as a set of points (Figure 2).

Together, with the SolarCal method accounting for solar adjusted MRT, a UTCI calculation that factors in this MRT, and a means of incorporating such UTCI in a Shaderade-style analysis, this paper outlines a new workflow that can produce a high-accuracy suggestion of where outdoor shading should be provided and where it may be harmful.

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**Figure 2.** Depiction of the time consuming radiation analysis of a human geometry mesh in comparison to a faster method that treats the body as a set of points and projects sun vectors from those points.
Figure 3. The component-based interface of the ComfortCover workflow. Each of the three main steps of the process are consolidated into three components, each of which include both required inputs as well as optional inputs to customize the model.

For more information on the options and how to use the components, see the tutorial videos here: https://www.youtube.com/playlist?list=PLruLh1AdY-Sho45_D4BV1HKcLz7oVmZ8v

SCRIPTING ENVIRONMENT OF THE NEW METHOD
This study merges the three aforementioned steps together by integrating them through the Grasshopper visual scripting platform, making each step available as a separate Grasshopper component.

As Figure 3 illustrates, the workflow begins by importing the different data types of an EPW weather file into the Grasshopper interface, each as a separate list. Next, the radiation and air temperature lists from this EPW import are fed through a second component along with location data from the EPW file that contains information for generating sun vectors such as latitude and time zone. This component computes a list of solar-adjusted MRT for a person in an outdoor space for every hour of the year (Step 1). This list of solar-adjusted MRT is then fed into a third component along with the air temperature, relative humidity, and wind speed lists from the EPW file. This third component computes a list of UTCI for every hour of the year (Step 2). Finally, this UTCI list is fed into a fourth component along with the EPW location data. Importantly, this last step also accepts the required geometry inputs, which are 1) a surface representing an area where people will sit and 2) a surface where shade desirability is being considered (see left side of Figure 1). This final component performs the shade benefit evaluation and produces the colored mesh of shade desirability seen in the middle of Figure 1 (Step 3).

Figure 3 depicts the minimum inputs required in order to run the outdoor shade benefit calculation, which are essentially a weather file and the two geometry inputs. However, as one can see, there are many more optional inputs on the components that can be used to adapt this default workflow to the variety of situations that designers might encounter.

Taking a closer look at the solar adjusted temperature component in Figure 3, some of these options are visible along with some assumptions of the required inputs. For example, it is important to note that, in this publication, the air temperature from the EPW file is connected as a starting MRT, which denotes an assumption that the outdoor MRT is the same as that of the air temperature. While this assumption is acceptable for fairly open outdoor spaces, users are advised that they should compute a starting MRT if they have a lot of context geometry that might be at a different temperature. Such a starting MRT can be calculated through observation of outdoor surface temperatures in building simulations or through other tools specialized for producing such values [15]. In addition to plugging in custom versions of required inputs like the starting MRT, users can also adjust a number of characteristics related to the geometry of the person including the posture of the body (seated, standing, or lying down), the location of the body in the 3D Rhino scene and, most importantly, they can input context shading geometries that might block the direct sun to the person. Lastly, users can change reflectivity of the ground and the absorptivity of the person’s clothing. It should be noted that this component has capabilities beyond the workflow described in this paper and, notable among these is the ability to compute solar adjusted temperature from a full radiation study of human geometry (left side of Figure 2). This will be used later to help validate the implementation of the SolarCal method.
The component for calculating UTCI does not include any major options that differ from the defaults. However, it should be noted that users may disconnect the wind speed or incorporate dampened wind speeds if they feel that the location where a person will sit has adequate wind protection. Figure 4 includes an hourly plot of UTCI for the Boston weather file in three cases that were chosen to illustrate the effects of different inputs: one with only temperature and humidity considered (signifying outdoor comfort in a shaded space with wind protection), one that incorporates wind speed, and one that includes solar adjusted MRT.

![UTCI Thermal Stress - Boston, MA](image)

**Figure 4. Annual UTCI with Different Weather**

Finally, taking a closer look at the shade benefit component of Figure 3, one notices options to adjust the balance temperature and offset temperature from the defaults of UTCI that define the range of no thermal stress from 9 °C to 26 °C. This can be useful in climates where there is a known preference for warmer or colder temperatures that may differ from the ‘universal’ standard of UTCI. Additionally, users are given the option to adjust the subdivision grid size in order to get either a high-resolution understanding of shade desirability at a slower simulation time or a low-resolution understanding quickly. Importantly, users are also given the ability to set a sky resolution, which can dramatically reduce calculation times by grouping sun vectors and their corresponding UTCI values together based on Tregenza sky patches. For this sky resolution, users can select an integer from 0 to 4, which denotes the number of times that the sky patches are subdivided into a higher and higher resolution. At a resolution of 4, sky patches are no longer used and the sun vector of each hour is intersected with the test shade.

Through the implementation of the method in the Grasshopper visual scripting interface, users are given a high level of flexibility to customize the shade benefit calculation to their unique case and even override parts of the process by inputting their own data.

**VALIDATION OF THE NEW METHOD**

Since this method is the first of its kind, there was no outdoor shade design tool that could be used to validate the results of the entire process. However, each of the three parts of the workflow was validated against the original methods in order to ensure an implementation that is consistent with the intentions of the original authors.

In order to validate the solar adjusted MRT component, the output of the component was compared to that obtained from a detailed radiation study of human geometry consisting of 481 mesh faces. The functions that were used to determine radiation over these 418 faces come from the validated rendering engine, Radiance [16]. Table 1 illustrates the results of the comparison over the course of a single day taken from the Boston, MA Logan Airport weather file. This chosen day is March 20th and this was selected because it included a diversity of both cloudy and sunny conditions. As one can see, the ComfortCover manifestation of the SolarCal method falls short of the higher accuracy human geometry radiation study, especially in cases of very low sun angles right after sunrise and right before sunset. However, it consistently lands within the correct order of magnitude and, as such, this implementation of the SolarCal method seems suitable for most design applications such as that considered in this paper.

<table>
<thead>
<tr>
<th>Hour of March 20 (Boston, MA)</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Geo Rad Study (°C)</td>
<td>0.0</td>
<td>0.19</td>
<td>12.20</td>
<td>28.41</td>
<td>32.97</td>
<td>23.37</td>
<td>23.26</td>
<td>35.18</td>
<td>39.05</td>
<td>27.10</td>
<td>15.30</td>
<td>7.64</td>
<td>6.28</td>
<td>3.92</td>
<td>0.0</td>
</tr>
<tr>
<td>SolarCal/ComfortCover (°C)</td>
<td>0.0</td>
<td>0.16</td>
<td>12.50</td>
<td>26.21</td>
<td>31.21</td>
<td>21.19</td>
<td>21.61</td>
<td>36.11</td>
<td>40.52</td>
<td>26.24</td>
<td>15.96</td>
<td>7.94</td>
<td>6.34</td>
<td>3.14</td>
<td>0.0</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>0</td>
<td>13.0%</td>
<td>-2.4%</td>
<td>7.7%</td>
<td>5.3%</td>
<td>9.4%</td>
<td>7.1%</td>
<td>-2.6%</td>
<td>-3.8%</td>
<td>3.2%</td>
<td>-4.3%</td>
<td>-3.9%</td>
<td>-0.9%</td>
<td>19.9%</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. Comparison of SolarCal solar adjusted temperature method to full radiation study of human geometry
In order to ensure a correct translation from the original FORTRAN manifestation of UTCI that is published on the UTCI website [17], the output of the Python Grasshopper component used here was tested against that of the original FORTRAN tool. Table 2 compares these outputs and it is evident that the differences between the two are consistently less than 0.1 °C (note that the original UTCI tool rounds all results to the nearest 0.1 of a degree). The error here is small enough that it should not interfere with the overall design application proposed in this paper.

<table>
<thead>
<tr>
<th></th>
<th>Jun21 9 AM</th>
<th>Jun21 12PM</th>
<th>Jun21 3 PM</th>
<th>Dec21 9 AM</th>
<th>Dec21 12PM</th>
<th>Dec21 3 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original UTCI (°C)</td>
<td>30.3</td>
<td>37.1</td>
<td>34.1</td>
<td>-15.2</td>
<td>-10.8</td>
<td>-17.3</td>
</tr>
<tr>
<td>ComfortCover (°C)</td>
<td>30.28</td>
<td>37.11</td>
<td>34.12</td>
<td>-15.21</td>
<td>-10.82</td>
<td>-17.31</td>
</tr>
</tbody>
</table>

Table 2. Comparison of Comfort UTCI to the original UTCI calculator for Boston.

Lastly, to validate the ray tracing functions that ultimately produce the map of shade benefit, the code in the shade benefit component that computes shade desirability from temperature about a balance point was compared to one in accordance with the original Shaderade method using heating load, cooling load, and solar beam gains. Values from the same EnergyPlus simulation were plugged into both the shade benefit functions of the component used in this paper and the most recent version of the Shaderade tool [9]. The best cells of the resulting shade were then used to make a new shade that was then re-run through the EnergyPlus simulation. The energy savings of the shades produced by both methods in the climates of Phoenix, Boston, and Anchorage were recorded and can be seen in Figure 5. Figure 5 also depicts energy savings of various other methods used to design shades prior to the development of Shaderade. As one can see, ComfortCover functions are producing acceptably similar results to other methods including the most recent Shaderade version of 2014. Discrepancies between the functions in this paper and Shaderade 2014 can be attributed to new features that have been implemented in the most recent version that were not a part of the original paper published by Sargent et al. [9]. Specifically, these include a consideration of diffuse solar gains in the calculation of shade benefit as well as thermal lag between incoming sun and eventual building cooling gains. While consideration of diffuse gains would improve the accuracy of the functions in this paper, it is clear that they are still meeting a high standard required in order to give accurate advice in the design process and offer a significantly more accurate alternative than other approaches.

CASE STUDY

In order to demonstrate the usefulness of the method, a case study is provided here in the form of application to the design of a bus stop shade. Following in the precedent of the original Shaderade paper, the shade desirability is depicted in 3 different climates that range from hot to cold: Phoenix, Boston, and Anchorage. Figure 6 illustrates the results of this process and, as expected, the hot climate of Phoenix produces a pattern that is dominated by high shade desirability while the cold climate of Anchorage includes one with a high level of shade harmfulness. From such initial studies, designers might make initial selections of materials for the shelter. For example, since the shade desirability of the Anchorage site is so small, designers might opt for a transparent roofing material such as curved acrylic to allow the sun to pass or might opt to not have any shade at all depending on whether rain protection is needed. In the climate of Boston, one might opt for an opaque material and deploy it intelligently over the area where shade is desired since the line between shade helpfulness and shade harm lies a reasonable horizontal distance away from the shelter’s seating area. In Phoenix where a large fraction of the sky must be covered to avoid discomfort, designers might opt for a wholly different strategy that deploys an opaque material curving over the sides of the seating area, helping avoid harmful East-West sun. Figure 7 shows how such a design process can be informed by ComfortCover as a designer might begin by inputting a curved box geometry that completely surrounds the seating area. After getting results, they might then make an appropriate judgment call about the height at which the shade could be trimmed in order to allow occupant access underneath and minimize the amount of shade material. After iterating, they might then test their final geometry by running it through ComfortCover and ensuring that they have shaded the majority of harmful hours.
CONCLUSION

This paper presents a novel workflow that empowers landscape architects, planners, environmental engineers, and other designers of outdoor spaces to account for outdoor thermal comfort in the design of static shades. Among the areas for future research and improvement, one must admit the drawbacks of UTCI that come along with the previously-stated advantages. Unlike some other outdoor comfort metrics such as Outdoor Standard Effective Temperature (OUT_SET) and Physiologically Equivalent Temperature (PET), UTCI does not include clothing level or metabolic rate as inputs and this may cause inaccuracies in cases where these criteria differ from normal ‘universal’ levels. As stated previously, the inclusion of these ‘universal’ standards can often be an advantage in the design process when such personal factors are not known. However, if a user is given a specific value for clothing or metabolic rate to use in the comfort assessment of shades, he or she will currently be at a loss with the proposed method here. Perhaps the largest limitation of the current proposed method that will necessitate future research is that this paper has assumed that the outdoor radiant temperature before solar adjustment is equivalent to that of the air. While this assumption is suitable for large open outdoor spaces, this can potentially be a high source of error in cases with high thermal mass materials or street geometry with deep urban canyons, both of which will often produce radiant environments that are much different than the air at a given hour. The simulation of these radiant environments within the time frame of design is the subject of much of ongoing outdoor comfort research and the future results of these efforts will be necessary to ensure ComfortCover’s relevance to a significant fraction of the cases in which people may wish to use it.

Figure 6. Suggested bus stop shades for Phoenix, Boston, and Anchorage

Figure 7. A design process using ComfortCover to help decide how to trim a curved overhanging shade for a Phoenix bus stop.
With these limitations noted, it is important to reiterate that the ComfortCover method proposed here uses the most recent and state-of-the-art standards, both in terms of outdoor thermal comfort and ray tracing processes. It also incorporates the fastest new schemes for estimating solar radiation on the human body in spite of the recognition that these techniques are still under development. Furthermore, the development and implementation of the method within the visual programming environment of Grasshopper offers parametric design capabilities and flexibility that would not have been achieved had they been implemented in another style. Finally, the method is novel in that there has historically been no agreed upon means to quantitatively account for outdoor comfort in the design of static shades. Never before have the three individual components of ComfortCover been merged into a single workflow and, as a result, designers of outdoor shades now have a high-accuracy means of designing such comfort sensitive shades.

The components are published as part of the open source plugins, Ladybug & Honeybee for Grasshopper3D [18] and will be accessible to designers working in the 3D software, Rhinoceros.

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Zaha Hadid Architects; University of Stuttgart; AA School of Architecture.
Simulating Human Visual Experience in Stadiums

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ABSTRACT
In this paper we describe progress to date of software that simulates occupant experience in high capacity sports venues. Our simulation aims to provide metrics that indicate view quality, and in doing so generates data that indicates levels of human comfort. This approach enables the design process to be driven from the perspective of the occupant. In particular we implement a novel means of simulating and expressing quality-of-view that addresses deficiency’s in the standard method of describing view quality. Visualisation of the simulation output is via an online 3D viewer shared with the entire design team. Views from any seat location can be inspected and data fields from the simulation can be compared. Data is represented with colour scales bound to a 3D seating bowl model. Using simulation to understand spectator experience from within a 3D environment challenges the validity of traditional design approaches that are based on two-dimensional thinking and drafting board logic. Our simulated study of view quality enables us to consider revisions to these traditional techniques which could lead to more spatially efficient seating facilities. Increasing spectator density is believed to enhance atmospheric qualities, this combined with better views will contribute towards an improved occupant experience.

Author Keywords
View quality, stadiums, ergonomics, spectator experience

INTRODUCTION
Simulation involves the creation of a model that attempts to allow the estimation of characteristics or behaviour of a system. The system that our software attempts to characterise is the organisation of spectator seating in a stadium, the characteristics of a specific seating configuration are measured in terms of view quality and physical comfort. Motivation for this work comes from a critique of the international standard for design and measurement of view quality in stadiums [1]. The current standard is inadequate because it uses 2D drafting logic rather than 3D computer graphic techniques, secondly it only considers view quality in a 2D domain, and lastly does not account for ergonomics. Our simulation operates within a 3D model space and applies computational techniques that incorporate concepts of human comfort in terms of range of view and body position.

In this paper we first provide a brief historical background and a review of the method given in current design standards. We then introduce our new simulation software, it’s input requirements and the sequence of simulation. In order to provide a frame of reference for newer metrics our simulation is designed to evaluate view quality according to the existing standard. To achieve this, our software implements an inverse of the current methodology taking a given design as the starting point. To calculate a spectator’s view quality using the current standard relative positions of neighbouring spectators are required. This need for context calls for a logic data structure of points representing the spectators. The series of algorithms that logically structure the data are discussed and then the method of calculation is described.

Next we discuss how the simulation captures three angles that suggest a range of comfort in movement of eyes, horizontal or vertical rotation of the head or even movement of the torso in order to perceive the full area of play. These simple angular metrics provide an immediate a ergonomic aspect to the simulation.

We introduce a new method of measuring view-quality that forms a key component in our simulation. This technique applies computational geometry to capture a 3D view for every spectator in a stadium. The view is orientated and cropped in a way a way which relates directly to the position of the spectator.

Given the quantity of data collected in the process of simulation we next describe how the numerical output is converted into a range of different coloured graphical forms included meshes and the export of data to a 3d web viewing environment. Last we discuss aspects of future work and design implications of our simulation.

MOTIVATION

History
John Scott Russell formalised what has become the standard methodology in 1838 with a published design method for auditoria [2]. Focusing on a stationary lecturer and direct lines of sight and sound, Russell identifies the need to progressively raise successive rows. The rate at which the row height changes is determined by a constant vertical offset from the top of seat back and a line drawn from the back of the seat to the speaker (figure 1). Russell describes a procedural drafting method. The result of this method is a set of points that describe as an equal-seeing or
equal-hearing (iseidomal or isacoustic) curve. The technique was first applied by Adler and Sullivan in 1889 in designing the Auditorium Building in Chicago [3].

Figure 1. Russell’s iseidomal or isacoustic curve generating method. Resketched by authors.

The current c-value method.
The current standard for stadium seating design is found in various statutory design guidelines for stadia [1, 4 and 5]. In these guides an equation is given to determine the vertical dimension \( C \) (the c-value) between the eye-point of one spectator and the sightline of the spectator behind. The focal point (the flag in figure 2) for field based sports is on the side line.

\[
\begin{align*}
C &= \frac{D(N + R)}{D + T} - R \\
D &= \text{horizontal distance from the eye-point to the focal-point} \\
N &= \text{riser height} \\
R &= \text{vertical height to the focal-point} \\
T &= \text{seating row width}
\end{align*}
\]

Where:
\( r = \text{row number} \)
\( rw = \text{row width} \)
\( c = \text{c-value} \)

Initial horizontal and vertical dimensions between the first eye-point and the origin are required to locate the first spectator and initialise the series, and the equations are usually extended (in the context of football) to allow for the view of the first spectator over an advertising board between the spectators and the playing area. Using vertical (height of a seated spectator) and horizontal offsets (distance to the front of the step) the vertices for a stepped section line can be generated. To define the three-dimensional seating bowl surface the section is swept around the stadium. The c-value is used to define the generating section and to refer to the quality of view for the entire stadium – a higher value indicating a better view.

Critique
Little has changed between Russell’s method of 1838 and that used to design international stadiums today. Although it has been in use for almost 180 years, it has not received a critical review or detailed empirical study despite changes in the design technology available and understanding of human vision. The primary critique of the method in current use is that it is 2D and based on a system where the objective was to ensure sight and acoustic lines to a stationary point. In this 2D system views are considered to be perpendicular to a spectator’s shoulders and to always pass above the heads of spectators-in-front. In fact views may be between the heads of those seated on the row in front and spectators move their eyes, head and shoulders during a game. The c-value method also does not account for height above the playing surface which provides a less obtuse viewing angle of the pitch plane. The c-value method uses a static focal-point located at the edge of the playing area, the focus of play in sports events rapidly changes and ranges all over the playing area.

Others have noted the deficiencies in the method and proposed a more rigorous computational approach [6]. In a low capacity context (theatres with less than a few thousand seats) a more robust approach has been investigated along with development of a series of metrics that relate to visual comfort [7] this has not yet been extended to sports facilities.

MODEL SET UP AND POINT SORTING ALGORITHMS
Basic model inputs and overview of simulation sequence
In order to directly address the shortcomings of the traditional method our simulation requires a 3D environment where every spectator eye-point is represented. The entire playing area is defined along with a point that represents the centre of visual attention for all spectators. A reference point is required to structure the
eye-points in a way that is analogous to the physical seating layout.

Our simulation is a plug-in for the Rhino3d modelling application [8]. The plug-in is written with C# and uses the rhinocommon software developer kit [9]. All inputs and output are accessed through the plugin’s graphical user interface. To initiate a simulation four geometric inputs (figure 3) are required:

1. **Eye-points** - a set of points representing spectator eyes.
2. **Pitch-boundary** - a closed planar curve that represents the edge of the playing area.
3. **Sorting reference point** - a single point located closest to the eye-point in the first row.
4. **Centre of visual attention** - a single point used for view orientation. Typically the pitch centre point.

This can be further generalised to work in any plane if the values for z and x are replaced with horizontal and vertical dimensions between a focal-point with any coordinates.

\[ c = (\Delta x_r - rw) \left( \frac{\Delta z_r}{\Delta x_r} \right) - \Delta z_r - (\Delta z_r - \Delta z_{r-1}) \]  \hspace{1cm} (5)

Where:

- \( \Delta x_r = x_r - fp_{x_r} \)
- \( \Delta z_r = z_r - fp_{z_r} \)
- \( fp = focalpoint \)

Calculation of the c-value is therefore context dependent. For every eye-point three items are required: the level of the row in front, the focal-point and the row direction. To find the focal-point we first define a view-vector which is perpendicular to the row direction (figure 4). The focal-point is found using one of three methods that the user specifies, closest-point, perpendicular and through-corner.

**INVERTING THE C-VALUE METHOD**

Our software enables analysis of view-quality in stadiums using geometry that describes an existing or proposed 3D environment. We implement new methodologies that indicate the spectators experience in terms of ergonomics and the amount of the playing area visible. In order to compare these metrics with the traditional means of describing quality of view we provide the ability to analyse the stadium in terms of the c-value.

Using equations (2) and (3) we can determine c-value for any eye position in the XY plane.
Eye-point sorting algorithm

The need for context determines a three stage point sorting system that organises eye-points into a data structure analogous to a physical row and seat numbering system. First eye-points are sorted by absolute level, second into a sequence along the row and third into groups along the row that lie on a common straight line.

Eye-points with the same z-coordinate (within a user defined tolerance) are considered on the same row and share a common array index. Each row of eye-points is next sorted into a sequential order. This is calculated by determining the angle at the centre of the pitch-boundary between the sorting reference point and the spectator point. The points are sorted by angle size with the smallest first. Along each row the eye-points are grouped according to which ones share a common straight line (which corresponds to the structural elements used to construct the seating bowl (referred to as the riser)). The riser determines the row direction and perpendicular to this is the spectator’s view-direction. The angle at each eye-point is measured between its two neighbours. If the angle between these 3 points is not 180 degrees (within a user defined tolerance) a new riser group is defined (the second dimension of the data structure). The data structure has three dimensions, the last dimension is determined by the sequential position of the eye-point along the riser.

The need for context to calculate the c-value is a further deficiency in the c-value method. Where c-value cannot be calculated view quality for these locations cannot be expressed. During analysis the eye-points are classed according to their physical context e, four conditions exist; front-row, open-row, single-seat or full-context. C-value cannot be calculated for the front-row of any tier – since a row in front is always required. An open-row situation is one where there is no row directly in front of the eye point but it is not a front row, for example the row directly above a vomitory opening. Single-seat is the situation where only one seat exists on the riser, here it is not possible to calculate the viewing direction and therefore the c-value focal-point cannot be correctly found and no c-value can be calculated. Full-context is where the c-value can be correctly calculated according the published method. Figure 6 shows point data structure and cases where insufficient data exists to calculate c-value.

Structuring of data in a meaningful manner provides the context that allows calculation of the c-value. This data structure also enables the simulation to include a seat-position-navigator interface that allows the user to set the model view to a specific seat on a specific row and visually assess the view.

HORIZONTAL AND VERTICAL VIEW ANGLES

Viewing angles indicate spectator comfort in terms of how far a spectator will need to turn their head or body. Our simulation provides three angular measures (figure 7):

1. Horizontal view angle - angle measured in a horizontal plane at the eye-point to the extreme left hand and right hand points on the projected playing area.
2. Vertical view angle - angle measured in a vertical plane at the eye-point to the extreme upper and lower points on the projected playing area.
3. Torsion angle - angle measured in a horizontal plane at the eye-point between the view-direction (perpendicular to row) and the centre of visual attention, represents the movement of the eyes (or turning of head or torso in extreme cases).
ALGORITHM FOR CALCULATING A-VALUE

A-value is an innovative method that aims to quantify view quality and address the shortcomings of the c-value method discussed above. A-value measures the area of the playing surface that is projected into the spectator’s view plane, expressed as a percentage of the total area visible. Firstly, unlike the c-value it takes into account the entire playing area and not just a stationary point. For each spectator the view of the pitch-boundary or playing area is simulated, this view includes other spectators and elements from the building and aspects of human vision.

Basic a-value simulation

The basic simulation of the a-value is the calculation of the area of the polygon found when the pitch-boundary is projected onto the spectator’s view-plane. The vector between the spectator’s eye-point and the centre of visual attention defines the normal vector of the view-plane. This view-plane is assumed to be orientated to the spectator’s centre of attention. The view-plane can be located at any point along the view-vector other than at the eye-point. Between each vertex of the pitch-boundary and the eye-point a vector is defined, each vector is intersected with the view-plane. The closed polygon defined by the intersection points is the projected pitch-boundary. Using a basic view frustum with a field of view of 60 degrees and orientated using the view-vector and a global z-vector a clipping rectangle or basic view-boundary is created on the view-plane. The projected pitch-boundary is clipped with the view-boundary using the Sutherland-Hodgman (S-H) algorithm [10]. The a-value is the area of the resulting clipped polygon expressed as a percentage of the total area of the view-boundary (figure 8).

Results and comparison

The quality that the A-value represents is the projected area of pitch, therefore seats in upper levels generally have higher A Values (figures 9+10). After a certain distance from the pitch the A-value can be seen to diminish, this can be seen on the upper rows in figure 10. Analysing C Value throughout a stadium shows higher values in lower tiers, constant values along the generative section and diminishing values with distance from the pitch. With the exception of the front rows in each tier and boxes diminishing values can be seen in figure 11. In general terms we can observe that higher A Values indicate a better overall view of the pitch while higher C Values indicate proximity to the action.

Simulating human cones of vision

The basic frustum is a crude simplification of the human field-of-view. The simulation can be configured to include ergonomically defined viewing cones that have been used in other fields [6]. The simulation enables the a-value to be calculated as that area which lies within the effective binocular field-of-view (as defined for driving regulations in the UK [11]). The form of the binocular field-of-view reflects the shape of the human head and specifically the position of the eyes in the skull. In particular the frontal...
bone above the eye restricts the view above while the lower zygomatic and maxillary bones are more recessed [12] permitting a wider angle of view.

Two fields-of-view can be simulated, a stationary head position and a dynamic cone-of-vision based that includes head rotation. 30 degrees of rotation is considered an unstrained rotation for a human [6 and 13]. The static binocular field-of-view is swept 30 degrees either side of the primary view direction to give a dynamic binocular field-of-view (figure 12). The result of this is a redefinition of the view frustum from a basic truncated pyramid to a more complex cone like form. The view-boundary is now defined by the intersection of the view-plane and one of these cones. Substituting one of these view-boundaries into the basic a-value calculation procedure provides a modified a-value that now comes closer to representing the projected-pitch area as a proportion of a more accurate human cone of vision (figure 13).

Figure 12. Human cone of vision frustums Left: Static binocular field of view. Right: Dynamic binocular field of view.

Figure 13. Simulating a-value with the static binocular field of view.

View Occlusion
The form and area of the visible projected pitch-boundary give an initial indication of view quality. To move towards a more detailed understanding of the relationship between the form of the seating bowl and quality of view from any seat we must consider the spectators sitting directly in front. The amount that these spectators can block the visible pitch-boundary depends on the difference in vertical height and the relative horizontal position between seats on two successive rows. If the vertical difference is great enough or if the view-vector passes between two heads the view may not be significantly occluded. The c-value method could not account for the second of these scenarios. Our simulation can efficiently calculate the proportional area of pitch-boundary that is blocked by the heads of spectators in front.

Given the visible, projected pitch-boundary the next step in pursuing a view with verisimilitude is to include outlines of the spectator’s seats in front. To maximise efficiency of this calculation we make two assumptions. First that the spectator in front can be represented with a planar polygonal outline orientated (see those in figure 14) to the seating row. Secondly that only those spectators in the four rows in front may have an impact. A standardised two-dimensional head-and-torso outline (of a seated human form seen from the back) is stored as a part of the simulation software.

![Figure 14. Simulating occlusion.](image)

To begin to simulate the view occlusion a sub-set of eye-points is defined that includes only those that lie within the selected view-cone and are located on the four rows in front. For each of these eye-points the orientation of the seat is needed to transform the predefined head-and-torso outline. The structuring of the original eye-point data set provides the necessary context to determine the direction of any seating row. Using the row direction and the global z-vector a plane is defined. The vertices of the head-and-torso outline polygon are transformed to this plane and then projected to the view-plane (figure 14). Using the S-H algorithm the head-and-torso outline can be clipped with the already clipped, projected pitch-boundary. Once clipped, the area of the clipped, head-and-torso outline is added to the cumulative total until eventually the total occlusion area is expressed as a percentage of the proportion of the total view-boundary.

View Obstruction using Image Segmentation
We distinguish between occlusion and obstruction. Occlusion (described above) in our simulation refers to the area of projected pitch-boundary blocked by other spectators and is a formal component in simulating a-value. The term obstruction is used to refer to all other objects that can disrupt the spectator’s view of the event. Our current
simulation technique calculates obstruction using an image segmentation method that captures rendered views and analyses them to determine the quantity of pixels of certain colours. (This method was in fact first implemented to calculate occlusion but found to be much slower than the current projective method). We render the pitch as green and the potential obstruction objects as red our simulation returns the percentage of each as a proportion of the total viewing-boundary area. The orientation for the camera of the rendered view is defined using the same geometry as the occlusion method. The camera position is set at the eye-point, the global \( z \)-vector defines the up-vector for the camera and the camera-target is the centre-of visual-attention. The captured bitmap can be masked with a form defined using one of the two ergonomic view-cones.

Differentiating between occlusion and obstruction provides the option of controlling what elements are being tested and can therefore be used in a variety of ways. Two examples of situations that have benefited from this approach are evaluating the impact of adding a horizontal advertising to an existing stadium and testing the intrusion of architectural metal work such as handrails. In both cases the geometry of interest is modelled and included in the model environment. For each eye-point the simulation returns the area of pitch visible with and without the test geometry and the total area of test geometry within the spectators view.

This obstruction simulation methodology serves the purpose of proof of concept and in future versions of our simulation software we intend to implement more sophisticated frustum culling methods. The objective is to efficiently evaluate complex scenarios that include all architectural geometry and objects within a contemporary sports stadium.

Implementing an image analysis method as part of the simulation allows views to be saved for later use. In some competitive processes for stadium bids this is a basic requirement. As the simulation generates the images each one is named and referenced to a physical location inside the stadium using the indexing generated when structuring the data. The images can be accessed using an html interface that allows specific views to be accessed via a web interface.

**VISUALISATION OF RESULTS**

Views from 50000 seats can be simulated in about 90 seconds, 10 different metrics are generated for each seat giving half a million data items. Processing and visualisation of results therefore forms an important component in the software in order to enable the comparison of several alternative designs. Any one of the metrics can be selected to generate a coloured graphical output that is placed on its own layer in the original rhino model. The colour scales and their numerical ranges are customisable, start and end colours can be selected and the number of divisions in the scale defined. To preserve saturation when interpolating linearly between colours HSL colour coordinates are used. Possible graphical outputs are coloured points, squares or circles, one for each eye-point. Using a Delaunay triangulation algorithm the eye-points can be used to generate a mesh (figure 15). The selected metric determines the colours that are assigned to the mesh vertices. Larger mesh triangles are removed to leave a mesh that represents the surface of the seating bowl. The mesh can be exported to a JSON file and shared using an online 3D viewer developed with a JavaScript and Three.js [14] a library enabling simplified implementation of WebGL animations.

![Figure 15. Coloured 3D mesh output.](image)

In addition to coloured graphical output any metric can be recorded in the model alongside its corresponding eye-point as a number in text. Viewing angles can be shown as a small triangle placed in the corresponding eye-point. Any data can be written directly to excel for further statistical analysis, we have also implemented a custom file format where the model structure and all simulation results can be stored and reloaded at any time.

**SUMMARY**

At the core of our simulation of spectator experience is a novel method of conceptualising view quality. A-value or area-value is a measure of view quality that uses the area of the polygon found when the pitch-boundary is projected into the spectator’s viewing-plane. By projecting outlines of spectators in front to the view plane we simulate the amount of occluded view and by including static architectural elements within the simulation environment we determine the amount of obstructed view. We extend this view quality concept further and the simulation includes recognized norms for human cones of comfortable vision when the head is static and with a small rotation about the neck axis. View cones, projected pitch-boundary and the heads-of-spectators-in-front are all represented as 2D polygons in a view plane, to combine these and derive A-value for the a-value we implement the Sutherland-Hodgman convex polygon clipping algorithm in an iterative fashion.

The a-value captures a series of aspects of view-quality that were previously inaccessible using the standard c-value methodology. This new simulation process implements basic computational geometry methods in contrast to the drafting techniques of the c-value method. Through the simulation of viewing angles and the construction of spectator views that are clipped to ergonomically defined
fields-of-vision our software provides insight into human comfort.

FURTHER WORK
The use of the A-value in the design of sports venues is at an early stage. We have applied this work directly to the development of three international stadiums. Our applications to date have involved the comparison of alternative designs. We believe however that the use of A-value and other metrics can be incorporated in generative methods that ensure certain minimum standards are met. In moving towards a generative mode our immediate work includes detailed study of the ergonomic role the view cones. We plan a series of detailed studies of typical existing stadiums and detailed analysis of the results to determine which metrics are the most significant and where correlations if any lie.

Our simulation has been developed with a focus on soccer and rugby stadiums, it is immediately applicable to most field sports and indoor stage based venues. The software generates indicators that can be used to evaluate view quality where attention is focused on a vertical or horizontal plane. Further research is required to extend applicability to track venues.

Spectator experience is not only limited to in-seat comfort and access to a clear field-of-view. We have identified a series of additional metrics which when implemented will add further dimensions to the ability to predict the quality of experience in stadiums.

Seat integration would describe of connectivity of a spectator to the stadium facilities. This metric would draw on the work of Space Syntax [15] and apply the concept of universal distance and analysis of spatial integration.

Pitch targeting. Contemporary sports analysis commonly involves the capture of data describing playing area usage through sensors attached to players and balls. These data sets could be used to identify and specify particular areas of playing field that each spectator must have a certain view of.

Social recognition metrics. The capacity to recognise fellow occupant’s faces and see facial expressions is particularly important in some venues (theatres, meeting rooms and lecture halls). Measuring the number of faces that lie within range of a spectator’s visual acuity would provide an indication of how well socially a space is configured.

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Self-Organizing City: Experiments using Multi-Agent Model and Space Syntax

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ABSTRACT
This paper describes a process of using local interactions to generate intricate global patterns and emergent urban forms. Starting with network topology optimization, agent-based model (ABM) is used to construct the micro-level complexity within a simulated environment. The authors focus on how agent-driven emergent patterns can evolve during the simulation in response to the “hidden hand” of macro-level goals. The research extends to the agents’ interactions driven by a set of rules and external forces. An evaluation method is investigated by combining network optimization with space syntax. The multi-phase approach starts with defining the self-organizing system, which is created by optimizing its topology with ABM. A macro-level “attraction map” is generated based on space syntax analysis. Then the map is used to control various construction operations of an adaptive urban model.

Author Keywords
Self-organizing, agent-based model, space syntax, urban simulation, urban design.

ACM Classification Keywords
I.2.11 [Artificial Intelligence]: Distributed Artificial Intelligence

INTRODUCTION
Michael Batty described the property of “Autonomy” and “the embedding of the agent into the environment” as the two key properties of agents in an agent-based model (ABM). An ABM consists of numerous agents, which follow localized rules to interact with a simulated environment, thereby formulating a complex system. Since Craig Reynolds’ artificial “bodies” and flock simulation, the concept of ABM has been widely used to study decentralized system including human social interaction. In urban modeling, agents can be defined as autonomous “physical or social” entities or objects that act independently of one another (Batty 2007). ABM focuses on the agent’s properties and processes used to respond to external changes, specifically how the agents can “sense” and “act” to form a bottom-up system. The actions are usually based on simple rules such as separation, alignment, and cohesion. Computer scripts such as Processing can be used to control agent’s velocity, maximum force, range of vision and other properties.

There were many computational methods applied to simulate agents involving movement, including “the simple statistical regression, spatial interaction theory, accessibility approach, space syntax approach and fluid-flow analysis” (Batty, 2007). In the early research phase, we compared the bottom-up ABM with the famous Cellular Automation (CA) methods to exam the generation of agents, their spatial properties, and their interactions with the environment.

It is important to understand the distinction between cells and agents. Batty describes agent as “mobile cells, which – objects or events that located with respect to cells but can move between cells.” (Batty, 2007) Alternatively, CA calculates cells’ changing state through time, based on the state of neighboring cells and context. During preliminary research, formal and spatial explorations concepts of CA allowed us to “grow” forms from seeds. We applied Conway’s Game of Life method to create a vertical path of a skyscraper. (Figure 1: Row 1) CA was used as a programmatic layout planner to establish a series of void cells and linked them vertically.

As two famous bottom-up systems, both CA and ABM compute the status of a changing object over time. However, we discovered that the behaviors of CA are often unpredictable and lack purposive planning goals. CA method was abandoned due to the difficulty to add rules and other “purposive goals” to the system beyond context awareness. Similar to Betty’s “global attraction surface” in his study on the agent’s movement, we need an agent system to introduce “external force rules” to influence the agents’ behavior. It became obvious for us to choose ABM method over CA method.

We also tested several other commercial agent-based tools in the gaming and animation industry. One of them is the Maya Miarmy, a powerful plugin for character animation and dynamic behavior simulation. This mass animation tool has been widely used to simulate the behavior of crowds,
where the agents’ movements are computed based on the interactions among themselves, as well as the interactions with the environment. We also explored A* pathfinding in Unity game engine. The promising A* pathfinding algorithm has been used to create the “cognitive agents”, which can populate a spatial model and navigate through a “cell” based map. Different from the “reactive” agent in Reynolds’ flock simulation, these “cognitive agents” have their pre-programmed goals. The agents have the ability to observe the context and other agents’ movement during the game play and modify their behavioral parameters. The computer controlled agents can make decisions while evaluating the result generated in a real time environment.

These tools and methods allowed us to understand the autonomous, bottom-up ABM approach and compare the effectiveness of various agent related computations.

Figure 1. Top: Cellular automation drive vertical path. Miller August. University of Cincinnati (UC). Bottom: ABM simulation using A* pathfinding algorithm. Craig Moyer, UC.

ABM FOR URBAN DESIGN
ABM for urban design is established in the same relational model and computational strategy from the early sociologists’ research. Some of the rigorous methods in the urban design practice involve utilizing ABM to generate micro level self-organizing urban forms that respond to the top-down rules and traditional planning methods. ABM allows a complex urban system to emerge from simple interaction among agents. Each agent can “sense” its neighbors and “react” to them by modifying its location, velocity, shape or other attributes. The ABM approach can be found in the Kartal Pendik urban design by Zaha Hadid, Shape grammar based procedural modeling by Pascal Mueller, self-organizing behavior research by Kokkugia, as well as the wet grid by Frei Otto. ABM also inspired Jeff Jones’ unconventional computing using the slime mold Physarum polycephalum to construct the natural multi-agent computational model. (Jones 2014) All of these methods modeled the interaction of agents, despite model the macrostructure directly. We may be able to understand the dynamics of urban elements better not by modeling them at the global level but instead simulating the local interactions among these components and automatically construct the global patterns at the relational level.

Path Optimization
Our process began with a straight network, which is constructed based on the desired movement among a group of points. The points are added manually along the property lines representing the connections to the neighboring context, with the goal being to form an initial network. (Figure 2: Row 1) This approach uses bottom-up interaction of individual agents to respond to other agents within the system. First, a group of spatial nodes are woven into a network. Once the respective nodes are found, the straight paths connect those nodes and form an intersecting network. The initial network is optimized using Frei Otto’s wet grid method, which is a physics-based analog method. Instead of a simple ‘dumb’ static network, each Control Vertex (CV) along a path becomes an active agent. The agent interacts with other CVs from neighboring lines based on their proximity, attraction, and collision. We optimized the movement network by the computer simulation based on the proximity and interaction of agents. The virtual environment is formed by a series of static collision objects, including buildings and none-destructive topographic boundaries. As a reactive agent, every CV along a path is analyzed in its relationship to other CVs within the system.

With ABM, the autonomous “action” of each path lies within modifying its CV point based on the repulsion or attraction to neighboring agents in addition to the environment itself. Over a period, a path organization is automatically formed as the agents stop and remain equilibrium.

We also assigned the Voronoi pattern to each agent (CV) along the path forming its territory, an enclosed cell. The point-to-cell method allowed several new behaviors of agents in the system to interact with each other. For instance, “keep a distance” action was added to enable agents to scatter from the highly concentrated area, but simultaneously make alignment to its neighboring agents. (Figure 2: Row 4). As a result, agents were able to resize its cell/territory and seek a more balanced relationship with its neighboring cells. With a recursive scripting tool named hoop snake, agents’ behaviors were calculated and manipulated over a period.
Evaluate the AMB with Space Syntax

Space syntax is a method to study movement pattern and accessibility of a network based on lines, nodes and connections. As an “agent analysis” tool, space syntax does not measure the interactions among agents. However, space syntax provides fast feedback between geometric elements and its accessibility value within a network.

We introduced space syntax as an evaluation tool for the network optimized by ABM. Through importing the Otto’s wet grid and Voronoi pattern into space syntax analysis tool, we extract spatial values such as accessibility and spatial integration and use them to evaluate the result of ABM. The warmer color represent higher spatial integration values. (Figure 3: Row 1) The centroids of adjacent Voronoi “cells” are connected and form a new network. This network is based on two variables. The first variable is the number of steps a cell take to move from its original status. (Figure 3: Row 2) The second variable is the number of neighboring cells, which are considered “visible” to a particular cell. (Figure 3: Row 3) We computed the integration value of each path by the segment analysis tools in space syntax and visualized the values with colors. The qualitative values extracted from space syntax analysis are imported into Grasshopper for further computing. In order to convert the space syntax result into a heat map representation, we created a data processing method to expand the color values automatically from paths to zones. We named the final image as “attraction map”. (Figure 3: Row 4)

Attraction Map

In the previous process, each agent is treated as a “cell” with a boundary defined by Voronoi pattern. Then the “attraction map” generated from integration values of space syntax is introduced as the “hidden hand” to control land values and land use on a global scale. The color coded map drives development intensity, floor area ratio (FAR), descriptive zoning code and other spatial attributes. Urban blocks defined by the cells interact with the attraction map and adapt to the best-fitted land use and building topology. We developed script to seek and populate various buildings
into the “best-fitted” cells. (Figure 4) This mapping process involves the agent’s movement, cell morphing and changing integration values over time. The resulting attraction map is updated by recursive calculations and visualized as a large number of animated “cells” over time.

Figure 4. Adaptive urban model constructed from “attraction map”. Row-1. Left: Cells concentrate in the “hot” zones of a heat map. Right: Cells move based on separation rules. Cells morph gradually during the move. A bigger well-integrated area evolves from previous smaller area. Row-2. Left: Agent seeks single closest neighbor and makes a connection. Right: Agent finds two closest neighbors and makes connections.

PROJECTS
“Silicon Valley of China” is a large urban design project in the TJW Valley near Zhuhai. The project goal is to create a 6,000,000 square meters sustainable and ecological valley, which includes residential, commercial, cultural and institutional spaces. A new water system is required to improve the existing hydraulic network. We applied the network optimization and space syntax to create the attraction map. An intricate order of urban pattern emerged based on the micro-scale interactions among agents. Multiple Voronoi shaped neighborhood automatically adopted a set of rules based on both bottom-up movements, as well as the top-down planning methods. Self-organizing pattern of the movement network emerged based on the connection between proposed neighborhoods and the proximity to the existing natural landscape. A microstructure oriented land use map, as while as a transportation system for pedestrian, vehicle and bike were achieved by ABM and space syntax. Then the traditional planning method was used to drive the further design decisions. (Figure 5).

Figure 5. Adaptive urban model, Zhuhai, China. Row-1: The self-organizing pattern was optimized through ABM. Row-2. Voronoi pattern and Metaball method are used to create neighborhoods. Row-3. Space syntax was used to analyze movement network and generated an “attraction map”. Row-4. Transportation system and Land use plan were developed based on the attraction map.
HYK economic zone is another project requiring a mixed use CBD blended with residential, commercial, business, tourism and education programs in Dalian, China. We applied the ABM and Space Syntax method and produced organic movement pattern on top of the existing recliner infrastructure. This new superimposed flow network relinked various green corridors and left over vacant lots. (Figure 6)

![Figure 6: Row-1, 2. Conceptual model to investigate the pedestrian movement in an existing urban context. Benjamin Tamarkin, Andrew Campbell. UC. Row-3, 4. ABM was used to optimize the pedestrian and bike paths in HYK district. Project team: Dalia Dushifazhan Design Institute, Ming Tang, Xinhao Wang, Mahyar Arefi, University of Cincinnati](image)

**CONCLUSION**

The research investigated how to integrate ABM into the urban design process and evaluate the result with space syntax. Compare with traditional top-down planning, this new method does not operate at the global level. It relies on the emergent properties and local interactions among agents. Together with traditional humanistic evaluation and ABM, a new relationship of designer and design agent has been forged. Within the process of ABM, design is a result of the interaction between agents and their environment and the modulation of agents’ behaviors within external rules. The new ABM can produce measurable improvement in the design. For instance, the ABM optimized curved network increased only 3% of traveling time compare to the original straight network. However, by joining and modifying paths into a new network, the overall length of the network was reduced by 43%. (Figure 7)

![Figure 7. A: initial network. B: optimized network. C: Green: individual travel time of initial paths. Red: individual travel time of optimized paths. D: Compare with the intimal network, the optimized network has 3% increase of overall travel time. (Blue line); 43% decrease in total network length. (Red line)](image)

The optimization is significant for saving construction cost. In the two urban design projects in China, we applied ABM for path optimization. The initial straight network was generated by connecting many existing intersections. We optimized the network to reduce the overall network length. The result of a wet grid is used to suggest the pedestrian paths, bike route, as well as the slow vehicular movement. For individual curved path, the traveling time is increased only 3% compare to the original straight path. The overall network construction length is reduced 35%-45% compare to the straight network.

However, this method is not appropriate for the vehicular based transportation design due to the small intersection angles. The optimized network is often irregular and very different from the typical urban grid. Because the ABM is generated as a highly abstract in the micro level, we have to combine ABM with other transportation planning methods.
to construct a realistic urban model in the later process. This post process can lead to confusion of the design logic and violate the early abstract model. The value of early ABM and self-organizing solution might be undermined.

We found another limitation of this method. The new network is evaluated by space syntax to facilitate design decisions such as land use, FAR, and development intensity. The one-way linear data flow is ABM → Space Syntax → Land Values → Development Intensity → Land use & FAR. The early stage micro level ABM was isolated from the influence of space syntax evaluation. In an ideal situation, the space syntax analysis should be able to affect the ABM and serve as a feedback loop in a non-linear fashion. We are currently experimenting the genetic algorithm in Galapagos to integrate space syntax into the path optimization process.

We are also investigating to importing geographic information system (GIS) data, and other geospatial related “big data” into the “attraction map”. The goal is to create a virtual urban laboratory allowing designers to manipulate environmental conditions and behaviors of artificial agents, and test various design theories in both micro and macro levels.

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ENDNOTES
1 Processing language can be used to construct agent-based system. For example, using the agent class from kokkugia and toxic Processing library, the script can control agent’s behavior.
2 http://en.wikipedia.org/wiki/Conway%27s_Game_of_Life
Any live cell with fewer than two live neighbors dies as if caused by under-population. Any live cell with two or three live neighbor’s lives on to the next generation. Any live cell with more than three live neighbors dies, as if by overcrowding. Any dead cell with exactly three live neighbors becomes a live cell, as if by reproduction.
Computing Curved-Folded Tessellations through Straight-Folding Approximation

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Figure 1: Prototype designed and produced using the method described in this paper.

ABSTRACT
The research presented in this paper explores curved-crease tessellations to manufacture freeform geometries for architectural and industrial design. The work draws inspiration from the ease of shaping paper into double-curved geometries through repeating fold patterns and the observed stiffening of curved surfaces.

Since production of large scale curved-folded geometries is challenging due to the lack of generalised methods, we propose an interactive design system for curved crease tessellation of freeform geometries. The methods include the development of curved folding patterns on the local scale as well as a novel computational method of applying those patterns to polysurfaces. Using discretized, straight-line fold approximations of curved folds in order to simplify computation and maintain interactivity, this approach guarantees developable surfaces on the local scale while keeping the double curved appearance of the global geometry.

Author Keywords
Curved-Folding, Edit-and-Observe Modelling, Design to Fabrication workflow.

INTRODUCTION
Curved folding offers a very economical method of manufacturing curved surfaces from flat sheet material but a significant obstacle in working with curved-folded geometries is the lack of appropriate computational tools in commercial CAD software for describing such geometries. As architects and designers, we favour interactive methods that offer direct control over three-dimensional geometry. Contrastingly, the methods we have surveyed either require scanning of physical models and planar-quad meshing [7], or work on smaller scales of bending a singular surface [9], or require sequentially deriving surfaces through the method of reflection [8], but do not scale well to geometries with high number of creases. Further, curved-folded surfaces are simple to model physically with a limited number of creases, but substantially increase in complexity with several repeating creases as in a tessellation. Thus, the primary contribution of this paper is the setting out of a method for designing curved-crease tessellations and describing a simple and intuitive computational framework to simulate these curved-creases on straight-line tessellations. Critically, it should be pointed out that the geometry simulated by this method is a visual approximation and not precise curved folded geometry. However it does ensure that the unrolled two-dimensional shapes can be folded and fit together into a predefined form.
As case studies we investigated Ron Resch’s straight folding patterns [10], as well as David Huffman’s studies on curved folding [2]. In Ron Resch’s pattern (Figure 2), polygonal faces (so-called inflated vertices) have straight fold-lines at each vertex, describing triangular faces. Aggregations of this folded pattern across a grid lead to global curvature. However, when all fold-lines converge into one vertex (so-called non-inflated vertex) instead of a polygonal face, it is not possible to fold the pattern with straight-line creases. David Huffman investigated patterns with even number of curved creases on inflated and non-inflated vertices.

Figure 2: Ron Resch’s folding pattern a. flat state; b. folded state.

For the purpose of our research we explored the possibility of achieving globally double curved geometries with aggregations of non-inflated vertices with curved creases.

METHOD
The method presented in this paper is broken down into two sections. The first part sets out a framework for designing curved-crease patterns at the local level (similar to Maekawa’s and Kawasaki’s theorems for straight-folding) [5] and the second part presents an interactive computational method for applying those crease patterns to freeform surfaces such that the resulting unrolled shapes are ensured to be developable.

Designing a Curved Crease Component
Non-inflated Vertex
We take a non-inflated degree-n vertex with an even number of alternating mountain and valley curved folds, similar to those developed by David Huffman [2]. In isolation, this configuration is versatile in terms of the number of mountain-valley folds at a vertex, and in terms of the curvature and type of two-dimensional curves that can be folded, which affect the three-dimensional depth of the folded geometry. For a given folding angle, a crease line with lower curvature will increase the three-dimensional depth of the folded component.

Boundary conditions
In order to develop a repeatable component that can be aggregated across a three-dimensional tessellation, the boundary of the non-inflated degree-n vertex in relation to its curved folds needs to be defined, so that each boundary edge can act as a developable seam between two folded components. In a curved folded tessellation, the surfaces adjacent to a crease are either cylindrical or conical, reflected by the plane on which the curved crease lies. This results in alternating concave-convex developable surfaces.

Hexagonal Boundary
Our initial attempt at aggregation is done with a folded non-inflated degree-3 vertex (Figure 3a). The aggregation is based on a regular hexagonal tessellation with the vertex of the folded module lying at the centre of each hexagon. No additional crease curves are added along the boundaries of the hexagon in this case. This results in the formation of secondary vertices of all-mountain or all-valley creases along the boundaries between components and in the formation of curved surfaces defined by four curved folds in the order mountain-mountain-valley-valley.

Figure 3: Aggregation of a folded non-inflated degree-3 vertex with hexagonal boundary (a, b) and triangular boundary adaptable to all n-gons (c).
Figure 4: Surface rulings: cylindrical rulings showing conflict (a); conical rulings on hexagonal (b) and n-gon boundary (c).

We tested this aggregation on a number of material samples: 80gsm paper, 120gsm paper, thin cardboard and polypropylene. The paper folds easily into the pattern, however the thicker materials tend to unfold with increased aggregations of the pattern. This results from the fact that the four-sided surfaces which are formed as a result of two adjacent folded modules need to accommodate the transition from concave to convex, which adds bending into each face; this is investigated by analysing the surface rulings (Figure 4a).

This was resolved by introducing a valley crease with alternating curvature, splitting the 4-sided surface into a convex and a concave conical surface (Figure 3b, 5b). Tests in paper, cardboard and polypropylene (figure 5a) reflect the resolved rulings. Critically, this requires an alternating convex-concave curvature sequence within the n-gon, making it unsuitable for odd sided n-gons.

Tessellation of freeform surfaces

We used discrete meshes to represent our geometry due to their ease of use across platforms and the wide variety of available tools to control and manipulate them. However, meshes are usually made up of only tri or quad faces, while our folded components are better suited to polygons.

To achieve a mesh with convex polygonal faces we used the dual-mesh based on a triangulated mesh where the centres of adjacent faces are connected. Thus, new faces are created in which the initial vertices represent the centres of the new polygonal faces. An even number of edges and therefore an even and alternating arrangement of mountain and valley folds is guaranteed by dividing each edge of each polygonal face into two parts, as explained above.

For a smooth and homogenous appearance of the resultant polygon mesh, the triangular faces of the initial mesh should be as close as possible to equilateral. (Figure 6).
Although meshing algorithms implemented in commercial CAD and analysis software packages are able to generate meshes with regular faces (triangles close to equilateral or quads close to squares), they tend to create irregular faces adjacent to seams of surface patches that are not conducive to curved folding. (Figure 7)

To overcome this issue an alternative re-meshing approach is needed. The proposed strategy is based on a relaxation method using a particle spring system in combination with the half edge data structure [1]. This way of storing topological information of a mesh makes it easier to iterate through all adjacent edges, faces and vertices, and to locally modify the mesh topology, overcoming irregularities around seams without remeshing globally. Each edge of a given input triangulated mesh represents a spring with certain stiffness and adjustable predefined target length. The mesh therefore relaxes in a state of equilibrium where the distance between adjacent vertices is converging to an equal length and therefore the resultant mesh consists of close-to-equilateral triangles. If the rest length is set to zero, the relaxation will lead to a minimal surface approximation between the boundary curves. To keep the information of the initial design geometry, the vertices are pulled towards the polysurface, acting as a secondary force during the relaxation process.

The edge length and aspect ratio of faces are evaluated after each relaxation iteration and edges are created or collapsed based on a given set of influencing rules and constraints, such as curvature of the base geometry (leading to smaller triangles in areas of high curvature while areas of low curvature will be populated with larger triangles) or refinement of boundary and edge conditions. The connectivity between vertices can be influenced by either emphasising consistent angles between adjacent edges (leading to more homogenous appearance) or equal valence of vertices (leading to a hexagon dominated dual-mesh) (Figure 8). After convergences are reached (approximately 100 - 200 iterations) the parameters can be modified and the system stays interactive during the relaxation process. We chose to weigh the relaxation towards maintaining consistent angles between edges as it is not possible to ensure a mesh in which all vertices have a valence of 6, meaning the dual mesh consist of only hexagonal faces. The used computational system is based on the particle spring system Kangaroo Physics 0.099, developed by Daniel Piker for Grasshopper 3D, a visual programming language for Rhinoceros 3D and the plankton half edge mesh library, developed by Daniel Piker and Will Pearson. Our algorithm was written in C# and python within the grasshopper environment.

**Approximating Curved Creases**
To convert a polygonal-faced mesh to the curved-folded geometry, we use a series of geometric relationships between the mesh polygons and the n-gon boundary curved folded crease pattern as described above, which enables an easy transition between the simplified triangular mesh and all its derivatives (Figure 9).
This provides an initial estimation of the curved creases on the three-dimensional geometry, the curvature direction of creases and the mountain-valley assignment of folds. It is important to mention that because each curved-crease replaces a straight edge from the triangular-subdivision mesh, we assume the distance between its endpoints remain constant even when folded. Using this in combination with the method of reflection [8], we are able to compute the correct orientation of each curved crease by iteratively rotating them about the straight-line connecting their endpoints until the surfaces on either side of the crease are reflections of each other. Figure 10 illustrates this for a high and a low curvature crease.

We implemented this method in Rhinoceros 5.8.4 using C# in Grasshopper 0.90076 without multi-threading or using any third-party plugins. To test its performance, we used a sample mesh of 25 n-gon faces with 95 creases on a laptop computer with 8GB of RAM and a 1.6GHz Intel Haswell processor with Windows 8.1. The solution took 17ms to compute on average with each crease being iteratively rotated 57 times on average. Some creases were rotated only once and some up to a 120 times, and the longest solving time for the method was 19ms. The computing time appears to increase linearly with 50 faces taking 34ms and 100 faces taking 68ms. To solve much larger meshes, the method could be multi-threaded with relative ease as it solves each crease independent of all others, thereby being very parallelizable.
Unfolding
A key difference between our method and the precedents we studied is that we unfold the underlying triangulated mesh instead of unfolding the curved folded dimensional geometry and convert the straight edges to curves as a two-dimensional operation. This eliminates the need to produce an accurate three-dimensional model of the folded geometry. Instead, the folded digital model only approximates the visual appearance of the object, which is critical to a designer.

As the base geometry is a freeform surface exhibiting Gaussian curvature, the triangulated mesh is required to be split into developable strips of contiguous mesh faces. We developed a custom version of Prim’s algorithm (4) on the face-centres of the mesh which culls edges on the minimum spanning tree graph to ensure that all vertices have a maximum valence of two, effectively converting the minimum spanning tree to chains of faces (figure 11). In addition, our algorithm also takes into account if the unfolded faces in a chain overlap and modifies the graph accordingly. The strips of triangles are unfolded by a simple trigonometric method to maintain edge lengths. The flattened strips of triangles are converted to curved creases, applying the geometric relationships described in figure 9. The distance between the vertices of the triangles remain unchanged when converted to curves (figure 12), ensuring the strips fit together correctly upon folding.

It should be noted that in order to maintain interactivity of the design method, the unfolding is computed only once the tessellation and curved creases have been finalized. As the unfolding does not affect the appearance of the surface, excluding it from the interactive method results in speedier performance.

RESULTS AND DISCUSSION
The folding of a sheet material either causes or is caused by a change in its boundary conditions. In the case of curved folded tessellations, the depth of the folding is a direct consequence of the boundary condition. Irregular folds can often be caused by non-uniform forces applied at the boundaries, or in the case of cylindrical tessellations (figure 13), unidirectional forces applied on a multidirectional tessellation.

Another critical relationship is that of the curvature of base geometry and the size of the tessellation. Curvature causes each polygon in the tessellation to bend with respect to its neighbours, and this bending in turn causes the polygon to fold. Figure 13 shows two different tessellation sizes on the same boundary condition, one barely folds, and the other folds significantly.
In our current process of approximating curved creases as mentioned in 2.3, we make a fundamental assumption that distances between vertices of the triangular mesh stays constant as the curved creases are folded. Although this is essential to how the process is setup, we have observed that this distance may reduce slightly during folding. To quantify this behaviour, we measured areas of unrolled triangular strips and compared them to the areas of their corresponding curved creased strips (figure 12), and observed a variation of 40-80% per strip. As is evident in figure 12, some of this can be attributed to each strip losing or gaining significant portions of triangles on being converted to curved creases. However, if this variation is summed up across all strips, the cumulative area change seemed to be less than 0.2%. Therefore, it appears that the final geometry produced will have a proportional shrinking, depending on the local arc curvatures of the tessellation pattern. A precise reconstruction of the three-dimensional geometry would improve our understanding of this phenomenon.

CONCLUSION
In this paper, we have demonstrated a method to design curved folded surfaces and a computational framework to apply them to freeform surfaces, producing fabrication data that ensures consistent assembly. Further, the method presented is applicable to any freeform surfaces that can be tessellated into convex polygons. Figure 14 summarises the method presented including future developments planned.

The domain of curved folding offers exciting potentials in architecture and manufacturing, but it remains largely unexplored. With the recent developments in computer hardware and the sophistication of tools available to architects and designers, it is becoming increasingly feasible to work with multi-constraint optimization algorithms such as those required for curved folding.

The method presented offers numerous opportunities to inform parameters such as folding depth, tessellation size, etc by external criteria such as required structural performance, material specific attributes, etc. We hope to further this work by enriching it with relevant contemporary research in related fields such as Gattas and You’s recent analysis [3] of structural performance of fold-core panels demonstrated the benefits of panels with curved-folded cores over straight-fold ones highlights the potential of using curved folds to lend stiffness to surfaces.
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Design and Fabrication Team:

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Session 10: Energy Modeling

Analyzing Indoor Comfort Conditions through Simulation and On-Site Measurements
Raghuram Sunnam, Annie Marston, Zhuzhou Fu, and Oliver Baumann
Baumann Consulting; Dept. of Civil and Environmental Engineering, Carnegie Mellon University.

Approaching Biomimetics: Optimization of Resource Use in Buildings Using a System Dynamics Modeling Tool
Mercedes Garcia-Holguera, Grant Clark, Aaron Sprecher, and Susan Gaskin
McGill University.

Development of a Modeling Strategy for Adaptive Multifunctional Solar Energy Building Envelope Systems
Nicholas Novelli, Justin Shultz, and Anna Dyson
Rensselaer Polytechnic Institute.
ABSTRACT

ASHRAE standard 55-2013 defines thermal comfort of occupants as a mental state of satisfaction with regard to the thermal environment. Mechanical designers design HVAC systems to condition an occupied space so as to provide thermal comfort to at least 80% of the occupants. Thermal comfort is dependent on various physiological and psychological aspects of the occupants and it is defined by ASHRAE standard 55 based on – 1. Metabolic rate, 2. Clothing insulation, 3. Air temperature, 4. Radiant temperature, 5. Air speed, 6. Humidity. This paper presents the thermal comfort study of five conference rooms in the ground level of a 16 story office building in Frankfurt. The conference rooms are conditioned by a direct outdoor air system (DOAS) and radiant ceiling panels for cooling and heating. This paper discusses the modeling approach and the simulation results that were used by the project team to determine the additional cooling capacity needed by the conference rooms. The simulation results were used to make informed decisions about the number of chilled beams required in the conference rooms. Further, the measurements recorded on the site during the commissioning process were used to compare against the simulation results.

Author Keywords

Simulation, Indoor thermal comfort, On-site survey, PMV, PPD, Commissioning, Radiant systems, Chilled Beams.

ACM Classification Keywords

Design, Measurement, Performance, Verification

INTRODUCTION

Simulation based approaches to designing mechanical systems to spaces are greatly useful in making design decisions. This is especially true in cases when changes are introduced at later stages of design. This paper presents one such scenario where the designed mechanical systems had to be modified to accommodate new features within the spaces. The design modifications resulted in changes in mechanical components thereby affecting the indoor thermal conditions. Thermal condition is one of the most important aspects of human comfort within conditioned indoor spaces. Much research has been done to establish the effect of comfort on occupant’s productivity. Previous research established the advantages of radiant heating and cooling systems coupled with conventional air systems over all-air systems with respect to human comfort (Mumma, 2004).

This study was conducted on five conference rooms at ground level in a 16 story LEED Gold certified building. The objective of the study was to ensure that the thermal comfort conditions within the conference rooms were maintained after the number of chilled ceiling panels was modified. The radiant ceiling panel capacity was sized to match the internal loads in the spaces. However, the design ceiling panel area had to be reduced during design due to the addition of recessed ceiling lights. This paper presents the study to assess the additional cooling capacity required in all the conference rooms to ensure thermal comfort. The zone operative temperature for these conference rooms was used to assess the thermal comfort conditions. ASHRAE standard 55-2013 defines operative temperature as:

“The average of the air temperature and the mean radiant temperature weighted, respectively, by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant.” (ASHRAE, 2013)

The acceptable levels of comfort were assessed based on the number of degree hours when the occupants were comfortable from the simulation results. The occupant comfort was assessed based on the operative temperature requirements that were specified by the building owner.

Based on the analysis of the simulation results, the designers determined the additional cooling capacity required for the conference rooms. This study was used to determine the number of chilled beam components needed for each of the conference rooms. Once the construction was complete, the thermal comfort conditions within the conference rooms were measured as a part of commissioning tasks using a globe thermometer. The final part of the study involved the measurement of the actual conditions in the conference rooms after construction for comparison against the simulation results. The challenges and also the limitations of comparing the simulation results with the actual on-site measurements will also be highlighted in this paper.
PROJECT OVERVIEW
The project is a newly constructed office building and is located in Frankfurt, Germany. The building has various types of spaces: open offices, private offices, atriums, conference rooms, data centers, restaurant, etc. The 16-storey LEED® Gold rated office building had the following energy efficiency measures (EEMs) integrated into the design:

i. High quality envelope
ii. Direct outdoor air system with heat recovery
iii. Natural ventilation
iv. Automated exterior solar shading
v. Occupancy sensors in circulation spaces
vi. District heating as the heating energy source
vii. Hydronic heating and cooling systems

The conference rooms in the ground level are ventilated by direct outdoor air systems (DOAS). They are also conditioned by chilled ceiling panels and radiators. The designers added recessed ceiling lighting to the conference rooms thereby reducing the effective area of the chilled ceiling panels in the periphery. Additionally, ceiling mounted speakers and projectors were added to the conference rooms at a later stage of the design. This resulted in further reduction of the effective area of the chilled ceiling panels. High occupancy in the conference rooms resulted in high internal thermal loads and hence there was a need to verify the capacity of the designed system. The DOAS supplied fresh air at 20°C to multiple office spaces in addition to the conference rooms and hence could only address part of the cooling load. Figure 1 shows the geometry created in open studio for the energy model.

Figure 1. Geometry for the energy model in OpenStudio plugin for SketchUp.

Table 1 presents the internal loads of the conference rooms that were analyzed. All the internal loads had a schedule from 09:00 am to 06:00 pm.

<table>
<thead>
<tr>
<th>Room</th>
<th>People</th>
<th>Equip.</th>
<th>Lights</th>
<th>Total Internal Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>24</td>
<td>920 W</td>
<td>795 W</td>
<td>4115 W</td>
</tr>
<tr>
<td>Conf 2</td>
<td>16</td>
<td>632 W</td>
<td>525 W</td>
<td>2757 W</td>
</tr>
<tr>
<td>Conf 3</td>
<td>24</td>
<td>920 W</td>
<td>795 W</td>
<td>4115 W</td>
</tr>
<tr>
<td>Conf 4/5</td>
<td>10</td>
<td>344 W</td>
<td>330 W</td>
<td>1674 W</td>
</tr>
</tbody>
</table>

Table 1. Internal loads of the conference rooms.

The weather data file for the city of Frankfurt provided by the EERE of the United States Department of Energy was used for the simulation. Frankfurt has mild summers and the winters are almost always cloudy. It is categorized to be in climate zone 5c. The 0.4% cooling design temperatures for the city of Frankfurt are:

- Dry Bulb temperature: **30.4°C**
- Wet Bulb temperature: **20.5°C**

The climate can be broadly described as moderately humid with rain during most of the year. Moderate humidity helps mitigate the issue of condensation over the radiant ceiling panels in Frankfurt.
RADIANT CEILING PANELS

Heating and cooling through radiant ceiling panels is an effective way to provide occupant comfort and save up to 10% of energy (Miriel et al. 2002). The following parameters related to the radiant panels have been identified by Chantrasrisalai et al.(2003) as the most critical:

i. Thermal properties of building materials
ii. System operation schedule
iii. System setpoint temperatures
iv. Schedules of the zone internal gains

The specifications of the chilled ceiling panels from the manufacturer are listed in Table 2.

<table>
<thead>
<tr>
<th>Overall Panel Size</th>
<th>1.25 m x 3.2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydronic Tube Inside Diameter</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>Distance between tubes</td>
<td>95 mm</td>
</tr>
<tr>
<td>Supply Water Temperature</td>
<td>15°C</td>
</tr>
<tr>
<td>Return Water Temperature</td>
<td>18°C</td>
</tr>
<tr>
<td>Performance at ΔT of 5.5 K (avg. room temp – Panel surface temp)</td>
<td>47.3 W/m² active area</td>
</tr>
<tr>
<td>Performance at ΔT of 10K (avg. room temp – Panel surface temp)</td>
<td>89.1 W/m² active area</td>
</tr>
</tbody>
</table>

Table 2. Manufacturer specifications of chilled ceiling panels.

ZoneHVAC:LowTemperatureRadiant component in EnergyPlus was used to model the radiant ceiling. The simulation inputs for this component were studied in detail in an earlier study for the same project (Sunnam et al., 2013). That study had highlighted the importance of verifying the results at each stage to ensure the accuracy in simulation.

Hence, verifying that the chilled ceiling panels performance in the simulation against the manufacturer specifications was the first step in this study. The cooling performance of the panels was plotted against the difference of the temperatures of the surface temperature and average room temperature as shown in Figure 3. The dark blue line in the graph represents the manufacturer specifications and the light blue dots represent the simulation data. Lower internal loads and lower solar exposure result in lower ΔT values for unoccupied hours. The chilled ceiling panels are much more efficient in controlling the zone average air temperature during these unoccupied hours. These instances can be noticed in the graph. From the graph, it was verified that the chilled ceiling panels’ performance in the simulation matched the manufacturer specifications for occupied hours.

Iteration 1 - Only Chilled Ceiling Panels

The first iteration of the simulation was done with the conference rooms conditioned by only the chilled ceiling panels. The architectural designers had added recessed lighting in the conference rooms which resulted in the reduction of active chilled ceiling area by 10%. Table 3 presents the details of the energy model that was created for this study.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Internal Loads</th>
<th>Total Ceiling Area</th>
<th>Radiant Ceiling Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>77.29 W/m²</td>
<td>53.24 m²</td>
<td>27.6 m²</td>
</tr>
<tr>
<td>Conf 2</td>
<td>48.24 W/m²</td>
<td>57.15 m²</td>
<td>34.5 m²</td>
</tr>
<tr>
<td>Conf 3</td>
<td>60.32 W/m²</td>
<td>68.22 m²</td>
<td>41.1 m²</td>
</tr>
<tr>
<td>Conf 4/5</td>
<td>57.55 W/m²</td>
<td>29.09 m²</td>
<td>19.7 m²</td>
</tr>
</tbody>
</table>

Table 3. Design specifications for the conference rooms.

This study was used to verify that the spaces still met the comfort requirements of the owner. The blue shaded region in the graphs in Figure 4 represents these thermal comfort requirements by the owner in terms of the zone operative temperature as a function of outside air temperature. The acceptable zone operative temperature was 22°C for outside air temperature below 25°C. It was required to be 26°C for outside air temperatures between 25°C and 32°C. The acceptable operative temperature value increased by 1°C for 1°C rise in outside air temperature after 32°C. The number of hours and number of degree hours when the zone operative temperature did not meet the owner’s thermal comfort requirements were determined from the simulation results. The results from the iteration 1 showed that these numbers were high for the conference rooms. The cooling provided by the chilled ceiling panels was not enough to meet the thermal loads within the spaces. Each blue point on the graphs of Figure 4 represents an occupied hour and each grey point represents an unoccupied hour from the simulation for iteration 1.
Figure 4. Plots of Room Operative Temperatures vs. Outside Air Temperature for Iteration 1

Table 4. Energy modeling inputs for the conference rooms.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Unmet Load hours</th>
<th>Degree hours out of comfort Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>1,276 hours</td>
<td>1,656 °/hour</td>
</tr>
<tr>
<td>Conf 2</td>
<td>131 hours</td>
<td>43 °/hour</td>
</tr>
<tr>
<td>Conf 3</td>
<td>695 hours</td>
<td>419 °/hour</td>
</tr>
<tr>
<td>Conf 4/5</td>
<td>452 hours</td>
<td>143 °/hour</td>
</tr>
</tbody>
</table>

Iteration 2 - Chilled Ceiling Panels and Chilled Beams

At this stage, speakers and projectors were added to these conference rooms which further reduced the active chilled ceiling area. Table 5 shows the reduced chilled ceiling areas used in iteration 2. The number of chilled beams required was determined based on the cooling capacity requirements and the manufacturer specifications of the chilled beam components.

Table 5. Energy modeling inputs for the conference rooms.

<table>
<thead>
<tr>
<th>Zone</th>
<th>New Radiant Ceiling Area</th>
<th>No. of Chilled Beams</th>
<th>Chilled beams cooling capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>22.9 m²</td>
<td>6 nos.</td>
<td>2058 W</td>
</tr>
<tr>
<td>Conf 2</td>
<td>30.6 m²</td>
<td>2 nos.</td>
<td>686 W</td>
</tr>
<tr>
<td>Conf 3</td>
<td>35.6 m²</td>
<td>4 nos.</td>
<td>1372 W</td>
</tr>
<tr>
<td>Conf 4/5</td>
<td>19.0 m²</td>
<td>0 nos.</td>
<td>0 W</td>
</tr>
</tbody>
</table>

Table 4 lists the total number of unmet hours and unmet degree hours from iteration 1 of the simulation. The results from the iteration 1 were not acceptable for conference rooms 1 and 3. Due to space limitations, the designers could not add additional chilled ceiling panels to these conference rooms but decided to add chilled beams. Additional design changes were introduced at this stage and hence another iteration of the simulation was done to analyze the thermal comfort in the conference rooms.
AirTerminal:SingleDuct:ConstantVolume:CooledBeam component in EnergyPlus was used to model the chilled beams in this iteration. Table 6 shows the unmet load hours and unmet degree hours for this iteration. The unmet degree hours for conference rooms 2, 4 and 5 from iteration 1 were acceptable. The simulation results determined that 686 W of additional cooling capacity that translates to 2 chilled beams were required in conference room 2 due to higher internal thermal loads and its orientation. Conference rooms 4 and 5 did not need additional cooling owing to their orientation and lower internal thermal loads.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Unmet Load hours</th>
<th>Degree hours out of comfort range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>908 hours</td>
<td>539 °/hour</td>
</tr>
<tr>
<td>Conf 2</td>
<td>134 hours</td>
<td>35 °/hour</td>
</tr>
<tr>
<td>Conf 3</td>
<td>314 hours</td>
<td>95 °/hour</td>
</tr>
<tr>
<td>Conf 4/5</td>
<td>586 hours</td>
<td>231 °/hour</td>
</tr>
</tbody>
</table>

Table 6. Energy simulation results for the conference rooms.

The room operative temperature from the iteration 2 simulation results were plotted as a function of outside air temperature as shown in Figure 5. Each blue point on the graphs represents an occupied hour and each grey point represents an unoccupied hour from the simulation results.

**Results and Recommendations**

This study focused on the analysis of the thermal comfort conditions within the conference rooms with different configurations based on the modifications to the spaces. The number of chilled beams for the conference rooms was recommended based on the difference between the cooling loads of the spaces and the cooling capacity of the reduced chilled ceiling panels. Manufacturer specifications of the chilled ceiling panels and the chilled beams were used in the model to get an accurate idea of their actual performance. The designers used the following results to modify the systems in the conference rooms.

**Conference Room 1**

This conference room was the most critical space due to its highest internal loads and also because it is next to a considerably hotter atrium space and is separated by a low
U-value internal wall. Based on the analysis, it was determined that this room required an additional cooling power of at least 2000 W which translates to 6 standard chilled beams of each 1150 mm length to meet the load. However, since the space still had over 400 unmet degree hours, it was recommended to have 8 to 10 chilled beams.

**Conference Room 2**
Owing to its orientation and higher thermal loads, this conference room required additional cooling capacity. This space required at least 686 W of cooling capacity that translated to 2 chilled beams of each 1150 mm length to meet the cooling load.

**Conference Room 3**
Due to its location in the corner of the triangle, this room had additional cooling requirements. This space required at least 1350 W of additional cooling from chilled beams to meet this cooling load. This translated to 4 standard chilled beams of each 1150 mm length.

**Conference Rooms 4 and 5**
Conference rooms 4 and 5 were identical and hence their requirements were similar. They did not need any additional cooling to meet the internal loads. Hence there was no need to add any chilled beams to these two rooms even if the active chilled ceiling area was reduced due to recessed lighting and speakers.

**COMPARISON OF SIMULATION RESULTS AND ON-SITE MEASUREMENTS**
The thermal conditions within the conference rooms were measured as a part of the commissioning tasks for the project. The commissioning team used a wet bulb globe thermometer (Delta Ohm HD32.3 instrument) to record the thermal comfort measurements in the conference rooms after construction. The ambient conditions were measured using a psychrometer (Extech HD500 instrument). Figure 6 shows both the instruments that were used.

The ambient conditions were first measured using the psychrometer. The surface temperatures of the chilled ceiling panels were observed to be above the dew point temperature of the spaces, thereby avoiding condensation issues. The ambient conditions that were recorded are presented in Table 7.

![Figure 6. a. Delta Ohm HD32.3 Wet Bulb Globe Thermometer; b. Psychrometer Extech HD500](image)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Air Temp</th>
<th>Relative Humidity</th>
<th>Dew Point Temp</th>
<th>Active Ceiling surf. Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>23.4°C</td>
<td>59%</td>
<td>15°C</td>
<td>17.1°C</td>
</tr>
<tr>
<td>Conf 2</td>
<td>23.1°C</td>
<td>58%</td>
<td>14.6°C</td>
<td>18.6°C</td>
</tr>
<tr>
<td>Conf 3</td>
<td>23.1°C</td>
<td>58%</td>
<td>14.6°C</td>
<td>18.6°C</td>
</tr>
<tr>
<td>Conf 4</td>
<td>22.8°C</td>
<td>62%</td>
<td>15.1°C</td>
<td>19.9°C</td>
</tr>
<tr>
<td>Conf 5</td>
<td>21.3°C</td>
<td>59.8%</td>
<td>14.8°C</td>
<td>19.3°C</td>
</tr>
</tbody>
</table>

Table 7. Ambient Condition Measurements Recorded using Psychrometer (Extech HD500)

Thermal comfort measurements are not a part of the requirements for typical commissioning projects. It was of special interest for the project team to verify the implemented design by comparing it against the simulation results. The points where the model calculated the operative temperature do not exactly match the points where the measurements were recorded. Hence the values are not expected to be exactly equal. It was observed that the calculated operative temperature for all the rooms was slightly higher than the owner’s requirements at the instant when the measurements were recorded. The discrete measurements recorded only give a snapshot of the system functioning. They do not reflect the overall system functioning. However, the measurements recorded by the Delta Ohm HD32.3 instrument can be used to assess the thermal comfort conditions of the space. Trend data collected by the building automation system (BAS) could be used to analyze the system functioning.

**Thermal Comfort Metrics**
ASHRAE standard 55-2004 defines thermal comfort conditions based on two metrics – Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD). ASHRAE standard 55-2004 suggests the acceptable value of PMV to be between -0.5 to +0.5 and that of PPD to be less than 10% for a space to be considered comfortable. The wet bulb globe thermometer (Delta Ohm HD32.3) automatically calculates these two indices of a given space based on the variables that are input into it. Table 8 presents the thermal comfort conditions that were recorded at two different locations of each room during on-site testing. The operative temperature for each set of measurements was calculated from the ambient temperature and radiant temperature.
Date and time of measurements | 18 July, 2013; 04:30 PM | Outside air temperature when the measurements were recorded | 21.9°C

<table>
<thead>
<tr>
<th>Zone</th>
<th>Air speed [m/s]</th>
<th>Ambient temp [°C]</th>
<th>Radiant median temp [°C]</th>
<th>Calc. Operative temp [°C]</th>
<th>PMV Index</th>
<th>PPD Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1 Loc. 1</td>
<td>0.04</td>
<td>23.0</td>
<td>23.3</td>
<td>23.2</td>
<td>0.06</td>
<td>5.07%</td>
</tr>
<tr>
<td>Conf 1 Loc2</td>
<td>0.04</td>
<td>22.9</td>
<td>23.3</td>
<td>23.1</td>
<td>0.04</td>
<td>5.03%</td>
</tr>
<tr>
<td>Conf 2 Loc. 1</td>
<td>0.03</td>
<td>23.4</td>
<td>23.4</td>
<td>23.4</td>
<td>0.13</td>
<td>5.35%</td>
</tr>
<tr>
<td>Conf 2 Loc. 2</td>
<td>0.08</td>
<td>23.3</td>
<td>23.2</td>
<td>23.3</td>
<td>0.10</td>
<td>5.25%</td>
</tr>
<tr>
<td>Conf 3 Loc. 1</td>
<td>0.03</td>
<td>23.1</td>
<td>23.4</td>
<td>23.3</td>
<td>0.05</td>
<td>5.05%</td>
</tr>
<tr>
<td>Conf 3 Loc. 2</td>
<td>0.00</td>
<td>23.3</td>
<td>23.2</td>
<td>23.3</td>
<td>0.08</td>
<td>5.16%</td>
</tr>
<tr>
<td>Conf 4 Loc. 1</td>
<td>0.01</td>
<td>23.3</td>
<td>23.4</td>
<td>23.4</td>
<td>0.11</td>
<td>5.25%</td>
</tr>
<tr>
<td>Conf 4 Loc. 2</td>
<td>0.00</td>
<td>23.4</td>
<td>23.4</td>
<td>23.4</td>
<td>0.14</td>
<td>5.40%</td>
</tr>
<tr>
<td>Conf 5 Loc. 1</td>
<td>0.01</td>
<td>23.5</td>
<td>23.5</td>
<td>23.5</td>
<td>0.17</td>
<td>5.53%</td>
</tr>
<tr>
<td>Conf 5 Loc. 2</td>
<td>0.00</td>
<td>23.7</td>
<td>23.6</td>
<td>23.7</td>
<td>0.20</td>
<td>5.02%</td>
</tr>
</tbody>
</table>

Table 8. Thermal Conditions Recorded using Wet Bulb Globe Thermometer (Delta Ohm HD 32.3)

PMV and PPD are defined by ASHRAE standard 55-2004 as:

- **Predicted Mean Vote (PMV):** It is an index that predicts the mean value of the votes of a large group of persons on the seven point thermal sensation scale. A minimum vote of -3 corresponds to very cold sensation and a maximum vote of +3 corresponds to very hot sensation.

\[
PMV = T_s \times (MW - HL1 - HL2 - HL3 - HL4 - HL5 - HL6)
\]

- \(T_s\) = Thermal sensation transmittance coefficient
- \(MW\) = Metabolic rate – External Work
- \(HL1\) = Heat loss through skin
- \(HL2\) = Heat loss by sweating
- \(HL3\) = Latent respiration heat loss
- \(HL4\) = Dry Respiration heat loss

- **Predicted Percent Dissatisfied (PPD):** It is an index that establishes a quantitative prediction of the percent of thermally dissatisfied people determined by PMV.

\[
PPD = 100 - 95 \times e^{-0.0353 \times PMV - 0.1279 \times PMV^2}
\]

The PMV and PPD indices for all the five conference rooms were observed to be within the limits suggested by ASHRAE 55-2004.

Figures 7a shows a photograph of the chilled beams and the chilled ceiling panels installed in conference rooms and Figure 7b shows the infra-red image of the same chilled beams and the chilled ceiling panels. These infra-red images were used by the commissioning team to verify that all the chilled ceiling panels and the chilled beams were operational during testing.

**CONCLUSION**

The climate of Frankfurt is very suitable for the use of radiant cooling components in office buildings. However, sizing the components appropriately to ensure the thermal comfort of the occupants is very critical. Thermal
simulations are particularly useful in assessing the cooling and heating loads to estimate the capacities of the components to condition spaces. Validation of the simulation results is critical to be able to base any design decisions on them.

Assisting the designers during design decision making process is one of the most critical applications of whole building simulations. Although it may not always be possible to analyze the design options using simulations, it is invaluable in the design of efficient systems for high performance buildings or efficient tool. This case study is an example where the simulation team worked in synergy with the mechanical designers to validate the design decisions. The on-site measurements by the commissioning team were further used to verify the actual implementation of the design. Constant monitoring of the system functioning to ensure the optimal control of the systems in these spaces would still be necessary to ensure that the design criteria are met during the operations and maintenance phase.

REFERENCES
5. Sunnam, R., Marston, A., & Baumann, O. Analysis of chilled ceiling performance to control temperature in a data control center using energyplus: a case study. BS2013
Approaching Biomimetics: Optimization of Resource Use in Buildings using a System Dynamics Modeling Tool

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ABSTRACT
The biomimetic field in architecture is developing tools for transferring processes and functions from biological systems to buildings. Buildings, like ecosystems, are dynamic and complex systems, thus studying their dynamics from a systems thinking perspective might bring insight to some environmental problems. STELLA®, a software commonly used to model environmental dynamics, was used to identify approaches for energy optimization in the Great River Energy Building. Long-term energy flows and thermal properties of the building were modeled to understand the feedback loops that control the behavior of the building system. The simulation showed that optimization of passive building parameters produced considerable energy savings, but more active strategies would be necessary to make the Great River Energy building a net-zero energy building. This exercise showed how the STELLA® software can represent the dynamic behavior of buildings as well as the dynamic behavior of environmental systems, and the potential of this tool for biomimetic research in architecture.

Author Keywords
Biomimetics; biomimicry; ecomimetics; net-zero building; system dynamics; STELLA

INTRODUCTION
Biomimetic research is rooted in the idea that there is great opportunity for innovation in learning from Nature. The primary goal of biomimetic research is to transfer knowledge from biology to human technology [1]. In architecture, biomimetic research is recent, and according to the categorization by Pedersen Zari [2] it might mimic organisms, behaviors and ecosystems. The latter, mimicking of ecosystems, is also known as ecomimetics [3], and refers to the transfer of processes and functions from ecosystems to architectural systems. Ecosystems are complex systems where interactions among biotic and abiotic elements occur. From a thermodynamic point of view, ecosystems are open systems that modulate inflows and outflows of energy, matter, and information. Similarly, buildings are also thermodynamic open systems that behave as complex systems. According to the general systems theory [4], systems from different fields may share structural characteristics and show similar behavior [5]. An ecomimetic approach presumes that structural organization and behavior of ecosystems might be transferred to and reproduced by architectural systems. The work presented here is part of a bigger effort to define a systematic ecomimetic method that optimizes resource use in buildings. A central part of this effort consists of the identification and development of transdisciplinary tools that might help to communicate the ecological and architectural fields. One approach identified for this purpose is system dynamics. The field of system dynamics was first developed by Forrester [6] at the Massachusetts Institute of Technology while studying feedback control theory. System dynamics is used to model the complex behavior of systems (e.g. ecosystems) by representing the feedback interactions happening among sub-systems. Although system dynamics is not a predictive tool, it helps to describe trends of the system under study, and it might be used in a varied number of fields such as environmental modeling, health care, organization of military forces, or management of natural disasters [7, 8]. System dynamics has also been implemented as a decision-making tool in the building and construction industry. Among these applications some are focused on sustainable construction and energy efficiency [9-12]. Dyner et al. [9] use a system dynamics approach to identify appropriate energy policies in an urban context. Shen et al. [10] analyze the feasibility of construction projects using iThink®, which is a modeling tool based on system dynamics focused toward a business audience. Oladokun et al. [11, 12] use another tool, Vensim®, to model the dynamic feedbacks of household energy consumption in UK. None of these examples focus on a single building analysis; however, there is great potential for resource use optimization in buildings by implementing system dynamics in architectural design.

This document presents how the STELLA® software tool [13], traditionally used for modeling dynamic systems [7] can be a suitable transdisciplinary tool for modeling building systems for ecomimetic design, and a valuable decision-making tool for optimization of resource use in buildings. The purpose of this exercise is to show the potential of this modeling tool within the building industry rather than provide exhaustive and exact results. Therefore data used in the modeling exercise might be considered general or not specific enough for the building under study since the priority of this work is to evaluate the overall performance of the tool.
DESCRIPTION OF THE BUILDING SYSTEM

The system under study is the Great River Energy Building in Minnesota; a commercial four-story office building constructed in 2008 that covers an area of 15,400 m². The structure is made of concrete and the envelope is a glass curtain wall. The building obtained the LEED Platinum certification level and data for this exercise was obtained from the US Green Building Council (USGBC) website [14] and also from the Great River Energy website [15]. The building combines the implementation of passive techniques for energy consumption reduction with active strategies and energy production on-site. This involves design measures such as optimal orientation for day lighting and views, under-floor thermal displacement ventilation, guidelines for operation of the building, training of operations personnel, public transportation access, native vegetation, storm water infiltration, rainwater harvesting, low consuming fixtures, wind turbines and photovoltaic panels to deliver electricity, durable and low maintenance materials, recycled and certified materials, flexible uses, and long life design (100 years), among other strategies. The Great River Energy building is powered by electrical energy that is imported from the grid or produced by photovoltaic panels or wind turbines. The main objectives of the owners were to design the “most electric-energy-efficient building in the state”[14], and also to become an example of workplace productivity and a platform for exhibiting energy efficient technologies to the public.

The climate in the region is continental with temperatures varying between -20°C during the cold dry winters and 30°C through the humid summers. Table 1 shows data retrieved from the Living Building Challenge and USGBC databases, and displays the energy use intensity (EUI) of several buildings.

<table>
<thead>
<tr>
<th>Building</th>
<th>Area (m²)</th>
<th>EUI (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matarozzi-Pelsinger Offices</td>
<td>1300</td>
<td>58.44</td>
</tr>
<tr>
<td>Painters Hall</td>
<td>302</td>
<td>65.71</td>
</tr>
<tr>
<td>IDeAs Z2 Design facility</td>
<td>669</td>
<td>66.68</td>
</tr>
<tr>
<td>0142 CNT Renovation</td>
<td>1390</td>
<td>178.94</td>
</tr>
<tr>
<td>Great River Energy Building</td>
<td>15400</td>
<td>201.93</td>
</tr>
<tr>
<td>IFAW World Headquarters</td>
<td>5130</td>
<td>213.84</td>
</tr>
</tbody>
</table>

Table 1 Comparison of Energy Use Intensity (EUI) data from office buildings. Data retrieved from USGBC website.

According to the report on the USGBC, the Great River Energy Building reduces “fossil fuel by 75% and cuts CO₂ emissions by 60%” as per the requirements of LEED version 2.2; however, the overall energy use intensity (EUI) of the building measured in kWh m⁻² yr⁻¹ is high when compared to other office buildings (Table 1) that had implemented less passive design strategies or active technologies (including production of energy on site). This shows that there are still opportunities to improve the performance of the Great River Energy building.

The optimization should focus not only on the single components of the building, which might be similar to those present in other office buildings; but rather on the dynamics and relationships among these components. Most of the energy used in the building is electrical energy and the modeling exercise will focus on understanding how to reduce the amount of electricity imported from the grid in order to strive toward a net-zero energy building.

MODEL DESCRIPTION

System dynamics is especially appropriate for analyzing complex systems that are highly dynamic and non-linear [16]. When building a model of a system it is imperative to first identify the boundary for that system and the time period for the analysis. The structure of the system is represented with diagrams that are made of stocks, flows and feedback loops [17]. The stocks are the state variables and represent the storage of energy, matter, or information through time. Flows represent the entry and exit of energy, matter, or information in the stocks. The feedback loops are closed chains of causal connections that modify a stock. In addition, converters help to modify the stocks and can be constants or variables. Systems may be represented through stock and flow diagrams and feedback loop diagrams. This document focuses on the first type of diagrams, but feedback loop diagrams can be provided if requested. The components of the model can be explained with more detail as follows:

Stocks

The boundary of the model is defined by the physical envelope of the building and its energetic dynamics. The period for the dynamic modeling covers the lifespan of the building plus an additional 50 years (i.e. 150 years). The units used in the model are kWh m⁻² for the stocks and kWh m⁻² yr⁻¹ for the flows. The model under study represents the flows of electricity entering the building, the outflows of energy that perform work and the outflows of dispersed energy. A diagram of the conceptual model is shown in Figure 1.

There are two stocks in the model: one represents all the electricity that is actively used in the building; the other represents the passive energy that is stored in the envelope of the building due to its thermal properties and its interaction with the environment. The first stock receives the inflows of electricity that are then transformed into work by the building systems. However, some electrical energy is lost in the process, and that lost energy is represented as a flow of dispersed heat inside the building. The dispersed heat interacts with the building envelope, and depending on several variables (e.g. thermal properties and
The composition of the envelope, external and internal temperatures, the envelope may transfer part of that heat to the environment. The remaining dispersed heat is then reused to reduce the amount of energy needed in the building.

**Flows**

There are three inputs of electricity entering the system (Figure ). There is one non-renewable input represented by the electricity that is imported from the grid, and there are two renewable inputs coming from the photovoltaic panels and the wind turbine installed on-site. There is one additional recycled input that represents the dispersed heat that is reused in the building (see explanation below).

<table>
<thead>
<tr>
<th>Annual Purchased Energy Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual On-site Renewable Energy Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Photovoltaics</td>
</tr>
<tr>
<td>Wind</td>
</tr>
</tbody>
</table>

Table 2 Great River Energy building: purchased and produced energy [18]

Data for the electricity flows comes from the USGBC database (Table 2). The equivalence between MJ and kWh is 1 kWh=3.6 MJ. Several converters also regulate the electricity imported from the grid. The logical function establishes that energy will be imported from the grid only when the renewable energy produced onsite is not enough to sustain the ‘building systems’; otherwise the remaining renewable energy will be exported to the grid.

There are three outflows exiting the ‘electrical energy’ stock in Figure 1. The first one is the ‘building systems’ flow which represents the energy used by all building systems with the exception of the heating system (e.g. lighting, cooling, plug load, equipment, pumps). The second flow is the ‘heating system’ flow. Data for these two flows is obtained from the USGBC database (Table 3).

<table>
<thead>
<tr>
<th>End Use</th>
<th>kWh</th>
<th>MJ</th>
<th>MJ/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>445,000</td>
<td>1,600,000</td>
<td>104</td>
</tr>
<tr>
<td>Cooling</td>
<td>302,000</td>
<td>1,090,000</td>
<td>70.5</td>
</tr>
<tr>
<td>Lighting</td>
<td>528,000</td>
<td>1,900,000</td>
<td>123</td>
</tr>
<tr>
<td>Fans/Pumps</td>
<td>414,000</td>
<td>1,490,000</td>
<td>96.7</td>
</tr>
<tr>
<td>Plug Loads and Equipment</td>
<td>1,090,000</td>
<td>3,930,000</td>
<td>255</td>
</tr>
<tr>
<td>Vertical Transport</td>
<td>38,400</td>
<td>138,000</td>
<td>8.97</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>69,800</td>
<td>251,000</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Table 3 Annual End-Use breakdown of energy for the Great River Energy building [18]

The ‘building systems’ flow is controlled by a logical function. This function regulates the minimum amount of energy consumed by the ‘building systems’ and its relationship with the ‘renewable energy’. The third flow represents the amount of energy that is dispersed into heat during the transformation of electricity into usable work. This flow depends on the efficiency of the building systems. This means that an efficiency rate regulates the amount of energy going to the ‘building systems’, the ‘heating system’ and the ‘dispersed heat’. The efficiency rate has been calculated as the mean from several efficiency rates acquired from the Department of Energy [19]. The heat dispersed becomes the inflow of the second stock (i.e. the energy stored in the envelope of the building).

There are two outflows exiting the second stock (i.e. ‘energy in envelope’). One represents the heat that crosses the envelope and is dispersed into the environment, and the other one represents the heat that is kept inside the building. To calculate the amount of energy that is dispersed to the external environment several criteria were considered. The
following equation describes the heat losses through the envelope:

\[ Q = A \cdot U \cdot \Delta T \]  

(equation 1)

Where \( Q \) is the heat transmitted in watts, \( A \) is the surface of the envelope in \( \text{m}^2 \), \( U \) is the conductivity of the envelope in \( \text{w} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \), and \( \Delta T \) is the difference between interior and exterior ambient temperatures.

A number of assumptions were made before applying the equation. First the design temperature of comfort for winter was set to 21°C and the design temperature for summer to 26°C. According to temperature ranges in the region (-20°C and 30°C) the greatest differences between the interior design temperature and the exterior temperature happens during the winter season. Consequently, the model will be run under winter conditions, with maximum energy dispersion from the building to the environment. This means that \( \Delta T = 21 - (-20) = 41 \text{K} \). Second, the surface (\( A \)) was fixed at 1m\(^2\) because all the energy units are given in terms of one square meter. Third, instead of calculating the thermal conductivity (\( U \)) for the whole building, a worst-case scenario was defined. The scenario is based on the \( U \) maximum value as per the Minnesota Energy code [20] for fixed glazing (\( U = 0.57 \)) because a great percentage of the building façade is glazed. As a result, the maximum allowable heat dispersion through the envelope would be:

\[ Q = 1 \text{m}^2 \cdot 0.57 \text{w} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \cdot 41 \text{K} = 23.37 \text{w} = 84.13 \text{kWh} \]

This is the worst-case scenario for a building with low envelope performance. The number arrived at from this equation represents 100% of the allowed heat dispersion to the outside environment. For the Great River Energy building there is no data about the thermal performance of the envelope or any mention about its insulation. However, it is indicated that the envelope was analyzed to reduce energy loads, so it will be assumed that its heat losses due to the envelope performance are less than those in the worst-case scenario. USGBC data suggest that the Great River Energy building saves 47% of energy when compared to building code standards [18], so the actual dispersed heat through the building is likely to be between 53% and 100% of the allowed heat dispersion. The model will start with 70% of the allowed heat losses (heat dispersion rate=0.70), that is, 58.89 kWh m\(^{-2}\)yr\(^{-1}\) (actual dispersed heat).

Additionally, sensitivity analysis will show the effects of reducing that amount, (i.e. improving the insulation of the envelope). Finally, the ‘heat dispersed outdoors’ is the minimum between the ‘actual dispersed heat’ and the ‘energy in the envelope’.

The second flow exiting the stock called ‘energy in envelope’ is the ‘reused heat’. This outflow increases the temperature inside the building, which reduces the energy demanded by the building systems. This reused heat becomes the fourth inflow in the building energy stock. It is calculated by discounting the energy dispersed to the environment and is modified by the heat dispersion rate.

**Converters**

Several converters control the flows of energy (Figure 1). The converter called ‘aging effect in systems’ signifies the deterioration of building systems as well as the deterioration of the envelope. In addition, it also influences the electricity demand from the grid. It is assumed that the building depreciation is directly related to the deterioration of the building. A graphical function (Figure 2) has been created combining graphs from two building depreciation studies [21, 22]. Both documents have interesting and complementary data regarding building value losses. The combined result is an S-shape graph that reflects smooth depreciation phases at the beginning and at the end of the life of the building.

\[ \text{Figure 2 Graphical function of the converter 'aging effect in systems'. The x-axis represents the depreciation rate and the y-axis represents the time in years.} \]

‘Energy increase trend’. This converter regulates the amount of electricity that is imported from the grid. The graphical function is derived from the U.S. Department of Energy report [21] where increases of around 12% in energy use intensity were measured for periods of 20 years. This data has been used to estimate a 50% increase for the first 100 years of the simulation.

‘Aging PV’. This converter affects the efficiency of the photovoltaic panels. The performance of the panels is expected to decrease due to deterioration of the components and limited lifespan of the panels. Data was obtained from the work by Vazqued and Rey-Stolle [22] and the graphical function was built according to Figure 1 of their document.

‘Aging turbine’. This converter reflects the loss of efficiency in the wind turbine. The lifespan of a turbine can vary from 20 to 30 years, although there is not conclusive data because most of the turbines under study have been working for less than 20 years. However, there is available data about their maintenance costs, and for this project it was assumed a direct relationship between the maintenance costs and the deterioration of the turbines. Data was found in the report for the U.S. Department of Energy by Wiser and Bolinger [23] and was adapted for a 100 years period.

‘Randomness’. In order to include the variations in the amount of energy produced by the wind turbine, a random
function was included. Data from the USGBC source estimates the maximum amount of energy produced by the turbine, so the random function was developed to oscillate between 62% and 100% of its maximum capacity. The minimum production could have been established at 0% as it can be assumed that there are times when the turbine is not working; however, for the reference model, a lower range variability was preferable.

‘System’s need MIN’. This converter refers to the minimum amount of energy that the building systems need. It is assumed that the minimum amount is equal to the sum of the values in Table 3, except for the heating values. This converter controls the flows of energy in the ‘building systems’ by restricting the flow such that it cannot drop below the minimum consumption value.

‘Renewable energy’. It is the sum of the energy produced by the photovoltaic panels and the wind turbine. It modifies the flows in the ‘building system’ and indirectly controls the export of energy to the grid.

‘Efficiency rate’. This converter is a constant that controls the amount of electricity that is transformed into usable work or into dispersed heat. Data for this value is obtained from the U.S. Department of Energy [19].

‘Maximum dispersed heat per code’, ‘Heat dispersion rate’, and ‘Actual dispersed heat’ are described above (‘heat dispersed outdoors’).

The length of the simulation is 150 years. The time step selected is DT=0.5 because all data is yearly data (DT refers to how frequently calculations are applied each unit of time). With a lower DT value (e.g. DT=0.25) variations in the results are negligible but the simulation runs slower. On the other hand with a higher DT (e.g. DT=1) the graphs oscillate and their interpretation becomes difficult.

RESULTS

The model was run using the data in the appendix as initial conditions. Some values went through a process of calibration in order to cover the whole length of the simulation (e.g. ‘aging effect’, ‘aging PV’, and ‘aging wind’, ‘energy increase trend’) and to combine data (e.g. ‘aging effect’). The starting conditions of the stocks were calibrated with the values obtained from the equilibrium simulation.

By the end of the 150 year period, the model reaches equilibrium. It is found to be stable (Figure 3) and behaves as expected: low increase in energy use at the beginning of the building life, then the increase trend gets stronger, and finally it returns to a slow increase at the end of the simulation. Similarly, the dynamics of the renewable sources perform as expected (Figure 3): steady production at the starting period of the simulation and progressive decrease due to aging effects. The energy in the envelope remains quite stable through the whole simulation, which speaks to the stable properties of building materials.

Several sensitivity tests were run to assess the robustness of the model. A model is considered robust when the same general patterns are observed despite the changes in some parameter values. Suggestions by Blanco [24] were followed: first a number of individual parameters were varied, and then several parameters were modified at the same time. For the first individual tests the model demonstrated great robustness (Figure 4).

Additional tests were run to assess the sensitivity of the model for multiple parameters at the same time: ‘electrical energy in building’, ‘energy in envelope’, ‘efficiency rate’, ‘heat dispersion rate’, ‘maximum dispersed heat’, and ‘system’s need MIN’ (Figure 5).
The model is robust for parameters changing in ranges of \( \pm 70\% \) from their original values. The only parameters that produce a slight alteration in the behavior of the model are the ‘heat dispersion rate’ and the ‘maximum dispersed heat’. In both cases the model reacts abruptly but subsequently recovers to an equilibrium. This reaction is linked to the equation that controls the ‘actual dispersed heat’.

**Evaluation and validation**

The Great River Energy company has created a database to collect data about the energy performance of the building [15]. This data has been gathered for almost a year (2012), but this is not very useful in terms of validating the behavior of the model over 100 years. However, the data can confirm the behavior of the building in its first stage (Figure 6). Ranges in consumption of electricity vary between 117 kWh m\(^{-2}\) yr\(^{-1}\) and 239 kWh m\(^{-2}\) yr\(^{-1}\). HVAC consumption varies between 25 kWh m\(^{-2}\) yr\(^{-1}\) and 109 kWh m\(^{-2}\) yr\(^{-1}\). Both, electricity and HVAC consumptions are within the ranges predicted by the model; therefore, the real data confirms that at this first stage the model is not invalidated.

![Figure 6 Monthly electrical use. Ranges in consumption of electricity. Great River Energy [15]](image)

**Simulation**

Several policies were introduced in the model to evaluate its relevance for adapting the Great River Energy building into a net-zero energy building. A policy in this context indicates a course of action and may vary from a simple regulation to more general principles.

‘Increase wind’. This policy explores the effects of increasing the number of wind turbines in the building site. The policy is based on the predicted increase in the number of wind turbines over the next 20 years [23]. Data from Wiser and Bolinger [25] has been extrapolated to create the graphical function in STELLA. The function in the model has been calibrated for 150 years. It is assumed that the number of wind turbines will not increase for the first 30 years; therefore, during this time the simulation is inactive.

‘Increase PV panels’. This policy introduces more photovoltaic panels in the building site to produce electricity. In order to define a graphical function for the policy the historical trends in installed photovoltaic panels are considered according to the IPPC report [25].

‘Maintenance’. This policy assumes that by improving the maintenance of the building systems and envelope, the ‘aging effect’ will be reduced. Therefore, the graphical function defined for the ‘aging effect’ converter is modified. The modification follows the graph by Mirza [26] that presents a diminished deterioration during the first years when maintenance is considered.

‘Consumption reduction’. This policy puts a limit on the ‘energy increase trend’. The limit is a maximum 20% increase in electricity consumption over the length of the simulation. This assumption is an estimated guess.

‘Envelope optimization’. This policy evaluates the effects of improving the insulation of the building by decreasing the ‘heat dispersion rate’. The rate is changed from 0.7 to 0.3.

‘Efficiency optimization’. This policy analyzes the consequences of improving the efficiency of the building systems. The initial value (0.15) is reduced to (0.05).

Initially the policies are implemented one at the time in order to identify the effects of each one. Then, several policies are simulated at the same time, and their values are calibrated so that the correct combination of measures can be determined.

**Discussion**

The policies described can be grouped in passive and active policies. First all active policies were implemented individually. The implementation of the ‘increase wind’ policy shows that the wind power needs at least 30 years to revert the import of electricity from the grid if this policy is fulfilled independently. In addition the investments required are enormous. However, if the policy ‘increase PV panels’ is implemented (Figure 7), the time needed to reduce the energy imported from the grid to zero is nearly 139 years, and again the investment needed would be very high. The next policy to be applied is the ‘maintenance’ policy. The simulation shows that this policy alone is not able to change the dynamics of the building in terms of import of electricity from the grid. Furthermore the reduction in the amount of energy purchased from the grid is minimal, just 14.4% at the end of the simulation. The following policy is the ‘consumption reduction’ policy. The simulation shows that the reduction in consumption does not change the general trends of energy imported from the grid. However, the energy imported is reduced by 25% at the end of the simulation. The ‘envelope optimization’ policy presents interesting results in terms of energy savings. However, these savings are too little when compared with the overall energy consumption of the building. By improving the thermal properties of the envelope the energy dispersed outside of the building is reduced by 50%. Finally, the ‘efficiency optimization’ does not produce any variation in the amount of energy imported from the grid. One
explanation is the lack of appropriate regulations of the energy used in the ‘building systems’ by the ‘efficiency rate’.

The next step is to analyze the passive policies together; that is, the ‘maintenance’, ‘consumption reduction’, ‘envelope optimization’, and ‘efficiency optimization’ policies. The model shows that together, the passive policies are able to obtain significant energy savings (Figure 8). Almost 34% of the energy imported from the grid can be saved, and the heat dispersed outside of the building can be reduced by 60%. Besides the ‘building systems’ reduce their consumption by 27%. This simulation shows that when the passive policies are implemented at the same time, the results are better than when they are implemented individually. However, the building still needs to import energy from the grid, so the implementation of active policies seems necessary. Considering that, in general terms, passive policies are less costly than the active ones; the next step will be to gradually introduce the wind and PV-panel policies in the model.

The implementation of all the policies shows that after 51 years, the building starts to export electricity to the grid (Figure 7); that is, ten years earlier than the ‘increase wind’ policy could do independently. However, if the ‘increase PV panels’ policy is not implemented, then the export of energy will begin in year 54. This suggests that the ‘increase PV panels’ policy should not be prioritized.

The performance of the envelope of the building is quite similar in terms of heat dispersed and reused when compared with the simulation of the passive policies. This means that the envelope is governed by the passive parameters rather than the active policies.

The graphical function that controls the ‘increase wind’ policy is an exponential function. Some modifications can be made to turn that function into an S-shape function in order to decrease the investments needed to implement the policy. Figure 9 shows the results of the simulation when the PV-panels policy is annulled and the ‘increase wind’ function is modified. The building starts exporting electricity in year 54 but the flows reach equilibrium at around 5 kWh m2yr, which means that the building becomes a net zero building.

CONCLUSION

There are several points in the model that will need further development. First, an economic analysis should be included to measure the appropriateness of each policy. Most of the time money is a limiting factor, so considering this point could improve the applicability of each policy. Second, the equation defining the flows for the ‘building system’ should also take into account the ‘reused heat’ as an input. The amount that this flow represents is not significant, but should be considered in a more detailed model. Third, it has been detected that a link between the ‘efficiency rate’ and the ‘building systems’ should be defined to reduce the flow when the efficiency is improved. This would allow the model to show more sensitivity to variations in the efficiency of the building systems. Fourth, a more accurate analysis should be carried out to characterize the thermal properties of the building. The present calculation is general and could be optimized. Finally it would be interesting to introduce more strategies in the model (e.g. the effects of a cogeneration plant) in order to reach the net zero point earlier in the lifespan of the building.
The exercise presented here, shows the potential of using a system dynamics-based software tool (i.e. STELLA®) to holistically analyze energy flows in buildings and to evaluate multiple optimization policies. This tool can be employed as a decision-making instrument during the early stages of new construction or renovation projects. This is also a promising tool for integrated design approaches because it allows the user to represent components from different sub-systems of a building, and might provide valuable insight in cost-benefit analysis. More importantly, the STELLA® software demonstrates great flexibility for analyzing architectural systems as well as ecological systems. This is significant in the framework of ecomimetic research because this transdisciplinary tool is able to simulate the dynamic behavior of ecosystems as well as buildings and the feedback loops that explain their behavior. For a building to mimic ecosystem processes and buildings and the feedback loops that explain their behavior. System dynamics facilitates the identification of these feedback loops and its integration in architectural systems. The process of transferring ecosystem’s feedback loops to architectural systems requires exhaustive calibration and simulation efforts that will be addressed in the following steps of this research work, but the results so far are promising.

REFERENCES
## APPENDIX

<table>
<thead>
<tr>
<th>NAME</th>
<th>EQUILIBRIUM VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STOCK</strong></td>
<td></td>
</tr>
<tr>
<td>Electrical energy in building</td>
<td>194 kWh m^{-2}</td>
</tr>
<tr>
<td>Energy in envelope</td>
<td>41 kWh m^{-2}</td>
</tr>
<tr>
<td><strong>FLOWS</strong></td>
<td></td>
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<tr>
<td>Electricity from grid</td>
<td>175 kWh m^{-2} yr^{-1}</td>
</tr>
<tr>
<td>Electricity from PV panels</td>
<td>7 kWh m^{-2} yr^{-1}</td>
</tr>
<tr>
<td>Electricity from Wind turbine</td>
<td>24 kWh m^{-2} yr^{-1}</td>
</tr>
<tr>
<td>Building systems</td>
<td>165 kWh m^{-2} yr^{-1}</td>
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<tr>
<td>Heating system</td>
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<td>Dispersed heat</td>
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<td>Reused heat</td>
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<tr>
<td>Heat dispersed outdoors</td>
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</tr>
<tr>
<td><strong>CONVERTERS</strong></td>
<td></td>
</tr>
<tr>
<td>Aging effect</td>
<td>1(graph func.)</td>
</tr>
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<td>Energy increase trend</td>
<td>1(graph func.)</td>
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<td>Aging PV</td>
<td>1(graph func.)</td>
</tr>
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<td>Aging Turbine</td>
<td>1(graph func.)</td>
</tr>
<tr>
<td>Randomness</td>
<td>24</td>
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<td>System's need MIN</td>
<td>145 kWh m^{-2} yr^{-1}</td>
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<tr>
<td>Renewable energy</td>
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</tr>
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<td>Efficiency rate</td>
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<tr>
<td>Maximum dispersed heat</td>
<td>84.13 kWh m^{-2} yr^{-1}</td>
</tr>
<tr>
<td>Heat dispersion rate</td>
<td>0.7</td>
</tr>
<tr>
<td>Actual dispersed heat</td>
<td>59 kWh m^{-2} yr^{-1}</td>
</tr>
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</table>

Table A.1 Starting conditions of the model
ABSTRACT
To achieve significant progress towards global targets for clean on-site energy self-sufficiency within the building sector, the integration of adaptive high efficiency solar collection systems into building envelope systems could offer broad additional benefits beyond power generation, such as: daylighting, hot water heating and purification, thermal comfort control, energy use reduction through lowered lighting and cooling loads, and tie-ins to direct current (DC) microgrids. Dramatic system efficiencies could be achieved with multifunctional envelopes by coupling to building systems to respond to fluctuations in weather and building use patterns. The development of active building envelope systems is impeded by current modeling workflows which do not provide adequate feedback or facilitate rapid design iteration within the context of building energy modeling (BEM). A simulation environment, Modelica, has purported extensibility and ease of co-simulation through the functional mock-up (FMI) standard. This environment is evaluated here through the development of a model for a novel multifunctional building envelope system, with concentrating photovoltaic and thermal collectors (BITCOPT) that incorporates multiple active and passive energy strategies simultaneously, while providing architectural benefits such as increased transparency and connection to views. The model is calibrated with measured data from an experimental prototype and is used to extrapolate the system’s theoretical power generation and energy efficiency effects. The simulation environment did indeed facilitate extensible model construction, encouraging future work to be pursued in co-simulation of the model with BEM via the FMI standard. The model structure, correlation to measured data, extrapolated results and future work are described here.

Keywords

ACM Classification Keywords
I.6.5 [Simulation and Modeling]: Model Development---energy; J.2 [Physical Sciences and Engineering]: Engineering---building science; J.5 [Arts and Humanities]: Architecture---integrated systems; General Terms: Design, Experimentation, Verification.

INTRODUCTION
As the building sector is responsible for 40% of primary energy use in the United States [10], it would be beneficial to evolve buildings into carbon-neutral systems that effectively exploit on-site energy resources and promote human health and well-being. Active envelope strategies have been identified as a promising route towards the development of these benefits while managing both program and environmental fluctuations at multiple time scales [9,19], however no building-integrated energy harvesting strategy currently exists that both meets environmental performance targets and accommodates year-round human comfort.

Modeling methods for active envelope strategies are likewise cumbersome. With currently available tools and workflows, it is difficult to express the dynamic, multi-domain effects of new strategies as they relate to established building physics models [13]. Consequently models are often created separately from BEM and then loosely connected through pre- and post-processing of data [23]. This method suffers from poor runtime feedback and excessive manual labor in the reduction of data, factors that that limit the application of these methods in the process of building systems design and implementation. Additionally there are two relevant behaviors that are difficult to represent through post-processing: controls, which update systems based on earlier states, and latency-related phenomena such as passive thermal massing or active thermal storage [24].

To expedite the development and integration of active envelope strategies as well as to impact design practices, policy and building codes, models of these strategies must be easy to calibrate, validate, and integrate with current-practice methods. For industrial acceptance, a modeling workflow should promote design iteration through informational feedback to the operator. Such a workflow conforms to the principle of progressive data input whereby a model offers initial results based on sparse input data and
results are refined as the inputs are refined [16]. To enable these qualities, a chosen modeling environment should exhibit adaptivity of modes of operation, encourage hierarchical and modular construction, and be interoperable with other environments (BEMs).

**Active Envelope: Building-Integrated Transparent Concentrating Photovoltaic and Thermal Collector**

A building’s envelope is tasked with controlling the shifting qualities of temperature, sunlight, wind, and moisture while maintaining tempered interior conditions [2,20]. With this gamut of responsibilities, improvements to the envelope are disproportionately consequential to building performance. Further, by integrating energy transformation technologies, the envelope can capture, store, transform, and redistribute energetic resources for use in building systems. A building-integrated, transparent concentrating photovoltaic and thermal collector (BITCOPT) system (shown in Figure 1) delivers these multiple benefits by intercepting and manipulating the direct-normal component of insolation ($I_{DN}$), the energetic component largely responsible for elevated cooling loads and uncomfortable, high-contrast lighting conditions in buildings of moderate to deep lease spans [5]. By intercepting $I_{DN}$ but remaining mostly transparent to diffuse insolation ($I_{Diff}$), the collector provides useful daylighting, maintains views, and reduces heat gain. Simultaneously, BITCOPT produces both electricity and high-quality thermal energy that can drive cooling and dehumidification (via sorption cycles), deliver service hot water and space heating, provide auxiliary electrical generation (via organic-fluid Rankine cycles) [22].

**BITCOPT Details**

The framework and results outlined in this paper are applied to a specific BITCOPT technology: the Integrated Concentrating Solar Façade (ICSF) developed at the Center for Architecture Science and Ecology, a research consortium co-hosted by Rensselaer and Skidmore Owings and Merrill LLP (Figure 1) [22]. ICSF is an array of collector modules hung within a curtain wall cassette. The modules are continuously tracked to the sun, each rotating around both horizontal and vertical axes. Each module comprises a flat Fresnel-like primary optical element (POE), a cast secondary optical element (SOE), a high-efficiency concentrator photovoltaic cell (CPV) and a water-block heat exchanger (HX). The last three elements form a sub-assembly, the receiver. The containing cassette is designed with a single-pane, low-iron glazing to the exterior and an insulated glazing unit (IGU) to the interior. As a curtain wall construction the cassette forms the envelope of the building and can be implemented vertically (as a standard façade), horizontally (as an atrium roof or skylight), or tilted.

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**Figure 1.** The BITCOPT system. Photographs of CASE Integrated Concentrating Solar Façade (ICSF) installation and data acquisition, with a diagram showing the adaptable energy conversion, storage and redistribution strategy.
The CPV within each module produces DC electricity ($E_{\text{gen}}$), collected from strings of modules wired in series and optimized per-string by a maximum power point routine. Thermal power ($Q_{\text{gen}}$) is transferred through the water blocks to a heat transfer fluid (HTF) that circulates through insulated hydronic tubing, transporting thermal energy from the array. Thermal energy is collected in a storage reservoir of high heat capacity (such as an insulated water tank) from which it can be extracted to drive processes.

Transparency is integral to BITCOPT. Most of the module and the super-structure parts within the window’s field of view are constructed from borosilicate glass or clear plastics, so while views directly through the lenses are obscured, at any given time most lines of sight through the array are available and the effect of visual transparency is maintained. Some daylight losses occur due to Fresnel (surface) reflectances as diffuse insolation passes through the clear materials of the modules and super-structure. Therefore BITCOPT separates direct and diffuse insolation, manipulating the two components differently.

Incentive for Model Development and Future Integration
As a responsive sub-system of a larger building system, BITCOPT cannot be modeled independently without mis-representing behavior such as daylighting control and the enthalpy changes of active thermal storage systems and/or thermal mass within building systems. Co-simulation—whereby a model’s sub-models are solved independently, with coupling through discrete domains—is therefore preferred to describe the behavior of a building with active envelope sub-systems. BITCOPT affects multiple values such as daylighting, glazing temperatures, solar heat gain, and zonal loads within the building (in addition to modifying the urban heat island contribution of the building to its local environment, which is beyond the scope of this paper). Because BITCOPT exchanges power with the building’s electrical and thermal systems across the entire building, its applications suggests distributing processes likewise throughout the building volume, changing not only the behavior of the building and its systems, but the fundamental design of the building and systems.

This gamut of effects from BITCOPT stands in contrast to the limited effects of alternative technologies for on-site generation (rooftop collectors, semi-transparent thin films, shading louvers, etc) which are not as tightly integrated into a building’s fabric and typically must trade-off between daylighting and energy collection [17]. Models of alternative envelope technologies (such as louvered blinds) do not need to address the multiple physical domains of daylighting, electrical generation, thermal collection, and load reductions simultaneously [15]. The BITCOPT model, however, should be developed in an environment that easily represents differential relationships and controls, meaning that co-simulation with adjoining models become important to system implementation.

METHODS
Previous models of BITCOPT-related systems have been developed towards specific ends [1,6,7] but new development is required to account for the full gamut of the array’s effects and to corroborate experimental results. The BITCOPT model in this paper processes inputs of environmental variables and system parameters and outputs of electrical generation, thermal collection, and heat transfer with adjacent systems (Figure 2 and Table 1). The input and output variables structure is intended to facilitate future integrations of the BITCOPT model with a BEM such as EnergyPlus or DETECT [4], leveraging existing

Figure 2. BITCOPT energy balance model and variable flow diagram. Component tags (denoted by #) are referred to in text.
modeling expertise to describe the range of BITCOPT whole building effects. The physics of the BITCOPT model have been developed from roughly-approximated energy balances and refined as necessary, with the goal of progressing towards more accurate descriptions of the array’s behavior in the whole-building context.

Motivation for Investigating Modelica

Although a dynamic physical system can be modeled in any computational environment, there may be a design advantage to a dynamics-specific environment if it allows a developer to focus more on the system description and less on solution methods. Modelica is one such high-level language for dynamic modeling and has been identified as useful for building modeling, with libraries actively developed and maintained for the purpose [24]. The language purports to speed model development by enforcing the principles of abstraction, modular re-use, and object-oriented structuring. It has been claimed that development of building models in Modelica is more expedient than other common tools [25]. Additionally, both Modelica and select BEM environments support the functional mock-up interface (FMI), a standard for model information interchange and co-simulation [24]. Previous work has focused on using Modelica to model heating, ventilation, and air-conditioning (HVAC), controls, facade-shading systems, and building-integrated solar [11,18]. The language has not yet been applied to an active envelope collector technology. Based on outcomes of the precedent research, it is expected that a streamlined workflow can be created by combining a BITCOPT model (created in Modelica) with BEM through the FMI standard.

BITCOPT Model Description

The computational model of BITCOPT is a quasi-steady state, lumped-capacitance representation of physical relationships. The relationships form a system of energy balance equations, outlined in Figure 2. The system of equations is solved at discrete time steps to determine the flow of energy between its components and their internal energy states. Although descriptive of the components of a specific technology (ICSF) the model is intended to be useful in characterizing BITCOPT generally, by describing the transformation of solar resources to electrical and thermal energy flows and modifications to thermal and optical behavior of the building envelope, in order to facilitate the modulation of these variables in future (customized) building envelope design processes.

The model’s inputs are listed in Table 1. $I_{DN}$ data is sourced (depending on the mode of analysis, either empirical or extrapolated) from experimental measurements or typical meteorological year (TMY3) data sets. A solar position vector is calculated from time and location data. Using the orientation of the envelope surface into which the BITCOPT is integrated, the angle of incidence ($\theta_{AOI}$) between the solar vector and the surface is calculated [8], as well as the surface-basis orthogonal pitch ($\theta_{pitch}$) and yaw ($\theta_{yaw}$) angles that correspond to the vertical and horizontal excursions of a solar tracking apparatus (Figure 2, #C).

As with two-axis tracking collectors systems generally (but unlike static collector systems) $I_{DN}$ is not reduced by the cosine of $\theta_{AOI}$ to determine power input to the collector. This factor is used, however, to calculate the insolation flux on an array area to determine momentary collector efficiencies. Additionally, transmittance through the external glazing due to reflectance and absorptance losses ($T_{Trans,glaz}$) is a function of $\theta_{AOI}$ (Figure 2, #GP). In this study the losses are combined and curve-fit from the bi-polar reflectance function (using Snell’s Law and assuming an index of refraction of 1.5) and manufacturer’s absorptance data [14]. The term $T_{Trans,glaz,norm}$ is applied to scale $T_{Trans,glaz}$ to either rated or measured glazing transmittance values.

<table>
<thead>
<tr>
<th>Model Inputs</th>
<th>Model Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building location</td>
<td>Electrical generation: net ($E_{net}$), efficiency ($\eta_{gen}$)</td>
</tr>
<tr>
<td>Orientation of BITCOPT envelope facet</td>
<td>Thermal collection: net ($Q_{col}$), energy efficiency ($\eta_{2gen}$)</td>
</tr>
<tr>
<td>BITCOPT array size and configuration</td>
<td>Heat transfer fluid outlet temperature ($T_{HTF,out}$)</td>
</tr>
<tr>
<td>Direct normal insolation ($I_{DN}$)</td>
<td>Heat transfer with outdoors, through glazing ($Q_{out}$)</td>
</tr>
<tr>
<td>Diffuse insolation ($I_{D}$)</td>
<td>Heat transfer with indoors, through glazing ($Q_{ind}$)</td>
</tr>
<tr>
<td>Heat transfer fluid inlet temperature ($T_{HTF,in}$)</td>
<td>Direct normal insolation to zone interior ($I_{DN,ind}$)</td>
</tr>
<tr>
<td>Outdoor Dry Bulb Temperature ($T_{out}$)</td>
<td>Cavity air temperature ($T_{cav}$)</td>
</tr>
<tr>
<td>Zone Mean Air Temperature ($\bar{T}_{ind}$)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Inputs and outputs of active envelope model.

The optical transmission efficiency ($\eta_{opt}$) is a constant in this model, a function of the f-number equivalent of a Fresnel/Kohler-type (non-imaging) lens pair with anti-reflective coating on the SOE [3] (Figure 2, #LT). The theoretical value ($\eta_{opt} = 88\%$) is treated as an upper bound and the efficiency is experimentally determined.

The un-shaded fraction of the POE ($F_{POE}$) must be calculated at each time step as the horizontal and vertical overlap between adjacent modules evolves from hour to hour with tracking geometry. $F_{POE}$ is interpolated from a two dimensional lookup table of measurements of the pitch and yaw in the experimental prototype (Figure 2, #MG).

Given these layered attenuations, the solar energy incident on the CPV ($\dot{Q}_{DN,CPV}$) is determined at a given time step (Equation 1), as is the effective concentration ratio at the CPV ($X_{eff}$, Equation 2), which represents flux relative to the ASTM G-173 (AM1.5) standard (Figure 2, #LT).

$$\dot{Q}_{DN,CPV} = I_{DN,car}A_{POE}F_{POE}\eta_{opt}$$

Equation 1. Solar power incident on CPV (#GP, #MG, #LT).
Equation 2. Effective flux concentration ratio as function of geometric concentration, CPV-incident irradiance, and AM1.5 reference insolation (G&T).

Module Energy Balance
The central energy flow relationship in the BITCOPT is through the receiver of each module. This energy balance is described in Equation 3 and the control volume boundary is described in Figure 2 (#REB) and Figure 3. Insolation, changes in HTF flow enthalpy, electrical generation, and convective losses (via overall heat transfer coefficients) are considered across the system boundary. For the sake of initial simplification, radiation losses from the receiver to the environment are considered negligible in the current model but this initial assumption will be challenged by the experimental data moving forward and the model will be adjusted accordingly.

\[
\frac{dT_{\text{receiver}}}{dt} = \frac{Q_{DN,CPV} - E_{\text{gen}}}{mc_{p,\text{receiver}}} - \dot{m}_{HTF}c_{p,HTF}(T_{HTF,\text{out}} - T_{HTF,\text{in}}) - U_{\text{receiver}}(T_{\text{receiver}} - T_{\text{cav}}) - \left( T_{HTF,\text{LMTD}} - T_{\text{cav}} \right)/R_{\text{tubing}}
\]


Electrical Generation
The electrical generation from the BITCOPT is a function of \( Q_{DN,CPV} \) and the conversion efficiency \( \eta_{E_{\text{gen}},CPV} \). (Conditioning losses exist as well, but are outside the bounds of the current model). \( \eta_{E_{\text{gen}},CPV} \) is a function of cell temperature \( T_{CPV} \) and \( X_{\text{eff}} \) [21].

Heterogeneous shading in serial CPV strings must be considered as a string is current-limited by its least-producing module. Although each CPV is paired to a bypass diodes that protects it from reverse-bias damage, the unshaded CPVs become forward biased and power output from the strings suffers by more than the fraction of shaded array area. Because the installation geometry of the BITCOPT system is assumed to be under the designer’s control, we assume all modules in an electrical string (typically one vertical stack of modules) are shaded equally by their neighbors and operate at full power. Shading effects are therefore not modeled presently, although they may be in the future. Experimentally some differential shading does occur in the top-row modules during higher module yaws, which predictably decreases measured electrical output.

To account for power conversion and conditioning, stacks of BITCOPT modules are assumed to be wired in parallel with each other via output-matching DC-DC converters such as those manufactured for panel PV markets. Maximum power point (MPP) tracking is performed for each string and the individual output DC voltages are scaled to match the MPP of the line load (such as a zone-scale low-voltage DC distribution network, or string inverter). Conversion losses are minimized with this technique (to less than 5%, as related through communication with Gene Krzywinski, CTO of eIQ Energy) so the BITCOPT array is currently modeled independently from these effects.

Thermal Collection
Thermal collection is a function of the energy available at the CPV and the water block heat exchanger characteristics and results in elevation of the HTF temperature (Equation 4). The water block’s resistance to heat flow \( R_0 \) is a function of HTF flow rate, but is treated as constant due to the limited range of flow rates in the experimental setup, and is determined via measurements of CPV, HTF inlet and HTF outlet temperatures.

\[
m_{HTF}c_{p,HTF}(T_{HTF,\text{out}} - T_{HTF,\text{in}}) = \left( T_{CPV} - T_{HTF,\text{LMTD}} \right)/R_0
\]

Equation 4. Relationship between HTF and CPV driving temperatures and collected heat at module receiver (#WBHS).

Thermal Losses (Receiver and Transport Hydronics)
Because the HTF temperature lift across BITCOPT is correlated to collection efficiency, knowledge of the insulation against heat losses is needed to gauge overall system performance. Two resistances in the model account for energy flow across the receiver control volume boundary: heat lost from the receiver surfaces and losses in...
the hydronic transport. Receiver heat losses are modeled with overall heat transfer coefficients (Equation 5).

\[
\dot{Q}_{\text{receiver}} = \frac{(T_{\text{receiver}} - T_{\text{cav}})}{R_{\text{receiver}}}; \quad R_{\text{receiver}} = \frac{1}{U A_{\text{receiver}}}
\]

Equation 5. Thermal energy lost at the receiver (#REB).

Transport heat losses are determined by a steady-state model of fluid flow through an insulated pipe with constant surface temperatures, a reasonable assumption due to high insulation value of the assembly and large operational difference between \(T_{\text{HTF}}\) and \(T_{\text{cav}}\) (Equation 6). These assumptions dictate constant temperatures in the material of the transport tubing (Equation 7) and a Nusselt number for both HTF and cavity air convections of 3.66 [12].

\[
\dot{Q}_{\text{loss}} = \frac{(T_{\text{HTF}} - T_{\text{cav}})}{R_{\text{tubing}}}
\]

Equation 6. Thermal transport loss as a function of tubing insulation and temperature difference (#TTL).

The insulation value \(R_{\text{tubing}}\) of the transport tubing assembly is modeled according to material geometry, conductivities, and convection coefficients [12]. The thermal transport efficiency \(\eta_{\text{tubing}}\) is related to tubing wall resistance, HTF mass flow rate, and HTF specific heat (Equation 8).

\[
\dot{Q}_{\text{outlet}} = \dot{Q}_{\text{inlet}}\eta_{\text{tubing}} \quad ; \quad \eta_{\text{tubing}} = e^{\left(-\frac{1}{R_{\text{tubing}} T_{\text{HTF}} T_{\text{HTF}}}\right)}
\]


\[
Q_{\text{loss}} = \frac{(T_{\text{HTF}} - T_{\text{cav}})}{R_{\text{tubing}}}
\]

Heat Gain Between Cassette Cavity, Indoors, Outdoors

Conditions in a curtain wall cavity are difficult to model because insolation, air flow, and pressure, temperature, and moisture gradients converge under fluctuating conditions. The heat transfer described here between the cassette indoors, and outdoors forms the second fundamental energy balance in the BITCOPT system and is currently a simplified representation of an active envelope system, a placeholder for future development. The cassette is considered to be sealed with well-mixed air and negligible infiltration. The cassette’s heat capacity comprises trapped air, fractions of the interior and exterior glazing, and the tracking components of the BITCOPT. Energy is exchanged with the climate, the occupied zone, and building systems according to Equation 9 and Figure 3.

\[
C_{p,\text{cassette}} \frac{dT_{\text{cav}}}{dt} = \dot{I}_{\text{DN,trans.glas}} (A_{\text{glas}} \cos(\theta_{\text{AOI}})) - Q_{\text{DN,ind}} + (A_{\text{glas}})(I_{\text{diff.cav}} - I_{\text{diff.ind}}) + \dot{U}_{\text{out}}A_{\text{glas}}(T_{\text{out}} - T_{\text{cav}}) + \dot{U}_{\text{ind}}A_{\text{glas}}(T_{\text{ind}} - T_{\text{cav}}) - E_{\text{gen}} - \dot{Q}_{\text{gen}}
\]


Boundary conditions for the cavity energy simulation include the outdoor dry bulb temperature \(T_{\text{outd}}\), gathered from TMY3 data, and a constant-temperature interior \(T_{\text{ind}}\). Heat transfers one-dimensionally between the exterior and the cavity according to an overall heat transfer coefficient \(U_{\text{outd}}\), calculated from convection on the exterior glazing surface, conduction through the glazing, and interior surface convection (Equation 10). The coefficient to the interior \(U_{\text{ind}}\) is similar but refers to the constant \(T_{\text{ind}}\), a lower convection heat transfer, and an insulated glazing unit (Equation 11).

\[
U_{\text{outd}} = \left(\frac{1}{h_{\text{outd}}} + \frac{L_{\text{glass}}}{k_{\text{ind}}} + \frac{1}{h_{\text{ind}}}\right)^{-1}
\]


\[
U_{\text{ind}} = \left(\frac{1}{h_{\text{ind}}} + \frac{L_{\text{glass}}}{k_{\text{ind}}} + \frac{1}{h_{\text{ind}}} + \frac{1}{k_{\text{gap}}} + \frac{1}{h_{\text{ind}}}\right)^{-1}
\]


Reducing Direct Normal Insolation to Building Interior

Although most direct insolation is gathered by the array, a fraction \(F_{\text{DN,ind}}\) passes through the spaces between POEs when the solar vector is near-normal to the array and the angle of incidence \(\theta_{\text{AOI}}\) is small. The module lenses are 100% opaque to I\(_{\text{DN}}\) (while tracking) but due to array geometry the POEs do not constantly overlap to fill the full aperture of the cassette. \(F_{\text{DN,ind}}\) peaks at 15% to 30% for short periods depending on module spacing, and falls to 0% when the array turns far enough (15°-25° depending on module spacing) around both axes. This area-fraction function is determined through measurements of the prototype and is represented in the model by an interpolated look-up table.

INITIAL RESULTS AND DISCUSSION

To explore the utility of the workflow, this modeling effort has two goals: calibration of the model to experimentally measured results and extrapolation to a BEM-compatible data set. First, the model should reflect the operation of the physical, experimental BITCOPT (currently testing at CASE in New York City). Correlation between collected data and model output serves both to validate the behavior of the model and to highlight aspects of the experiment that are operating as expected (or otherwise). The second goal is to extrapolate the behavior of BITCOPT in a configuration that is compatible with BEM, as a set of data points in hourly intervals with a length of one year, towards the design and estimated values of the system for multiple climate types, during the design process.

For calibration, the model is configured to represent the geometry and material properties during a period of data acquisition. The output of this configuration is compared to empirical electrical generation, thermal collection, and receiver temperature data from that period by applying measured \(I_{\text{DN}}\) and \(T_{\text{HTF, in}}\) as boundary conditions.
**Data Acquisition**

A configuration of the BITCOPT prototype was tested that comprised nine active modules, corresponding to roughly 1m² of façade area. $E_{gen}$ data was collected from an electronic load (BK 8500), into which power was sunk from the series-wired modules. The string’s MPP was periodically maintained by adjusting the load’s voltage input. This data was compared to $I_{DN}$ measured by two pyrheliometers (Hukseflux DR01) mounted in the tracker.

$Q_{gen}$ data was gathered by measuring HTF flow rates, and temperature differences. Flow rates were read with Porter float-type meters with a full-scale reading of 3.3ml/s. Temperatures were measured at inlets and outlets of the water blocks with K-type, sheathed, ungrounded thermocouples (Omega) in contact with HTF. Specific heat of the HTF (distilled water) was calculated continuously relative to measured temperatures. Temperatures at the water block-CPV mating surface were measured with T-type sheathed thermocouples (at two modules). Control was written in LabVIEW, and data logged with NI-9213 and -9205 modules in a cDAQ-9178 chassis.

**Model Calibration**

In an example data set, modeled $E_{gen}$ and $Q_{gen}$ show good response to the trends in measured $I_{DN}$ (Figure 4). There are three notable exceptions. Prior to 1:48pm the top row of modules were shaded by the frame of the window in which the prototype is installed. The two deviation spikes at 1:58pm and 2:28pm correspond to deactivation of the tracking, where the prototype lost optical alignment with the sun. Although the insolation focused on the CPV decreased, decreasing electrical generation, energy was still directed to the receiver, increasing thermal collection.

![Figure 4. Measured and modeled power generation.](image)

The parameters $R_0$, $\eta_{opt}$, and $R_{receiver}$ are modeled analytically and their values measured experimentally. They are calibrated to minimize the root mean square (RMS) error between the modeled and measured $Q_{gen}$, $E_{gen}$, and $T_{CPV}$ data (relative to sample mean) (Table 2).

![Table 2. Parameters for measured-modeled data calibration.](image)

Results of parameter calibration suggest improvements to the BITCOPT prototype. Optical efficiency ($\eta_{opt}$) is low compared to the theoretical value (88%), which suggests lens build quality can be improved. The thermal resistance of the water block ($R_0$) is higher than the resistance in other considered exchanger designs (1.6 vs 0.2) at similar flow rates suggesting that a more performance-optimized exchanger would improve collection efficiency.

![Figure 5. Year-long simulation of energy collection with experimentally-derived model parameters.](image)

The calibrated model is extrapolated to year-long results by using the $I_{DN}$ vector from TMY3 data (New York City climate) as a point of comparison (Figure 5). It’s noticeable that the thermal generation is higher, relatively, in the warmer months, possibly due to elevated cavity temperatures (which reduces thermal losses).

![Figure 6. As modeled BITCOPT intercepts 96% (yearly) of $I_{DN}$ transmitted past exterior glazing of south and west facades.](image)

The reduction of $I_{DN}$ to the building interior was modeled with New York City TMY3 data (Figure 6). Results indicate that BITCOPT has good potential for daylighting modification, reducing gains from $I_{DN}$ by 96% relative to a comparable double-skin curtain wall system.

It has been observed that heat lost from BITCOPT will elevate cavity and glazing temperatures, increasing loads during cooling periods, but that the effect is insignificant relative to the reduction of $I_{DN}$ to the indoors and attendant loads reduction. Future experimentation and modeling will be conducted to challenge these findings in the context of different climate types.

**CONCLUSION**

To explore new workflows for adaptive building technologies, a model was constructed in the Modelica language for a dynamic solar building envelope system.
The model was calibrated to experimental results and used to extrapolate full-year data sets (energy generation and the blocking of direct insolation) to facilitate future integration within building energy models. Development in Modelica proved successful, in part by demanding hierarchical structures encouraging users to iteratively increase the complexity of a model’s physics. Once calibrated, the model exhibited good predictive ability and suggested future modifications in the experimental setup and the system development. In the next phase, a functional mockup unit (FMU) of the model will be generated in Modelica to co-simulate with an Energy Plus building model by connecting the models’ variables for insolation penetration and glazing temperature to observe the effects of the system on the heating, cooling, and lighting loads of a modeled building. Although the integration of this model with building energy models has not yet been attempted, the framework for that integration is native within the environment, which is expected to facilitate future variations on systems design and customization according to specific variations in local climate conditions, building types, occupation patterns and aesthetic requirements.

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REFERENCES
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Holly Ferguson is currently a PhD student at the University of Notre Dame in the Computer Science and Engineering Department and she additionally holds both a Masters in Computer Science and a Masters in Building Architecture. Her recent research projects are in collaboration with the Notre Dame Center for Research Computing and the Green Scale Research Group to advance the fields of Big Data, Linked-Data, the Semantic Web, and Decision Theory Frameworks directly related to 3D spatial challenges and risk assessment. Holly is passionate about several areas of study that advance technology-enhanced architectural practices, environmental systems, and methods for positively impacting the knowledge bases from which we all gather information and make decisions.

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Priya Gandhi is an MS student in the Building Science program in the Department of Architecture at the University of California, Berkeley. After earning a BS in Mechanical Engineering from the University of Illinois Urbana-Champaign, she worked as an environmental design consultant at Atelier Ten, performing daylight and envelope performance studies, and conducting whole building energy modeling for new and existing buildings. She is currently a graduate student researcher with the Center for the Built Environment, investigating the variability of plug load energy consumption and the role of occupant behavior on plug load energy use in commercial buildings.

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Axel Körner

Axel Körner received his Diploma in Architecture at the University of Applied Sciences in Munich 2008 and his MSc. in Emergent Technologies and Design from the Architectural Association School of Architecture in London September 2013 with distinction. He worked for several architecture practices in Munich, Vienna and London, as well as for Createx and Northsails TPT in Switzerland where he was part of a multi-disciplinary team of mechanical engineers, chemists and computer scientists working on carbon fibre material research. Since October 2014 he has been working as a research associate at the ITKE, Institute of Building Structures and Structural Design, University of Stuttgart, where his research is focused on kinematics of planar, curved and corrugated plant surfaces as concept generators for deployable systems in architecture and bio inspired adaptive façade systems.
Stelios Krinidis

Stelios Krinidis is a postdoctoral research assistant in CERTH-ITI. He received the Diploma degree and the Ph.D. degree in Computer Science from the Computer Science Department of the Aristotle University of Thessaloniki (AUTH), Thessaloniki, Greece, in 1999 and 2004 respectively. He has also served as an adjunct lecturer at the Aristotle University of Thessaloniki, the Democritus University of Thrace, and at the Technological Institute of Kavala during the period 2005-2012. His main research interests include computational intelligence, computer vision, pattern recognition, signal processing and analysis, 2D and 3D image processing and analysis, image modelling, fuzzy logic and visual analytics. He has authored twenty (20) papers in international scientific peer review journals and more than twenty (20) papers in international and national conferences. He has also been involved in ten (10) research projects funded by the EC and the Greek secretariat of Research and Technology.

Chris Mackey

Chris Mackey is a graduate student at MIT who is currently pursuing a dual degree for a Masters of Architecture and a Masters of Science in Building Technology. With an expected graduation date in Spring 2015, Chris is currently working towards a combined thesis between these degrees, which will focus on thermally adaptive occupant behaviour and the design possibilities presented by occupants moving around a space to make themselves comfortable. His work experience has ranged from being a climate researcher at Yale University, to a designer at an architecture firm, to an energy modeler and software developer at Thornton Tomasetti. In his free time, Chris is an avid coder and contributor to the Ladybug + Honeybee environmental analysis plugins for grasshopper and is in the process of adding several new tools to the suite that will allow for in-depth thermal comfort analysis.

Annie Marston

Annie Marston is the head of the Building Performance team at Baumann Consulting. She is an expert in energy modeling, CFD modeling and daylight modeling. Annie completed her Ph.D. in Architecture and Renewable Energy in 2008. Part of Annie’s PhD included the invention of a device that blocks wind turbines from being seen by Air Traffic Controllers (ATC) and has since been patented. During her PhD, Annie created her own software package that performed steady state calculations on buildings for the Millward Partnership to test various passive and active energy saving techniques for their designs. In addition to her industry commitments, Annie also taught energy modelling to graduate students at the Catholic University of America. Outside of her work, she is the Vice-President of the IBPSA National Chapter and is on the IBPSA-USA board.

Kirk Martini

Kirk Martini teaches structural design at the University of Virginia School of Architecture. He received an A.B. in Architecture in 1980, an M.S. in Structural Engineering and M.Arch. in 1982, and a Ph.D. in Structural Engineering in 1990: all from U.C. Berkeley. He is a licensed Civil Engineer in California and has worked at Skidmore, Owings and Merrill in San Francisco. In 1989 he worked as a graduate student summer intern at Taisei Construction in Tokyo, and completed post-doctoral studies at Tokyo University in 1992. Since then, he has taught at U.Va. In 2007 his Arcade software for nonlinear structural analysis won the Premier Award for Excellence in Engineering Education Software. In 2008 he won a University of Virginia All-University teaching award. His research interests include seismic design, non-linear structural analysis, and optimization to support creative design.

Clayton Miller

Clayton is a Doctorate Fellow at the Institute of Technology in Architecture (ITA) at ETH Zürich and with a focus in monitoring building performance metrics. His research is based at the Chair of Architecture and Building Systems (A&S) in Zürich, Switzerland and the Future Cities Laboratory (FCL) in Singapore. He was formerly the CTO of a Singaporean startup company focused in building performance monitoring and has also worked as a Mechanical Systems Designer and Energy Engineer. Clayton holds a MSc. (Building) from the National University of Singapore (NUS) and a Masters of Architectural Engineering (MAE) and BSc. from the University of Nebraska - Lincoln (UNL). He is a former Fulbright Student Scholar to Singapore at NUS and a Walter Scott Jr. Scholar at UNL. More information about Clayton’s research can be found at: www.datadrivenbuilding.org
Matthew Naugle

Matthew Naugle is member of Thornton Tomasetti’s CORE studio team, responsible for establishing digital workflows for the multifaceted modeling processes within the firm. He is responsible for teaching and developing methods that utilize parametric modeling, interoperability, integrated analysis, BIM management and geometry rationalization. Naugle has taught and lectured on the topics of parametric design, digital fabrication and building systems at Philadelphia University, Stevens Institute of Technology, and the University of Pennsylvania along with a host of industry conferences throughout the United States.

Nick Novelli

Nick Novelli received a B.S. in Mechanical Engineering from Tufts University and practiced in device-scale R+D for several years. He is currently a PhD Candidate at the Center for Architecture Science and Ecology (CASE) at Rensselaer Polytechnic Institute, where he helped to define research into the building-scale collection, distribution and application of thermal energy by applying thermodynamic principles and engineering analyses to architectural problems. In the course of research he has designed and led workshops and courses in parametric modeling and subjective environmental feedback design. He has participated in the design, prototyping and construction of zooming infrared optics and their controls, backpack-portable alternative power generators, solar tracking and collection systems at various scales, multi-domain energy models, sensing and visualization techniques for energy flows, composting toilets, and houses.

Alexandra Rempel

Alexandra Rempel is an Assistant Professor in the Center for Architecture Science and Ecology at Rensselaer Polytechnic Institute, where her research and teaching focus on passionate solar heating, passive cooling, and natural ventilation design. Her research combines field investigations and modeling to reveal thermal and airflow patterns that cannot be fully revealed by either approach alone. The intent of this work is to bridge the gap between theory and practice, ultimately helping architects and engineers develop climate-responsive passive and hybrid heating and cooling systems with greater confidence. Previously, as a microbial ecologist, she investigated aspects of biodyrrogen production, bioremediation, forest ecology, and atmospheric chemistry, and she welcomes discussions of the roles of ecological ideas in building design. She holds an M.Arch. from the University of Oregon, a Ph.D. in Biology from MIT, and a B.A. in Biochemistry from Harvard.

Mostapha Sadeghipour Roudsari

Mostapha Sadeghipour Roudsari is a designer and software developer focused on building environmental design. He is currently an Integration Applications Developer at Thornton Tomasetti’s CORE studio and, over the last few years, he has been dedicated to the integration of parametric environmental analysis and architectural design. Mostapha is the creator of two open-source environmental plugins for Grasshopper, Ladybug and Honeybee, and recently started development of epwmap and Pollination - two web-based applications that ease the access to epw weather files and enable the exploration of multi-dimensional data. He lectures and teaches seminars frequently throughout Architecture and Engineering schools, the AEC community, and, recently, as a staffed lecturer at the University of Pennsylvania.

Holly Samuelson

Dr. Samuelson is an Assistant Professor at the Harvard Graduate School of Design (GSD). She teaches architectural technology courses, specializing in the energy and environmental performance of buildings. Her research focuses on computerized simulation of energy and daylight in buildings and the future of the building industry as it embraces such technology. Among her authored and coauthored papers, she has contributed articles to Building and Environment, the Journal of Building Performance Simulation, and Ecological Urbanism (Lars Müller, 2010). Prior to joining Harvard, Holly practiced full-time as an architect (2000-2007) and sustainable design consultant (2007-2008). She earned a Bachelor of Architecture from Carnegie Mellon as well as a Master and Doctor of Design from Harvard University.
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 topics involve human behavior simulation in not-yet built environments, spatial knowledge representation, development and application of ethnographic data collection methods to correlate user activities with the built environments in which they are performed, and utilization of virtual environments to support evaluation and communication in the architectural design process.

Yair Schwartz


Zixiao (Shawn) Shi

Zixiao (Shawn) Shi is a Ph.D. student in Civil Engineering and a research assistant in the Human-Building Interaction lab at Carleton University, Canada. He received his B.Sc. and M.Sc. in Civil Engineering from Purdue University, U.S.A., in 2011 and 2012, respectively. He worked as a building sustainability consultant before joining the Architectural Conservation and Sustainability Engineering program at Carleton University, in 2014. He currently researches on building diagnostics and fault detection of Carleton University's Digital Campus Innovation Project, in collaboration with Autodesk Research. Other main areas of his research interest are building performance simulation, model predictive control and building data mining. He is also actively involved in the development and evaluation of sustainability programs for major community housing organizations in Ottawa.

Justin Shultz

Justin Shultz received a B.S. in Energy Engineering from The Pennsylvania State University with Minors in Environmental Engineering and Energy Business and Finance. He is currently a PhD Student at the Center for Architecture Science and Ecology (CASE) at Rensselaer Polytechnic Institute (RPI), where he helps to advance modeling techniques in architecture through a working collaboration with RPI’s Scientific Computational Research Center (SCOREC). In the course of his research he has explored modeling techniques including: device scale performance simulations, whole building energy modeling with integrated future energy capture technology, year-long daylight studies for dynamic glazing systems using the 3-phase raytracing method, computational fluid dynamics of double skin facades, and conservation law modeling for simulation of dynamic envelope systems. His current research focuses on advancing future energy technology in building design by integrating new modeling strategies for dynamic building envelopes into current practice energy modeling applications.

Raghu Sunnam

Raghu Sunnam is a Building Performance Analyst at Baumann Consulting in Washington D.C. He has been involved in Energy Modelling and HVAC Commissioning projects. He has also been working on Operation Diagnostics which is a visual approach to analyze sensor trend data that was developed at Baumann to diagnose HVAC control issues. Raghu has also been working on projects related to Building Enclosure Commissioning and M&V (Measurement and Verification). Raghu has a background in Architecture and Construction Management. In previous commitments he was working with Architectural firms in India and Australia. Currently he is also pursuing his PhD in Civil and Environmental Engineering as a part-time student at Carnegie Mellon University on the topic of Building Information Modeling for HVAC controls.
Martin Tamke

Martin Tamke is an Associate Professor at the Centre for Information Technology and Architecture (CITA) in Copenhagen. He is pursuing design led research in the interface and implications of computational design and its materialization. He joined the newly founded research centre CITA in 2006 and shaped its design based research practice. Projects on new design and fabrication tools for wood, textile and composite production led to a series of digitally fabricated demonstrators that explore an architectural practice engaged with bespoke materials and behavior. Martin initiated and conducted a large amount of funded research projects in the emerging field of digital production in building industry and architectural computation. The research connects academic and industrial partners from architecture and engineering, computer and material science and the crafts. The good connection to communities allowed him to setup several international conferences and networks with extensive funding. Currently he is involved in the EU framework 7 project DURAARK, the Danish funded 4 year Complex Modelling research project and the adapt-r and InnoChain PhD research networks.

Ming Tang

Ming Tang, AIA, LEED AP, Assistant Professor, School of Architecture and Interior Design (SAID), College of Design, Architecture, Art, and Planning at University of Cincinnati. He is a registered architect, and founding partner of Tang & Yang Architects. The firm has won numerous design awards, including first place in d3 Natural System Competition, IAAC self-sufficient housing contest, and Chichen Itza lodge museum design competition. His research includes parametric design, digital fabrication, building information modeling, virtual reality, human-computer interaction (HCI), and performance-driven design. His book, Parametric Building Design with Autodesk Maya was published by Routledge in 2014. Homepage: http://ming3d.com

Mani Williams

Mani Williams is a PhD Candidate and Research Associate in the Spatial Information Architecture Laboratory (SIAL), RMIT University. Mani has a multi-discipline background of engineering, mathematics and architecture. Her current research interest is in adapting and extending current complex network theory to reveal the dynamics of social interactions. She has published international papers in the areas of digital design, design studies, ubiquitous computing and image processing.

Gabriel Wurzer

Gabriel Wurzer is a researcher focusing on early-stage hospital planning using agent-based simulation. He furthermore holds a keen research interest in simulation for archaeology, a field in which he has recently published a Book on "Agents in Archaeology". Having been trained as a computer scientist, he has switched over to architectural sciences for completing his PhD and writing his "habilitation thesis" (Austrian tenure track). He is currently researching at Vienna University of Technology and the Vienna University of Economics and Business.
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A Physical and Numerical Simulation Strategy to Understand the Impact of the Dynamics in Air for the Design of Porous Screens
Mani Williams, Rafael Moya, Daniel Prohasky, Mehmoush Latifi Khorasgani, Simon Watkins, Jane Burry, Philip Belesky
RMIT University
Mark Burry
University of Melbourne

Curve-folded Form-work for Cast, Compressive Skeletons
Shajay Bhooshan, Vishu Bhooshan, Ashwin Shah, Henry Louth, David Reeves
Zaha Hadid Architects

Digital Campus Innovation Project: Integration of Building Information Modelling with Building Performance Simulation and Building Diagnostics
Zixiao Shi, Aly Abdelalim, William O’Brien
Carleton University, Human-Building Interaction Lab
Peter Akiki, Katie Graham, Barbara Van Waarden, Steve Fai
Carleton University, Carleton Immersive Media Studio
Ramtin Attar, Alex Tessier, Azam Khan
Autodesk Research

Toward Pre-Simulated Guidelines for Low-Energy High-Rise Residential Design in Megacities
Holly Samuelson, Alejandra Romo-Castillo, Yujiao Chen
Harvard University
Apoorv Goyal
LMN Architects
Sebastian Claussnitzer, Arpan Bakshi
SOM
Computing Curved-Folded Tessellations through Straight-Folding Approximation
Suryansh Chandra
Zaha Hadid Architects
Axel Körner
University of Stuttgart
Antiopi Koronaki, Rachelle Spiteri, Radhika Amin, Samidha Kowli, Michael Weinstock
AA School of Architecture

Aware Design Models
Martin Tamke
Centre for Information Technology and Architecture (CITA)

David Jason Gerber, Evangelos Pantazis, Leandro Marcolino, Arsalan Heydarian
University of Southern California

Simulating Human Behavior in not-yet Built Environment by Means of Event-Based Narratives
Davide Schaumann, Yehuda E. Kalay
Technion – Israel Institute of Technology
Seung Wan Hong
Inha University
Davide Simeone
Sapienza University of Rome

Self-Organizing City: Experiments Using Multi-Agent Model and Space Syntax
Ming Tang
University of Cincinnati
Author Index

A
Abdelalim, Aly 25
Akiki, Peter 25
Amin, Radhika 221
Ashour, Yassin 59
Attar, Ramtin 25

B
Baksh, Arpan 119
Barg, Steve 51
Baumann, Oliver 231
Belesky, Philip 155
Berry, Jane 93
Bhooshan, Shajay 145
Bhooshan, Vishu 145
Brager, Gail 173
Breslav, Simon 77
Buccellato, Aimee P. C. 17
Burry, Jane 155
Burry, Mark 155

C
Chandra, Suryansh 221
Chen, Yujiao 119
Clark, Grant 239
Claussnitzer, Sebastian 119

D
Dritsas, Stylianos 131
Drosou, Anastasios 85
Dutton, Spencer 163,173
Dyson, Anna 249

F
Fai, Steve 25
Ferguson, Holly 17
Fischer, Martin 51
Flager, Forest 51
Fu, Zhuzhou 231

G
Gandhi, Priya 173
Garcia-Holguera, Mercedes 239
Gaskin, Susan 239
Gerber, David Jason 67
Glock, Barbara 97
Goldstein, Rhys 77
Goyal, Apoorv 119
Graham, Katie 25

H
Hafner, Irene 97
Heydarian, Arsalan 67
Hong, Seung Wan 7
Hornbaek, Kasper 77
Hudson, Roland 207
Ioannidis, Dimosthenis 85

K
Kalay, Yehuda E. 7
Khan, Azam 25, 77
Kolarevic, Branko 59
Körner, Axel 221
Koronaki, Antiopi 221
Kowli, Samidha 221
Krinidis, Stelios 85

L
Latifi Khorasgani, Mehrmous 155
Likothanassis, Spiridon 85
Lorenz, Wolfgang E. 97
Louth, Henry 145

M
Mackey, Christopher 197
Marcolino, Leandro 67
Marston, Annie 231
Martini, Kirk 43
Miller, Clayton 33
Moya, Rafael 155
Mumovic, Dejan 103

N
Naugle, Matthew R. 189
Novelli, Nicholas 249
<table>
<thead>
<tr>
<th>Author</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O’Brien, William</td>
<td>25</td>
</tr>
<tr>
<td>Pantazis, Evangelos</td>
<td>67</td>
</tr>
<tr>
<td>Popper, Niki</td>
<td>97</td>
</tr>
<tr>
<td>Porras-Amores, César</td>
<td>163</td>
</tr>
<tr>
<td>Prohasky, Daniel</td>
<td>155</td>
</tr>
<tr>
<td>Rao, Asha</td>
<td>93</td>
</tr>
<tr>
<td>Raslan, Rokia</td>
<td>103</td>
</tr>
<tr>
<td>Reeves, David</td>
<td>145</td>
</tr>
<tr>
<td>Remington, Stephen J.</td>
<td>111</td>
</tr>
<tr>
<td>Rempel, Alexandra R.</td>
<td>111</td>
</tr>
<tr>
<td>Romo-Castillo, Alejandro</td>
<td>119</td>
</tr>
<tr>
<td>Rössler, Matthias</td>
<td>97</td>
</tr>
<tr>
<td>Sadeghipour Roudsari, Mostapha</td>
<td>183, 189, 197</td>
</tr>
<tr>
<td>Samaras, Panagiotis</td>
<td>197</td>
</tr>
<tr>
<td>Samuelson, Holly</td>
<td>119</td>
</tr>
<tr>
<td>Schlueter, Arno</td>
<td>33</td>
</tr>
<tr>
<td>Schumann, Davide</td>
<td>7</td>
</tr>
<tr>
<td>Schwartz, Yair</td>
<td>103</td>
</tr>
<tr>
<td>Shah, Ashwin</td>
<td>145</td>
</tr>
<tr>
<td>Shi, Zixiao</td>
<td>25</td>
</tr>
<tr>
<td>Shultz, Justin</td>
<td>249</td>
</tr>
<tr>
<td>Simeone, Davide</td>
<td>7</td>
</tr>
<tr>
<td>Spiteri, Rachelle</td>
<td>221</td>
</tr>
<tr>
<td>Sprecher, Aaron</td>
<td>239</td>
</tr>
<tr>
<td>Sunnam, Raghuram</td>
<td>231</td>
</tr>
<tr>
<td>Tamke, Martin</td>
<td>137</td>
</tr>
<tr>
<td>Tang, Ming</td>
<td>215</td>
</tr>
<tr>
<td>Tessier, Alex</td>
<td>25</td>
</tr>
<tr>
<td>Tzovaras, Dimitrios</td>
<td>85</td>
</tr>
<tr>
<td>van Waarden, Barbara</td>
<td>25</td>
</tr>
<tr>
<td>Vardeman II, Charles F.</td>
<td>17</td>
</tr>
<tr>
<td>Waelkens, Anne</td>
<td>183</td>
</tr>
<tr>
<td>Watkins, Simon</td>
<td>155</td>
</tr>
<tr>
<td>Weinstock, Michael</td>
<td>221</td>
</tr>
</tbody>
</table>