ARCHITECTURE OF COMPLEXITY
DESIGN, SYSTEMS, SOCIETY AND ENVIRONMENT

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**Design, Systems, Society and Environment**

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OPENING PLENARY
THINKING IN BUILDING/ENVIRONMENT SYSTEMS:
A RESPONSE TO THE “SYSTEMS THINKING VIDEO” OF THE LATE RUSS ACKOFF

Brook Muller
'University of Oregon, Portland, Oregon

Russ Ackoff describes the architect as the model of a systems thinker and the house a fine example of a system. Through a process of adjusting layouts of rooms in relation to a house in its entirety, and by fine-tuning the design of the house through modifications to the rooms, the architect embraces an understanding that a whole consists of parts that influence its properties, and that the effectiveness of any one part depends on the effects of others. Acknowledging these essential system traits, it becomes possible to implement an improvement program directed toward what is wanted: a well-designed house.

The video pans to the audience; conference attendees nod in comprehension. The obviousness that a house is a system with rooms as its parts makes it an apt example. And yet arguably it is an insufficient characterization of the system given dependencies of the house and its rooms on the effectiveness of others, the typically hidden infrastructures that make a dwelling livable and functional: those systems that supply energy, information, and water and that dispose of waste (wastewater, condensate from the cooling unit on the roof, etc.). So while they are there, with all their network-like tendrils to other systems and to the environment, and in part because the architect relegates these to back-of-house and allows others to design and specify them, these ‘invisible’ systems seldom contribute to our image of the house-system.

Perhaps Le Corbusier’s famous dictum that the house is a machine for living in, a self-contained unit made of interdependent, industrialized parts, has helped hardwire this isolationist systems view. Whatever the cause, it warrants relating this clearly demarcated image of a system to the ARCC 2017 organizers mention of Ulrich Beck’s claim “that we wrestle today with the side effects of yesterday’s successes.” One of the reasons past successes – among them those manifest in our built environment – demand such wrestling is insufficient appreciation of the ways the system one is designing depends upon and impacts others. An overly insular conceptualization of a system corresponds to an overly narrow definition of success and leads to conditions where side effects are customary and where externalities with detrimental impacts (eco-systemic, other) are permitted.

A commitment to addressing these interdependencies and proceeding from a more expansive view of the system(s) one is working has ushered in promising new sustainable design initiatives and pathways. Net zero energy buildings, life cycle analysis, the Living Building Challenge and many like efforts fold externalities into the system such that successes produce fewer side effects. A desirable short-circuiting occurs, electrical energy and water for example are collected on site instead of arriving via the grid or interbasin transfer. Criteria of effectiveness become more sophisticated, the manipulation of rooms more consequential.

And yet as promising as these initiatives are, there is a lingering tendency to view the building as the boundary of the system and therefore to undervalue potential contributions (and impacts) to the ‘parent’ system of which buildings are a part. Architects design LEED Platinum buildings clad in zinc; rain events produce runoff containing zinc particulates that devastate aquatic life downstream. Even with as laudable an example as the Living Building Challenge, the conceptual construct, the metaphor that a building is alive, delimits mutually beneficial transactions between a project and its surroundings. The building is attended to as that which is animated, and biological processes and life cycles that might occur on the site are de-emphasized. Swept up with the idea of biomimicry, designers may unwittingly make high performance buildings inspired by the morphology of bugs that in aggregate hasten the decline of macro-invertebrate populations.

If the simplification of complex natural processes is one side effect issuing from the way we conceptualize systems and consequently the way we construct the built environment, might there be beneficial ecological implications by viewing the system as a building/environment pairing? Working on urban redevelopment sites that have been compromised ecologically as a result of previous human activity, would it be possible for built interventions to minimize externalities while delivering benefits to the parent (eco)system?

In a process he describes as opportunistic ecologies, urban naturalist Mark Wilson visits building sites near riparian corridors where historic wetlands have been largely obliterated (and where the city in question has encouraged their reintroduction). He observes locations of staging areas, movement of construction equipment, and the reshaping...
of terrain. He conducts percolation tests where soils have been compacted and identifies locations where proper subsurface conditions for constructed wetlands have been established. Building processes become regenerative processes contributing to ecosystem services. Or to take another example: projects by the ecological design firm Rana Creek Living Architecture typically utilize recycled water from cooling towers and other forms of rejected moisture to irrigate living roofs that serve as habitat and seedbanks for endangered grasses and wildflowers (the living roofs also help reduce cooling loads and decelerate storm-water flows).

These examples point to the value of conceptualizing an architectural system as a synchronization of building and landscape processes, where mutual benefits obtain. Waste in the form of moisture or residue in the form of compacted soils become constituent elements in an expanded system that includes ecological phenomenon. This expansion in turn improves the operational effectiveness of the building subsystem, as in the case of Rana Creek projects where cooling loads are reduced.

These examples also suggest that the metaphorical pole may have swung too far, that the machine, the paradigmatic metaphor for modern architecture now supplanted by the organism in an era of green, is not necessarily so sinister and life threatening. If machines are simply devices that modify and transmit force in order to produce desired effects, the question becomes what we are asking our machines to do and what inputs are necessary to make them run effectively given an expanded definition of success. Perhaps our architectural machines become prosthetics, systems assemblies that perpetuate transactions between the organic and inorganic in support of human needs and dramatically improved (urban) ecosystem function.
Our modern times are fraught with fragmentation, drowning in data, and confused about the means to realize a brighter tomorrow. We struggle to make sense of our highly complicated milieu in which right and wrong are deemed relative constructs and the perservasiveness of dualities proves paralytic. In the West our mantra is all too often “If you can’t count it, it doesn’t count.” Institutions increasingly invoke specialization as a means to advance and manage, while departmentalization serves to build walls, invent jargon and splinter communities. Russ Ackoff astutely mused that performance is not driven by the behavior of an organism’s or a machine’s individual parts but rather by the rich interplay of components comprising the whole. Gestalt psychology informs us such a whole is greater than the sum of the parts. It is in this completeness, and its ‘value-add’, that we as designers generate solutions that are relevant, meaningful and potent to our intensely complex world. Through much of the past century, as technology eclipsed art and science trumped humanities, our ability to tackle ‘wicked’ problems eroded. Many contemporary problems evade our comprehension – they are too big, too multifarious, too complicated and too global. They often prove resistant to linear, empirical and narrow efforts to rein them in and steer them in directions of our desire. Instead they mutate, shift, morph and move in unpredictable, clever and disturbing ways. Examples of such unbridled incomprehensible problems include the Ebola virus outbreak, Fukushima nuclear disaster, and Syrian conflict, to name but a few. Our present dilemma didn't simply appear, but evolved over recent centuries and decades as our knowledge expanded, egos mushroomed and ignorance blossomed. The great British essayist, C.P. Snow, in his seminal 1950's piece ‘The Two Cultures’ accurately prophesied crises we would confront if we continued with our divorce of science & technology from the arts & humanities. Unfortunately today we advantage science and technology at the expense of other established ways of knowing, including wisdom traditions and indigenous means. All too commonly our developed societies equate facts with truths, a dangerous and frequently erroneous assumption that ushers in major problems. As we know from history facts are only as good as the methods used to determine them – facts change as theories gain efficacy, instruments probe further, and tools illuminate better. In our troubled times we need to be especially prudent in our quest for the truth. A part of this judiciousness comes through understanding systems in play. To appreciate systems we must change our viewpoint. We need to concurrently distance ourselves to grasp the broader contextual field and immerse ourselves to determine the intricacies of interactions of parts. Western ways of knowing are fueled in large measure by reductionist posturing – breaking apart, separating, distilling, measuring and analyzing. However, to transcend to a novel vantage point we need to counter such moves. Rather than subscribing to dualistic modes of seeing we need to aggressively cut through such delusion and illusion to seek a deeper and more profound understanding. We need to dissolve the arbitrary separations and destructive polarizations that inform and influence much of our decision making in the current ethos – including within education, governance, health care, economies and the environment. Science versus Art. Technologies versus Humanities. Thinking versus Feeling. Objectivity versus Subjectivity. A part of this path of reconciliation demands the securing and deployment of Wisdom. Wisdom, to my mind, is the coupling of Head and Heart. In the West we are exceptional at celebrating, preferring and harnessing the Head. The Heart is to be kept away and held at bay. Matters of the Heart are seen as weak, slippery, soft and irrational. However, over much of our history on this planet our steps have been informed by a rich systemic play of both thinking and feeling, of head in resonance with heart. Architecture, as a discipline, as a profession, as a method and as a mindset, runs counter to much of this modern obsession with clinically dividing up our world and our ways. Architecture relishes in the uncertain and is at home with the unknown. Ackoff’s recognition of Architecture as a systems-oriented pursuit is apropos to our challenge to find pathways to a better tomorrow. Science is in many ways reaching some dead ends that are disconcerting and frustrating. Some realms within science, such as physics, are looking beyond conventional boundaries to see problems in dramatically different ways. Such searches are colliding, and often overlapping and resonating with, long established and extremely systemic ways of knowing (such as Buddhism, Taoism and Indigenous Spirituality). Architectural design is comfortable with indeterminacy and a plethora of factors in flow & flux. Through feedback loops, explorations of iterations and heightening levels of resolution, such as delineated in cybernetics & systems thinking, design finds solutions that aim at appropriateness (versus the more dualistic right or wrong). As we have witnessed repeatedly over recent years, more narrow, prescribed and formulaic ways of problem-solving are increasingly ineffective. Design, on the other hand, remains robust and resilient despite growing complexities of our cities, our buildings, our communities and ourselves. The design of a building, of a neighborhood or of a town, in a contemporary sense, demands agility, fitness, diversity and delight. Aiming our sights in only one direction, or attending to only a small section of a problem (as is very commonly the case), renders impotent solutions. Ackoff’s objective of continuous improvement warrants manoeuvrability in the system – some ‘elbow room’ and ‘breathing space’.
If we truly understand the complexities at play, view our world in a systemic manner, and approach design with holism front of mind, our chances of producing solutions that work are surely elevated. Given the serious stakes at hand, escalating dimensions of modern conditions, and dire consequences of getting things wrong, we as architects need to educate, inculcate, propagate, operate and celebrate via design. In our quest for a better tomorrow we must pursue holism and embrace systems thinking with greater vision, verve and determination.

Sinclair Holistic Framework for Design + Planning


https://ucalgary.academia.edu/DrBrianRSinclair
CRITICAL INQUIRY REGARDING THE ‘SYSTEMS THINKING’ OF RUSSELL ACKOFF DURING A SOCIAL CRISIS

Ezgi Balkanay

‘North Carolina State University, Raleigh, North Carolina

‘Systems Thinking’ as developed by Russell Ackoff provides a productive framework for analyzing a normative truth (Brant, 2010). His method, nonetheless, has been under scrutiny since it is not operative in a moment of crisis, which is to say; it is not designed and conceived to function under such condition. Thomas Kuhn characterizes the moment of crisis, as a period, which in contrast to ‘normal science,’ demands ruptures and entails discontinuities. Kuhn suggests that a paradigm shift emerges out of a ‘period of crisis or scientific revolution’ (Kuhn, 1962/1970). Can this characterization enable us to argue that design methodology in architecture, concerning urban spaces, also face a paradigm shift?

This question is more pressing when we realize that the very definition of the ‘urban’ has lost its certainty during the time of social crisis. Emerging global phenomena such as rapid urbanization and massive refugee crisis result not only in social catastrophes but also generate mass urban mobilizations. Well-established systematic urban design strategies are fundamentally inadequate as they are structured to respond to different modalities but not so much to complex formations. As the former tools and techniques are increasingly becoming obsolete, developing alternative methodologies for urban space seems critical. Given the inevitable flux as an inherent nature of the current situation, would it be still viable or possible to adhere to systems or pre-structured formulations?

These questions of ‘systems thinking’ will be discussed further within the framework of our chaotic, rather ‘rhizomatic’, built environment, which is contrary to pre-structured formulations. This will provide us with two possibilities; searching autonomous zones in built environment and re-definition of an epistemological positioning for urban space.

Ontological Positioning: Searching Autonomous Zones rather than ‘Anti-Systemic Applications’ (Brant, 2010)

Ackoff defines the ‘anti-systematic applications’ as a failure. He claims that the system as a whole consist of parts, which are indivisibly connected to each other, in terms of their behaviors or properties. In this sense, focusing solely on the behavior of a part rather than the system as a whole is inevitably impractical. He clarifies this by concentrating on the principle of ‘products of interactions’. He uses an analogy stating that collecting different engines from different automobiles could not constitute a ‘whole’; an ‘anti-systematic application’ acting autonomously could not provide a holistic solution (Brant, 2010).

These assumptions for normative, technological entities are more questionable for multi-layered, superimposed and ‘rhizomatic’ (Deleuze and Guattari, 2004) constructs such as urban forms. It is true that a product ‘designed’ as a system, such as an automobile, cannot be understood without systematic thinking. It is important to emphasize that these products are ‘designed’ physical entities constructed by their authors with the focus on technological systems. However, the specification of definite systems for an urban space using a linear thinking approach can lead one to a deterministic and reductionist point of view ignoring the intangible components of space, such as memory and identity. Memory in the emergence of a symbolic place or identity in the resistance of urban transformation can surface in the urban form temporally during a social crisis. They are not directly a part of the pre-structured formulations of any system. Then, can we define memory and identity of a space as ‘anti-systematic applications’ and failure or can we see them as unimagined but intrinsic portions of the space?

The latter can support a possible autonomous zone i.e. transitory conflict or possibility in urban space. These autonomous zones can have potential ties to alternative methodologies for urban space beyond the rigid boundaries of the current system or systems. For example, squatter housing areas, designed by their residents can present clues to designers.
Searching autonomous zones in a 'rhizomatic' (Deleuze and Guattari, 2004) construct directs one to redefine an epistemological positioning for urban space. Ackoff claims that a system cannot be divided into its independent parts since each part is interconnected to each other and the system as a whole. He elucidates this statement with an analogy to human anatomy, like a hand severed from the body; a divided part loses its essential properties and cannot function without the system (Brant, 2010).

This very logical positioning can be questioned, when our subject matter, 'space' is defined as a social construct. Space, more specifically, an urban space is not a mere physical entity or a morphological outline of different rooms. Also, it is not an autonomous being that has the power to direct a movement by itself. However, it can encapsulate autonomous zones in a time of social crisis. Within the consideration of these various meanings of space, it is becoming harder to define different parts. Therefore, we can evaluate it as a 'Body without Organs' (Deleuze and Guattari, 2004), a whole without its organizational subdivisions, rather than specific 'systems' or rooms. Rather than specific borders, we can evaluate the process. For example, when an urban space is faced with a social crisis, the people within the space change their built environment accordingly, like squatter housing areas or refugee camps. These places are not only adapted physically but they are also equipped with intangible assets within it. In other words, it necessitates a principal positioning in-between two sides of definitions for space, morphological-physical entity and the autonomous construct, rather than dividing it into different 'rooms'.

System thinking could be a productive tool for focusing on a morphological query, but it comes together with its own limits. It comes with the borders of our very own definition of 'parts' or rooms. It hinders the development of a truly holistic understanding of multi-layered structure comprised of different systems or tools. However, the peculiar characteristics of urban space cannot be discarded during the examination and elucidation of related social problems or actions.

REFERENCES


ENDNOTES

1 Deleuze and Guattari defines ‘rhizome’ with its six principles: “connection, heterogeneity, multiplicity, as-signifying rupture, cartography and decalcomania.”
SYSTEMS THINKING
IN ARCHITECTURE
ABSTRACT: Complexity of information in architectural design methods requires an understanding of the underlying process frameworks as a point of access to the structure of information and priorities, encouraging both greater success and more relevance to the outcomes (Plowright 2014). However, in addition to designer selected priorities and disciplinary requirements (environmental forces, social interaction, cultural projection), there are embedded values which are used to make many judgments within the system but are not recognized. This paper explores an aspect of this issue through the application of Conceptual Metaphor Theory (CMT) to a corpus of architectural theory.

CMT and conceptual metaphor analysis is one of the strongest tools to examine knowledge sources as it is based on the transfer of knowledge across domains. The paper uses a corpus of contemporary architectural theory and criticism texts to analyze the source domains, conceptual metaphors, primary metaphors and image schema used in architectural cognition through Cognitive Linguistic and Discourse Analysis methodology. The analysis highlights a fundamental way architects operate in pursuing their discipline is through the projection of being human – both as an act of formal design as well as in interpretation of our environment. Source domains of HUMAN ACTIONS, HUMAN INTERACTIONS, HUMAN MOTION and other types of ACTIONS and MOTIONS dominate discussions when talking about buildings, building elements and architectural ideas. These are organized through larger, more complex gestalts of human agency and personification. The interesting point of this analysis is that while the current research utilizes textual analysis, it should be highly relevant to other modalities of production within architectural design. This is due to what is known as the cognitive commitment, a theory that positions the human mind as a single system and fundamental in any discussion of embodied cognition. As such, the content of criticism and discourse would be indivisible from issues of design generation and span multiple modes of communication and interpretation. This paper examines the notion of projected humanness in more detail, addressing nuances in situatedness as present in architectural discourse.

KEYWORDS: cognitive systems; source domains; conceptual metaphor theory; architectural theory

INTRODUCTION
The introduction of non-architectural terminology and concepts is a significant feature of architectural discourse. The reliance on external sources of knowledge is well recognized by architectural theorists and historians who acknowledge the crossover between architecture and other disciplines as a central operation in the construction of architectural knowledge and meaning (Johnson 1994). Architecture is considered to “always represent something other than itself from the moment that it becomes distinguished from mere building.” (Hollier 2000, 190). Of course, the very act of “not being itself” brings a crisis into architectural theory. Some architectural theorists are concerned that the introduction of non-architectural terminology is required to have any meaning and see it as a threat. As a late 20th century designer and theorist lamented, “After more than half a century of scientific pretense, of system-theories that defined it as the intersection of industrialization, sociology, politics and ecology, architecture wonders if it can exist without having to find its meaning or its justification in some purposeful exterior need” (Tschumi 1994, 33). Other theorists see the sharing of terms and ideas across disciplines as natural rather than problematic as it aids in the labeling and discussion of “elusive concepts” by architects (Johnson 1994, 45). A cognitive linguist would immediately recognize the process of applying information from one domain of knowledge to another domain of knowledge as being the operation of a cognitive metaphor. Those theorists would claim that rather than being significantly problematic for the identity of architecture, metaphorical transfer is a natural part of cognition that permeates all aspects of architecture.

Through research in the cognitive sciences (linguistics, psychology, anthropology, sociology), metaphor has been shown to be inherent to, and embedded in, cognition (Lakoff and Johnson 1980, 1999; Johnson 1987, 2007; Lakoff 1987, 1993; Lakoff and Turner 1989; Gibbs 2008). It has also been shown that the use of metaphor has semantic and pragmatic relevance as well as being very important in reasoning, interpretation and assembling meaning (Carbonell and Minton 1983; Goatly 1997; Johnson 1987; Charteris-Black 2004, Cameron et al 2009). Traditionally, metaphors have been treated as surface phenomenon in linguistic and literary studies with language considered as a simple literal operation of binary coding-decoding. Recent research has shown that, in fact, human communication “involves no presumption of literalness and no default interpretation, and that metaphors are in no way exceptional with human communication
being one of inference rather than decoding (Sperber & Wilson 2008, 87). As a primary operation in inference, metaphors are a matter of concepts and not words. Metaphors are also used in discourse for explanation, motivation, persuasion and informativeness (rhetoric). In their rhetorical role, they contain evidence of the ideological position of a participant in a discourse (Partington 2006, 268). Whether used dynamically through ad hoc expressions or latently through conventionalized terminology, source domains involved in conceptual metaphor structures will communicate a set of values simply in their presence.

1.0. Corpus and method
The research data comes from a corpus of thirty articles by individual authors belonging to the genre of architectural theory as defined by Forty (2000). The corpus totals 207,898 words and articles vary in length from 2000 to 26,000 words. The texts were chosen from authors with prominence in the intellectual architectural community and their influence on the development of the next generation of architectural designers. The sample selection filtered for authors who were educated as architectural theorists and historians with a professional architectural background (practitioner) or critics with deep applied disciplinary knowledge. All sample texts were written for other members of the architectural discipline rather than the general public. The texts contain a variety of ideological positions (post-functionalist, feminism, phenomenology, post-criticism, for example) to maintain a balance of approach. While the ideological positions and intellectual priorities are divergent, there is equivalency between the texts in their focus on the manifestation of architecture as a formal and experiential event (form-body-space). This theme maintains equivalency of focus on formal discussion for analysis – the idea of tangible, physical architecture rather than non-situated intellectual positions.

The research method for metaphor identification used in this paper follows the experientialist tradition of CMT (Lakoff and Johnson 1980; Lakoff and Turner 1989) with adaptations from cognitive theories of metaphor through genre and corpus studies (Geeraerts 2006; Caballero 2006; Deignan 2008; Cameron and Maslen 2010; Kimmel 2012). The approach uses the identification of literal incongruence within a sentence or sentence fragment as a general procedure of metaphor identification, with the understanding that there will still be variation in interpretation when analyzing for words in discourse (Pragglejaz Group 2007: 13). The corpus yielded a total 2069 metaphoric expressions containing 2610 metaphors, found singularly or as a series of clusters involving at least a full sentence and sometimes extending to span several sentences. Metaphor are used in all discourse contexts so in order to understand how they are associated with explicit architectural ideas, it is necessary to isolate expressions that where directly applied to a discussion of form, space or building as a target domain – the realm of architectural thinking. There were 1735 of these instances in the corpus. Of these, 71.7% (1242 instances) were conventionalized metaphors used as a latent expression while the rest were dynamic metaphors used more consciously (c.f. Caballero 2006). By examining these expressions and recognizing what source knowledge is valued, we can start to understand architectural priorities.

2.0. Metaphors used knowingly and unknowingly
It is important to understand that metaphors are used both knowingly and unknowingly in architecture. Metaphors used knowingly are part of design strategies and considered tools to either help guide a design process or to explain the formal or relational meaning of a project. The human body has been a dominant metaphorical source into the Renaissance and early Enlightenment. By the Industrial Revolution, the body was eclipsed by concepts of biology and machines – with the choice of one over the other often based on larger belief systems rather than the particular instance of use (Moloney 2011). Biology could be considered as extending from the existing metaphor of the body, however there is a difference between the two concepts. The use of anatomical terminology before the Industrial Revolution tended towards equating buildings to body elements and body schemas (arms, legs, head, heart, feet on ground, heart as central etc.) and this included a parallel view of CITY AS BODY. The metaphor could go so far, as McClung illustrates through a literary reference, that a building’s “medieval arrangement of apartments (hall with kitchens to one end and private quarters to the other) is imposed upon a point-by-point correspondence of the castle to the human body” (1981, 283).

The growth of biological knowledge in Western society through the Enlightenment changed the type of information expressed through metaphor. The dominant understanding shifted from the body as an anthropomorphic mapping between the environment and human physicality to instead focus on the body as a biological organism which stressed systems and natural laws (De Palma 2006). The organic metaphor was used in this way as part of early architectural Modernism, which applied biological principles to project completeness. This was useful as the building was then perceived as a final expression of natural, dynamic forces with a form that emerges from its context, and therefore cannot be questioned for its meaning (McClung 2981; Hvattum 2006). The metaphor also stressed issues of health and illness found in formal representation that ranged from early Modernist concepts of purity, hygiene, and cleanliness (Till 2007; Muller 2009) to late 20th-century fixations on scars, scabs and parasites (Caballero 2006; Kanekar 2010).

The consideration of the organic as an emergent, evolutionary system indicated a shift away from the body as a topographical object (appearances) to the body as a complex manifestation of relationships based on context (relations).
The machine as a metaphor could be said to occupy the same territory as the organic in representing forces as well as operating as a metaphor for the organic. For example, Violet-le-Duc wrote about the example of mechanical innovation occurring through the transfer of biology. Looking at the different bone length in the hind legs of stags, reindeers or elks, he explained that the relationship between the femur, tibia and calcuneum (heel) allowed for quick powerful action such as leaping over large obstacles. Using the biological source domains of anatomy and kinesiology, he transferred the relationship between the bones of the hind legs to designing a machine that would make a quick and power tension (Hearn 1990, 227). Other architects used biology and the organic as a source domain to address universal laws and to attempt to avoid issues of human fashion and temporary styles (Proctor 2006) as well to stress concepts of emergence and author-less design (Hvattum 2006).

While conceptual metaphors used knowingly by the designer are recognized by architects, they are based on similarity construction between sources and target domains. There is another type of conceptual metaphor that goes unnoticed by architects. This is the correlational metaphor that extends experiential knowledge based on embodied cognition. Correlational metaphors use associations between knowledge domains which is not logically determinable, as can be illustrated by the example:

(1) “the unfolding of the space in time.” (Allen 2000, 107)

In the passage above, there is a violation of literal incongruence as space and time are not objects and cannot be unfolded making the expression a metaphor. Yet, it is not possible to understand the passage through mapping the similarity of elements found in the source to elements in the target domain. There is no simile constructed, no comparison through resemblance and no clear association found within the expression – space is not like something and time does not resemble anything else. Instead, both space and time are considered to be objects with space able to be manipulated while time is further conceptualized as a container that surrounds space. Where do these mappings come from if they are not created within the expression? As there is no similarity that drives this metaphor, the only way to understand the expression in the context is through previously formed associations between concepts and experiences – what has been defined as correlational knowledge (Grady 2007). Correlational mappings are highly conventionalized and use a type of information that is about “the role of our perceptions and representational schemas” rather than facts about the world (Grady 2007, 325). In this case, space is directly associated with the properties of objects through the conceptual metaphor SPACE IS AN OBJECT and then extended through the action of unfolding. Time is a conceptual theory developed by human culture and has no physical existence yet is conventionalized through the conceptual metaphor TIME IS AN CONTAINER, where a container is also an object. Both space and time are then put into a relationship with each other based on these basic correlational mappings. A critical difference between resemblance and correlational metaphors is that while “resemblance metaphors may involve correspondences between concepts of the same type, [...] correlation metaphors link concepts of different types.” (Grady 2007, 331). Many metaphors using similarity go unnoticed by the speaker, however all correlational metaphors are used unknowingly with the rare exception.

3.0 Patterns in conceptual metaphors in architecture as a physical experience

The type of knowledge that architects prioritize in the pursuit of their discipline can be examined through looking at the source domains present as part of metaphor structure. The most populous source domain found in metaphors with architectural target domains is HUMAN ACTIVITY (326 instances) followed by NATURE (193 instances), then ARTIFICIAL (175 instances), MOTION (95 instances) and, finally, HUMAN BODY (62 instances). It is clear that within source domains, not all sub-domains have equal representation. For example, the source domain HUMAN BODY is dominated by only two sub-domains – references to the body and its organs as objects as resemblance metaphors, and references to health and sickness as correlational metaphors. The other topics in this area, including references to the senses (sight, sound and taste), medical processes and biological relations (father, sister, etc.) generated only 13 instances across five source sub-domains compared to 93 instance for the first two source sub-domains. This pattern was common for all the source domains with two or three dominant categories. The most populous source sub-domains applied to just physical aspects of architecture are presented in Table 1.

<table>
<thead>
<tr>
<th>Metaphorical Frame</th>
<th>Source domain</th>
<th>Source Sub-domain</th>
<th>Target: Architecture (physical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Instances</td>
</tr>
<tr>
<td>HUMAN</td>
<td>HUMAN ACTIVITY</td>
<td>Actions (body)</td>
<td>136</td>
</tr>
<tr>
<td>HUMAN</td>
<td>HUMAN ACTIVITY</td>
<td>Social interaction</td>
<td>105</td>
</tr>
<tr>
<td>NATURE</td>
<td></td>
<td>Actions (enviro.)</td>
<td>93</td>
</tr>
</tbody>
</table>
The three most common metaphor sources are not resemblances between buildings and machines, organism and the body as an object. Instead, they are based on applying physical actions (either those of the human body or from the environment) and social interactions to objects in the built environment. In fact, these three source categories are by far the most numerous by several factors of occurrence – they make up 38.9% of all metaphor sources applied to the physical aspects of architecture in a corpus with 58 source domains identified. The action/interaction source domains are followed distantly by physical references to machines, organisms and the human body as an object. Between organisms and human body, aspects of the landscape and natural features of the environment (hill, mountain, lake, river, island) and objects are found mapped to buildings and cities. Finally, motion is present, and if considered as a single domain rather than divided into different senses of motion, would supersede actions (environment) with a total of 85 occurrences. Considered as separate sub-domains, the strongest motion references are to movements based in the human body (dance, shamble, squirm, spring, leap, swim) and to liquids (flow, cascade, ripple, swirling, rolling, float, turbulence).

Metaphors based on the relationship between the source domains of actions and interactions being applied to target domains of physical architecture can be illustrated through examining a few examples. The first is an example of actions based on the human body mapped to the space within a building.

(2) “the pool is pushed out into the landscape” (Eisenman 1986, 195)

In the example above, a static object, a pool, is interpreted through the physical action “push”. The target domain is clearly an aspect of physical buildings – a “pool” would be an element in the design of higher-end residential design. The source domain is less clear as there is not any particular object, attribute or relationship being compared with the pool. However, there is clearly literal incongruence as the pool is not actually being pushed – it simply does not, nor cannot, move. Rather, the source domain is based in projecting an action into the built environment activating a sense of the human body engaging with objects. The metaphor is a correlational and maps visual interpretation of formal relationships to physical actions. The source and target domains together suggest a variation of the conceptual metaphor FORM IS ACTION, one that stresses spatial location, identity and normative appearance.

Actions are projected into the built environment in more active and complex ways as well, as can be seen by the following example:

(3) “[the eye is directed towards] the interior, which turns its back on the outside world” (Colomina 1992, 88)

The target domain in this example is not the building itself but the “interior” of the building both as a physical space and a conceptual idea. The source domain is the mapping of a body, most likely that of a human for a body is needed in order to “turn its back”. Rather than simply (human) body, this metaphor activates the source domain of actions (body) as it is the action as an event rather than the body as an object which is important. The action produces a social context and brings with it the social meaning of removing the attention of the gaze, and therefore interest and the ability to interact. Two metaphors are present to allow for discourse meaning to be understood. First is the metaphor (architectural) space is a person which introduces the mapping of the interior space to a person. The second conceptual metaphor is visibility is relationship and is the more important one in terms of meaning. Movement and action, in this case, carries social meaning.

The examples above lead us into an examination of what metaphors are present in the source-target relationships. When we look at metaphors rather than just source domain information, the results reinforce the data above but also provides a slightly different perspective (Table 2).
Table 2: Summary of top occurrences of metaphors to ARCHITECTURE [PHYSICAL]

<table>
<thead>
<tr>
<th>Metaphor</th>
<th>Source domain</th>
<th>Schema</th>
<th>Occurrences</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBJECTS ARE PEOPLE</td>
<td>HUMAN BODY</td>
<td>Personification</td>
<td>132</td>
<td>8.0%</td>
</tr>
<tr>
<td>FORM IS MOTION</td>
<td>MOTION</td>
<td>Spatial motion</td>
<td>55</td>
<td>3.3%</td>
</tr>
<tr>
<td>FORM IS ACTION</td>
<td>HUMAN ACTIVITY</td>
<td>Agency</td>
<td>54</td>
<td>3.3%</td>
</tr>
<tr>
<td>OBJECTS HAVE RELATIONSHIPS</td>
<td>HUMAN ACTIVITY</td>
<td>Personification</td>
<td>49</td>
<td>3.0%</td>
</tr>
<tr>
<td>OBJECTS INFLUENCE SURROUNDINGS</td>
<td>HUMAN ACTIVITY</td>
<td>Agency</td>
<td>42</td>
<td>2.5%</td>
</tr>
<tr>
<td>OBJECTS ARE ENTITIES</td>
<td>NATURE</td>
<td>Entity</td>
<td>40</td>
<td>2.4%</td>
</tr>
<tr>
<td>IDEAS ARE OBJECTS</td>
<td>NATURE</td>
<td>Object</td>
<td>39</td>
<td>2.4%</td>
</tr>
<tr>
<td>BUILDINGS ARE PEOPLE</td>
<td>HUMAN BODY</td>
<td>Personification</td>
<td>36</td>
<td>2.2%</td>
</tr>
<tr>
<td>CONNECTION IS POSITIVE</td>
<td>NATURE</td>
<td>Growth</td>
<td>29</td>
<td>1.8%</td>
</tr>
<tr>
<td>CONTROL IS GOOD</td>
<td>HUMAN ACTIVITY</td>
<td>Control</td>
<td>29</td>
<td>1.8%</td>
</tr>
<tr>
<td>ASSEMBLIES ARE PEOPLE</td>
<td>HUMAN BODY</td>
<td>Personification</td>
<td>25</td>
<td>1.5%</td>
</tr>
<tr>
<td>ENTITIES HAVE SOCIAL STANDING</td>
<td>HUMAN ACTIVITY</td>
<td>Personification</td>
<td>23</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

The most common metaphors are those based on PERSONIFICATION schema which includes HUMAN AGENCY (Lakoff and Johnson 1980; Lakoff and Turner 1989; Lakoff 1990) with the projection of human abilities, perceptions, actions, interactions and emotions into the environment (OBJECTS ARE PEOPLE, OBJECTS HAVE RELATIONSHIPS, BUILDINGS ARE PEOPLE, ASSEMBLIES ARE PEOPLE, ENTITIES HAVE SOCIAL STANDING). This is followed by metaphors based in general AGENCY – the ability to give inanimate objects the abilities to act on their surroundings but without any explicitly human characteristics (FORM IS ACTION, OBJECTS INFLUENCE SURROUNDINGS). Finally, SPATIAL MOTION is strongly present where the interpretation of form is given a sense of movement (FORM IS MOTION). The presence of both MOTION and ACTION schemas in the metaphors where motion is a type of action that pertains to change in spatial location. While concepts such as PERSONIFICATION and AGENCY have been considered as ontological metaphors (Lakoff & Johnson 1980), the concepts are non-specific in their mappings and are “a feature shared by source and target,” (Grady 2005, 49) on which metaphors are constructed.

4.0 Causation and agency
The projection of action into an inanimate environment is usually considered to be through the conceptual metaphor EVENTS ARE ACTIONS, classified as either a generic-level metaphor (Lakoff and Johnson 1980) or a primary metaphor (Grady 1997). In both accounts, EVENTS ARE ACTIONS has an abstracted structure that can be applied to many situations regardless of specific source and target content. The metaphor “imputes agency to something causally connected to the event” (Lakoff and Turner 1989, 37), activating an inert and static situation with implied action which also includes spatial motion or interaction. This metaphor is part of a larger cognitive framework that has been expanded into the EVENT-STRUCTURE metaphor, a very abstract skeleton that links causation with all aspects of movement, events, actions, changes in location, changes of visibility and changes of state (Lakoff and Johnson 1999, 170). Causation as a generic concept is at the core of human development (Mandler 1992) and has been considered inseparable from concepts of events (Lakoff and Johnson 1999, 206). Causation has also been linked with almost every concept that involves locations, movement and/or action. The prototypical causation is confined to concepts of agency or “the manipulation of objects by force, the volitional use of bodily force to change something physically by direct contact in one’s immediate environment” (Lakoff and Johnson 1999, 177). While causation engages many primary metaphors (STATES ARE LOCATIONS, EVENTS ARE ACTIONS, CAUSES ARE FORCES, CHANGE IS MOTION, for example), when direct projection of actions into the environment is involved, the causation at the heart of this metaphor is considered to be based on the inference of animacy through the result of a human agent (Lakoff and Turner 1989, 37; Grady 1997, 288).

Agency has two meanings. The first meaning of agency focuses on causation where the agent is the entity doing the causing and the patient is the thing being affected. In this understanding, the form of prototypical causation has only “a single specific agent and a single specific patient” (Lakoff and Johnson 1980, 70) although other versions include “action at a distance, nonhuman agency, the use of an intermediate agent, the occurrence of two or more agents, involuntary or uncontrolled use of the motor program, etc.” (Lakoff and Johnson 1980, 71). The second meaning considers agency as a synonym for control as a human capacity. In this sense, there is a "correlation between goal-oriented action and interaction with other people" or "between observable events in our environment and the presence of human agents" (Grady 1997, 288). This version of agency explicitly construes the metaphorical mapping as a projection of human
qualities into the environment.

Both agency of action and agency of control are present in the corpus with the former based on direct sensori-motor knowledge and the latter using inanimate motion or a projection of more complex actions of a human agent (i.e. having human capacities). The projection of agency in architecture, thus, moves from direct application of forces onto the environment to actions of the body to actions of social or emotional control. The first set of examples below address examples of agency through direct forces creating metaphorical actions.

(4) “These walls cleave space;” (Eisenman 1986, 195)

In the example above, there is no particular aspect of the force which suggests the involvement of human capacities or the interaction of a body (human or nonhuman). The agent in (4) is clearly the building elements, “walls” and “(spatial) volumes” respectively, which are construed to interact with other building elements but are not projected as having bodies. Space is the patient through the metaphor SPACE IS AN OBJECT that allows space to be conceived as physically dividable.

There are examples of nonhuman agency in the corpus where a body is inferred, but still does not reach the threshold of human specific capacities.

(5) “this surface could brush up in exquisite proximity to the architectural surface” (Lavin 2011, 82)

The passages above present a building element as being considered to have animate self-motion and implied bodies. In order for something to “brush up” against something, become “entangled” (Lavin 2011, 112), to be “captured” or “caught”, it is necessary for that thing (i.e. building, building element) to operate as an organism with the independent ability to move. Example (5) suggests the presence of a mammal with fur as “brush up” is an action normative to this type of organism and is generally experienced through house cats or dogs. The presence of a body introduces the capacity to actively engage in the surroundings beyond simple force dynamic actions. Rather, once a body is involved, there is a relationship created through interaction rather just action.

Nonhuman agency is very much a minority in the corpus with most instances of action being produced by human capacities and implying the role of body parts (generally hands). As seen through the corpus data, the architectural discipline routinely projects human agency into the environment once objects and concepts have been mapped to being people as physical entities (i.e. have bodies).

(6) “the walls that reach up to connect you with the starry sky” (Buchanan 2012, 17)

The quotation above infers agency through the authority to act towards the environment with explicit human capacities, which includes blending physical objects with conceptual content. The example allows built environment objects to perform actions as if they were people by activating spatial location and touch through PROXIMITY IS RELATIONSHIP. In this metaphor, the human arm/hand is inferred as the major mechanism of connection. The walls in (6) can be interpreted to operate in two capacities – first as a person which can reach towards the sky and second as a prosthesis of the human (“you”). The latter allows the extension of person, as a real entity in real space, to form a metaphorical relationship between themselves, the wall and the sky to create a single entity. To do this, the sky needs to be conceptualized as an object which cannot only be touched but also can be part of a relationship through merging. The conceptual metaphors and metaphorical processes in (6) use the primary conceptual metaphors PROXIMITY IS RELATIONSHIP and OBJECTS ARE PEOPLE. The example has several mappings that shift between being an object that moves, an entity that acts and an object or substance that can merge all within the same sentence – all while still being an inert, physical object in the built environment.

There is another form of human projection which does not engage the physical body but rather the emotional and social capacities of being human. The causation is not as simple as direct action but involves the social pressure of human–human relationships and implied action. Examples of this causation is presenting in the following examples:

(7) “No restful composure exists between elements and, instead, a kind of jostling for position excites the space,” (Cadwell 2007, 23)

(8) “A steel-grate platform steals the ground from under you” (Kipnis 2013, 121)

There is clearly a form of agency at work in (7) and (8) as there is the inference of a reaction in the surrounding environment or the suggestion of a necessary response. The referenced action is more complicated that is seen in the previous examples and without the clear activation of the human body. In (7), the building elements are being given a social life and the ability to interact independently where “jostling for position” is both an implied physical action but...
also a reference to social status. In (8), the ground is projected as a human agent capable of taking a possession away from a human visitor, a purely conceptual act but in response to the inference of the surrounding built environment. In this case, to steal the ground refers to the use of a material that allows the view to pass through the surface to the area below as if the dematerialization of the ground surface material was an act of theft to the person occupying that plane. To characterize this interpretation as an action of theft projects authority and power into the environment where none exists, giving the ground control over the human user.

While the examples above address understanding the built environment as projection of human agency through action, there are also examples of agency (as causation and control) which do not imply physical movement and effect. Instead, the agent is based on social pressure but still with an underlying mapping of BUILDINGS ARE PEOPLE or IDEAS ARE PEOPLE.

(9) “Concrete construction is made to behave with the taut precision of aircraft engineering” (Allen 2000, 112)
(10) “there are some very interesting recent projects which flaunt the principles, rules and methods that combine to fix the normal dwelling;” (Evans 1997, 86)

In each of the passages, there is causation but no implied physical action in the expression. In (9), the material properties of a building are “made to behave” as if a human or domesticated animal, such as a dog, under the social control of another. The next example represents rejection of control by another. The architectural projects in (10) interact as part of society by “flaunting” social conventions. In this context, this means that they do not conform to housing typology but that rejection is based in emancipation. While both passages above contain causation, this agency stresses social pressure and control rather than physical action. These metaphors consider ideas and environmental objects as having the same social context as people do, allowing inert contexts to be considered as playful, undermining, liberated, embracing and so on. This is purely a projection of human cognition into that space and agency is acting to define, above all else, relationships. This includes relationships between occupier and environment, environment to its context and parts of the environment to each other.

CONCLUSION
In architectural theory, intellectuals and critics are discussing the role of architecture in culture through the interpretation of buildings rather than designers using analogies as generative devices or as design inspiration. However, discourse and knowledge structures operate in the same way between design generation and interpretation, otherwise we would have a fundamental inability to communicate anything. What dominates information sources revealed through the corpus research is not the traditional source categories of the human body, machines, and organisms. Instead, the prevalent pattern is metaphors using active projections of human capacities and human identity onto objects in the built environment. The body is activated through correlational mapping of perceived actions into nonhuman things, mostly through the inference of hands through touching, holding, grasping and reaching. This category includes the mapping of the human body onto nonhuman things through agency where the inanimate is given animacy. While there are some instances of sources that most would understand as classic literary metaphors (boats, trees, clowns, literature, mythology), the majority of the source domains in the corpus are expressions and projection of humanness.

Humanness is projected into our built environment through the conceptual metaphor OBJECTS/BUILDINGS ARE (HUMAN) AGENTS. The metaphorical expressions using this category apply source knowledge from the environment (weave, tangle, fold, wrap) or as basic force schema (DIVIDE, PENETRATE, PUSH, WRAP, EXPAND) in direct association with architectural objects as an agent affecting a patient. Human agency is expanded with the image schemas of COUNTERFORCE, RESISTANCE and BLOCKAGE which stress the concept of control as a type of agency interacting with the environment. These instances of agency still involve causation but focus on influence rather than direct action. Personification underlies agency as control as a gestalt and mega-metaphor found throughout architectural discourse. Personification is not just present in metaphors using agent but is also associated with instances of OBJECTS/BUILDINGS HAVE HUMAN BODIES, (BOUNDED) ABSTRACTIONS ARE PEOPLE, OBJECTS/BUILDINGS ARE PEOPLE, INANIMATE PHENOMENA HAVE HUMAN AGENCY, and metaphors based in effects of having a human body such as PROXIMITY IS EFFECT, PROXIMITY IS RELATIONSHIP, SEEING IS TOUCHING, UNDERSTANDING IS GRASPING or INFLUENCING IS TOUCHING. Personification allows the projection of human capacities that are not actions or motions into nonhuman things. This includes projecting identity, a sense of being and emotional capacities. In contrast, or more precisely as an extension, human agency allows a personified element to act in the world as a way to exert influence while personification allows awareness of existence.

It is common to find metaphors in the corpus that project human agency of control into the environment resulting in the ceding of authority into aspects of that environment. When inanimate architectural objects have control over their environment, this includes the users of that environment – i.e. humans. Through the transfer of authority that is part of human agency in the corpus, humans do not interact with their environment so much as the environment is conceived to make users of to act in a certain way. Ramps pull people through a building, windows allow views, doors encourage or deter entrance, and so on. In this way, power and control are very much part of the value structure of architectural
discourse, but it is the built environment or abstract ideas that have authority as if they were human.

Architects are quite aware of the power of the environment to affect the experience of human users, as one author states “the exterior gains social agency and the capacity to shape with gentle force the collective experience of the contemporary city” (Lavin 2011, 92) The interesting aspect from a cognitive point of view is the role of human agency and personification suggest that the overall role of metaphor in architectural discourse is less about understanding buildings as having human bodies or human capacities. Rather, an important way that we human understand our environment is through projecting ourselves into that environment as a tool of interpretation. At the same time, the projection of ourselves is cognitively ignored and the environment is allowed to take on a separate identity which then has control over its occupiers.

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ABSTRACT: We review three dimensions of architecture's complicity in institutionalized social oppression and offer a trans-disciplinary lens for transformative opportunities. Equity deals with the history of elite classes dominating the common populace, and rulers in marble palaces and servants in dirt floor homes. Social justice is then a contemporary residual of class discrimination and a force of emancipation toward equal access to public resources, aspirational prosperity, and well-being. Finally, sustainability attends to underlying damages that accrued in previous eras of short-term thinking, unfair commodification of resources, and institutionalized greed.

This paper is not, however, an exercise in political, legal, planning, or technical solutions. Instead, we frame the relation of architecture and institutionalized oppression within the concept of intersectionality (i.e., the complex social dynamic that compounds those multidimensional problems). To balance architecture's naïve and negligent guilt, we conclude with emerging opportunities in architecture towards promoting broad welfare, social justice, and class equity. Three such opportunities are discussed: social activism, stakeholder engagement, and sustainability.

KEYWORDS: Intersectionality, oppression, equity, agency, class

INTRODUCTION
Architecture's contract with society is a bargain of care toward “health, safety, and welfare.” Stewardship over the built environment is thus inherent in the profession's collateral monopoly. Nonetheless, the architect's burdens toward political, legal, technical, economic, and behavioral toxicology aspects of their charge have been relatively ignored. Consequently, there is increasing evidence of architecture's complicity in institutionalized oppression. Thankfully, there are also corresponding opportunities to promoting broad social equity.

1.0 ARCHITECTURE AND OPPRESSION
In this paper, a few historical notes must suffice as background. We basically argue that monumentality, class distinction, and ecology are fundamental aspects of architecture's complicity in institutionalized oppression.

1.1 Class, dependency, and monumentality
First, consider the contradiction of rich architectural monuments as they have coexisted across history side-by-side with poverty and squalor. How many great buildings were in some way exploitive of the public realm in all the ages of class segregation? How many temples, castles, and palaces were built from social capital largely for the privileged elite (Fig. 1)? And how many workers labored in poor conditions with little or no compensation? Although chattel slavery has advanced to organized labor, and self-determination has increased within democratic frameworks; how much of the architecture that we celebrate today resulted from bondage, servitude, exploitation, and dependency? Monumentality itself contributes to class distinction and exclusivity as an awe inducing element of social control. Such control is exercised through sensory exploitation, either as opulent signals of class segregation; or as appeasement via public spectacle such as the Roman Coliseum or “look how good you have it” World Fairs (Ley and Olds 1988).

1.2 Segregation, gentrification, and walled neighborhoods
Charleswell (2014) posits that the “built environment is socially constructed and has historically been formed and maintained through residential segregation.” Legal literature shows how various design methods are used to prohibit people from areas where they are not wanted (Schindler 2015). City planners have, for example, constructed physical barriers to keep people segregated from more desirable areas: a low bridge, a busy highway, a one-way street... all elements designed to manipulate mobility.
American cities in general show high levels of inequality and poverty. Increased income and resource inequality since the 1970s has worsened “exclusionary zoning, heavy regulation, real estate steering, lending and insurance policies, purchase contracts and private surveillance” (Silver 2012). Gentrification brings higher property values, dislocates low SES residents and entices high SES influx. Slowly neighborhoods become more segregated by income and race. Meanwhile, an increasing number of Americans move to “suburban enclaves surrounded by walls” while others, mostly Black and Hispanic people, live in controlled neighborhoods with limited access to adequate services and schools (Goldsmith & Blakely 2010). “Walls, fences and highways separate historically white neighborhoods from black ones” (Schindler 2009). The built environment thus acts as a form of illicit regulation by limiting diverse interactions and increasing class isolation. Schindler’s example of the Jones Beach’s bridge which was “built intentionally low” to prevent buses from accessing the public beach is typical in this regard. Schindler also emphasizes how design can regulate access, pointing out how wealthy white residents of the Northern Atlanta suburbs opposed the construction of the Metropolitan Atlanta Rapid Transit into their neighborhoods to exclude people of color. Limited transportation is a form of discrimination that restricts job opportunities, education, recreation and housing.

1.3 Ecology and public health
Although the Romans knew of lead and asbestos poisoning 2200 years ago, the built environment has often included such toxins. Lead in gasoline, paint, and ink has, for example, been scientifically linked to crime, learning disabilities, aggressivity, low IQ, low infant birth weight, and colic (Needleman 1999, Reyes 2007). Removing lead from gasoline under the 1970 Clean Air Act directly resulted in an estimated 56% drop in US violent crime in the 1990s (Reyes 2007). Despite that, the lead in old plumbing, fungal dust, and garden soil are still concerns (Salares, Hinde, and Miller 2009). Today, carbon dioxide, ozone, and methane are known links between the built environment, architectural design, and public health. Given the history of tobacco, CFCs, PBP, MTB, PBA, and other toxins, the issue is cause for concern.

1.4 Architecture’s complicity
[The] “built environment [is] ... a man-made space, where people live, work and recreate, ... and includes one’s neighborhood and all of its available resources – parks, bike lanes, libraries, schools, clinics/hospitals, full service grocery markets, etc., one’s home and family unit as well as their place of employment. As such the built environment encompasses legislators, city planners, engineers, and architects.” Charleswell (2014).
Norman Foster (2014) believes that “architecture is an expression of values: the way we build is a reflection of the way we live.” He states that “buildings and the infrastructure, or urban glue, that binds them together do not design themselves—they are designed by people...” As such, architects are responsible for reducing the impacts of undesirable environments. They should raise “public awareness of critical social and environment issues, and take an active role in influencing the built environment” (Stelmack, Foster, and Hindman 2014).

Complexity in the built environment compounds our difficulties. All democratic societies have inherent social stratification, but when class differences result in segregation, social control, and exploitation, several elements collude...
(Fig. 2). The primary factors create a self-perpetuating downward cycle. It is what Ackoff aptly termed “a mess:”

- Elitist privatization of high profile architecture (Laws 1994)
- Social construction of authority and power (e.g., Yannick and Dewitte 2016)
- Commodification of public space (e.g., Arnqvist 2006)
- Exploitation of sensory awe by opulence or spectacle (Joye and Verpooten 2013)
- Exploitation by bondage, servitude, and dependency (e.g., Buckley 2013)
- Disadvantaged public health and local ecology impacts (e.g., Reyes 2007)
- Locational isolation and distance from employment or other resources (Schindler 2015)
- Food deserts where grocery retailing becomes unattractive to merchants (Urban Land Institute 2013)
- Gentrification of neighborhood culture and disruption of intergenerational continuity (Hamraie 2013)
- Increased susceptibility to climate change and climatic disasters (Pachauri et al. 2015)
- Increased susceptibility to secondary factors: crime victims, obesity, disease, under-education, unemployment...

Figure 2: Deplorable working conditions in the United Arab Emirates exemplify the exploitation of low socio economic construction workers, mostly expatriates from Bangladesh and India (Buckley 2013). Unsanitary living conditions, low pay, withheld compensation, and high worker suicide rates are rampant. Photograph courtesy of Thomas Mülchi.

2.0 USING INTERSECTIONALITY AS A FRAMEWORK

Intersectionality helps explain institutionalized oppression. It also links to the conference theme of complexity and to this paper’s transdisciplinary goals. The term originated with Crenshaw’s (1989) Black feminism approach, which emphasizes the “multidimensionality” of marginalized individuals’ experiences. Initially, intersectionality research focused on the juncture of sex and gender to explain inequalities. This concept has since been used extensively, especially in gender studies. Davis (2008, 68) describes intersectionality as the “interaction between gender, race and other categories of difference in individuals’ lives, social practices, institutional arrangements, and cultural ideologies; as well as the outcomes of these interactions in terms of power.” While intersectionality emerged largely as a way to fight racism, it also explains how norms are created and power relations interact (Kaijswer and Kronsell 2014). For architects then, intersectionality links design to issues of social oppression, policy development, and class discrimination. Understanding the dynamic should help avoid benign neglect. Quoting Ackoff again:

A problem never exists in isolation; it is surrounded by other problems in space and time. The more of the context of a problem that a scientist can comprehend, the greater are his chances of finding a truly adequate solution.

2.1 Intersectionality and the built environment

Many intersectionality studies demonstrate how race is often central to disparity. In the built environment however, poverty and socio economic status (SES) better explain how class categorization contributes to discrimination (lower education, poverty, and poor health). Inequalities of affluence and wellness are rising due to disproportionate differences in SES. Consequently, neighborhood stratification is largely based on SES, race, ethnicity, employment locations, population density and distances (Silver 2012). Class structure often determines low economic development, limited access to health facilities, and low levels of educational attainment. Low SES is also associated with community problems such as residential and racial segregation (Sennett 1992, Sennett and Cobb 1972), and thus isolates
Despite individual foci on past, present, and future dimensions, it is clear that the built environment has always been subverted by monumentality, class distinction, and ecology. Minority neighborhoods with high rates of social inequity and disparities are obviously the most affected (Charleswell 2014). Since oppression is mediated through social, cultural, legal, and economic structures, using intersectionality allows us to examine the interactions that produce oppression and inequity, and perhaps identify ways to provide a more democratic future.

2.2 Stakeholders and social justice

Approaches to social justice emphasize either the redistribution of goods (Rawls 1971) or social processes (Young 1990); but all approaches concern equity (Sen 2006). Theories of social justice frequently challenge inequities at their source and require people to question social and power relations. According to Potts and Brown (2005) social justice is about: transforming the way resources and relationships are produced and distributed so that all can live dignified lives in a way that is ecologically sustainable. It is also about creating new ways of thinking and being and not only criticizing the status quo (284).

A social justice approach to health equity thus has the potential to transform social structures, which is essential in addressing the root problems of institutionalized oppression.

Closely tied to social justice, equity is concerned with fairness. Per Braveman and Gruskin (2003), equity in public policy exists when social systems are designed to equalize outcomes between more and less advantaged groups. Equity is not interchangeable with equality; inequality may refer to differences in outcomes of interest while inequities exist where those differences are unfair or unjust. Architects must consider projects through not only an intersectional equity lens, but also contemplate the impacts of the intersections of multiple positions of privilege and oppression (Hankivsky, Grace, Hunting, Ferlatte et. al. 2012). Resistance and resilience have recently been added as key principles of intersectionality-based analyses (see Hunting et al., forthcoming) because both empower marginalized populations to disrupt oppression. One such resistance from subordinated groups is to use collective actions to destabilize dominant ideologies. Policies and discourses that label groups of people as inherently marginalized or vulnerable undermine the reality that there are no ‘pure victims or oppressors’ (Hankivsky, et al. 2012). Categorical top-down policy approaches reinforce conceptions of difference between groups, obscure their shared relationships to power, and prevent collaborative work. These problematic situations demand bottom-up stakeholder perspectives; so when projects are skewed towards top-down priorities by policy or client, then architects must advocate for better balance. If intractable project parameters lead unavoidably to social oppression, architects should know when to walk away.

3.0 CONCLUSION: ARCHITECTURE, THE BUILT ENVIRONMENT, AND SOCIETY

Since early industrialization, social progress has promoted self-governance, broader participation, and more enlightened perspectives about how we share the world. Our current globalized situation should now lead to even more inclusive viewpoints. Given the now commonplace evidence of everyone’s systemic interrelatedness within our world’s collective economy, ecology, and politic; the opportunity to contribute to harmonious and healthy habitat is increasingly likely to become the forefront of architectural practice.

The architect’s current role in the dynamic of money, power, and knowledge is typified by Gadanho (2016) as an overly “top down versus bottom up” approach that is more obedient to the short-term commercial aspects of architectural practice and less responsive to long term user-needs and to society at large. In terms of patronage, this critique illustrates how every work of architecture has five client stakeholder clients; an owner who pays, a user who occupies, a government that regulates, critics who analyze, and, ultimately, the society which collectively owns, occupies, and animates the built environment. As law professor Clowney (2013) puts it:

Landscapes do not arise through the work of a divine hand to celebrate the deserving and promote truthful accounts of history. Rather, the built environment is shaped by the tastes of government leaders and ruling elites--the only groups with sufficient resources to organize costly building projects and install permanent memorials on the land. It takes little effort to see that those with dominion over the land may use their power to teach the public their own desired political and historical lessons. The landscape, as a result, tends to either exclude the heritage and memories of subaltern groups or appropriate their stories for dominant-class purposes.

Without denigrating “top down” responsibility to the owner-client, the architect’s “bottom up” contract with users at large and society in general must be accepted. Public health, safety, and welfare are not to be unheeded in search of personal success. But is architecture relevant to these issues of oppression? Currently a number of other crises threaten architects’ autonomy and claims to mastery: corrosion of professional boundaries, increased regulation, performance commissioning, value engineering, loss of public trust, and dismissal of the architect’s heroic figure for example (Bachman 2014). Worse, those challenges are compounded by architecture’s “permanent conflicts between autonomous...
ideals and external demands” (Sahin-Dikman 2013). At the crossroads however, postindustrial society and its emerging globalized, interconnected, complex dynamic offers a new perspective; and perhaps multidimensional intersectionality is a useful lens to that transition (Bachman 2013). Anderson (2014) writes:

> By incorporating values of inclusivity, social justice, and equity, public interest design inserts a critical lens into contemporary architectural thinking, practice, and pedagogy. Its emphasis on inclusive process and action over product creates a praxis that draws on trans-disciplinary knowledge to create change.

Three opportunities for that change shape our conclusion and counterbalance architecture’s complicity in institutionalized oppression.

### 3.1 Social activism
Social activism is a general form of architectural resistance to oppression. As benevolent agency, it now transcends the limited bounds of pro-bono and academic design work. The Auburn University Rural Studio, founded by Mockbee and Ruth in 1993 is a notable precursor. Habitat for Humanity is another such social project that architects and architecture students engage with some regularity. Design/Build programs in architecture schools also come to mind, as do the post-catastrophe design efforts that followed hurricane Katrina. More essentially, architects such as 2016 Pritzker winner Alejandro Aravena “has clearly demonstrated the ability to connect social responsibility, economic demands... and the city” (Pritzker 2016). With socially minded Glenn Murcutt and Richard Rogers on Aravena’s Pritzker jury, perhaps a fundamental shift is afoot.

### 3.2 Stakeholder engagement
To practice social activism, architects must embrace Gadanho’s bottom-up inclusivity. The struggle for balanced priorities, resistance and project refusal was covered in section 2.2 above. Cupers’ book (2014) provides an excellent set of perspectives to that end. Likewise, Vorhees (2015) focuses on how building partnerships among project stakeholders can help avoid discriminatory gentrification.

The emergence of Public Private Partnerships (P3) offers another tool for leveraging public interests with private and corporate resources. P3 arrangements are typically long term contracts to finance, build, operate, and maintain a project wherein a private developer assumes all costs and responsibility. In return the investing developer keeps all profits from the project for a contracted period of time, after which local government assumes ownership. Normally at the turnover stage, said developer provides a maintenance warranty to assure continued value. Sustainability is even part of some such P3 endeavors. It is easy to imagine how urban development could employ such strategies to promote social welfare with no upfront expense to city budgets or occupant investment.

### 3.3 Sustainability and the commodification of resources
Our global population of about 0.6 billion in 1500 had a negligible physical and ecological footprint on total land area. This persisted even as population doubled to some 1.2 billion people at the beginning of the 1800s’ industrial revolution (Fig. 3). By 2000 however, with the population exceeding 6.0 billion, human use had disrupted 60% of total land area and negatively impacted all the waters and ice areas of the planet as well as every layer of our atmosphere. While urban areas still cover only 3% of the earth’s land area, the infrastructure that surrounds and supports our cities and towns is part and parcel of what it means to craft the built environment. Note that the commodified urban, cropland, and pasture areas of the earth now approach 50% of the total land area. With recovering secondary forest and non-forest areas, only 20% of the natural world remains.

Links between sustainability and ethical design practice are framed by how we promote well-being through occupation of the built environment at all scales. If we further understand design as a preferred way to realize a better future, then the needs and aspirations of present generations are clearly linked to the sustained well-being of future generations.
Figure 3: Land use change since 1500. Includes 50,166,447 miles² (129,930,555 km²) of ice free land area. Source: Graph by authors; data from Goldewijk 2001, and Goldewijk et al, 2011.

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ABSTRACT: In the 1960s, the “design pattern” developed by Christopher Alexander provided a promising starting point for reflection on architecture that is increasingly produced by digital and generative systems. Alexander’s theory left a limited mark on the architectural design process, but it was radically adopted by computer science. Fifty years later, design algorithms and parametrics are a new field situated directly at the crossroads between computer science and architecture. We are in an era when digital intelligence can not only solve complex mathematical problems on the level of software, but also augment human intellect by generating architectural meaning. This paper compares computer science and architectural design, analyzing the fundamental differences and identifying the point of convergence.

KEYWORDS: Computer science, Augment Intelligence

1.0 CHRISTOPHER ALEXANDER AND COMPUTER-AIDED DESIGN

At one of the first international conferences on the relationship between architecture and computers, Christopher Alexander, then 30 years old, polemically confronted the pioneers of computer-aided design such as Steve A. Coons and Serge Chermayeff. In sharp contrast to their prevalent philosophy, which defined the computer in architecture largely as an intelligent drawing machine, Alexander represented the viewpoint of a structure-oriented, experimental design culture, whose primary focus was neither on forms of representation nor on a subsequent digitalization of finished design concepts. To Alexander, the computer’s true strength was its extraordinary ability to calculate (Gleiniger, 2009).

A computer was nothing more to him than “a huge army of clerks, equipped with rule books, pencil and paper, all stupid and defined operations” (Alexander, 1965). He was vehemently opposed to the popular tendency to ascribe artificial intelligence to computers. The mainstream thought about computers among software developers and believers in computer-aided design is that the computers were able to quickly generate a mass of diverse plans and elevation alternatives from every conceivable perspective; in contrast, Alexander declared soberly: “At the moment, the computer can, in effect, show us only alternatives which we have already thought of. This is not a limitation in the computer. It is a limitation in our own ability to conceive, abstractly, large domains of significant alternatives” (Alexander 1965).

Alexander’s insight into the limitation of computational design is not only incisive but also remarkable. He captured the potential and nature of the computer with regard to architecture application. Indeed, his perspective might illuminate some fundamental reasons that portend the integration of computers or other forms of digital tools into the design process. Even today, opinions diverge widely on whether a digital tool could, and would, be regarded as a design component and a fear that digitalization or computerization could jeopardize design creation. “Those that fear the computer itself are invariably those who regard design as an opportunity for personal expression. The computer is a threat to these people because it draws attention to the fact that most current intuitive design is nothing but an outpouring of personal secrets in elastic form” (Alexander, 1965). His major contribution was to view the computer’s true application potential in architecture as largely at a structural level. His understanding of architecture and technology differed from that of the majority on visually oriented computer graphics at the beginning of the 1960s. This concept is still very relevant to today’s context, as new computer tools are being created every year with the intention of helping architects and designers enlarge the boundaries of design creativity as well extend our capability to manipulate our own imagination—in another sense, to augment human intellect. Despite the original intention of new and advanced technologies, one can hear the lament for and agony over the architect’s space or scope having been “encroached on” by fabricators and contractors. Other design-related disciplines have been progressively taking on a more leading and aggressive role by integrating those technologies into their practice in order to amplify their capabilities.

We clearly need to examine why we still fear automation and computerization, and on what philosophical level we, compared to related disciplines, are lagging behind in terms of broadening of our intellectual capability.

1.1 Algorithms and parameters: Computer science

Instead of examining closely related disciplines such as construction and engineering, this paper compares computer science and architectural design. The two disciplines were at a point of convergence in the 1960s but have followed
dramatically different development paths since then. Computer science has exploded in the last 50 years or so to become a critical component of societal infrastructure, while architectural design's development has stagnated. The following points illustrate the major differences between the two fields on a basic organizational and structural level.

1.10. Christopher Alexander's influence on computer programming
Christopher Alexander's pattern language has had a bigger impact on computer science than on architectural design. Even though his theory caused quite a stir when it was introduced, it was not integrated into architectural practice. However, 10 years after the publication of A Pattern Language, American computer scientists Ken Beck and Ward Cunningham applied Alexander's theory to problems in software engineering (Beck et al. 1987). That is how pattern language, originally conceived as a system for architectural design, was eventually applied to the world of computer science, which at that point was experiencing a paradigm shift due to what are known as object-oriented programming languages. (Gleiniger, 2009) This remarkable cross-disciplinary transfer of knowledge happened because software engineers gained an insight into the work of an architect that proved very useful. Ultimately, the software that was developed based on programming languages now helps to power Macintoshes, iPhones, games, etc.

Meanwhile, Alexander's theory drew criticism from the architecture profession for oversimplifying the design elements: the 253 design patterns he identified would not be sufficient for a built environment. More to the point, however, many architects and urban planners were fearful that identifying the patterns could diminish the complexity of the built environment. (Mehaffy and Salingaros 2011)

1.11. User-driven vs. generator-driven
The design patterns for architecture concept development software development differ a great deal in dimensionality, the degree of abstraction, and the target group within their own field of interest. Alexander defined design patterns based on criteria that are important to users, no matter whether they are the residents in a house or pedestrians on a street. Ward Cunningham, a founder of "Object-oriented programming" whose design patterns were fundamentally conceived independent of the type and dimensions of the software and its specific application. Basically, they relate to the dependencies and the flow of information and control within the software, but not to individual users. In Wassim Jabi's book of Parametric Design of Architecture, he demonstrates the capacities of different digital tools to create user-generated patterns. (Jabi 2003)

1.12. Scale differences
Alexander's theory and design patterns cover an enormous range, from urban planning to construction. The examined structures span multiple orders of magnitude, from kilometers to millimeters in size. Some of the patterns used in construction scale can be replicated in urban scale and vice versa. On the other hand, in computer science, an interesting self-similarity exists. A basic principle of computer science is the subdivision of complex, complete systems into compounded, interdependent layers, as, for example, in hardware, system software, and applications. (Gleiniger, 2009) The layers do not present any shift in dimension, but rather serve as the principle of order, and thus neatly separate individual responsibilities and make them accessible only via a defined interface. To certain extent, software or information exchange can be scaled up or down, at least while it is being programmed, without alteration of basic patterns, the software and program could naturally evolve into next state—unlike architecture, where methods change fundamentally with the respective different scale and dimensions.

2.0. BUILDING INFORMATION MODELING (BIM)
Both architecture and computer science deal with specific segments of reality, and both aim to fulfill an actual purpose: one in the built environment and the other in efficient programs. Standard computer-aided design plans are merely a collection of lines and symbols, as are plans on paper; even three-dimensional Computer-aided Design (CAD) models are simply geometric objects. As Rob Woodbury pointed out in his book Element of parametric design "Language is what we say; design and making is what we do. Computers are simply a new medium for this ancient enterprise" (Woodbury 2015). In a typical set of CAD file only the geometric representation of the design process is stored, beside the geometry, it does not explicitly explain the information concerning the means and method of building process and construction methods. In this type of representation lines, objects are merely symbols.

The conceptual underpinnings of the Building Information Modeling (BIM) system go back to the earliest days of computing. As early as 1962, Douglas C. Englebart provided an uncanny vision of the future architect in his paper "Augmenting Human Intellect" (Englebart 1962). He suggested object-based design, parametric manipulation, and a relational database—dreams that would become reality several years later: "The architect next begins to enter a series of specifications and data—a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. (Englebart 1962) When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it... These lists grow into an ever more-detailed, interlinked structure, which represents the maturing thought behind the actual design."

BIM has played a paradigmatic role in changing the traditional way computer-aided design suited the design process.
The use of BIM is aimed at much more than just creating a model to see what the building should look like; BIM intends to create a model that contains all kinds of information and "meaning" from spaces and geometry, to cost, personnel, programming, quantities, specifications, suppliers, and other information types. To be well managed and qualitative, this information is contained in such a way that it is all related and built on the different kinds, in order to provide the best solution, enhance decision-making, improve production to the high level of quality, enhance prediction of building performance, be a major time saver, and control the budget in a safer environment within an organized, collaborative way of working. (Saravanan 2016) BIM can currently store the origins of the objects in the model, along with their properties and meaning. This is done by evaluating individual interdependencies between objects: if, for example, a door object knows that a wall object surrounds it, the door object is able to automatically adjust the thickness of its frame to match that of the thickness of the wall. The properties of the objects thus become parameters that can be manipulated and adjusted by other objects; the model becomes an associative, parametric model (Gleiniger 2009).

The next step in this development is to use stored information to simulate performance in order to minimize conflict and optimize interdependencies between objects and attributes. For instance, if the construction schedule depends mainly on the concrete superstructure's volume and construction time, then what could be the best alternative options to concrete construction be?

CONCLUSION

Parametric models are basically algorithms. On the one hand, the demands on the designer change, because much of the information—until now implicitly hidden in plans and with room for interpretation—has to be explicitly formulated into specific parametric models. On the other hand, designing parametric models is subject to the same rules of complexity and computability as software engineering. The approach thus far of storing as much information as possible in one model does not generally lead to a solution, but rather to models that are unmanageably complex and, ultimately, of no value. For the architectural context, this implies that the actual art of creating a parametric model is to find the correct level of abstraction, which means entering only the most necessary information and correlations into the model and omitting as many unnecessary details as possible. In the computer science context, it is about code and program: this particular objective of the minimal model is only partially compatible with the need to react flexibly to changes in the design. The choice of parameters and their dependencies predefines a certain solution space within which the model can operate. Any further changes require an adjusted or completely rebuilt model. Wide-ranging decisions have to be made in advance, without full knowledge of the later application. As is true in software engineering, design patterns can also be a helpful instrument here in determining the correct balance between efficiency and flexibility.

Design algorithms and parametrics are a new field situated directly at the crossroads between computer science and architecture. A new professional discipline is now developing precisely in this area—namely, on the border between architecture and engineering, as well as in independent consulting firms. Regarding architecture, working with parametric models constitutes a departure from the traditional of using computer-aided design as a digital drawing table. One might even go so far as to describe this departure as a paradigm shift, comparable to the shift that occurred when object-oriented programming was first introduced to computer science as an influence from Christopher Alexander. These innovative methods open completely new possibilities, such as overcoming standardization and designing complex forms for facades that have to be assembled from thousands of single components. (Salingaros) A new type of design/construction firm has emerged, such as ShoP. As one of the partners, Gregg Pasquarelli, said: “We make instruction sets for other people to build buildings.” (Polsky 2014) The use of technology (particularly digital technologies) and the blending of computer science into the decision-making enabled ShoP architects to become the last great generalist profession, with specialties in multiple areas. Literacy in computer science and deep imbedded parametric thinking, with aims and purpose, is the key to their success.

The Alexander-influenced software design principle developed in computer science was an effective tool that helped programmers solve precisely these structural tasks so they can focus more on important, content-related issues. Though the general concept and technology behind BIM is approaching its thirtieth anniversary, the industry has only begun to realize the potential benefits of building information models. As we reach the point at which a majority of buildings are being crafted digitally, an existing building marketplace where building materials and structural components can be bought and sold locally will emerge. Sustainable design practices reinforce an attitude of designing for disassembly, and a marketplace of these parts is essential. (Quirk 2012) Currently, virtual reality, augmented reality, cloud computing, generative design, and human-computer interaction continue to expand their influence on the development of new version of computer-aid design tools. Looking back, it is easier to realize that the present moment is an exciting time for designers and programmers in this evolving industry, and that a new professional discipline suited to the in-between might provide architectural design another chance to catch what we missed half a century ago.
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ABSTRACT: This paper describes a third- and fourth-year pilot design studio at the University of Texas at San Antonio (UTSA). Two instructors—one with expertise in building performance and the other in architectural design—implemented a systems-based approach to teaching undergraduate design studio that allowed students to explore the oft-misunderstood relationship between architectural performance and form. The instructors integrated advanced performance modeling into the design curriculum, restructuring the studio around 10 parallel and interactive lab sequences: 5 covering topics specifically related to building performance and 5 covering general design topics. The reconfigured studio required participants to pursue issues of sustainability and design in parallel, allowing students to leverage building performance as a form generator, not a technical overlay. Both iterations of the studio produced a winning entry in the American Institute of Architects (AIA) Committee on Technology and the Environment (COTE) Top Ten for Students Competition, which recognizes ten winners annually from a national pool of entries.

KEYWORDS: building performance, sustainability, COTE, studio pedagogy, Architecture 2030

INTRODUCTION
The negative impacts of climate change present an existential concern for architects, as the built environment is a major contributor to the global environmental crisis. The severity of this crisis means that architects have a disciplinary obligation to accelerate the design and construction of carbon-neutral and carbon-positive buildings. Within the professional realm, architects are meeting this challenge, channeling their efforts through programs like the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED), begun in 1994, and the Architecture 2030 Challenge, begun in 2006. Both are widely accepted standards within the industry.

The response from the academy to date has been less clear. While the National Architectural Accrediting Board (NAAB) maintains significant curricular requirements related to environmentally sustainability and building performance, most schools have yet to integrate this critical material into traditional design studios. This paper describes a pilot studio curriculum at the University of Texas at San Antonio (UTSA) that recasts the architectural design studio as a multi-disciplinary, systemic undertaking, one that considers the potentially dynamic interaction between issues of building performance and architectural form in the design studio. The two studio instructors—one with a background in environmental systems and the other in architectural design—initiated a curricular feedback loop, prompting students to engage a continuous dialogue between issues of building analysis and design. In this regard, the pilot course addressed a perceived curricular shortcoming, embedding issues of ecological literacy and performance metrics into a third- and fourth-year undergraduate design studio.

The studios fulfilled multiple learning objectives, seeking to

• advance the design of a carbon-neutral built environment in accordance with the Architecture 2030 Challenge.
• embed issues of ecological literacy into a traditional studio setting.
• create a critical feedback loop between issues of building performance and design.
• embed advanced performance modeling and metrics into a traditional studio setting.
• provide students with the opportunity to enter an international design competition.
• explore contemporary and competing theories of suburban design.
• develop new housing typologies that correspond to the suburban condition in South Texas.

To date the instructors have implemented this curriculum twice, first during the fall semester of 2015 and again in the fall of 2016. Both iterations of the studio focused on programs related to the geographic and demographic expansion of San Antonio, Texas, one of the fastest growing cities in the United States. 1.1 million people will move to San Antonio in the next 25 years, a demographic influx that will bring the population of the city from 1.4 million to 2.5 by 2040. This rapid expansion will require the city to add 500,000 new jobs and 500,00 new units of housing, a significant challenge in a city that already added 430,00 people in the last decade (Rivard, 2014).
The first iteration of the studio called for the adaptive reuse of a commercial big box, the most common and mundane of suburban building typologies. Students recast a prototypical Walmart Neighborhood Market in San Antonio as a neighborhood branch library, taking advantage of the typography's most compelling traits: ubiquity, obsolescence, low-cost and flexibility. The second studio generated new typologies for suburban infill housing, considering the optimal location, design, and construction of these units.

In both cases, the instructors adopted the structure of the AIA Committee on Technology and the Environment (COTE) Top Ten for Students Competition. The AIA COTE Top Ten Competition required students to simultaneously generate formal and environmental responses to issues of innovation, regional design, land use and site ecology, bioclimatic design, light and air, water cycle, energy, materials, adaptability, and feedback loops.

1.0 CURRENT CURRICULAR MODELS

For decades, leading professional and academic organizations including the American Institute of Architects (AIA), the National Council of Architectural Registration Boards (NCARB), NAAB, and Architecture 2030 have advocated for a more thorough integration of building performance topics into core architecture curriculums across the United States. While many architectural educators enthusiastically embrace this principle, actual implementation has proven difficult. Today, most schools continue to deliver material related to environmental sustainability in discrete courses that do not relate directly to design studios. Attempts to address building performance topics within the design studio framework are met with multiple challenges, including a lack of credit hours, limited budget for instruction, and a lack of collaboration among faculty. In the absence of agreed-upon pedagogical methods and curricular structures, most architecture schools rely on trial-and-error when seeking ways to incorporate building performance and design issues. The authors believe that the greatest potential to achieve this integration lies in the design studio, which occupies the intellectual center of architectural education, and typically captures the greatest percentage of credit hours within the curriculum.

Currently, most schools appear to utilize one of three models to teach building performance issues (Figure 1). In the Integrated Model, which remains rare, building technology faculty work side-by-side with design instructors to deliver content associated with environmental control systems and structures in a studio setting. Texas A&M University has implemented a version of this model at the undergraduate level, which requires students take a preliminary systems and structures class, followed by a collaborative studio that integrates building technology and design. This fully integrated arrangement offers a critical advantage: emphasizing the reciprocal relationship between technical topics (structures and environmental systems) and design topics (aesthetics, form, program). Of course, the approach does present challenges, increasing the required resources for administration and faculty. Another version of this model occurs when a building technology faculty with a strong design background leads the studio. While this arrangement offers the advantages of the integrated model, likely at a lower cost, it is limited by the number of faculty who are able to fulfill both the technical and design components of the studio simultaneously.

In the Linked Model, studio and building technology instructors coordinate the terms and sequence of assignments and projects, sharing content and outcomes wherever possible. Like the Integrated Model, the Linked Model reinforces the simultaneous application of technical and design skills in studio, albeit with less direct contact between collaborating faculty. The main challenge here involves guaranteeing that a sufficient scope and depth of building technology topics will be covered in the design studio. Again, a high level of coordination is required among faculty.

In the Unlinked Model, the building technology and studio courses run in parallel, with no direct integration. Students are left to their own devices to integrate the material that they learn in Environmental Systems and Structure courses into their studio designs. This model, by far the most common in U.S. schools, shares most of the limitations of the previous models and, in addition, does not offer a mechanism to help students apply newly acquired technical knowledge to design projects. It also does not provide the opportunity for collaboration among technical and design faculty, which exacerbates the lack of integration within the curriculum. A number of educators have made efforts to address limitations of the Unlinked Model, integrating limited building technology exercises into design studio (Gurel, 2010; Nigra, Grosso, Chiesa, 2016). An example of such efforts is reported by Nigra et al, where graduate studio instructors at the Polytechnic of Turin in Italy used six assignments within an Unlinked Model to integrate sustainability in the studio. These assignments addressed spatial organization, microclimate analysis, technological research and architectural design, envelope system design, ventilation system design, and construction of technological and architectural solutions (Nigra, Grosso, Chiesa, 2016). Their objective was to create environmentally-conscious design alternatives, introduce performance-driven design early in the design process, and create a method for students to handle the complexity of a sustainable design studio.
2.0 THE PILOT STUDIO AT UTSA

2.1 Overcoming the limitations of the Unlinked Model

At UTSA, undergraduate students complete a traditional four-year Bachelor of Science in Architecture degree, which requires them to take seven design studios and four total courses in building technology. The latter includes two environmental systems course that cover heating, cooling, lighting, and acoustics. Students also complete two courses in structures. UTSA's curriculum is highly traditional in that there is no direct connection between environmental system topics and design studios. In effect, UTSA is operating using the Unlinked Model, as described above. As we have seen, this model presents a number of disadvantages, most related to the lack of integration between curricula and faculty. This pilot studio began as a way to address the perceived disconnect between environmental systems and design topics within the Unlinked Model of the B.S. program at UTSA. The instructors' short-term objective was not to move towards a Linked or Integrated Model, as this change would require a fundamental transformation of the B.S. curriculum. Instead, their objective was to integrate course materials within the Unlinked curricular model, thereby providing students with the skills necessary to design climate-responsive, high-performance buildings.

The instructors began by restructuring an advanced elective studio around 10 parallel and interactive lab sequences: 5 performance labs covered critical topics including bioclimatic design, energy flows and futures, light and air, water cycle, and materials and construction; and 5 parallel design labs focused on related topics including regional and community design, land use and site ecology, programmatic adaptability, collective wisdom and feedback loops and design & innovation. These 10 labs corresponded directly to the 10 required measures in the AIA COTE Top Ten for Students Competition. The larger goal of the reconfigured studio was to require students to pursue issues of performance and design in parallel; never in isolation. Ultimately, the curriculum prompted student designers to pursue the topic of sustainability as a form generator, not a technical overlay.

2.2 The building performance labs

![Figure 1. Models for the integration of building performance and design pedagogy. Source: (Authors 2016)](image1)

![Figure 2. UTSA COTE model for Integration of building performance topics into design studio. Source: (Authors 2016)](image2)
The building performance section of the studio began with a lab dedicated to “Bioclimatic Design.” The students analyzed the local site using Climate Consultant software, identified and prioritized climatic issues, and finally generated appropriate passive strategies capable of minimizing energy loads while maintaining thermal and visual comfort.

**Figure 3.** Dr. Azari introduces software (left) while Professor Caine discusses site ecology (right). Source: (Authors 2016)

The next two labs, “Energy Flows and Futures” and “Light and Air,” prompted students to learn Sefaira, a building performance plugin to SketchUp that predicts the energy and lighting performance of buildings. Students used the complementary software packages to generate multiple design alternatives that maximized energy performance, daylighting, and passive ventilation. During this phase students leveraged a variety of metrics to measure success: the Energy Use Intensity (EUI) to measure energy use against targets from the Architecture 2030 Challenge, Spatial Daylight Autonomy (SDA) to maximize day daylighting, and Annual Sunlight Exposure (ASE) to minimize unwanted direct sunlight. Students leveraged the combination of software and metrics to initiate an iterative process that involved testing the relative efficiencies of multiple geometries, plan organizations and fenestration patterns.

**Figure 4.** Student work from one of the building performance labs. Source: (Elsa De Leon, 2016)

In a subsequent “Water Cycle” lab, students learned strategies to reduce consumption through the introduction of low-
flow fixtures and collection, filtering and treatment strategies. Finally, a “Material and Construction” lab introduced students to Athena Impact Estimator, allowing them to quantify the lifecycle impact of materials on global warming, acidification, eutrophication, and smog formation.

2.3 The architectural design labs

The instructors ran 5 architectural labs in parallel with the 5 performance labs. The first design lab, titled “Regional and Community Design,” asked students to consider the relationship of their design proposal to the larger metropolitan context, highlighting topics such as neighborhood form, typologies, and vehicular and pedestrian circulation systems. During the housing studio, the lab required students to perform a careful analysis of existing and proposed residential densities in order to understand the potential impact of infill strategies.

A subsequent lab, “Land use and Site Ecology,” required students to consider how their site intervention might impact existing ecosystems, watersheds, flora, and fauna. Students began by selecting and mapping an existing ecosystem such as hydrology, food, or migration. Once the mapping was complete, students examined the potential impact of their design intervention on the system, identified the parts of the system that would be directly affected, and then considered potential feedback loops.

Figure 5. Student work from the architectural design labs. Source: (Reyes Fernandez and Carmelo Pereira, 2016)

The “Long Life Loose Fit” portion of the COTE rubric is intended to measure a design’s potential for long-term flexibility and adaptability. The instructors interpreted this lab differently in each semester. In the first studio, which considered the adaptive reuse of a commercial big box, students focused on the material efficiencies of the renovated structure. In this case, issues like the cost of assembly, disassembly and the durability of materials and systems over time became important. In the second studio, which dealt with suburban infill housing, students utilized the American Fact Finder to make a demographic and socioeconomic argument for increasing the diversity of housing typologies. Focusing on issues like age, income, and family type, students constructed a series of graphics that demonstrated the relationship between housing diversity and sustainable communities.

In the “Collective Wisdom and Feedback Loops” lab, the instructors asked students to document their formal decision-making process throughout the semester, retroactively evaluating the impact of various labs on their design process. For many students, this exercise revealed the enormous opportunities and potential complications of the parallel lab structure. It also prompted an important discussion within the studio about the preferred sequence of labs. It finally provoked studio members to pose critical strategic questions such as: what comes first, analysis or form? This lab generated a number of highly productive and revealing discussions amongst the students and instructors.

Finally, the “Design and Innovation” lab challenged each student to select one environmental strategy and make it the
subject of an in-depth design development drawing. Popular topics included sunscreens, landscape strategies and, for the housing studio, prefabricated envelope systems. The instructors required that these drawings simultaneously illustrate architectural concept, environmental performance, and human experience, thereby illustrating the philosophical intent of the studio.

CONCLUSION
The pilot studio succeeded on a number of pedagogical levels. First, and most critically, the studio prompted students to pursue the topic of building performance as a form generator, not a technical overlay. The curriculum accomplished this by implementing a highly-structured feedback loop that advanced issues of analysis and form-making in parallel, never in isolation. To exaggerate the creative tension between these two often-opposing topics, the instructors discussed the conflicting priorities on a daily basis, with Professor Azari advocating for sustainability and Professor Caine emphasizing architectural design. Students appeared to appreciate the diverging faculty perspectives, viewing them as a source of constructive tension rather contradiction.

Second, the labs provided a solid organizational foundation upon which to structure the semester's work. We typically held labs on Wednesdays, which broke up the week and provided the studio with a useful rhythm. The course evaluations indicated that students enjoyed the intense instruction and tightly scripted exercises, which provided a break from the typically open-ended nature of the design process. The labs also provided the instructors with an opportunity teach skills related to software, metrics, drawing, diagramming and research. Skill-building is something that is often missing from design studio curriculums, which typically focus on the pursuit of ideas.

Third, the lab structure—which alternated weekly building performance and design labs—obliged students to pursue an integrated and multi-disciplinary approach to their projects. Quite simply, it was impossible to ignore either the performative or formal development of one's project for more than one week, because every Wednesday students had to confront another set of topics and exercises.

Fourth, each studio participant had the opportunity to assemble and submit an entry for the AIA COTE Top Ten Competition for Students, one of the most prominent student competitions in North America related to the field of sustainable design. The students enjoyed the competitive aspect of the work, as well as the sense that they were involved in a discourse that transcended the boundaries of UTSA. Students frequently viewed and critiqued the winning submissions from previous years, while discussing how their entries might stack up against work from other universities. Many students took advantage of the (voluntary) opportunity to team up with a classmate for the entire semester. This collaboration was a first for a number of participants, many of whom had never worked on a team while in school.

Finally, the studio work and curriculum generated a significant amount of external recognition. One project from each studio received recognition from the AIA COTE Competition Jury, which selects ten winners annually from a large
pool of entries submitted from the U.S., Canada, and Mexico. Representatives from the two winning teams traveled to AIA National Meetings in Philadelphia and Orlando, trips that exposed the students to multiple lectures, workshops, and thousands of architects from across the country. Additionally, leading national and regional journals like Architect magazine and Texas Society of Architects published the winning designs (Madsen and Blahut, 2016; Texas Society Architects, 2016).

Last year, Architecture 2030 selected the UTSA studio for inclusion in the 2030 Pilot Curriculum Project, a program committed to promoting courses that “transform the culture of sustainable design education not only within their own schools, but in architecture and planning programs nationwide” (Architecture 2030, 2016). The Architecture 2030 Challenge, initiated by architect Ed Mazria, calls for architects to design built environments with zero emissions by the year 2030. The UTSA studio curriculum, one of seven inaugural selections for this program, is now receiving technical, logistical and publication support from Architecture 2030.

The overall success of the pilot curriculum notwithstanding, the studio presented more than a few sets of challenges to instructors and students. The first involved the large amount of skill-building required of students. The instructors introduced a significant amount of advanced performance modeling software and metrics during a short four-month time frame. Virtually all of it was unfamiliar to students. Not surprisingly, at times the volume of material was difficult for students to absorb, which led to a decline in the quality of lab results. Other times, the in-class training and working sessions proved insufficient in scope to allow students to master the necessary software. The training sessions also consumed time—typically one studio period per week—that would have normally been devoted to more traditional drawing and model-making.

A second set of challenges involved the capacity of many students to treat building performance as an integral component of the design process. While all were quick to adopt this philosophical position, putting this motivation into action proved more difficult. Too often, when faced with a faltering or unclear design concept, students buried themselves in environmental analysis, perhaps hoping that the software would lead them to a design solution. Other times, students intuited a form-based solution, then used the software to justify their pre-conceived result. Neither of these strategies proved successful.

Perhaps the greatest set of challenges, however, involved encouraging young designers to pursue formal innovation at the intersection of building performance and architectural design. Too often, the studio members reverted to generic environmental strategies, adding sun screens, bioswales, or permeable pavers to otherwise traditional formal strategies.

The instructors are planning a series of modifications for future iterations of the studio. First, we would like to encourage students with pre-existing knowledge of advanced performance software to sign up for the studio. This would partially alleviate the burden of skill-building that has slowed the studio’s progress. Second, we would like to emphasize the “Design and Innovation” lab, perhaps with an emphasis on simultaneous physical and digital modeling. We hope this will encourage students to view building performance as a catalyst for formal innovation, rather than as a post-rationalization or mere accounting of the design process. Finally, the studio would benefit from the input of other disciplines, particularly landscape architecture. This will be a challenge, given that UTSA does not sponsor a landscape program. Still, the instructors have the luxury of drawing on an excellent professional community in San Antonio.

![AQAL Diagram](image1.jpg) ![Four-Quadrant Curriculum](image2.jpg)

**Figure 7.** Wilber’s AQAL diagram (left); Buchanan’s four-quadrant curriculum diagram (right). Source: (Buchanan 2012)

While the curricular intervention described above is limited to a single studio exercise, and therefore limited in scope, both instructors are strong advocates of the Linked Model, which more fully integrates sustainable principles into core
architectural curriculums. Still, there is another level of pedagogical integration that occurs at a trans-disciplinary scale. One recent and compelling suggestion comes from South African architect and urbanist Peter Buchanan, who proposes a pedagogical model that he calls Four Quadrant Curriculum. Buchanan's model posits that sustainability in the built environment exists at the nexus of architecture, urbanism, and landscape architecture—disciplines that became artificially separated during the modern period. Buchanan proposes a Four Quadrant Curriculum meant to simultaneously reintegrate the disciplines, while elevating the importance of sustainability in architectural education (Buchanan 2012).

Buchanan bases his Four Quadrant Curriculum on the Ken Wilber's Integral Theory's All Quadrant All Level (AQAL) diagram, which asserts that in order to fully understand a phenomenon an individual must develop a range of comprehension that he describes as interior, exterior, individual and collective. By doing so an observer gains a variety of perspectives that he describes as personal, behavioral, cultural and systemic.

Buchanan leverages Wilber's AQAL diagram (Figure 7, left) to argue for a year-long series of foundation courses that would be taught to students from different disciplines. The larger goal of such a curriculum would be to provide students with a broad and shared understanding of the issues related to sustainability. Buchanan goes on to diagram course requirements for architecture students (Figure 7, right). On the left side of the diagram he places courses that provide a subjective understanding of sustainability, while on the right he offers courses that cover objective issues. The subjective courses focus both on personal experience and psychology—which he calls “Delight”—and on worldviews and subjective aspects of community—which he calls “Culture.” On the right-hand side of the diagram he places courses that provide an objective perspective on the sustainable built environment—he calls these “Function.” These courses are primarily design studios and explore space standards and program. The right-hand side also covers different aspects of environmental and structural systems, including their impacts on building use and occupant comfort—he calls these “System” courses. This comprehensive approach emphasizes the importance of teaching not only core building performance concepts, but also the synergies and tradeoffs that are often ignored in the discussions of sustainability in built environment.

Today's architectural education, at its core, must train students to confront the environmental challenges—phenomena like sprawl, water, infrastructure, carbon and housing—that increasingly define life in the twenty-first century city. Both instructors believe that the best way to help students engage these issues is through the successful incorporation of technical coursework and studio efforts. It's only through such integration that students will develop the technical skills necessary to evaluate building performance and put them into the service of their architectural designs. We are gratified that the teaching model and materials developed in this course, soon to be published nationally by Architecture 2030, will become available to additional instructors who are working to transform their own studio culture and core curricula to meet twenty-first century environmental challenges.

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DEVELOPING DATA-DRIVEN APPROACH FOR OCCUPANTS-BASED ON ENVIRONMENTAL CONTROL

Chen Zhong*, Joon-Ho Choi*, Marc Schiler*
*University of Southern California, Los Angeles, California

ABSTRACT: The design and operation of building systems frequently face a conflict goals between providing acceptable thermal comfort conditions and reducing building system's relevant energy consumption. Integrating individually different occupants' thermal comfort preferences into the building thermal environment control strategy has high potential to contribute to overcoming this conflict issue. Therefore, the goal of this study was to develop an intelligent control algorithm to maximize energy conservation efficiency while enhancing the occupants' thermal comfort and satisfactions. Considering individual occupants' different thermal preferences, two occupancy conditions were selected in this study: single-occupancy condition (SOC) and multi-occupancy condition (MOC). The control logic is different between SOC and MOC, but the control for SOC can be adopted as the fundamental principle of the multi-occupancy condition. The SOC experiments were conducted to survey subjects' thermal preference pattern while the thermal environmental conditions changed from 18 ºC to 30 ºC in the climate chamber. Meanwhile, subjects' physical parameters were collected by heart rate sensors and survey forms to confirm the correlation between the indoor thermal condition and subjects' individual features. With the consideration of real-time environment conditions and human individual features (such as gender, BMI, and heart rate), subject's individual thermal preference pattern were captured and learned by machine learning algorithm. The occupants' thermal comfort preference under different environmental condition can be predicted by the developed machine learning algorithm. Based on individuals' thermal preference pattern, Overall Thermal Dissatisfied (OTD) index was developed to determine the optimal set point temperature for minimizing the overall thermal dissatisfactions. The study result revealed the energy conservation potential up to 42% savings while significantly increased occupants' thermal comfort in a workplace environment.

KEYWORDS: Data-driven; Thermal comfort; Machine learning; Building system; Energy conservation

INTRODUCTION

Heating, ventilation and air conditioning (HVAC) systems has been playing an important role in providing occupants comfortable thermal environment, and are the largest energy consumption part in buildings (Vahid Vakiloroaya et al. 2014). The energy cost of the building operation accounts for approximately 40% of the world energy consumption. One of the most cost-effective method to save energy is increasing the energy efficiency of the building operations (Atilla Y. 1995). Improperly configured building systems waste approximately 20% of building energy usage, which is about 8% of the total energy usage in the United States (Brambley et al. 2005). Therefore, topic of saving on energy consumption of the building operation attract great attention by companies and scientist (Kolokotsa, D., et al. 2001). However, energy saving should not sacrifice user's welfare (F. Nicol, M. Humphreys, 2002.) occupants thermal comfort is the fundamental task of the HVAC system. It is necessary to adopt advanced control strategies on HVAC systems. The main objective is providing comfortable thermal environments for the occupants, and minimizing energy consumption at the same time (A. Hernández, 1994).

The multi-occupancy condition (MOC) is the occupancy condition that several occupants share one thermal zone. Occupants have different thermal preference and thermal stress tolerance, which make the control of the typical central HVAC system difficult to balance different occupants' thermal requirement. However, multi-occupancy condition is dominant, especially in office building. Simply finding a consensus cannot solve the problem since different individuals' thermal comfort range might not overlap.

With the rapid development of the artificial intelligence technologies researchers made effort to develop intelligent system for HVAC system considering both energy conservation and users' thermal comfort conditions (Huang S, Nelson RM. 1994.). Started in 1990s, artificial intelligence (AI) method has been applied to the control of the building systems. Both conventional and bioclimatic buildings adopted artificial intelligence (AI) techniques to improve the system control. The development of evolutionary algorithms optimizes the intelligent controllers, which can contribute to the control of the intelligent buildings' subsystems (Lopez L, et al., 2004). The synergy of the neural networks technology and evolutionary algorithms optimize the control of system to overcome the non-linear features of PMV calculations, time delay, and system uncertainty. (Dounis AI, Manolakis DE. 2001; Singh J, Singh N, Sharma JK. 2006 ; Kolokotsa, 2001; Kolokotsa, 2001)Taking occupants' participation into the control system is becoming more and more popular control
strategy, since occupants directly involvement can significantly improve occupants' thermal comfort condition. There are many artificial product coming into the market and became very popular, even though there are some limitation of these products. Nest Learning thermostat is one of the most popular artificial thermostat product in the market. Even though it got a great success in consumer market and had a good performance in energy saving as well as thermal comfort improvement, there are still some limitations that cannot be ignored. Nest only focus on residential buildings and cannot solve multi-occupants thermal requirement conflict. Moreover, Nest did not consider occupants physical condition. The only learning feature is users' living pattern, which is not reliable enough. However, users-based control strategy is a significant merit of Nest learning thermostat.

2.0 OBJECTIVE
Importance of the smart HVAC control system and problems the current HVAC system faced especially the thermal requirement of the multiple occupants' condition. The current industry standard and PMV model cannot meet the occupants' thermal requirement. The goal is to develop the control algorithm that can improve the thermal comfort condition while reduce the energy consumption. The proposed algorithm can generate the set-point considering the multiple occupants' thermal preference in one HVAC zone. Thus, the objectives of this research is to develop occupants-based data-driven thermal environment control approach that maximize energy conservation efficiency while enhancing the occupants' thermal comfort and satisfactions.

3.0 METHODOLOGY
3.1 Overview of methodology
In this research, both individual and multi-occupants experiments were conducted in the climate chamber B11, located in the basement of Watt Hall at the University of Southern California. The individual experiment is single occupancy experiment. Each participants took individual experiment to track their thermal preference pattern. Data of each participant’s experiment was collected in individual database. Based on the individual experiment data, individual artificial neural network (ANN) model was developed. The ANN model can predict participant’s thermal comfort for the similar environmental condition. Overall thermal dissatisfied index was developed to solve the multi-occupants thermal conflicts based on their individual thermal comfort curve. The optimal set-point temperature was generated by calculating the overall thermal dissatisfied index, and was compared with the performance of common industry HVAC set point.

![Research methodology workflow](image)

**Figure 1:** Research methodology workflow

3.2 Overall Thermal Dissatisfied (OTD) index
In order to solve the thermal comfort problem for multi-occupancy condition, the Overall Thermal Dissatisfied (OTD) index was developed. F(t) is the function to calculate the OTD index, which can indicate overall thermal uncomfortable condition of the multi-occupant condition. The lowest value of the F(t) is the optimal condition, and the corresponding value t should be adopted as setpoint of HVAC system.
The benefit of this OTD index evaluation method can minimize the total number of occupants who feel uncomfortable. By finding the lowest value of OTD index, the optimal environment condition can be found.

3.3 Experiment design

3.3.1 Climate chamber setting

The human thermal comfort experiment was conducted in the B11 climate chamber (Fig. 2), which is located in the USC Watt Hall at the University of Southern California. B11 climate chamber provides a heat-balance environment and is carefully controlled with lab AC system connected with LabVIEW. The air-speed in the chamber was controlled within 0.2 m/s according to the ASHRAE-55 standard. The CO2 density was controlled around 700 ~ 900 ppm during the experiment. The amount of radiant heat transferred from a surface can be ignored since there is no window in the chamber and it is located in the basement. In the center of the chamber, a chair and a desk were placed in order to provide a working condition for subjects. The metabolic rate of the subjects was 1.0 as seated in the office condition. The environmental temperature and relative humidity were measured by tripod sensor package at 1.1 m level. All the data were recorded per 10 seconds, and automatically transported into LabVIEW database. For this study, the environmental condition is the climate chamber setting, which is more stable and less variable than actual working space. Only the air temperature is considered as environmental factor that will influence the thermal comfort. Others factors such as relative humidity, mean radiant temperature (MRT), clothing index, air speed and etc. can be ignored because of the strictly controlled environmental condition in climate chamber.

Figure 2: Fisheye photo of chamber setting

3.3.2 Physiological measurement

There are 13 subjects attended the experiments. Subjects’ individual information including body mass index (BMI) and gender were recorded by the survey form. The real-time heart rate, surrounding environment temperature, and surrounding environment relative humidity were collected by wireless Heart Rate sensor, temperature, and relative humidity sensors. The data were automatically transmitted to the DAQ system with the LabVIEW software.

3.3.3 Procedure

The experiment lasted around 65 minutes, and environmental temperature was gradually increasing from 18 °C to 30 °C (Fig. 3). Before the experiment start, there is 15 minutes adjusting time for subjects prepare and get used to the chamber environment. The chamber environmental temperature maintained 20 °C during the adjusting period. Subjects filled the consent form and individual information form for recording BMI and gender. After 15 minutes adjusting and preparation, the experiment started. The environmental temperature gradually increase from 18 °C to 30 °C in 65 minutes.
Every 5 minutes, subjects were asked the feedback of Thermal Sensation (Table 1) and Thermal comfortable condition (Table 2). The feedback from subjects were recorded by the survey form with corresponding experiment time. All their data were collected in the individual database.

<table>
<thead>
<tr>
<th>Value</th>
<th>Thermal Uncomfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Comfortable</td>
</tr>
<tr>
<td>1</td>
<td>Slightly Uncomfortable</td>
</tr>
<tr>
<td>2</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>3</td>
<td>Very Uncomfortable</td>
</tr>
</tbody>
</table>

3.4 Scope of the work

The scope of this research is only focus on lab setting with the strict environmental control. The purpose of this work is to explore the potential use of artificial intelligence in thermal comfort control. Therefore, the ideal environment is necessary in order to prove the theory. Based on the result of lab setting research, the application in the real world could be discussed.

There are two precondition for the application of ANN based thermal control, one is how to collect occupant’s thermal comfort preference data without disturbing occupants work. It would be annoying if we do survey every 5 minutes to collect their feedback. Another precondition is how to identify occupant who stay in the room. Because MOC ANN-based control is based on the individual thermal preference data, it is important to identify who stay in the room and their individual thermal preference.

The above two precondition can be potentially solved by application of smart device such as smart watch and smart thermostat. Smart watch such as APPLE WATCH can collect user’s feedback without filling some paper survey. Smart watch can send the data and corresponding time to the control center. Similarly, smart thermostat can collect the real-time environment condition and send the data to the control center. The control center use the ANN-based control algorithm to analysis the data and adjust the environment condition based on occupants individual thermal preference. The workflow is displayed in Fig.4.

![Figure 4: Potential workflow of MOC ANN application](image-url)
4.0 DATA ANALYSIS

4.1 Database summary

There are 5 participants in the experiment. The collected data was imported from LabVIEW database and integrated with the subjective recorded data. Database was built based on the experiment data (Fig.4). There are 8 attributes in the database including identification information. The total record is 6660 including male record 3882 and female record 2778. The Heart Rate, Gender, BMI, Relative Humidity, Environmental temperature are 5 attributes (Input attribute) were used to training the ANN model. The label attribute (Output attribute) is Thermal comfort condition.

![Figure 4: Database summary in Rapidminer](image)

4.2 Artificial Neural Network (ANN) model development

In order to ensure that all attributes are in numerical form and on same scale, all the data from database was transfer from nominal type into numerical type by Nominal to Numerical operator in Rapidminer. Dummy coding type was used to deal with un-ordered values such as Gender and thermal comfort condition. Min-max normalization method (S.B. Kotsiantis 2006) was used to transform feature values into the same scale. Input preprocessed data into training set in the Rapidminer software and developed the ANN model (Fig. 5). 10-fold cross-validation was used to detect the performance of ANN model. The one of the participants ANN model performance was taken as an example (Table.3). The overall accuracy of the ANN model is 79.06% +/- 3.57%. The ANN model has better performance of comfortable prediction (88.72%) and very uncomfortable prediction (86.29%). The performance of accuracy of slightly uncomfortable prediction is 76.26% and the uncomfortable prediction is 69.59%. The reason of the ANN model's better performance in extreme condition is the thermal comfort feeling is easier of the participants to sense extreme conditions. The sensation of slightly uncomfortable and uncomfortable is more difficult for people to determine, which results in larger difference sensation feedback record among different experiment.

<table>
<thead>
<tr>
<th>Class</th>
<th>True very uncomfortable</th>
<th>True uncomfortable</th>
<th>True slightly uncomfortable</th>
<th>True comfortable</th>
<th>Class precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pred. very uncomfortable</td>
<td>151</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>86.29%</td>
</tr>
<tr>
<td>Pred. uncomfortable</td>
<td>65</td>
<td>206</td>
<td>25</td>
<td>0</td>
<td>69.59%</td>
</tr>
<tr>
<td>Pred. slightly uncomfortable</td>
<td>5</td>
<td>48</td>
<td>257</td>
<td>27</td>
<td>76.26%</td>
</tr>
<tr>
<td>Pred. comfortable</td>
<td>0</td>
<td>0</td>
<td>29</td>
<td>228</td>
<td>88.72%</td>
</tr>
<tr>
<td>Class recall</td>
<td>68.33%</td>
<td>74.10%</td>
<td>82.64%</td>
<td>89.41%</td>
<td></td>
</tr>
</tbody>
</table>

Accuracy: 79.06% +/- 3.57% (micro: 79.06%)

The accuracy of all participants ANN models (Table 4) indicate the artificial neural network had a good performance in prediction of human thermal comfort condition.
Table 4: Accuracy of all participants ANN models

<table>
<thead>
<tr>
<th>ANN model</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Accuracy</td>
<td>79.06% +/- 3.57%</td>
<td>79.37% +/- 2.72%</td>
<td>72.82% +/- 6.95%</td>
<td>75.82% +/- 5.36%</td>
<td>82.98% +/- 1.98%</td>
</tr>
</tbody>
</table>

Figure 5: Artificial Neural Network model

4.3 Individual thermal comfort curve
Participants’ thermal comfort curve were generated by ANN model. One of the participants ANN prediction thermal comfort curve was taken as an example. According to the comparison between prediction curve and actual experiment data (Fig. 6), the ANN model has a good performance of the prediction, and can generally capture participant’s thermal comfort pattern.

Figure 6: Comparison between ANN prediction model and experiment value
Correspondingly, paired t-test (Table 5) were conducted to test whether there is a significant difference in the boundary temperature between prediction value and actual value. Boundary temperature is the minimum and maximum environmental temperature in a certain thermal comfort condition. For example, the comfort boundary temperature of above prediction sample is $t_{\text{min}} = 22.6^\circ \text{C}$ and $t_{\text{max}} = 25.3^\circ \text{C}$. The T-Test compare the boundary temperature of comfortable, slightly uncomfortable, uncomfortable, very uncomfortable conditions to examine the performance of ANN model prediction.

| Table 5: Paired T-Test of boundary temperature in the ANN prediction vs Experiment data |
|----------------------------------|---|---|---|---|---|
|                                  | N | Mean | StDev | Difference | p-value |
| ANN prediction                  | 18 | 23.383 | 3.995 | 0.2 | 0.005 |
| Experiment data                 | 18 | 23.472 | 3.954 | 0.2 | 0.005 |

The resulted p-value of paired T-Test of boundary temperature in the ANN prediction and experiment data indicates that there was no significant difference between the ANN model prediction and experiment data. The difference value of 0.2 $^\circ \text{C}$ indicated that the ANN prediction has a good performance to prediction the boundary temperature of participant's thermal comfort condition.

4.4 Optimal setpoint temperature

All participants ANN prediction thermal comfort curved was generated (Fig. 7). Input participants' thermal comfort prediction into the Overall Thermal Dissatisfied (OTD) index to determine the optimal setpoint temperature. The value of $F(t)$ is 0 when the temperature is between 24.6 $^\circ \text{C}$ and 25.7 $^\circ \text{C}$. The blue highlighted area (Fig. 7) is the optimal setpoint temperature. The calculation indicated that all occupants would be satisfied in the climate chamber setting environment (Relative humidity is between 30%-40%) with temperature is between 24.6 $^\circ \text{C}$ and 25.7 $^\circ \text{C}$.

![Figure 7: All participants' ANN thermal comfort prediction](image)

The industry common designed temperature in U.S.is between 22 $^\circ \text{C}$ and 24 $^\circ \text{C}$ (Hoyt, Tyler et al. 2005) during the cooling season (see red highlighted area in Fig.7). The Overall Thermal Dissatisfied (OTD) index is from 16 ~ 121. The best result would be 4 occupants slightly uncomfortable and 1 occupant uncomfortable. The worst condition is 4 occupants uncomfortable and 1 occupant very uncomfortable. The difference of multi-occupants thermal comfort condition is significant between U.S. industry common designed temperature and proposed data-driven optimal setpoint. Moreover,
increasing the one degree setpoint temperature during the cooling season can potentially save 7~15% energy. (Hoyt, Tyler et al. 2005) The optimal setpoint temperature has a significant energy saving potential while maintain the certain level of occupants' thermal comfort condition. The difference setpoint temperature between data-driven optimal setpoint and industry common designed temperature is 0.5 °C ~ 2.8 °C, which indicated a potential 4%~42% energy saving.

**CONCLUSION**

In this study proposed a data-driven approach for user-based thermal environmental control. The approach consist of the artificial neural network (ANN) model and the overall thermal dissatisfied (OTD) index. ANN model was used to predict occupants' thermal comfort condition and OTD index was used to determine the optimal set point temperature that can minimize the overall thermal dissatisfaction. Experiment data indicated that ANN model has a good performance in capturing occupants' thermal preference pattern and making the thermal comfort prediction (over accuracy is between 72.82% +/- 6.95% to 82.98% +/- 1.98%) based on individual features and environmental conditions. For this research settings including environmental setting and occupants features, data-driven approach for user-based environmental control conducted a good performance in both energy-saving side (up to 42% energy-saving) and thermal comfort significant improvement. Above all, the data-driven approach revealed a great potential significance in smart thermal environmental control for both energy-saving and thermal comfort aspect.

**ACKNOWLEDGEMENTS**

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ABSTRACT: While technology has rapidly become more accessible to more people, its benefits are not always evenly shared. This paper searches for methods of identifying and defining gender inequality in architecture as it relates to digital technology and computation. The authors begin by documenting and then questioning existing metrics for measuring women's participation in architecture, then look outside the field to STEM disciplines, educational research, and economic theory as means of framing this research agenda. By examining and critiquing current patterns of technological distribution and academic culture, the authors seek to foster greater equality in education, architecture, and, consequently, the built environment.

KEYWORDS: computation, education, equality, methods

“The future is already here, it’s just not very evenly distributed.”
-attributed to William Gibson (See References)

INTRODUCTION
While many believe that technology is a way to create equality and provide opportunities, in practice this is not always the case (Servon, 2008). Particularly in architecture, access to technology and knowledge about technology continues to be unevenly distributed, which can result in the perpetuation and intensification of existing inequalities. Technology is a broad term but used here to indicate those digital technologies specific to architecture. While many types of inequality exist with respect to technology and architecture, such as race and class, this paper will focus on the issue of gender inequality. As technology is now essential to the practice and discipline of architecture, the ability to create with and shape technology is critical. This paper highlights the issue of gender inequality with respect to technology in architecture. It identifies the existing research gaps and argues that architectural education, in its role of affecting disciplinary culture, is essential to advancing technological equality. What follows is the beginning of a research agenda rather than its culmination.

WHO COUNTS?
Architecture as a discipline has been slow to fully acknowledge, incorporate, and integrate women into architectural practice and discourse. These past and present inequalities appear to be at work in the under-representation of women in technology. However, acknowledging the scope of the issue is difficult because, presently, specific data are not being collected about technology and gender in practice or in academia. To successfully argue for gender equality, detailed and accurate statistics are needed to move beyond anecdotal evidence. The current understanding of gender in architecture remains limited, as does our understanding of how women access and influence technology. One reason for this is the challenge of determining whom to study and how to measure. With regards to technology, how should participation be defined? As Matthewson writes, “It is easy to slip into anecdote and colloquial understandings of gender discrimination in architecture and much more difficult to parse out who counts” (Matthewson, 2014).

While architecture now recognizes its problems with gender equity, accurately measuring the nuances of women's participation has remained elusive. The question of who is an architect is more complicated than it might first appear. For example, in 2013, 43% of students enrolled in NAAB-accredited architecture programs were female; 45% of architecture graduates were female (Chang, 2014). NCARB’s “By the Numbers” report indicates that 42% of ‘record holders’ are women (NCARB, 2016), indicating an intention to pursue licensure, while the number of licensed women hovers around 18% in 2016 up from 9% in 2000 (Business of Architecture, 2012), but still far from parity as indicated by the ‘The Missing 32% Project’ (Dickinson, 2017). These numbers seem to indicate a dramatic loss of women in architecture, post-graduation, and low representation in the workforce, but there are other factors to consider. Architecture is more than the profession and those who strictly practice within the profession. NCARB numbers exclude university instructors, urban designers, writers and critics, and many others who identify as architects (Matthewson, 2014). In order to better understand the true state of gender inequality, more data from more sources is needed.

DECRATIZING ACCESS AND IDENTIFYING INEQUALITIES: GENDER, TECHNOLOGY, ARCHITECTURE

Shelby Doyle, AIA’, Nick Senske

1Iowa State University, Ames, Iowa
Figure 1: Adapted by authors from the ACSA article ‘Where are the Women?’ (Chang, 2014). Additional references are within the text. This is not a complete list of metrics but rather an effort to establish those metrics available to measure women in technology as it relates to architecture.

While, anecdotally, there seem to be fewer women than men in architecture, exactly how few is difficult to say with certainty. Data about graduation rates and licensure are an incomplete representation of the discipline. At higher levels of achievement, the gender gap becomes even more stark (Fig. 1). At AIA firms, just 17% of principals and partners are women (Hurley, 2017). The percentages of women awarded the Pritzker Prize for Architecture and the Topaz Medallion for architectural education is even lower: both 5% (Chang, 2014). These numbers indicate further inequality in the influence and recognition of women, which is disproportionate to their representation. Counting women is an important step in acknowledging and reducing inequality, but as a methodology, it has its problems and its limits. There are lessons to be learned and further questions to be asked.

MEASURING PARTICIPATION IN TECHNOLOGY

In Science Technology Engineering & Mathematics (STEM) disciplines gender inequality is a recognized and quantified problem. Data from STEM is relevant to the discussion about women’s participation in architectural technology for two reasons. First, the field of computing bears many similarities to the ways that technology is used in architecture. Developing and modifying computational software and systems for design has many parallels in computer science research and practices. Indeed, some of the training (learning programming, etc.) is the same. Second, there is significant data collected by computing academics and professionals on the issue of gender diversity as well as research into how to address the problem.

According to the STEM data, women are significantly underrepresented in computing. Women currently earn only 18% of all Computer Science degrees (AAUW Report, 2013). Indeed, it is the only STEM major to report declining representation of women over the last decade. This gender gap extends to academia and industry where research has found that 70% of authors on published technology papers are men (Macaluso, 2016). A 2013 report found that just 26% of computing professionals were women -- a percentage which is about the same as it was in 1960 (AAUW Report, 2013). Collection of this data has been an important step in helping to highlight and address this issue, though it has not led to gender parity in STEM.
Figure 2: The above graph indicates the number of papers authored or co-authored by women in a selection of popular architecture conferences. Gender was identified by the pronouns used in author biographies. ACADIA has approximately 20% fewer women co-authoring papers than ARCC or NCBDS. This percentage has changed very little during the last decade. Data collection and graph by authors.

While STEM fields recognize a gender gap in their enrollment and workforce, architecture has yet to acknowledge that its gender equity problem also extends to those who engage with technology. A reason for this could be that there is no data which proves that such a gap exists; it remains an anecdotal circumstance. One metric that does exist is the representation of women in technology publications in architecture (Fig. 2). The authors’ study of Association for Computer Aided Design in Architecture (ACADIA) papers from 2010-16 found that 26% of authors were women. (This percentage is strikingly similar to that of STEM computing fields and professionals.) Only 8% of papers had women as the first or sole author. Gender participation in technology is not typically measured within institutions. However, a brief study of the authors’ own department over the past year (2015-2016) found that, while 49% of architecture students are women, on average, they comprise only 19% of the students attending digital technology and computation electives. While the number of women participating in architecture is not at parity, the number of women participating in technology in architecture appears to be lower still.

Unfortunately, architecture does not yet measure participation in technology. This is a challenge of legitimate scholarship; the problem must be clearly named and defined (Boyer, 1990). While many have anecdotes about the use of technology by women in the practice of architecture, at the moment it is difficult to produce the empirical evidence necessary to study and address inequality. Moving forward, we propose that better measurement is needed and that data collection efforts from STEM fields could serve as a model. In this case, we are using technology as a proxy for power in the architectural discipline and, by measuring technology use, aim to better understand the grain of women's participation in developing technologies (Denardis, 2017).

GENDER GAP
Why does a technology gender gap exist? Research in STEM fields has identified several possible causes which may parallel those in design. These causes may have been inherited by architecture in the transfer of knowledge and technique. In a speech given at the Grace Hopper Celebration of Women in Computing Conference, Susan Wojcicki (CEO of YouTube), proposed two possible reasons women choose not to study computing: they think it is boring and they do not think they would perform well at it (Wojcicki, 2016). From the outside, working with technology can
seem unexciting. Because they lack access to mentoring, clubs, courses, etc. many young women have not had the opportunity to learn firsthand how technology can be creative and empowering. Women who are exposed to technology in K-12 education are much more likely to participate in STEM (Rogers, 2013). The second reason, concern about performance, may be caused by ‘stereotype threat,’ which is when an individual fears that they will confirm a stereotype about a group to which they belong. This has been shown to affect performance and to impact decisions. In this manner, negative stereotypes about women's performance in math and science are thought to be a factor in the inequality found in computing fields (Corbett, 2015).

There is no evidence that women are less capable users or creators of technology. To the contrary, data shows that women have the qualifications and test scores to join STEM-related subjects and perform well when they do (Fisher, 2002). Furthermore, history is filled with great pioneers of computing such as Ada Lovelace, Joan Clark, and Margaret Hamilton who demonstrate women's capabilities in the field. Ability is not the deciding factor. Many women choose not to study technology because they find its values to be insular and antisocial. They do not feel that a career in computing will allow them to collaborate with other people or make things which create social good (Mossberger, 2007). Another aspect of this is the male-centered gamer culture of today that emerged out of early personal computing, which can appear inaccessible to women 'outsiders' (Fisher, 2002). As Wojcicki explains, when it comes to technology, many women today feel that they do not belong, and because of this, they do not want to belong. The problems discouraging women from participating in technology are cultural and institutional. Education, which has traditionally held the power to shape culture and produce equality, is part of the solution.

WHY DOES IT MATTER?
The gender gap in technology is harmful not only to women, but to everyone. Women often see themselves as consumers of technology, rather than its creators. This has consequences in architecture, when being left behind in technology can limit one's participation in the design process (Williams, 2014). The importance of gender diversity in architecture is more than fairness or opportunity (although these are critically important, as well). When women are underrepresented, there is a risk of their needs being overlooked as design decisions are based upon the experience and opinions of only men. In the past, this has resulted in costly problems such as voice-recognition systems that do not recognize women’s voices because they were calibrated for male voices (McMillan, 2011). However, the potential impact of under representation is more than mere inconvenience. Early airbags resulted in the deaths of women and children because they were not considered as end-users (Why Carmakers Always Insisted on Male Crash-Test Dummies, 2012). The stakes for democratizing access are high. Thus, inequality in digital design education has far reaching implications for the discipline.

DOES TECHNOLOGY HAVE A GENDER?
Although progress has been made to measure the participation of women in the architectural profession, as a subset of architecture, technology has been categorically overlooked in studies on gender equity. While research in documenting gender disparity often champions progressive ideas of who can be ‘an architect,’ organizations such as Equity by Design [EQxD] (Equity in Architecture, 2011), Parlour (see References), and Architexx (see References) tend to overlook the professional presence of technology in favor of more conventional metrics: degrees, licensure, salaries, and awards. This conservative definition is likely because technology is often seen as infrastructure rather than integral and defining and measuring the users and influence of digital technology is a complex and difficult task. However, because digital technology is so important to the future practice of architecture, reflecting upon its current state (and possible role in promoting) gender inequality within the discipline must be critically examined.

One could argue that the low numbers of women specializing in digital design technology is unsurprising given that the practice combines fields that have historically been lacking in gender equity: management, information technology, computer science, engineering, and architecture (Davis, 2016). However, the importance of this gap in today's technologists cannot be understated. Historically, a technologist in an architecture firm played an auxiliary role, limited to maintaining computers and equipment. Concurrently, technology courses in architecture schools are often relegated to specialized electives rather than integrated into design courses. Today, as computers have become essential to the processes that define contemporary practice, the role of the design technologist has also become central to architectural means, methods, and concepts.

“Computer-aided design is about creativity, but also about jurisdiction, about who controls the design process,” says Yanni Loukissas, a researcher who has studied the adoption of technology by architecture firms (Davis, 2016). At the moment, control over computer aided design – who develops the tools and who administers them within the profession – rests overwhelmingly with men. This creates a condition where inequalities can become institutionalized, even as other aspects of the profession become more diverse. As Lieberson wrote, dominant groups remain privileged because they write the rules, and the rules they write, “enable them to continue to write the rules” (Lieberson, 1985). As a result, they can change the rules to thwart challenges to their position. While technology presents an opportunity for women to challenge stereotypes and privileges, it is also a site of gender imbalance within the profession:
consequently, the implementation of technology is not general neutral.

The design, distribution, use, and education of technology can either challenge or reinforce existing gender structures. Now that technology dominates the design process, the technologist – he or she – defines how the profession works and who works within it. The promise of technology as a medium is that it can allow an individual to be empowered in ways that are not pre-ordained by an institution – the state, the university, the discipline – and as such creates space for a multiplicity of voices to resonate within architectural discourse (Tapscott, 2008). How inequality is defined plays an important role in how an institution, such as the university, can work to undo that inequality.

DIGITAL DIVIDE + INHERITING BIAS
This research also looks to economic theory as one way to define inequality and the accompanying concept of redistribution as a means of addressing it. Economic inequality serves as a proxy for technologic inequality as a means for bringing this discourse into architecture where there is currently little theory to rely upon. Economic inequality is relevant to notions of equity, equality of outcome, and equality of opportunity (Fletcher, 2013). This definition stems from Thomas Piketty’s The Economics of Inequality (Piketty, 2015). The notion of inequality implies the concurrence of redistribution through institutions - economic, political, or social mechanisms. In the case of digital technologies, education and specifically the university, is the system of redistribution. Piketty's work on schools, for example, postulates that disparities among different schools, especially class sizes, is a cause for the persistence of inequalities in wages and the economy (Piketty and Valdenaire, 2005). Additionally, digital technologies are uniquely positioned to disrupt the very systems which are imposing the original inequalities. Indeed, there exists a certain consensus in regard to fundamental principles of social justice: if inequality is due, at least in part, to factors beyond the control of individuals, such as inequality of initial endowments owing to inheritance or luck, (that which cannot be attributed to individual effort), then it is just for the state (or university) to seek in the most efficient way possible to improve the lot of the least well off (that is, of those who have had to contend with the most adverse factors). In this case, the 'university' functions in lieu of 'the state' as an institution which redistributes knowledge.

The redistribution of digital knowledge is particularly fraught as it has so little context upon which to rely. Nicholas Negroponte, founder of the MIT Media Lab writes that ‘a man-machine dialogue has no history’ Therein lies the myth of the new unburdened language of technology: technology may promise new equalities but instead is recreating existing hierarchies (Negroponte, p. 79). It is therefore disconcerting to observe much of the architectural discourse around the computerization and software-driven design ignoring these dialogues. As Sanford Kwinter writes in The Computational Fallacy:

“These developments are either extolled as ‘exciting’, ‘new’ and ‘full of new freedoms and possibilities’ (by those most blissfully unconcerned of what is being so celebrated is but an extension of all that is oldest and most repressive in our political and corporeal history), or these are seen a posing an unavoidable or even welcome challenge to an already weakened or near-obsolete domain of cultural practice, namely the slow, grave, viscous world of matter. (Kwinter, 2003)”

Kwinter’s charge returns this discourse to the question of ethics: what is architectural technology, who defines it, who teaches it, and who disseminates it? If the internet can be used as a proxy for other technologies, then there is much to learned by aligning this work with architecture. The rise of the Information Society has come with the promise of altering the way society works and in doing so has produced deeply opposed ideas about the future of our collective and individual relationship to technology. Optimists assert that the Internet has the capacity to reduce inequalities between the information-rich and –poor. Pessimists expect that digital technologies will fortify and intensify existing disparities (Norris, 2001).

One of the reasons discussions about technology inspire highly contested images of the future is the that new technology might act a ‘great leveler’ by restructuring the dissemination of knowledge and communication (Norris, p. 237). These are questions which disrupt the very existence of the university as the mediator of knowledge. As the Internet and digital technologies have become increasingly embedded in nearly every aspect of daily life it becomes more important to establish how and whether certain groups are excluded from this resource: “whether poorer neighborhoods and peripheral rural areas, the older generation, girls and women, ethnic minorities, and those lacking college education” (Norris, p. 245). Specifically, how are these technological exclusions occurring in architecture?

CONCLUSION
The ‘digital’ has a relatively short history in architecture when compared to the previous two thousand years of architectural education models (this assumes Vitruvius’ Ten Books of Architecture (100 BC) to be the beginning of architectural education and discourse). If we accept Mario Carpo's dating of the digital turn around 1992 then there are barely twenty-five years of pedagogy and practice from which to mine for information. Therefore, it is necessary to look outside the discipline for questions of how to describe and address the digital divide (Carpo, 2012).
Identifying Inequalities: Senske/Doyle

Defining technological exclusions in architecture, providing theoretical rigor and context, then proposing methods for redistributing technical literacy are the goals of this research agenda. The text here does not endeavor to produce solutions but rather searches for ways to create and position the discourse necessary to ask the right questions. Architecture's disciplinary struggle for the ideal of equity – class, race, gender – is innately tied to contemporary social, political, and economic milieus. The promise of technology as a medium is that it can allow an individual to be empowered in ways that are not pre-ordained by an institution – the state, the university, the discipline – and as such creates space for a multiplicity of voices to resonate within architectural discourse. In this case, the university is presented as the actor necessary to redefine, redistribute, and rethink technological literacy in pursuit of a more just built environment. The next digital turn, defined by inclusiveness and equity, begins here.

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ARCHITEXX is an independent, unaffiliated organization for women in architecture that seeks to transform the profession of architecture by BRIDGING THE ACADEMY AND PRACTICE. We are a cross-generational group of academics and practitioners. http://architexx.org/


Equity in Architecture: Metrics, Meaning & Matrices http://eqxdesign.com/ The Missing 32 percent resulted from an incubator event conceived and produced in 2011 by the AIA SF Communications Committee. In turn, “Ladies (and Gents) Who Lunch with Architect Barbie” was inspired by a partnership between AIA National and Mattel on “Architect Barbie” whose place on the toy manufacturer’s line-up was insured by Despina Stratigakos and her colleague, architect Kelly Hayes McAlonie. At the event, fellow practitioners Dr. Ila Berman, Cathy Simon FAIA, Anne M. Torney AIA, and EB Min AIA joined for a lively panel discussion on the state of women’s participation in the profession, including the impact of “Architect Barbie”.


Negroponte, Nicholas. Toward a Humanism Through Machines p 79.


PARLOUR: Women Equity Architecture http://archiparlour.org/ PARLOUR: a space to speak – bringing together research, informed opinion and resources; generating debate and discussion; expanding the spaces for women in Australian architecture.


ABSTRACT: The 1970 international competition for the Centre Beaubourg (later renamed the Centre Georges Pompidou) proposed a new cultural institution for the information age: a museum and library conceived as a giant computer. The competition brief represented this enormous cultural information processing system through a program comprising meticulously tabulated requirements, diagrams of spatial relationships, and specifications for all technical aspects of the building’s performance. At Beaubourg, rational programming was applied for the first time to an elite cultural building. This paper examines the visual and notational languages of programming used at Beaubourg to control the performance of this information machine and to model the complex exchanges upon which the new institution's metabolic processes were based. Borrowing the conceptual frameworks, rhetoric, and notational conventions from the new discipline of systems engineering, the programming team created novel graphs, topological diagrams, and flow diagrams that formed a new zone for architectural creativity, and in so doing challenges the possibility of a clean bifurcation in the early 1970s between the formal avant garde and an emerging positivist technocracy.

KEYWORDS: Centre Pompidou, architectural programming, technocracy, software studies

Few buildings are as closely associated with the names of their architects as the Centre Pompidou. Although Piano and Rogers were relatively unknown in 1971 when they were announced as the winners of the international design competition, they quickly rose to fame through the countless articles, interviews, and media appearances in which they explained and defended the strange object slowly rising over the Plateau Beaubourg. Today, their names are synonymous with that building, while the building, more than almost any other of its day, stands as testimony to its authors’ clarity of vision and their heroic commitment to its realization. They were the first starchitects of the media age.

Shortly before the building’s completion, however, the historian and critic Reyner Banham pointed out that the building’s success as a realized vision was due not only to the determination of its architects and engineers but also to the “less public but far longer sustained managerial determination of its programmaticien (so much more than a mere ‘manager’!) François Lombard” (Banham 1976, 211). Who was this technician who worked behind the scenes to produce one of the 20th century's most recognizable and notorious buildings? Initially, hired to write the brief for the 1970 competition, Lombard ran the Programmation et études team that oversaw all of the project's functional requirements from conception through completion. Relentlessly demanding of the architects and wielding formidable administrative techniques powered by the new systems thinking, Programmation was the invisible co-author of the building we see today. This paper examines its methods. In particular, it considers the languages of form inherent in its managerial techniques, arguing that they signal an attitude to design that denies the false opposition between performance and form.

THE BRIEF

Any architect who entered the 1970 Centre Beaubourg competition would have been surprised by the sheer weight of the package arriving in the mail. The competition brief presented a detailed program with meticulously tabulated requirements, diagrams of spatial relationships, and specifications for all technical aspects of the building's performance, from lighting and acoustics to computers and networks. In contrast, the brief for the Sydney Opera House competition, launched fifteen years earlier, offered mainly site photographs and competition regulations, with the building program sketched out in two short pages in the Appendix. While the differences between the Beaubourg brief and its predecessors unquestionably reflected the technocratic methods of its authors, they also point to a more general disciplinary shift in which systems methods such as programming were added to the architect’s professional toolkit for dealing with increasingly complex buildings. It was not until 1959, four years after the Sydney competition, that Peña and Caudill’s seminal article on programming appeared in Architectural Record (Peña and Caudill, 1959). In 1966, an AIA report announced that “one of the scientific techniques for problem solving appearing on the horizon is that of systems analysis or systems development” (Wheeler 1966), and by the end of the decade, systems were everywhere, and one could not visit an architecture school or art museum without being reminded of the fact.

If Programmation believed such methods were the only hope of realizing this complex project and meeting its unreasonable deadline, Piano and Rogers held an equally firm suspicion of those methods, particularly when they were wielded...
by a state bureaucracy. Despite the ubiquity of systems discourse, the use of techniques normally applied to anonymous building types such as hospitals, mass housing, and schools in the design of an elite cultural building was entirely new. To flaunt them in a high-profile international design competition bordered on heresy. The brief overreached, and its “highly formalized, super rationalized” approach, as Rogers put it, flew in the face of the humanist, emancipatory, even libertarian, values latent in the early years of his practice (Rawstorne, 408). The brief raised another more insidious and troubling problem. Such an overbearing managerial approach surely warned competition entrants of potential future difficulties in its tacit challenge to the individual agency of the architect. Architectural postmodernism was already sensitive to the incursions of methods from the social sciences, and even Piano and Rogers, who unlike their neo-avant-garde colleagues were committed to a democratic and pragmatically-minded architecture, valued the architect's hallowed position as chief organizer.

After a week of deliberations, they decided to enter the competition. Reflecting back on the project, they considered the collaboration with Lombard’s team productive. Not everyone agreed. Shortly after the opening in 1977, Rogers's mentor Alan Colquhoun wrote a critical review that revived many of the architects' early concerns. Colquhoun attacked client, programmer, and architect alike for complicity in an insincere rationalism. He argued that technocracy and its sublimation in the radically open plan and the trope of flexibility demonstrated an abdication of the architect’s fundamental responsibility — the articulation of content through a language of form, as exemplified, say, in the Beaux-arts plan. Even earlier functionalist architects, Colquhoun argued, were “less concerned with creating a rational architecture than they were with creating the symbolism for a new social and cultural order” (Colquhoun 1977). What Colquhoun could not see was that this rationalist technocracy offered a new type of architectural creativity, with techniques drawn from a range of outside influences such as computation and systems engineering, whose attitudes to architectural form suggested ways the discipline might navigate the unknown territory of the 1970s. In other words, the open plan did not eliminate the logic of the Beaux-arts plan but merely demonstrated its transposition to new practices.

Programmation embodied French technocracy. Lombard had studied engineering at the École Centrale des Arts et Manufactures in Paris, and after finishing graduate studies in engineering at Berkeley returned to work for the Architecture division of the Ministry of Cultural Affairs. There, he applied new techniques of programming to the planning of cultural amenities for De Gaulle’s Villes Nouvelles on the outskirts of Paris. Pompidou decided to run the project directly out of his offices, bypassing the Ministry under whose responsibilities a cultural building of this scope would normally fall. Lombard left to join the Établissement publique, the autonomous public agency created to execute the project, and was charged with writing the brief and running the Programmation et études group. To start, Lombard recruited Patrick O’Byrne from a small engineering firm in Montréal whose research into the programming and fabrication of school buildings was funded by the Ford Foundation's influential Educational Facilities Laboratory (EFL). Where Lombard had experience with programming at the Ministry of Cultural Affairs, O’Byrne brought experience in what in EFL circles was known as the Performance Concept, in which programming was part of a broader performance-based approach to industrialized building.

The somewhat clandestine nature of Programmation's operation meant that few funds were available from the Ministry, and so the team worked improvisationally in somewhat impoverished conditions. Despite this, the competition program was detailed beyond anyone’s expectations. In late 1970 the funds for the competition were released, the brief adopted by presidential decree, and the competition announced that November. The brief was much more than a specification for a library or a museum. Reading it carefully it becomes clear that the myriad activities whose performance is described in such detail constituted a meta-program for a new institutional type—a meticulously engineered information machine in which visitors no longer went to a museum to merely view artworks nor visited a library simply to read books but rather were users of a more general apparatus of cultural exchange, education, self-improvement, and discovery powered by the flow of information. In short, the brief described a cultural center conceived as a giant information processing system. This was no mere metaphor. Earlier that year, three members of Pompidou’s client team participated in a series of Unesco workshops where they developed a conceptual diagram of museum conceived as an information system consisting of four concentric rings corresponding to four different levels of information processing (Fig. 1).

In the brief’s main diagram, the concentric rings of the Unesco diagram exploded into a constellation of activities linked by interfaces and interactions (Fig. 2). This schema was provocatively non-hierarchical: one would find the relatively tiny documentation and research center, or even parking, given as much attention as the library or museum, which the brief shows not central as one would expect but pushed to the margins. In their place at the heart of the building the diagram showed a network of minor activities such as temporary exhibitions, documentation and research, reception, and a range of new experimental galleries and resources. These activities were the interfaces between public and the flow of objects and documents, and between public and the circulation of experts, interpreters, and reference workers. Within this environment, links were more important than the elements they connected. Television monitors, satellite broadcasting, computer terminals, signage, and circulation systems were the adhesive. As with all information utopias—from Le Corbusier’s Mundaneum to Malraux’s Museum Without Walls—more was more, and so functional efficiency was made secondary to the proliferation of information: visitors were to pass through the public reception spaces not simply on
their way in and out of the building but as often as possible and in so doing continually and accidentally encounter and
produce constantly renewing information. The brief thus asked not for the mitigation of complexity but rather for its
exploitation and the amplification of its effects.

Figure 1: Unesco diagram: Museum as Information System. Source: (Museum 1970)
Figure 2: Competition brief program diagram. Source: (Competition Brief 1970)

THE PROGRAMME SPECIFIQUE
Once the brief was completed and distributed, Programmation immediately started work on the Programme Spécifique,
working in parallel with the competing architects as they developed their competition entries. By the autumn of 1971,
when Piano and Rogers started work on the definitive scheme, Lombard’s team already had produced two large vol-
umes of detailed diagrams and tables that made the competition brief look schematic and rudimentary in comparison.
The brief was by definition a starting point for design work. In contrast, the Programme Spécifique can be seen as an
architectural work in itself in that, like the competition entries, it responded the brief by giving form to its speculative
visions.

It did so through innovative uses of graphic representation. Early programming researchers had established the central-
ity of flow charts and spatial relations diagrams in the pre-design toolkit. For user-needs specialists and users alike, the
diagram was democratizing: it played a central role, both rhetorical and practical, in bridging the needs of non-expert
users and the abstractions of architectural representation. The canonical early sources on programming, however, show
little commitment to representational innovation. Diagrams were often limited to aphoristic commentary on design pre-
conditions or the design process itself. In some cases, diagrams merely restated tabular data. For most researchers, the
diagram was simply one of a set of practical tools available for pre-design work. Horowitz, for example, mentions only
briefly the graphic diagram as one of three options for describing spatial requirements, the other two being verbal de-
scription and a two-dimensional matrix of spaces (Horowitz 1967). Early programming researchers introduced the main
formalism upon which these diagrams were based. The spatial adjacency diagram was a variant of the network graph
in which spaces were represented by nodes scaled to show required floor area, with edges scaled to represent desired
distances between spaces (Fig. 3). This type of diagram merged the geometric logic of the architectural plan with the
more spatially abstract topological graph, which had been introduced into architectural discourse by Alexander in 1964
and was commonplace by the early 1970s.
Figure 3: Spatial relationship diagram with weighted nodes and edges. Source: (Horowitz 1967, 96)

The Programme Spécifique exuberantly explored the space between the hard-headed spatial relationship diagram and speculative architectural representation. Programmation launched a two-pronged graphic attack on the problem. On the one hand, a spatial approach addressed the relationships between functional elements through an expanded syntax of network graphs and spatial-relation diagrams. On the other, a temporal analysis examined the flows of objects and information through those same functional elements. In the former, Lombard and his team transformed the basic bubble diagram of the competition brief into a graphic language with far greater representational capabilities. For each functional category, the program dedicated a single page showing the principle functions and the qualities and attributes of interactions between them—desirable and undesirable views, sound isolation, interfaces between people, goods, documents, and relationships to outdoor spaces (Fig. 4). Homologous systems such as telephones and computers were shown using overlays drawn on translucent vellum (Fig. 5).

Figures 4–5: Spatial relation diagram and overlay, Programme spécifique. Source: (Archives CFP, 2007)
The notations shown in the bubble diagrams were based on a predefined taxonomy of material and immaterial attributes of interfaces (Fig. 6). This taxonomy represented the invisible protocols by which administrative or social behavior coagulated, as well as the reification of those protocols through visual, acoustic, and physical boundaries of varying degrees of permeability. Boundaries were classified by the type of agents they mediated (people and machines, people and artworks, documents and archives), the specific quality or parameter being controlled or exchanged (natural light, views, access privileges), and the degree to which the interaction was required or desired, and the degree of allowed overlap (adjacent, partially overlapping, embedded). Potential movement across each boundary was marked with attributes such as the reciprocity of exchange (non-directional, unidirectional, bidirectional), the actors and objects involved (people, information, artworks, food, cars, natural light, views), and various other criteria (unrestricted, restricted, high-density, low-density).

In what ways did these diagrams prefigure the form of the building? Researchers at the time had struggled with the complex relationship between the topological graph and the architectural plan (Cousin 1970; March and Steadman 1971). Where the graph showed an edge linking two nodes, the plan showed the common limit surface between the two spaces running 90 degrees to that edge (Fig. 7). Although the graph at first appeared planimetric, it differed from the plan in that it described the quality and attributes of the spatial boundary as it is transgressed, not the geometry of the boundary itself. In other words, the graph might describe the qualities of the wall’s performance in separating two spaces rather than the wall’s qualities as an object as such. Thus, in the Programmation diagrams, the curvilinear shape of the boundary surfaces was intended merely as a tactic of evasion to discourage the architects from reading them as plans per se. The precise shapes themselves had an indeterminate effect on architectural form, since both rectangular shapes and curvilinear shapes do not affect the logic of the network graph’s topology. More important was the quality of the boundary as a protocol of exchange.

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**Figure 6:** Taxonomy of symbols, Programme spécifique. Source: (Archives CFP, 2007)

**Figure 7:** Topological graph versus floor plan. Source: (Cousin 1970, 493)
As topological models, then, the bubble diagrams are not meant to be read as plans. For example, in a given diagram, two lobes making up one activity might very well represent distinct spaces on different floors in the final building, in which case the arrows connecting them would correspond not to doors or corridors but rather to vertical circulation. Nor do the curved boundary lines necessarily represent walls. An interface between storage and museum gallery, for example, might in the most straightforward case be reified as a wall, but it also might be plausibly translated, as it was in the final building, into a jukebox-like machine by which visitors could call up a picture on demand from an overhead storage system (Fig. 8).

![Bubble diagrams](image)

![Internals of the museum](image)

**Figure 8:** Kinakotheque system for viewing and storage of paintings (B6.2.8 in plan). Source: (Archives CFP, 2007)

One of Programmation’s main doctrines stated that a solution to a functional problem might be found in any combination of spatial organization, personnel, furniture, and equipment. In this way, the tendency for these bubble diagrams to communicate a parti, in the traditional typological sense, requires us to understand that, as functional types, they might be instantiated through any combination of walls, floors, materials, machines, and workflows. Thus, a diagram showing the library as having two lobes organized around a central spine, or showing the museum as having three lobes organized around central core, represents a type that is both formal and performative.

The second type of diagram in the Programme Spécifique concerned the flows of people, objects, and messages through the various functional units (Fig. 9). A detailed examination of these diagrams is beyond the scope of this paper. Briefly, these diagrams are temporal where the bubble diagrams are spatial. They comprehensively track the flow of visitors, artworks, books and journals, equipment, mail, even garbage. Here, everything is rendered equivalent as it is subject to the same analytical and organizational regime.
As Piano and Rogers developed the winning competition entry into the definitive scheme, the complex relationship between program diagram and architectural form played out in a meticulous process of matching requirements to design. A third set of diagrams notated this process. In the sections, we fully understand the range possible modes of reification of the abstract bubble diagrams (Fig. 10). Here, no deterministic relationship between functional activity and architectural form governs the end result. Instead, activities are fitted iteratively into the generic frame as if solving a puzzle, and the resulting organization clearly breaks any causal relationship between architectural form and functional signification since activities are straightforwardly accommodated following a logic of pure opportunism and optimization.

The architectural approach of Piano and Rogers made this relatively easy. With Team 4 and Norman Foster, Rogers had advanced what Bryan Appleyard described as “an increasingly available, serviceable and reticent architecture” (Appleyard 1986, 159). This ethos was sympathetic to Lombard’s intention that the program be a living document that doesn’t merely operate at the start of a project but overlaps with the entirety of the building’s design, construction, delivery, and occupancy. Earlier programmers emphasized pre-design: Peña and Caudill called the program a “prelude” to design, and Horowitz described the program as something handed over to the architect at the end of analysis (Peña and Caudill 1953; Horowitz 1967). In contrast, Programmation insisted on an ongoing working relationship with the architects throughout the life of the implementation, and with the users after the building was handed over. The Programme Spécifique had already demonstrated that its graphic language could serve as a visual lingua franca in discussions be-
between programmer and user in the discovery of new requirements. Heads of departments, from curators of contemporary art to managers of loading docks, were encouraged to use it to document their needs (Fig. 8). Its conventions even served as a graphic tool in the rubric for evaluating the submitted competition entries. But shortly before the building’s opening, Lombard wrote to his superiors asking for continued involvement after building operations started. “Putting a building into service is not the end of programming,” he implored, and complained that the only place one could find the Programme Spécifique was on the shelves of the library’s archives (Lombard 1976).

CONCLUSION
Among the risks of any pictorial representation in systems-based design practice was that it encouraged the use of prior forms in problem solving. Indeed, this concern was not restricted to graphical representation. Even in the program text, Lombard rejected such seemingly innocuous terms as “library,” “civic center,” or even “city” lest they impose prejudice upon the discovery of an innovative architectural outcome. In much the same way, the topological graphic approach rejected appeals to both intuition and geometric types. Despite the deliberate naïveté of the program’s visual language, its diagrams thus shared with computable mathematical graphs the potential of revealing unforeseen solutions—either latent or synthesized anew—by freeing architectural problem-solving from the grip of geometric thinking and prior form.

It was precisely this rejection of prior forms in architectural problem solving that had bothered Alan Colquhoun when he wrote his critical review of the building after it opened. In his essay “Typology and Design Method” of a decade earlier, Colquhoun attacked the new rational design methods for their assumption that it was desirable, or even possible, to sweep away all preconceptions, biases, and prior solutions in the search for solutions to complex problems. He pointed out that if one looked at examples of systems design in particularly complex domains such as aeronautics engineering one immediately saw that prior forms offered the only way to mitigate intractably complex problems. Colquhoun acknowledged that “[t]he characteristic of our age is change,” but went on to argue that “it is precisely because this is so that it is necessary to investigate the part which modifications of type-solutions play in relation to problems and solutions which are without precedent in any received tradition” (Colquhoun 1969).

Colquhoun may have been right. The 1970s saw the birth of software engineering as a discipline, and as computers became more powerful and their uses more wide-ranging, the complexity curve of its design problems quickly steepened. In response, engineers proposed a formal object-oriented method to replace the improvisational approaches on which these practices had until then survived. By the end of the decade, the shift from procedural thinking to object-oriented thinking in the design of software systems had taken hold, fully arriving in the 1980s with design patterns, borrowed directly from Christopher Alexander’s Pattern Language, a work that in itself signaled the architect’s own object-oriented turn. With design patterns, the engineer started with the identification of prior models, arrangements, and behaviors. In France, methods such as MERISE and RACINE offered a particularly managerial vision of object modeling for system design. In the evolving domains of systems design, complexity had reached a point where, as Colquhoun had anticipated back in 1969, the only reasonable approach to its mitigation was to turn to the collective wisdom of prior solutions expressed through articulate formalisms.

What Colquhoun later failed to see when he wrote his critical review of the Pompidou was that architecture’s will-to-form, which he accused Piano and Rogers of denying, had migrated to the programmer along with its implicit object-oriented thinking, while the architectural reductivism he criticized in the building constituted an equally willful architectural response to that migration. If the original competition entry showed, in good 1960s fashion, a mechanistic and largely symbolic apparatus of clip-on devices and moveable floors, the final building offered a precisely delimited monolith with no moving parts, a “smooth monument,” as its engineer Ted Happold called it (Happold 1977). The famous escalator is most indicative of this shift: in early versions of the project it appears as an articulated clip-on mechanism, while in later ones it tautly traverses the west façade in a continuous, abstract diagonal that would later inspire Jean Widmer’s design for the institution’s logo. It would be a mistake to attribute this formal trajectory exclusively to value engineering. Instead, it must be seen as a wordless denunciation of the imagistic approaches of earlier technological utopians like Friedman, Archigram, and the Metabolists who sought direct formal correspondences between architecture and new information technologies. In the resulting empty space, Programmation embraced architecture’s form-giving practices and their fascination with pattern, symmetries, typology, and even the pure pleasure of the drawing.

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ABSTRACT: The built environment is a complex physical record created by people over time, and as such, it necessarily embodies contradictions and competing agendas. As part of the larger project of architectural epistemology, this research seeks to bring new technologies to bear on the built environment, as unique means of generating, structuring, exchanging, and activating architectural knowledge. To this end, the research describes and tests the method of parasitical analysis of digitally modeled built environments. As an analytical method, it is fundamentally comparative, effectively constituting a means of “reading” a digital model by indirect means. In order to illustrate the method, I consider a chronologically organized digital model of the Pruitt-Igoe housing project in St. Louis, Missouri. Pruitt-Igoe. Due to its chronological organization, the model contains geometry representing two distinct conditions, i.e., “before” and “after” the demolition of historic structures and construction of the Pruitt-Igoe housing project. Each of these conditions is subjected to parasitical analysis and the results compared. While parasitical analysis does not promise to resolve the multidimensional questions and contradictions embodied by Pruitt-Igoe, it nevertheless holds promise as a unique analytical method.

KEYWORDS: Parasite, Pruitt-Igoe, algorithmic design, architectural epistemology

INTRODUCTION
Urban environments are characterized by collisions between old and new, or collisions between competing agendas and between conflicting political desires. The well-known and now-demolished Pruitt-Igoe housing project in St. Louis, Missouri provides a potent example of just such an environment. The area formerly occupied by the Pruitt-Igoe project, north and west of downtown St. Louis, is generally bounded on the north side by Cass Avenue, on the south side by Carr Street, on the west by Jefferson Avenue, and on the east by North 20th Street. Prior to its near-complete demolition for the project in the early 1950s, the then predominantly African-American neighborhood contained mixed-use buildings including two- and three-story multi-family apartments, single-family detached and semi-detached houses, retail, warehousing, and some light industrial structures. In order to make way for the Pruitt-Igoe project, all of the buildings in the neighborhood were demolished with the exception of the St. Bridget of Erin Catholic Church (built in 1859 and demolished in 2016) and St. Stanislaus Kostka Catholic Church (built in 1891 and in use as of 2017), together with some minor structures ancillary to each of the two churches. The presence of the two churches in the neighborhood reflected the area’s earlier Irish and Polish immigrant populations. Following the demolition of the historic neighborhood, the Pruitt-Igoe housing project, consisting primarily of 33 11-story midrise apartment buildings, was constructed on the site. The entire project (with the exception of its four-story public school) was abandoned and demolished within twenty years of its construction. The site, still largely vacant, has seen only incremental development since 1975.

Contemporary discourse widely characterizes Pruitt-Igoe as a politically charged and contentious project existing at the intersection of racial segregation, government involvement in public housing, economics, architectural design, and urban planning (Newman 1972, Bristol 1991, Birmingham 1999, Heathcott 2012). Scholars and designers of the built environment have much work to do before all of the divergent, politically charged questions surrounding Pruitt-Igoe can be adequately articulated, let alone answered, whether this attempt is grounded in history or carried out in a politically and emotionally intense contemporary social context (Ferguson 2015, Benton 2017). My research, while purposefully narrow in scope, proceeds with the expectation that relevant questions concerning Pruitt-Igoe can be productively highlighted and foregrounded through the use of digital technology, at least to the extent that they are embodied in digital models of the project buildings.

In this research, I define parasitical analysis as a set of methods for propagating forms within digital models and then subjecting these forms to analysis, with the aim of disclosing latent attributes of the models under study. I have chosen the term parasitical analysis purposefully, with the intent to convey that the method is analytical rather than form-generative, and moreover, that the propagated forms result from a direct, i.e., a “parasitical”, reading of the initial model, i.e., the host. As a specific mode of algorithmic analysis, parasitical analysis constructs additional geometry within the digital model in response to the geometry that already exists; it relies on a very simple algorithm to generate form. The algorithm is parametric in that its basic structure can be made responsive to varying input. The additional geometry
thus created can be defined as a parasite because it effectively depends on the host model for its structure and support, and its exact configuration depends on its ability to “read” the host structure and respond to what it encounters.

In summary, the research described in this paper seeks to position parasitic analysis as a mode of inquiry capable of revealing otherwise undisclosed, yet potentially significant and highly charged, differences between two sets of given conditions. Emphatically, it is not proposed as a comprehensive analytical method, but rather as a highly specific approach to reading and comparing models, in the hope of foregrounding latent attributes of the models and the environments which they represent. In a larger context, parasitical analysis is generally positioned as a part of the larger project of architectural epistemology, which inquires into the ways in which architectural knowledge is produced, structured, represented, and disseminated. It is an ongoing attempt to recover, from within a contemporary realm characterized by exuberant visual and formal complexity, a set of very old ideas concerning the mutually constitutive relationships between medium, thought, and act.

1.0 THE METHOD ILLUSTRATED
The basic methodology of parasitical analysis can be conceptualized as the production of endwise-connected rays within a given boundary; these rays in turn are used as the skeletal basis for modeled form. The first part of the method – the production of rays – can be thought of as like the tracing of a billiard ball's trajectory on a frictionless table, assuming that the ball rebounds from the table's cushions at an angle equal to its angle of incidence. The number of bounces can be allowed to continue until a defined threshold is reached, thus defining an arbitrarily long trajectory (Figure 1).

![Figure 1](image1.png)

**Figure 1:** The “billiard ball” analogy, showing (from left) the initial trajectory, a collision with a cushion, a bounce, and the developed trajectory after 10 bounces.

It should be obvious that if the ball begins its journey in a different direction, or from a different location, different trajectories will result. This is also true if the boundary is reconfigured while keeping other variables constant (Figure 2).

![Figure 2](image2.png)

**Figure 2:** Variables leading to multiple trajectories. From left: same table as Figure 1, but with a different initial trajectory; same table with a different starting point; different table.

Two additional variations to the basic methodology are significant for the present discussion. First, obstacles (analogous to bumpers) can be introduced within the boundary, and second, the boundary need not be continuous, i. e., holes or openings (analogous to pockets) can be introduced. The ball's trajectory is affected by internal obstacles in the same way as it is affected by the external boundary, and should the ball's trajectory cause it to pass through an opening, the process stops.

In particular, we can define a boundary that represents the floor plan or section of a building (Figure 3). As with the simpler analogue, differing trajectories can be brought about by small changes to the initial “seed” location, the initial direction, and any changes to the boundary.
Figure 3: Floor plan as a boundary.

The production of rays within three-dimensional space can be conceptualized as tracing the path of a moving particle which encounters reflective surfaces within a spatial volume (Figure 4). Once again, the parameters of initial seed location, initial trajectory direction, and the manifold configuration of the boundary result in an arbitrarily large number of possible distinct trajectories. Just as the two-dimensional case can correspond to plans and sections, the three-dimensional case can correspond to three-dimensional models of architectural form (i.e., buildings or neighborhoods).

Figure 4: 3D digital model as boundary.

Finally, consider any given trajectory T1 produced within a digital model. The trajectory consists of several endwise-connected vectors (V1, V2, ..., Vn) such that the entire trajectory has length L1, i.e., it is a three-dimensional polyline. Several trajectories (T1, T2, ..., Tn) can be averaged for length, number of “bounces,” and so on. Furthermore, any set of two or more trajectories can be lofted in order to create modeled surfaces (Figure 5). In this respect, the trajectories form the skeletal basis for modeled form in three dimensions. These aggregated data and modeled forms make up the raw material for analysis.

Figure 5: Lofting. At left: two trajectories. At right: Lofted form.
2.0. THE METHOD IN ITS SCHOLARLY CONTEXT
Considered generally, an algorithm or series of algorithms can be capable of revealing latent attributes of an existing building. I discuss such an approach in Christenson (2009), in which I compare the processes of parametrically modeling two buildings in terms of meaningful (digital) parameters and their associated semantic relationships, resulting in the foregrounding of certain latent qualities. Similar approaches, related specifically to parameterization, are also evident in Burry & Burry (2006), Potamianos & Jabi (2006), Barrios (2004), Barrios (2005), and Potamianos, Turner, & Jabi (1995). The method of parasitical analysis is positioned as a unique means of generating, structuring, exchanging, and activating architectural knowledge. Despite its unique approach, the method borrows from other research and design such factors as aggregation phenomena (Branzi 2005), weathering (Mostafavi and Leatherbarrow 1993), repurposing (Brand 1995), and appropriation (Papalexopoulos 2003). The method as described here also shares some features with the tools of Space Syntax research – for example, isovist analysis (Benedikt 1979) – because it involves the production of graphical information within models or drawings in order to facilitate analysis of the built environment. Additionally, parasitical analysis shares some features with algorithmic modeling, because it relies on algorithms (for example, as initiated with Grasshopper) to produce form.

The present research also proposes three distinct characteristics of parasitical interventions: infiltration, resistance, and a mechanism or process of self-propagation for new geometry. Infiltration refers to the possibility of thorough inhabitation or propagation within an existing model (i.e., as distinct from attaching to the surface of an existing model). Resistance refers to the possibility of parasitic geometry to recognize the simultaneous resistance and support of its host: it needs to be seen to push against the host model, and the host shown to be capable of resisting, sustaining, or steering the parasite’s propagation. Finally, a mechanism for self-propagation means that there should be a simple algorithm or set of rules (e.g., a Grasshopper definition or a procedure in Rhino) guiding the process of the parasite’s growth or its extension through and beyond its host.

To expand on the distinction between forms of knowledge and novel architectural form – both of which allow for, and indeed encourage, the possibility of complexity – this research acknowledges a debt to contemporary research and design strategies aimed at generating architectural form from various inputs (Shi and Yang 2013), or as a means of integrating performance requirements (Turrin, von Buelow, and Stouffs 2011), or as a strategy for optimizing a solution space (Besserud and Cotten 2008). Furthermore, parasitical analysis shares some aims and strategies with researchers who rely on algorithmic techniques to reveal design principles specific to a body of work (Gomez de Silva Garza and Maher 2001) or principles of a building’s structural behavior or energy performance (Diaz-Vilariño, Lagüela, Armesto, and Arias 2013). While the formal results of parasitical analysis share some attributes with contemporary algorithmic design, the research method is firmly intended to constitute a way of seeing rather than a way of building. Thus, it seeks to position parasitical analysis as a hybridized approach in which techniques usually associated with form-generative design are employed for analytical purposes.

3.0. APPLICATION OF THE METHOD
3.1. Pruitt–Igoe as a Test Case
Parasitical analysis facilitates comparison between models, although as mentioned, the comparison is not necessarily accessible in quantifiable terms. Yet, fundamentally, the main use of parasitic analysis is comparative, and to illustrate this, the research described here compares two different conditions at two different scales. The specific choice of comparable examples – in the case of this research, selected “before” and “after” conditions at Pruitt–Igoe – derives from two radically differing motivations for structuring urban space. On one hand, parasitical analysis is tested against a “before” condition representing a typical nineteenth-century urban neighborhood, characteristically dense, finely-scaled, low-rise, and high-density. On the other hand, the method is tested against the “after” condition following the demolition of the historic neighborhood and the construction of the Pruitt–Igoe project – a powerfully expressed example of twentieth-century large-scale, mid-rise, high-density housing. Both “before” and “after” conditions are tested at different scales (neighborhood scale and room- or building-scale) using representative digital models from two years: 1917 (prior to the demolition of the historic, pre-Pruitt–Igoe neighborhood) and 1967 (following the demolition of the historic neighborhood, but prior to the demolition of the Pruitt–Igoe project).

3.2. Application of the method at the district scale
Given the two digital models of the district, a grid of seed points is established. Each seed point serves as the origin of a seed vector indicating one of several initial trajectories to be studied. The disposition and configuration of the seed grid is arbitrary, and as discussed above, different choices of seed location and initial trajectory direction should be expected to produce different results. However, for purposes of comparison the two conditions should be studied with identical seed grids.

Any seed point which falls within the plan outline of a building is ignored in further calculations, and seed points which fall outside the perimeter being studied are similarly ignored. Once the seed points are determined, the bounce algorithm is initiated for all seed vectors (Figure 6).
Finally, the resulting bounced trajectories for each condition are lofted to produce a three-dimensional form (Figure 7).

**Figure 6**: 1917 condition (left) and 1967 condition (right), showing bounced trajectories.

3.3. Application of the method at the building scale

The method can also be applied to a digital model of a group of rowhouses along Jefferson Avenue (prior to the demolition for Pruitt-Igoe) and by comparison to a digital model of a residential building in the Pruitt-Igoe project.

**Figure 7**: Forms resulting from lofting the trajectories shown in Figure 6 for the 1917 condition (left) and the 1967 condition (right).

**Figure 8**: 1917 condition (top) and 1967 condition (bottom), showing bounced trajectories.

Note that in the case of the 1917 condition, the arbitrary module for the seed grid coincides with the module of the rowhouses. This has the effect of generating a repeating pattern on the same module. The same module applied to the 1967 condition (Figure 8, bottom) produces a non-repeating condition.
Figure 9: Forms resulting from lofting the trajectories shown in Figure 8 for the 1917 condition (left) and the 1967 condition (right).

The lofted forms shown in Figure 9 reflect the repetitive trajectories generated and shown in Figure 8.

CONCLUSION

Although the method of parasitical analysis necessarily results in the production of novel forms, its goal is not novelty, but rather the implementation of a particular lens through which to study and compare one or more digital models. In particular, forms produced through parasitical analysis can be aggregated and compared, with the aim of revealing unique characteristics among a collection (or population) of models. The forms thus produced exhibit characteristics typical of chaotic behavior: they are sensitively dependent on initial conditions, insofar as small changes in the “seed” location result in radically different formal outcomes (Lorenz 1963). It follows that parasitical analysis does not aim to explain observed conditions in reductive terms, but rather a form of reflection upon those conditions, a means by which one kind of complexity can be visualized as another. Unlike certain other methods for analyzing digital models of the built environment, parasitical analysis is not easily susceptible to quantification. For example, it is unlike the kind of analysis carried out with Revit, which due to its hierarchical and categorized approach, enables multiple approaches to quantification (e.g., energy analysis, structural analysis, lighting analysis, etc.). Rhino, coupled with Grasshopper, can also introduce multiple forms of analysis, insofar as a given digital model is the result of parametric or algorithmic operations.

This research is ongoing, and is being developed in two distinct trajectories. As it potentially impacts pedagogy, I have tested its implementation within a final-year M. Arch. design studio, focused on the design, using algorithmic methods, of a parasitical intervention within, attached to, and atop an existing building, or “host.” The evaluation of student projects in this studio addressed, among other factors, how well the projects make the host building and the city uniquely perceptible (Christenson 2014). Furthermore, as an independent research project (Christenson 2013), I continue to test parasitical analysis as a process of reading and extending existing buildings: the project centers upon scripts for generating self-replicating geometries within digital models of existing buildings.

Future work will attempt to further specify the applicability of parasitical analysis over an extended range of scales. Furthermore, aggregate data for a given set of trajectories (for example, average trajectory length, average number of segments or “bounces”, percent of “unbounded” trajectories) could potentially be seen as indicative of certain qualities held by the digital model (e.g., degree of openness, density of forms, etc.). Comparisons of such aggregated data between two projects, or applied within a single project at various scales, could in turn reveal additional qualities of the built environment otherwise remote from direct perception.

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ABSTRACT: The 20th c. French theorist Guy Debord devised a method for investigating the subjective qualities of an urban environment. He termed this method a dérive, which he defined as “...a technique of rapid passage through varied ambiences.” This method, a psychogeographic survey, would privilege experiential characteristics over objective, geometrically measurable ones. A reinterpretation of the dérive retains the subjectivity of Debord’s concept but capitalizes on the strengths of contemporary mapping technology, namely the aggregation and filtering of many data points and sets. This new method serves as a strategy for crowdsourcing the location of a temporary intervention in an introductory environmental design course offered to 150 students including architecture, landscape architecture, and city planning majors. This project, for which the digital dérive is phase one, suggests that in order to design for the built environment, we must be aware of the many complex elements and systems that compose it. A two-phase exploration gives students the opportunity to reflect on their immediate and surrounding environment, and to develop skills in mapping, cataloging, representing, and abstracting those conditions. This paper describes the history, significance, and contemporary understanding of psychogeography and its cartographic representations, a specific methodology for (and outcomes of) a digital dérive, and the role of these cartographies in the design and transformation of the built environment.

KEYWORDS: geography, mapping, site, perception

INTRODUCTION
This paper describes the appropriation and adaptation of a technique for exploring and analyzing an urban environment – Guy Debord and the Situationist International’s dérive. This technique, in its revised form, is being investigated as a tool for site analysis. This paper will describe the history, significance, and contemporary understanding of psychogeography and its cartographic representations, a specific methodology for (and outcomes of) a digital dérive, and the role of these cartographies in the design and transformation of the built environment.

Geography, as an inherently interdisciplinary field, provides a scaffold for a course designed as an interdisciplinary introduction to the principles of environmental design. Artist and geographer Trevor Paglan describes the field of geography as building on two fundamental ideas: materialism and the production of space (Paglan 2008). Paglan explains geographer-philosopher Henri Lefebvre’s theory of the production of space, saying:

“Space is not a container for human activities, but is actively “produced” through human activity. The spaces humans produce, in turn, set powerful constraints upon subsequent activity.” (Paglen 2008, 29)

This feedback loop between the built environment and the people that inhabit it is a meta-principle underlying the course. Experimental geography, more specifically, is a realm of investigation of the built environment, which according to Nato Thompson in his book Experimental Geography, is “a field combining ambiguity, empiricism, techniques of representation, and education...” (Thompson 2008, 24) This definition also holds true for fields engaged in the design of the built environment, including architecture, landscape architecture, and urban planning.

1.0 HISTORY AND SIGNIFICANCE OF PSYCHOGEOGRAPHY
1.1. History of Psychogeography
Psychogeography, a subset of experimental geography, highlights the psychological component of our perception and experience of the built environment. This includes the concept of affordances, a term and concept introduced by the psychologist J. J. Gibson. Affordances are the opportunities that the environment may offer to someone occupying that environment – it is relative and speaks to the interaction between the environment and the occupant - in contrast with the physical characteristics of the environment (Gibson 1979).

Psychogeography is commonly associated with the Situationist International, an interdisciplinary and politically-motivated organization active in Europe in the mid-20th century. Guy Debord, co-founder of the Situationist International, defined psychogeography as: “the study of the specific effects of the geographical environment...on the emotions and behavior of individuals.” (Internationale Situationniste #1 1958) Under the rubric of psychogeography,
the Situationist International developed the dérive as a tool for their theory of unitary urbanism, defined as a strategy by which: “The environment is explored and challenged...to provide alternative ways of using and living in the environment.” (Barnard 2016, 108) The dérive is a method of analysis which provides the framework for intervention. Adam Bernard, in his essay “The legacy of the Situationist International,” describes the value of unitary urbanism as a strategy which values sensory perception and emotional provocation, critiquing the prevailing strategy which privileges financial models (Barnard 2016). Subjective and sensory experience become lenses through which the urban environment is viewed. Debord articulated the dérive as a method for investigating the subjective qualities of an urban environment.

In a dérive one or more persons during a certain period drop their relations, their work and leisure activities, and all their other usual motives for movement and action, and let themselves be drawn by the attractions of the terrain and the encounters they find there. Chance is a less important factor in this activity than one might think: from a dérive point of view cities have psychogeographical contours, with constant currents, fixed points and vortexes that strongly discourage entry into or exit from certain zones. (Debord 1956)

With regard to representations of the dérive, Debord appropriated the Surrealist collage technique called the exquisite corpse, and applied it to cartographic representations of psychogeography. Existing maps of cities were cut up and reassembled, often with gaps between areas of the city to more accurately reflect the experience of the city, specifically its discontinuities. It is important to note, however, that while Debord was influenced by Surrealism, he was critical of Surrealism's emphasis on the unconscious of the individual, neglecting external forces (Thompson 2008). The Naked City map from 1957 was created from the Plan de Paris, a popular map of Paris at the time (Fig. 1). Nineteen sections of the map were extracted and reassembled, and red arrows were added to illustrate “spontaneous turns of direction” that one is compelled to make when moving between these sections, each of which has a “unity of atmosphere” (McDonough 1994, 60). The “renovated cartography,” in Debord's words, constructed here creates a synthesis between existing conditions and the human experience.

The cartographer Denis Cosgrove explains the significance of the dérive:

Thought of cartographically, the dérive was a conscious challenge to the apparently omniscient, disembodied and totalizing urban map that had become the principal instrument for urban planning and ‘comprehensive redevelopment’ during the post-war years. (Cosgrove 2005, 39)

Resistance to the disembodied, visually dominated approach to designing for the urban environment continues to be of concern over a half-century later. Both conceptually and as a practical tool, the dérive speaks to the contemporary interest in systems thinking as a strategy to manage complex and multivalent contexts for architectural intervention. The method does not presume to be comprehensive, but rather brings awareness to our richly layered and nuanced built environments and their affordances.
1.2. Psychogeography and Pedagogy
While it is difficult to ascertain the extent to which the dérive has been employed as a pedagogical tool, there is evidence of its use by the Situationist Constant Nieuwenhuys, who prompted students from the Institut d'urbanisme de l'Université de Paris to conduct a dérive in Amsterdam in May of 1969. After reviewing the maps and sketches created by the students, Constant voiced his disappointment, saying that they didn't understand the dialog between space and social practices. Situationist scholar Lucasz Stanek writes that Constant thought the students showed “a lack of interest in their own presence there, not seeing that their own presence changes this very street.” (Stanek 2011, 221) The evidence of this interaction is found in text only: unfortunately, we can't view and analyze the physical artifacts (maps and sketches) of this particular dérive assignment.

More broadly, the concept of situated pedagogy is relevant to this discussion. This concept builds on the influential late-19th / early-20th century educator John Dewey's emphasis on the importance of experience in learning, on creating situations for interaction. Leading contemporary educators Ira Shor and Paulo Freire, described situated pedagogy as a way: “to challenge the givens of our lives and the surrounding system dominating daily life.” (Kitchens 2009, 246) Bringing awareness to context and circumstances that have faded to the background and seem to no longer warrant our attention is one agenda of the project described in this paper. It is an agenda for the education of future designers of the built environment, but certainly sits in a broader context of situated pedagogy, which Kitchens describes as asking students:

“...to attend to their environment as psychogeographers, reflecting on the subjective and the objective, the internal and the material, with their bodies as well as their minds, and listening to what places have to tell us. Students read the world, experiencing living landscapes, and decode those politically, socially, historically, and aesthetically, participating in a remapping of those landscapes. A situated pedagogy attends to specific places and localities, but not merely as places for discursive analysis and academic study, but as the spaces for action, intervention, and perhaps transformation. (Kitchens 2009, 259)

Situated pedagogy provides an educationally-validated motivation for this project - bringing students out of the classroom provides greater learning opportunities as students link experience with abstract concepts to build knowledge.

1.3. Contemporary Psychogeography
The artist, designer, and educator Christian Nold has built his career on psychogeography with a contemporary agenda. He employs current technology for participatory mapping, or mapping in which data is contributed by a large group of participants. His book Emotional Cartography describes a bio mapping project, a participatory mapping project in which 98 participants wore GPS devices and galvanic skin response sensors to track their movements on an hour-long walk through San Francisco and record their emotional responses along their route (Fig. 2) (Nold 2009). What is unique about this strategy is that it collects personal, idiosyncratic, data which remains archived in the final map, but thanks to the large number of participants, the aggregated data points to commonalities in perceptual experience. Color indicates emotional data: the bright red dots indicate arousal, while the darker dots show points of calm. (Nold 2009) Nold has also conducted similar studies in Stockport and Greenwich in the UK, using similar technologies but experimenting with different cartographic representations. While Nold clearly builds on the dérive method of the Situationists, he critiques the narrowness of their agenda, saying:

Rather than the continuous drifting through the city that the Situationists imagined, the Greenwich Emotion Map suggests an experience of the city as a series of distinct ‘events’, by which we mean moments of distinctive attention. The actual nature of these ‘events’ varies from meeting people, taking a photo, crossing roads, to being annoyed by one’s surroundings. What these events have in common is an element of novelty which has caused the person’s attention to become focused. This vision of the environment as a stage for events suggests an active engagement not covered by the normal concept of the ‘walk’ or ‘drift’. It suggests an embodied being within the environment actively interacting with people, objects and places. (Nold 2009, 67)

Nold's methodology served as a precedent for the reinterpretation of the dérive that will be subsequently described. Nold's method, however, acts solely as an analytical tool, rather than a basis for intervention.
3.0 DIGITAL DÉRIVE METHODOLOGY AND ASSESSMENT

3.1. Digital Dérive Methodology

This reinterpretation of the dérive retains the subjectivity of Debord's concept but capitalizes on the strengths of contemporary mapping technology, namely the aggregation and filtering of many data points and sets. This new method serves as a strategy for crowdsourcing the location of a temporary intervention in an introductory environmental design course offered to 150 students including architecture, landscape architecture, and city planning majors. As a general education elective, learning objectives include understanding the physiological, psychological, and social influences on thinking and behavior, how the mind and body work in concert, the impact of history on the present and the future, and how the environment affects human behavior. Cal Poly's campus is an ideal setting to reflect on the relationship between people, the built environment, and nature. The campus is adjacent to downtown San Luis Obispo and occupies a unique and dynamic natural landscape, surrounded by rolling hills and distinctive geological features, the Nine Sisters, which are ancient volcanic plugs. One's experience of places on campus inevitably includes foreground, middle ground, and background perceptual stimuli, due to the rolling terrain and dramatic views.

This project, for which the digital dérive is phase one, suggests that in order to design for the built environment, we must be aware of the many complex elements and systems that compose it. One way to cultivate this awareness is to disrupt our expectations and make the perception and interpretation of the existing context a conscious process. The dérive serves as the first step in this process, laying the groundwork for the deployment and documentation of a portable camera obscura. A camera obscura, which projects the exterior environment onto the interior of a dark space, requires active participation and awareness as one context is superimposed on another. This two-phase exploration gives students the opportunity to reflect on their immediate and surrounding environment, and to develop skills in mapping, cataloguing, representing, and abstracting those conditions.

In order to prepare for the deployment of the camera obscura, students conduct a dérive to analyze the context (campus) from an experiential perspective. This dérive and mapping method was developed in collaboration with the university's GIS Specialist. We began with Debord's guidelines for a dérive:

- Number: several small groups of two or three people
- Duration: average of one day, but can be a few hours midday
- Area: “if one sticks to the direct exploration of a particular terrain, one is concentrating primarily on research for a psychogepographical urbanism.” (Debord 1956)

Our methods of representation of the dérive include both analogue and digital components. Students were asked to create an analogue psychogeographic map in their sketchbook, as a way to provoke a subjective observation, experience, and recording (Fig. 3). Beginning with a blank page rather than a campus map, students had to rely on their observations, highlighting the difference between what they can experience and the omniscient view of the commercial map.
The digital dérive method utilizes free geotracking applications in which students record their dérive route and add placemarks when they identify a place (Fig. 4). A discussion about place versus space, and the definition of place as the intersection of physical attributes, activities, and conceptions, preceded the dérive (Canter 1977). Students also take analytical photographs that are geotagged to their route map, cataloguing both physical and experiential characteristics of each place. After completing the dérive, students are asked to edit their placemarks to a maximum of four, after reflecting on the value of each place and its suitability for a camera obscura. The digital dérive maps with placemarks are then aggregated and made public through the ArcGIS website. This web interface allows the user to toggle between the 37 route maps, to see a single map with all 37 routes and placemarks, and to view the density of placemarks as a heat map (Figs. 5 and 6). Through this process of data collection, aggregation, and filtering, we are able to identify the most commonly marked places, and determine an ideal site for our camera obscura.

Figure 3: Student, analogue psychogeographic map drawn in sketchbook during dérive, 2016. Source: (Author, 2016)
Figure 4: Student, digital dérive map: route and placemarks shown on Google Earth, 2016. Source: (Author, 2016)

3.2. Digital Dérive Assessment

The digital dérive provides an opportunity to take many idiosyncratic and subjective data points and mine them for commonalities. While there is a diverse array of placemarks, several places on campus are foregrounded through the heat map visualization. After identifying the most-placemarked spots on campus, other filters are applied; for example, placemarks within a 1/8 mile radius of where the portable camera obscura is stored, for ease of transport. This paper

Figure 5: Class, aggregated digital dérive map with routes and placemarks, 2016. Source: (Author, 2016)
Figure 6: Class, aggregated digital dérive heat map showing density of placemarks, 2016. Source: (Author, 2016)
will not expound on phase two of the process, the deployment of the camera obscura: however, Figure 7 shows examples of the images experienced by the students inside the camera obscura. Once the general site is chosen, the portable camera obscura is brought to the site. It is then up to the students to fine-tune the siting, by determining the exact placement and orientation of the aperture relative to the immediate and distant context.

Based on the outcomes of this methodology, one critique is that a dérive as it was originally defined by Debord is conducted without an agenda. Here, the students are primed for their dérive by being informed that the data will be used to identify a site for a camera obscura. However, Debord’s dérive was really a starting point for this method; as a tool for site analysis, priming (identifying qualities or characteristics to look for) is paramount.

Figure 7: Student, photographs from inside the camera obscura, 2016. As students sit in darkness, an image of the external environment is projected through an aperture upside-down and backwards on a screen inside the space. Source: (Author, 2016)

CONCLUSION

This method, a psychogeographic survey, privileges experiential characteristics over objective, geometrically measurable ones. Debord, in his 1958 essay “Theory of the Dérive,” notes the instability of the urban environment from a perceptual standpoint. A sense of unity in a given area of the city and the threads that connect these areas are highly variable. Situationist scholar Thomas F. McDonough highlights the value of this variability, both in concept and in representation:

Debord’s map...foregrounds its contingency by structuring itself as a narrative open to numerous readings. It openly acknowledges itself as the trace of practices of inhabiting rather than as an imaginary resolution of real contradictions. (McDonough 1994, 69)

As a narrative open to multiple readings, this type of cartography can be didactic – an end in and of itself – or part of a design methodology for intervention. In future iterations of this project, it could be useful to add a third media to the mapping method: following the analogue psychogeographic map and digital dérive, students could create their own The Naked City map using an existing map of Cal Poly’s campus, cutting fragments and reassembling them to more closely approximate their experience. As this project continues to be refined and re-engaged, a strategy for comparing the results of the analogue and digital mappings must be developed.

In a broader context, information gathered through a digital dérive and the other components of the method could prove a useful tool for designers as they consider the relationship between intervention, user, and context. Participatory or crowd-sourced mapping continues to grow as a tool to harness the knowledge and experience of inhabitants of a city or neighborhood to build a knowledge base, allowing designers to make more informed design decisions. The power of the digital dérive as it might be utilized in practice is two-fold: the collective memory and experiences of the inhabitants are typically untapped resources, and the technology to capture, share, and aggregate the data is user-friendly and readily analyzed to provide a basis for design intervention that can more appropriately address the needs and preferences of future users.
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Internationale Situationniste #1 (June 1958) Translated by Ken Knabb.


ABSTRACT: Grounded Theory (GT) is a systematic methodology used to reveal patterns in qualitative data and to develop theoretical positions or frameworks from these patterns—the theory is “grounded” in the words. Since its inception in the late 1960s, GT has emerged as a preeminent qualitative research methodology and is widely used in diverse disciplines such as nursing, education, and the social sciences where researchers look to better understand the why and how questions related to human decision making and action—questions that frequently interest architects and designers.

Grounded Theory is a robust and intuitive approach and set of procedures suitable for a wide variety of architectural research objectives that should be considered and used more often. It can be used as a stand-alone qualitative method or in conjunction with quantitative methods as part of a mixed methods approach. This paper includes an elegant plan of action for researchers who are not content to let the richness of interviews and observations go to waste. The process for beginning a Grounded Theory analysis is laid out simply with key references highlighted. GT is equally powerful in analyzing existing data, resulting in new answers and unexpected questions.

KEYWORDS: Grounded Theory, qualitative methods, participant narratives, research methods, complexity

INTRODUCTION
Architectural researchers and practitioners often rely on various qualitative research methods. Grounded Theory (GT) is one of several qualitative methodological traditions. Other traditions include narrative psychology, phenomenology, ethnography, incident technique, intuitive inquiry, etc. (Wertz et al., 2011). While quantitative research is a “top-down” approach from theory, to hypothesis, to data, qualitative research is a “bottom-up” approach from participant views, to general themes, to theory. Qualitative research may appeal or be applicable for researchers interested in understanding phenomena exclusively through participant words and views (Creswell, 2007) or as part of a pragmatic approach common in architectural research.

Grounded Theory is a rigorous, robust, and intuitive approach, and a set of procedures suitable for a wide variety of architectural research objectives that should be considered and used more often. It offers researchers a way to strengthen, support, refute, or challenge other research data through the words of the myriad stakeholders in our built contexts. What distinguishes GT from other qualitative traditions is the complexity of its iterative process whereby researchers reveal potential linkages between ideas and concepts found in the data, and these connections eventually evolve into broader conceptual or theoretical discoveries. GT has the power to enhance architectural research outcomes by lending rigor and validity to subjective qualitative data often dismissed as “anecdotal evidence.” Design researchers familiar with complex and iterative design development processes are likely to find that GT procedures encourage and facilitate the same kinds of thinking and working in a qualitative research context.

In this paper we provide a brief overview of GT, describe benefits for architectural research, illustrate the application of GT methods through two research case studies, and conclude with recommendations for researchers interested in using GT methods in their inquiries.

1.0 GROUNDED THEORY
1.1. A brief history
Grounded Theory is the qualitative method through which theories and variables are “discovered” through the research process, not presumed beforehand (Creswell, 2012). Barney Glaser and Anselm Strauss introduced the idea of Grounded Theory (GT) in the late 1960s and outlined an approach to qualitative research whereby theory is “grounded” in the data (1967). GT emerged reactively to a preference in the social sciences for purely quantitative research, a view which held qualitative data as anecdotal, subjective, and impressionistic. Juliet Corbin, one of the key figures in the development of grounded theory notes: “Who will listen to you if you don’t present your findings in a credible scientific manner — not quantitative scientific but qualitative scientific?” (Cisneros-Puebla, 2004). In Grounded Theory, the intent is to move beyond description in order to generate, discover, or construct an overarching theory or understanding of a
phenomenon or condition. The theory does not come “off the shelf,” but from analysis of experiences expressed by
the participants related to the processes under study (Strauss & Corbin, 1998). Glaser and Strauss endeavored to make
qualitative research rigorous, methodologically systematic, and generalizable. In doing so, they opened-up qualitative
methods to a new host of disciplines such as sociology, psychology, nursing, and others.

GT methods evolved over time, with a large shift occurring in the early 2000s when social science researcher Kathy
Charmaz developed Constructivist Grounded Theory (CGT) to move Grounded Theory in a social constructivist
direction. Charmaz adapted the work of Strauss and Corbin to create a more interpretive, reflexive, and flexible
grounded theory process. She urges that the role of the researcher in the process should not be minimized as the
researcher brings questions to the data, advances personal values and priorities, and makes decisions about the
categories throughout the process (Creswell, 2008). CGT is predicated on multiple realities and positions the researcher
as a participant in the process. Charmaz presumes that theories are constructed by the researcher (Charmaz, 2006).

The case studies presented later in this paper rely on the major schools of Ground Theory research design. A more
detailed explanation of the specific analysis methods is presented in Section 4 with suggestions specific to architectural
research and lessons learned from previous projects.

1.2. The process of Grounded Theory
Grounded Theory is one method of analyzing and understanding qualitative data. Its strength is its clear and rigorous
method of coding qualitative data, categorizing these codes, reflecting/commenting on the codes and categories,
and developing theoretical positions from the iterative analysis process. The methodological framework (Figure 1)
is a simplified outline of the process whereby the researcher moves from raw data, or literal words, to an abstract
theoretical understanding of the meaning embedded in the words. Sometimes described as a series of steps toward
higher levels of abstraction, the process is also iterative and forces researchers to go back to previous steps to re-
examine issues, collect more data, etc. This paper will specifically address each of these steps through case studies and
suggestions for researchers.

Figure 1: Outline of the GT analysis process

1.3. Grounded Theory in architectural research
Grounded Theory is appropriate for many architectural research projects for the following reasons. The first reason is
that GT allows for a rigorous and structured approach to be taken in answering very open questions. The second reason
is the scarcity of design research relative to other fields. Third, observation methods common in architectural research look critically at the actions, interactions, and social processes of people as they relate to their designed environments. The following sections provide in-depth examinations of two recently conducted mixed methods architectural studies that illustrate applications of Grounded Theory. Because these studies were multi-year research projects, both employ what Pidgeon and Herwood (1997) call "hard" Grounded Theory because they utilize the full range of GT methods, including theoretical sampling. "Lighter" Grounded Theory utilizes a project-appropriate selection of the techniques of GT for the development of categories and concepts and an analysis of the relationship between concepts and categories.

2.0. CASE STUDY 1
The first study focused on occupancy in affordable housing and used Grounded Theory for variable generation during the qualitative phase of the work. Through interviews of key stakeholders, the researcher uncovered variables that were unexpected and that were subsequently statistically tested in the final quantitative phase of the project. Although this was a mixed method study, the case study will focus specifically on the GT qualitative analysis process.

2.1. Premise
The central claim of this study, “No Vacancy,” was that design decisions influence the economic and social sustainability of affordable housing. The goal of the study was to determine which design decisions, and to what degree. Vacancy, and the data it produces, was a lens through which to see the units. The research design for this study followed a sequential mixed methods process starting with a short quantitative phase for project selection, then a long qualitative process of variable generation and analysis, and finally a multiple regression analysis process.

2.2. Methods of data collection and analysis
Grounded Theory was chosen for this study because of the dearth of information on the topic of vacancy in multifamily housing and because of the potential for multiple, conflicting viewpoints from a wide range of stakeholders. Qualitative data collection for this study was primarily through interviews and focus groups. Multiple viewpoints were an essential component of the qualitative research design. For this study, interviews were not recorded. Instead, the researcher took notes and typed the notes immediately after the interviews to ensure accuracy of memory. The means of taking field notes by hand on site closely followed the methodology developed by Glaser, who upholds that transcriptions are not part of GT because relying on taped conversations discourages the delimiting of data during data collection (Glaser, 1978).

The qualitative research software used for this study was Atlas.ti which allowed coding and memo writing to exist in the same user interface. During the first stage of the analysis process, the researcher coded the notes using a set of predetermined codes, emergent codes, and “in vivo” codes (codes that are drawn directly from the words the informant used). The analysis of each set of interviews increased the number of pre-determined codes as patterns emerged in the stories and descriptions of the stakeholders. The final list of codes numbered over 100 and included codes related to the built environment, such as “floor level,” “balcony,” “corridor,” “window,” “view,” “storage,” “stairs,” and codes related to the management, such as “voucher,” “kids,” and “large household.”

As coding proceeded, a series of categories, or “code families,” were created to organize the codes. These included: “layout,” “unit scale,” “building scale,” “rent-ready,” “lease up,” and many more. A third layer of codes was created as the theory was being developed: “Crowding,” “Troublesome,” “Solvable,” and “Moderator.”

During the next stage of analysis, the researcher wrote dozens of memos: simple memos exploring a code and deeper memos that delineate the theories generated by the analysis. The complex memos included topics such as, “Delusions,” “Contagious Dissatisfaction,” and “Difficult Personality.” While many of these themes may have been uncovered using narrative inquiry or other qualitative methods, GT allowed an interconnectedness of themes and the ability to draw connections between memos by using the constant comparative methods which resulted in a greater number of ideas to pursue in developing the theory.

2.3. Results
The GT process generated several independent variables appropriate for testing during the quantitative phase. Through this combination of qualitative and quantitative methods, the following attributes had the most influence on occupancy overall: the type and size of the apartment, the floor level, the position within the building, and proximity to noise sources. The demographic variables that explain the highest percentage of the variance in tenancy duration are related to the tenant's status as a Section 8 voucher holder, as elderly, as a single parent, and household size. In addition to providing testable independent variables, the GT process made other valuable contributions unrelated to the unit-by-unit analysis of the project. Project-scale attributes, such as playgrounds, parking, locations, and durability, were revealed as key indicators of a building's success in terms of occupancy.

After the quantitative phase of the project, the researcher returned to Grounded Theory methods as a means to tie the project together and develop an overarching theory on the topic. Grounded Theory is well-suited for this return to
the data and for mixed method studies. Two emergent themes resulted from this return. One: architectural attributes, while rarely the sole and direct cause of a tenant moving, did contribute to the phenomena that were influencing the move. While the design itself is not causing people to move, it appeared to be exacerbating the social dynamic which could then influence whether people move. Two: Tenants may give a single reason for moving, but the true causes are multivariate. The focus on one reason has prevented an accurate assessment of the relationship between architectural attributes and demographic or site attributes. GT provided a structure to examine these two themes in combination, which generated a conceptual framework of multi-causality with unique interactions between factors. For these case study projects, the architectural attributes often have an indirect but demonstrated influence on occupancy; because it is indirect it is often unacknowledged by the stakeholders.

3.0. CASE STUDY 2
The second study focused on the influences of design, operations, and occupancy on plug load energy use in student residence halls. The mixed methods study used interviews with building occupants and GT methods as a follow-up to an extensive quantitative field study that measured energy usage in six existing buildings. Although the qualitative phase of the study could very well have been a stand-alone study, the mixed methods design allowed the qualitative data to inform the questions and discussions in the interviews and to give the researcher a deeper understanding of the influential processes under study.

3.1. Premise
Plug loads are electricity consumed by devices that are not hard-wired into buildings and where occupant behaviour plays a major role in usage. Physically measuring plug loads is useful, but it does not provide a full understanding of the various influences on occupant plug load usage behavior in buildings. Interviews provided a useful method for understanding plug loads from the perspectives of three groups of people associated with energy use in student housing: designers, building managers, and student occupants.

3.2. Methods data collection and analysis
Grounded Theory, and in particular Constructivist GT, methods were used for the interview data collection and analysis. Grounded Theorists recommend that researchers begin an inquiry with a general set of research interests or ideas, and that these ideas then become “sensitizing concepts” that act as points of departure for interview questions and discussions (Blumer, 1969 and Charmaz, 2006) and a number of “starting points” that allow them to articulate their experience with the topic. For example, the researcher had prior experience living and doing research in student housing, and these experiences informed the research.

Responsive interviewing techniques provided a framework of six main interview questions that allowed participants take the discussion in directions that revealed, in greater depth, how they felt about issues. This approach also provides a mechanism for the researcher to get the discussion back on track (Rubin & Rubin, 2011). The study had three different sets of questions for the three different stakeholders. An example of a question for students was: “How much do/did you think about electricity use while living in your residence hall?” Interviews were conducted primarily in-person but also via phone when necessary. The completed interviews were transcribed before all interviews were complete. Good representation among the stakeholder groups determined the final number of interviews given and saturation was reached at approximately 24 interviews. The interviews averaged about 40 minutes in length and required up to 6 hours of transcription using audio software with a slow playback speed setting.

The data analysis was iterative in nature, but gradually moves from the actual words of the participants to more abstract ideas that helped to illuminate connections and linkages in the data set — from transcripts, to codes, to salient themes, to analytic categories, to a single coherent process. In essence, the process used the participant narratives to construct an abstract conceptual or theoretical understanding of plug load energy usage in student housing (Figure 2). While other qualitative methods, such as phenomenology, require that the researcher bring a very strong and robust knowledge of phenomenology theory and precedent to their work, GT is rooted in the words themselves and what they mean at a higher level.
3.3. Results
The data analysis process used emergent coding, whereby tags were assigned to words or lines of text in interview transcriptions that help to explain processes in the participant narratives. These tags emerged directly from the text itself, not from some pre-assigned list of codes or categories. For example, one emergent code was “modeling behavior,” and any word or line of text associated with this description was assigned this code. Some words or lines of text were assigned to multiple codes. This process generated 471 unique codes, sometimes called the codebook. Similar codes were later combined or merged. The codes came directly from the text and the memos resulted from the researcher beginning to understand meanings in the text. For example, a code related to “proximity of building amenities” resulted in this memo: “When students can't have a certain device in their rooms, but there is one in a common area, then the proximity becomes very important.”

Emergent themes brought together ideas contained in several codes. For example: the theme “managing costs” captured ideas contained in codes such as: “Controlling Cost,” “Financing Limitations,” “Financing Opportunities,” “Misunderstanding Intent,” etc. The process resulted in 30 themes. From these themes, two analytic categories were raised that attempted to explain and clarify how the themes overlapped. The two analytic categories were: “doing more with less” and “supporting the student experience.”

One coherent process appeared to powerfully describe and explain the influences on plug load usage in student housing. The coherent process was called “balance of power,” and it suggested that students had the power to bring electronic devices and to use them as they chose; campus facilities managers and housing offices had the power to create, change, or impose policies that impact student energy use and were the final decision makers on how energy is managed within the buildings; and designers had the power to influence which energy efficiency strategies, technologies, and capabilities are considered as part of the design process. It was the negotiation between the stakeholder groups that appeared to give residence halls their unique character with respect to plug load energy usage (Figure 3). This understanding of coherent processes was aided by the iterative, analytical and process-oriented nature of Grounded Theory.
4.0. Suggestions
A unique flexibility of GT is illustrated by the case studies above. GT can either be a stand-alone method, or it can come at the beginning or end of an architectural research project. This section of the paper offers specific suggestions for architectural research, divided by phase of data collection, analysis, and theory generation.

4.1. Data Collection
Though Grounded Theory is an analysis method, not a data collection method, there are some types of data that are more appropriate than others. The richer, the more complex, and the more layered the data is, the more applicable they are for GT methods. Architectural research, because of the complexity of its contexts, provides a wealth of sources with multiple viewpoints on specific phenomena. Interviews and focus groups are obvious sources of data, but videos, photographs, drawings, and free-form answers to survey questions, etc. can also provide rich source material. Annotations written as notes during periods of observation can be used in the qualitative coding process as well. The data does not need to be newly collected: a researcher who has an existing word or image dataset can also apply GT methods.

The logistics of planning, scheduling, and conducting interviews is challenging. Traveling to conduct interviews is time consuming but allows researchers to interact directly with participants and to see their facial expressions that phone or internet interviews do not. In-person interviews allow the discussions to take place in building contexts, significant for architectural researchers. More interviews are not always better. Collecting and transcribing data from interviews, focus group discussions, ethnographic observations, etc. is incredibly time consuming. Starting the transcription process before completing the data collection allows the codes and memos that emerge from transcribed data to inform questions asked in future data collection. As noted in Sections 2 and 3, choosing whether or not to record and transcribe does not affect robustness; either is acceptable, lending flexibility to the researcher.

4.2. Coding
The first step of data analysis in GT is the coding of the data. Coding is like sifting through sand — an iterative process that reveals the patterns in the data. There are choices for the researcher in how to code the data: first, predetermined versus invivo versus emergent coding; and second, whether or not to conduct selective coding. In predetermined coding, the researcher creates a set of codes in advance and searches for text that matches these codes. In invivo coding, the code list is created from the actual words in the data as the coding is conducted. Emergent coding builds on the idea of invivo coding, but with ideas and concepts, not literal words. Given the expansive data of qualitative architectural inquiries, emergent coding allows the researcher to analyze “on the fly.” Selective coding consists of coding every single line of text: essentially using a fine-toothed comb on the data.

Coding is an essential step in many rigorous, qualitative analysis methods. The initial coding in GT is distinguished by its systematic and thorough approach, and by the idea that initial coding does not assume that researcher has yet developed a theory. GT coding is also distinguished by a final, iterative step: the coding of the codes. Categorizing the codes into what Glaser calls, “coding families,” is a means to understand the emerging patterns. This process of sorting and diagramming the data provides a logic for organization that aids the theoretical development of analysis (Charmaz, 2006). Regardless of the method used, one essential code is “Great Quotes,” a tag that helps to find and employ the gems discovered but possibly forgotten in the interview transcripts or notes.

4.3. Memos
After the first round of coding, the researcher begins to write memos, the heart of the Grounded Theory process and, perhaps, the analytical step most valuable to qualitative researchers in architecture. Memos, or short written notes, address ideas or perspectives and allow researchers to reflect on what they are seeing in the data. Steve Borgatti notes: “Writing theoretical memos allows you to think theoretically without the pressure of working on ‘the’ paper” (Borgatti, 2005). Kathy Charmaz emphasizes that memos “explicate analytic notes, fill out categories, and allow the researcher to make comparisons between data and data, data and codes, and so on” (188 Brink, 2006). Early memos can direct the writing of “advanced memos” which can be used to describe how categories emerge, and in making comparisons. Ultimately, in Grounded Theory, the theory emerges through the process of memoing, during which the researcher creates ideas about the evolving theory throughout the process of open, axial, and selective coding.

From the case studies, some lessons learned for memoing are to: write memos about ideas and concepts, not about the people in the data; keep the memos separate from the data; write memos as often as possible; write a separate memo for each idea; and modify memos iteratively. For architecture researchers, who tend toward the intuitive, it is important to note that memos can be based on a hunch (if stated clearly as such), but for memos to be grounded, they need to emerge directly from the data and coding (Glaser, 1978). The memo–writing process is unique to Grounded Theory among qualitative methods. Memos are a productive and structured way to reflect on the data while sorting and categorizing it. Memo writing is also an efficient aspect of GT: many memos can simply be edited and included in the final report or paper.
4.4. Software programs
Although the traditional method of coding and analyzing qualitative data by hand is still a viable option, computer assisted qualitative data analysis software (CAQDAS) is now fairly common. There are several software options including Atlas.ti (Figure 4), Nvivo, and Dedoose. The primary advantage of these programs is to assist the researcher in streamlining and facilitating what can be a slow and laborious process. The software allows the researcher to select words, lines, or chunks of text; tag or code them; easily retrieve all similar codes; and compare coded material or themes. When working with a large dataset, CAQDAS can be an excellent organizational and sorting tool to the qualitative researcher. All of these programs can be learned fairly quickly by anyone with basic computer skills.

Figure 4: Example from the Atlas.ti qualitative analysis software used.

The software greatly assists the qualitative researcher in their task, but it does not actually perform the analysis for them (Basit, 2003; Bringer, 2006). There is still a manual process of using the software to code the data. The disadvantages of CAQDAS are primarily due to the cost associated with purchasing the software and the time necessary to develop proficiency learning the programs. The less expensive software programs have fewer capabilities, but this may not be a major issue for novice users.

4.5. Theoretical Sampling & Saturation
The idea of saturation is a key component of Grounded Theory, and it answers the difficult question that arises in qualitative research and GT analysis: when do I have enough data? There is no hard and fast rule for how many interviews one must collect, which confounds researchers new to GT who are familiar with quantitative techniques based on statistically significant samples. In GT, the idea of "saturation" suggests that a researcher will know when they have enough data at the point they begin to hear the same kinds of responses from different participants (Charmaz, 2000). Theoretical saturation of the collected data limits how much data collection takes place. Saturation is not the same as repetition of the same events or stories but rather "the conceptualization of comparisons of these incidents which yield different properties of the pattern, until no or new properties of the pattern emerge." (Glaser, 2001). Charmaz notes that "categories are 'saturated' when gathering fresh data no longer sparks new theoretical insights nor reveals new properties of these core theoretical categories" (113 Charmaz, 2006). Procedurally, the idea of saturation is more systematic and efficient, but it relies on the researcher’s ability to stop and reflect during the data collection and analysis stages of the project.

CONCLUSION
Although it is fairly common for architecture researchers to include subjective perspectives from people (occupants, designers, clients, building managers, etc.), this qualitative data is rarely rigorously analysed or conceived as an integral piece of the research design. Open-ended questions that generate narrative responses are not a problem for architectural research; they are an opportunity that should be harnessed, embraced, and celebrated. The Grounded Theory methods, approach, and procedures described above provide a straightforward primer for researchers interested in leveraging rich and complex participant experiences to enhance research outcomes. GT is predicated on the idea that researchers can approach and work with qualitative data in a rigorous and systematic manner to reveal new meaning and answers to unexpected questions. A number of time-tested GT analysis procedures exist that can be employed and adapted by architectural researchers to suit specific research goals and objectives. These procedures take time to master and use, but are relatively simple to understand and accessible to researchers unaccustomed to qualitative research and analysis. With limited architectural research precedents using GT and a set of established analysis procedures, the time to begin using GT in inquiries of the built environment is now.
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ABSTRACT: Historically, architecture's cultural role has changed in sometimes radical ways. A theory of contemporary architecture must deal with the proliferation of information and communication technologies, seeking a transformed role for the physical setting in a digital age. This paper reviews perspectives from computational disciplines, proposes the outline of a theory of interactive architecture, and presents a preliminary exploration of heuristic methods as a tool for the design of interactive architecture.

Computation began agnostic about physical setting, focusing on symbolic systems. But in diverse disciplines, theorists and researchers are questioning the validity of abstraction without an understanding of physical and cultural settings. Ecological psychology investigates how perception must be based on the physical setting rather than only interior mental processes. Actor Network Theory proposes that humans and physical artifacts are interchangeable within a network of meaningful activity. Embodied interaction demands that the meaning of human behavior arises from the physical and behavioral setting. Physical cognition studies how we reduce cognitive load by storing information in both physical settings and symbolic systems. Based on this understanding of the role of the physical in meaningful settings, a case is made for a theory of interactive architecture. This theory is aligned with the activity model of interaction design, privileging the experience of the users of space in mixed settings containing both physical forms and media. This paper will explore these approaches with a specific question: does the physical setting influence in important ways the manner in which we understand and use information? Using both a modification of Nielsen's heuristics and the use of a design science experiment focused on a taxonomic understanding of design possibilities, this paper speculates on a set of interactive architectural heuristics.

KEYWORDS: Responsive architecture, ICT (Information and Communication Technologies), HCI (Human Computer Interaction), Media

INTRODUCTION

As the developmental logics of contemporary architecture are being conceived increasingly more for the display of audiovisual information than for the framed location of real bodies, a mode of built environments, as overwhelming as the datameshes that they seek to ground, is now being jettisoned globally.

John Beekman, “Merge Invisible layers” (Beekman, 1998, p14)

In 2004, Blockbuster Video operated more than 9,000 stores both in the US and across the world. These stores em-
ployed 60,000 and controlled 45% of the video rental market. The trip to a Blockbuster store, the stroll down the aisles and the search for a video on Friday and Saturday nights was an integral part of life for millions of users. In 2010, Blockbuster declared bankruptcy and was down to 500 stores, and its share of the video rental market has shrunk from 45% to 3%; it has since disappeared altogether. Netflix had initiated a service that delivered DVDs directly to consumers, using an Internet site for browsing, sales and scheduling. The search and the stroll had become virtual.

While it is a stretch to claim any exulted architectural status for Blockbuster stores, it is clear that in this case at least, the physical has been replaced by the virtual. It is cold comfort to Blockbuster that Netflix itself is under pressure from services, both legal and illegal, that do away with not just the architectural setting of the store but the physical artifact of the DVD. Bits will be bits.

And, of course, this is not a new story. William J. Mitchell draws a series of contrasts between sites on “the Net” and sites in the traditional city. He uses the terms spatial/antispatial, corporeal/incorporeal, focused/fragmented, synchronous/asynchronous, narrowband/broadband and contiguous/connected to highlight the challenges that digital settings make to architecture. In the end, we are left with an open question: does architecture matter or will it be replaced by the virtual?

An extreme position, prominently taken by Hans Moravec, is that the physical setting is irrelevant, or worse, a hindrance (Moravec, 1998). He imagines a “brain in a vat”, gradually relocating the contents of the brain to electronic form, eventually erasing any vestige of its original body. He imagines that we will find our sense of awareness distributed over many locations, carbon based life replaced by silicon, meatspace by cyberspace. This view holds no special place for the tangible and specific settings that have been assumed to be fundamental to architecture. At best, the skills, cognitions and insights that underlie architecture may find digital expression, virtual desktops supplanting tangible armoires and metaphorical space replacing physical extension. It is difficult to imagine an architectural theory that does not include the tangible in a prominent role. It is equally clear that for Moravec, architecture has been erased.

This shift in the position of architecture has been the subject of a long historical discourse. In 1831, Victor Hugo devotes an entire chapter in one of his novels to a discussion of the changing and diminishing role of architecture (Hugo, 20120. Hugo begins with the premise that the invention of the printing press and the concomitant spread of literacy changed the role of architecture in the most fundamental way possible. Before the printing press, the building was the primary source of knowledge and enlightenment, and as he points out, one that can be tightly controlled by the hierarchy of the church. The position and content of architecture can shift over time, and it can address different issues at different times.

Walter Benjamin, in “The Work of Art in the Age of Mechanical Reproduction”, is focused on the manner in which new forms of art engage their viewers in new ways (Benjamin, 2008). He contrasts earlier ideas of presence in art, which have been destroyed by new techniques that render authenticity impossible to determine, with new forms of engagement with art such as motion pictures. In contrast to Hugo, he understands new forms of art as requiring radically new forms of engagement and analysis. New forms of art require new forms of engagement, both political and aesthetic.

Marshall McLuhan focuses solely on the mode of expression, believing that content is shaped by the medium (McLuhan,1967). Over and over, he rejects ideas that the content of television (his primary object of study) can be somehow aimed toward “correct” goals. His archetypal example of a pure medium is the light bulb, free of any content but redefining the way in which we confront and understand the world. The critical issue is the medium, and it determines the quality and possibilities of engagement by a community of users.

Summerson’s “Case for a Theory of Modern Architecture” is oblique about the theory itself, instead referring to a “source of certainty” for designers (Summerson, 1957). He observes the change in this source of certainty from history to program, from a repository of inherited form to a fragment of a social organization. If we were to construct a theory of contemporary architecture, it would undoubtedly need to deal with the onslaught of the virtual and of information within the culture. The question has become “what is the role of the tangible setting in an age of information.”

The new disciplines arising around the issues of computation and information began agnostic about the idea of physical setting. Computer science, engineering and information science have until recently focused on algorithms that are abstract and repeatable. But increasingly, in a number of venues, there have arisen voices that question such abstraction and instead look to the particularities of settings to understand meaning. These questions have arisen from fields as diverse as ethnography, science and technology studies, human computer interaction and perception. In each case, prominent theorists have questioned the idea of abstract processes without an understanding of the physical and cultural settings in which they arise. None of them are explicitly architectural, but each has a particular place for the tangible as a central part of their formulation of meaning. And, of course, none of them by themselves lead to an architectural theory. But in the sense that Summerson invokes the need for a source of certainty, each of them suggests ways in which we
might sees the emergence of a new position for architecture.

1.0 INFORMATION AND SPACE
In diverse disciplines, theorists and researchers are questioning abstraction without an understanding of physical and cultural settings. Ecological psychology investigates how perception must be based on the physical setting rather than only interior mental processes. Actor Network Theory proposes that humans and physical artifacts are interchangeable within a network of meaningful activity. Embodied interaction demands that the meaning of human behavior arises from the physical and behavioral setting. Physical and distributed cognition studies how we reduce cognitive load by storing information in physical settings and shared systems.

This paper will briefly explore each of these approaches with a specific question: does the physical setting influence in important ways the manner in which we understand and use information? Our goal is develop a coherent position for architecture in contemporary culture, one which acknowledges its intimate connection to its physical settings while at the same time connecting to emerging concepts of information and computation.

1.1. Ecological psychology and affordance
Ecological psychology began as a reaction to behaviorism, emphasizing the role of the physical settings to the perceptual capabilities and apparatus of human perception. J. J. Gibson, the leading exponent of this field, is interested in the role of the physical setting in reflecting the ecological niche within which perception operates (Gibson, 1979).

Gibson focused on the reciprocal role of cognition and the environment. Until his work, cognition had been treated as an internal process, separable from the external environment. Gibson begins by noting that men, like all animals, have developed cognitive and perceptual systems that are uniquely suited to their ecological niche. Hawks have eyes that can see details at very great distances to enable them to hunt prey; dogs have hugely development sense of smell to track their pack and their dinner. Gibson labels this reciprocal relationship with the environment with a term of his own invention “affordance”. By this he means that the physical environment makes possible certain kinds of behavior, based both on the physical properties of the organism and of the environment. Gibson's seminal work focused on problems with aircraft landings, and the failure of existing models to help with issues of complex perceptual fields combined with motion.

The salient feature of the concept of affordance is that it combines objective qualities of the environment with assessments by individual animals within the environment, and that it values some aspects of the environment over others based on their usefulness for possible actions. The floor plane, occlusion, and wayfinding are all aspects that will become important to such a view. The concept of affordance has also become an important idea within HCI through the work of Donald Norman, who extends the term affordance to mean both the physical as well as the cultural setting.

As a framework for an interactive theory of architecture, affordance offers advantages. It connects human action with physical space in a direct and measureable way. Many measurements and positions are possible, but some are more important than others because of the manner in which they afford human behavior. This separation of the specific contribution of the physical space connects space and behavior.

1.2. Actor network theory
Actor Network Theory is primarily the work of Bruno Latour and Michel Callon (LaTour, 1979). The unique characteristic of ANT is that it regards all actors, both physical and human, to be equivalent. Rather than treating sociology as one discipline and technology as another, it attempts to understand them together.

ANT studies society in terms of the relationships between people and objects, understood as nodes of a network and relations between them. The theory was grounded on English science and technology studies, but it shares some common themes with the French post-structuralist: instability in the human sciences, due to the complexity of humans themselves and the impossibility of fully escaping structures in order to study them. It utilized existing French academic knowledge from multiple fields and the studies on large technical systems. The initial goal was to try to understand how innovation and knowledge are created.

ANT focuses on the mechanics of life: the ways in which people and objects interact with each other. The main aim of ANT is to overcome the subject-object divide, the distinction between the social and the natural worlds and to see the reality as enacted. Translations are about continual displacements and transformations of subjects and objects, and the insecurity and fragility of the translations and their susceptibility to failure. An illustrative example of LaTour’s approach is his paper describing the human and physical “actants” using the example of the humble door closer (written under a pseudonym to apply the same analysis to academic papers as a construct.) (Johnson 1988)

The importance of actor network theory is its insistence on seeing the physical setting and human behavior simultane-
1.3. Embodied interaction

Within Human Computer Interaction, embodied interaction is a position that seeks to understand interaction within a specific social and physical setting. Paul Dourish, the most prominent proponent of this approach, combines an understanding of phenomenology with an historical understanding of the evolution of computer interfaces (Dourish, 2004). Dourish merges ideas from social computing and physical computing to propose a new interface paradigm that is specifically situated in physical and social space.

In his book, Where the Action Is, Paul Dourish summarized the motivating ideas behind two emerging research fields: tangible computing and social computing. Physical computing allows the user to interact using multiple external input devices, such as cameras, RFID tags, and everyday objects that have been programmed to respond to the system. Social computing takes into consideration that there are multiple factors in a setting that affect the activity of users. These activities, embedded in the social, organization and cultural setting and the everyday visual settings of work, influence what and how users interact.

Embodied interaction includes both of these ideas. Tangible computing is intuitively interactive and inherently integrated into everyday objects and places, not separated as desktop and world. Social computing is involved not only with the computer but also with the surrounding space and environment including social and cultural aspects. Embodiment involves existence in the world, including but not exclusively physical.

These aspects of the HCI field can be important to architecture through the design of space. Architecture will become a large part of the new interface of computing. This can include the integration of computing into architecture and space, such as a media walls, facades, and interactive materials, and the effect of the embodied interaction of non architectural objects on an architectural space.

1.4. Distributed cognition

Work done by Edwin Hutchins, "cognition in the wild", seeks to uncover the relationships between the physical and social settings relating to research in physical cognition and distributed cognition, both of which emphasize the use of the settings as part of the process of understanding and solving complex problems (Hutchins, 1995).

The organization and division of cognitive labor creates the means by which information is gathered and processed by members of a group, and by which appropriate actions are taken to accomplish tasks and achieve goals. Some of this coordination is accomplished through communication practices of spatial arrangements that may clarify aspects of the current situation or that generates expectations about an unfolding situation. Hutchins’ archetypal study focuses on navigation aboard carriers within the US Navy. He carefully studies the use of cultural and social structure, organization procedures and spatial positions aboard the bridge of the ship.

Distributed cognition looks at how social organization influences patterns of the transmission and transformation of information within a group. It seeks to understand how cognitive processes may be distributed across the members of a group. This approach is helpful to understand how a group works together in order to solve a problem that is too complicated for one individual to perform. A group has this ability because their combined cognitive process has greater knowledge, processing capacity, and speed, which enable them to complete a task too complex for a single person.

When applying the theory of distributed cognition to a social group, it is essential to observe their activity "in the wild". While Hutchins' approach is wide ranging, the physical setting that a group occupies during their interaction provides critical context in understanding how they work with each other and with their relationship with materials or tools within their environment.

2.0. INTERACTIVE ARCHITECTURE & HEURISTICS

An interactive architecture requires a model of human computer interaction as an important theoretical foundation. The dominant theory of human computer interaction has been the cognitive model (Card, 1983) that imagines two information processing units, one in the machine and one firmly in the user's head. These are conceptualized as directly parallel and reciprocal, and are based on the internal structure of the computer programming as it evolved during its first 30 years. An alternative to the cognitive model is activity theory (Kaptelinin, 2006). Rather than assuming that humans are only symbolic information processors, it proposes a more holistic understanding of the use of computing in physical cultural and social settings. Two key concepts are consciousness (considering mind as a whole) and activity (considering interaction with all dimensions of reality). Activity theory places an emphasis of the study of computations tasks in their natural settings. It is clear that activity theory approach reflects many of the issues raised by the four approaches discussed in Section 1.
Therefore, heuristics for an interactive architecture will rely on activity theory as a paradigm. Two approaches are discussed in this paper; a transformed set of existing HCI heuristics and a test implementation of augmented reality interface in an architectural setting. Together, these approaches speculate on the outline of an interactive architecture.

2.1. Translated heuristics
Evaluating interface design has been the subject of extensive research, and has led to the development of accepted heuristic evaluation techniques. The most widely used methodology is Nielsen's 10 heuristics (Nielsen, 2014), which is used both as a general evaluation metric and as a baseline for developing heuristics for innovative and emerging interface technologies. This paper speculates on a set of architectural heuristics for the role the physical and digital dimensions in architectural settings by presenting a brief description of each existing heuristic and its possible transformation for application in architectural settings.

1. **Visibility of system status**: keep users informed about what is going on
   - Movable or changeable architectural elements (door, lights, etc.) can indicate status
2. **Match between system and the real world**: Follow real-world conventions, natural & logical order.
   - User movement and position are primary affordances in architectural settings
3. **User control and freedom**: Users often choose system functions by mistake; support undo/redo
   - Allow architecture and information to decouple and reconnect later
4. **Consistency and standards**: Follow platform conventions
   - Use clear and consistent architectural vocabulary
5. **Error prevention**: careful design which prevents a problem, ask confirmation
   - Architecture will work with or without digital interaction; allow for catch up
6. **Recognition rather than recall**: Minimize the user's memory load; make objects options visible
   - Only present spatial information aligned with architectural elements; present only when needed.
7. **Flexibility and efficiency of use**: Accelerators for the expert user; tailor frequent actions
   - Afford enhanced views for different groups of user with different needs or interests.
8. **Aesthetic and minimalist design**: Dialogues should not contain irrelevant information
   - Keep all information simple and infrequent
9. **Help users recognize, diagnose, and recover from errors**: Error messages in plain language
   - Distinguish between information and architectural errors. Assume errors can be ignored until later time by one media or the other.
10. **Help and documentation**: documentation easy to search, on task, small
    - Density of information should vary with proximity to key locations (public displays, intersections)

2.2. Design taxonomy
A second approach to the development of heuristics for interactive architecture involved research on the use of augmented reality in architectural settings employed a design science research methodology (author, 2017). We considered the design of architectural space and augmented reality applications simultaneously. Combining the efforts of twelve architectural designers with a team of AR developers, we develop a taxonomy of affordances, feedback mechanisms, and output/display options. This taxonomy constitutes preliminary usability heuristics for the use of AR as an embodied device for interaction in architectural settings and is indicative of larger issues for interactive architecture. These include afforded and interactive inputs and tangible and display based outputs.

Afforded inputs are those that because of physical or cultural factors are understood without need for visual feedback. These include: **proximity**, moving closer to or further from an object in the model was understood without the need for feedback; **gaze target**, the direction of a user’s gaze was immediately apparent to user of the system; **gaze duration**, because obvious after a few minutes of use by the Holo Lens; and the **orientation** that a user faces is apparent in at least two ways; inside/outside can be understood wherever the architecture makes it obvious; **geometric orientation** is made obvious when the architectural arrangement is strongly delineated.

Interactive inputs require some visual feedback from the Hololens to make it cognitively present: **angle of view**: head motion can be understood as an input in either the vertical or horizontal direction, but require visual feedback to be understood; **hand gesture**: the standard interface in Hololens of finger or hand gesture require significant feedback to be obvious; and **voice**: the use of voice recognition can be used to provide rich input to the system; feedback verifies the system is engaged.

The output of the architectural/AR system can assume either display or physical aspects; **physical computing**: the rearrangement of physical objects based on a user’s position; **overview/detail**: details can be made to appear to come closer to user and be available for inspection; **transparent/opaque**: details can be made to appear to come closer to user and be available for inspection; **x ray vision**: one can creates display that appear to allow users to see into other rooms or into the city beyond; **virtual space**: can be generated around a user as they move through space, guiding or circumscribing movement; **a heat map** can show
the locations of classes of objects; **cognitive maps** can capture the interest of an individual that later guide a customized tour of the site; explanatory **text** can appear at appropriate locations, and can become more detailed as one approaches; **virtual objects** can appear in the space to connect other objects from the site or from a larger corpus); and a **direction path** can be created to guide users.

![Figure 2](image_url)

**Figure 2**: A design science based exploration of the integration of augmented reality and architecture design. Left, architectural space with markers; right, the Hololens interface for design of interaction and space; Source: (Author 2017)

**CONCLUSION**

The development of interactive architecture will require the simultaneous integration of information and setting. Neither the computational disciplines such as HCI nor the traditional conceptual basis of architectural design will be sufficient to understand and design for this mixed environment. This paper presents some early attempts to combines these fields. Without some new conceptual framework, we will be left with technology that only haltingly understands its settings or architecture that uses technology as decoration.

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(author, 2017)
WEATHER REPORT: 
STRUCTURING DATA EXPERIENCE IN THE BUILT ENVIRONMENT

Marc Swackhamer1, Andrea J. Johnson1, Daniel Keefe2, Seth Johnson2, Ross Altheimer3, Aaron Wittkamper4

1School of Architecture, University of Minnesota, Minneapolis, Minnesota 
2Department of Computer Science and Engineering, University of Minnesota, Minneapolis, Minnesota 
3TEN x TEN, Minneapolis, Minnesota 
4Wittkamper / Reiff, Minneapolis, Minnesota

ABSTRACT: With the influx of data into the everyday, users demand an interactivity that is localized and immediate, connected to and informed by exhaustive information across space, time, and discipline. As the data cloud burgeons through a plethora of types of inputs, designers grapple with frameworks for analysis and visualization, and the experience of interacting with information remains visually strapped to surfaces of digital display or pre-set as largely static objects. As the Internet of Things develops and the built environment becomes sensing and automated, the ability for all people to engage with, understand, and have a role in the complexity of data input and output requires a new paradigm for building, one in which data is an intelligible component of an environment that is continual, receptive, and communicative. This paper analyzes Weather Report, a constructed environment driven by user-informed data collaboratively designed by an interdisciplinary group of architects, landscape architects, and computer scientists. The aim of this paper is to discuss the assets and liabilities of a spatial data experience posed by the project, framed through questions of design agency related to data input, user interaction, and a plurality of design voices, and the implications of this innovative approach on broader practices. It suggests that a field we term “spatio-data design” might be an emergent area of study, where the built environment is as informed by the management and choreography of data as it is by the traditional assembly of physical materials and components.

KEYWORDS: data visualization, mixed computer and human data, spatio-data design, interdisciplinary design collaboration, design agency

INTRODUCTION

The availability of large amounts of data with the rise of computing has led data visualization today to be predominantly digital, using high-definition displays to organize pixels. Yet with expanding technological possibilities, data that is managed digitally need not only be represented digitally. As physical controls and displays emerge within the field of information visualization (Jansen, 2014), researchers in the arts and design are exploring links between the digital with the physical. Some recent examples of physical data visualization range from static displays, such as Centennial Chromagraph (Marcus, 2014), to dynamic displays, such as Daniel Rozin’s 1999 Wooden Mirror. Though a majority of physical visualizations are object-scaled, some are building-scaled, such as the full- façade Greenpix media wall by Simone Giostra & Partners (Etherington, 2008). Most architectural media walls, however, are still limited to surface, and arguably glorified digital displays. By working at the intersection of architecture and computer science, we challenge approaches that merely represent data on a two-dimensional surface, offering instead data that is experienced as a thickened space. In a world moving towards virtual reality for its capacity to convey data spatially, this project offers another approach to immersive data visualization.

Bernard Tschumi said “architecture is about designing conditions, rather than conditioning designs,” and that it is about “identifying, and ultimately, releasing potentialities hidden in the site.” Through Weather Report, an interdisciplinary project constructed for the 2016 Northern Spark Art Festival in Minneapolis, we aimed to design a condition driven by data, memories, and exchange. The project is an environment under continuous change; a light-filled, spatial experience in which architectural character is determined as much by those who experience the space and by streaming data feeds, as it is by the hands of the designers. Challenging the idea that designers must remain in constant control of their work, Weather Report represents a strategic and choreographed approach to design authorship. As its designers, a group of architects, landscape architects, and computer scientists, we developed a system in which we “released the potentialities hidden” in a place and its people. This approach shifted design agency by emboldening users to participate in the conception of their environment and repositioning the designers to serve, not as willful artists, but as strategic thinkers—ones who set up the conditions under which architecture is unpredictably and organically, but thoughtfully, grown out of influences external to their control.

Weather Report challenges conventional notions of design agency in three ways. First, it is driven by data. The project is constructed of a frame and an air-filled skin, upon which historic weather data is projected as an abstract, color-coded visualization in constant fluctuation. Second, it is driven by users. Visitors provide memories of weather conditions,
which are recorded and played back on the surface of the environment. As such, the installation is under further continuous change in accord with user feedback. Third, it is driven by a plurality of design voices. We took a democratic approach to the project’s conception; by focusing on the development of a system and an attitude, rather than a specific esthetic character, the final outcome is novel, surprising, responsive to its context, and continuously dynamic.

This paper will examine how these three drivers (weather data, user interaction, distributed authorship) might contribute unconventionally to a bottom-up, spatialized, data-design approach. We first discuss this in part one of the paper through a description of how each driver specifically informed our project. In part two, we more broadly speculate on the implications of this way of working for the disciplines of architecture, landscape architecture, and computer science. We conclude with a speculation on what the work contributes to discourse around the topic of intersections between data and space.

1.0 WEATHER REPORT PROJECT: driven by data, users, and distributed authorship

1.1 DRIVER 01: Visualization of weather data

The first of the three primary drivers informing Weather Report is weather data. The project was constructed of an inexpensive, off-the-shelf steel tube frame supporting a gridded array of white balloons, upon which we digitally projected historic weather information in the form of a color-coded animation. This produced a rapidly changing environment. Every half-second, one hour’s worth of weather data was flashed onto one of the “pixels” (one balloon) of the screen. Read from left to right, the screen communicated weather information about decades, years, months, days, and finally hours, ultimately covering sixty years of recorded history. This yielded a flashing, evolving environment that changed slowly on one end and very rapidly on the other. The experience of visiting the installation is likened to occupying a colorful disco ball.

![Figure 1: Weather Report at Northern Spark Festival (Authors 2016)](image)

We considered the weather data to be quantitative, and it served as a baseline condition comprised of collected, precise data, to use as a comparative tool for testing the accuracy of users’ memories of weather conditions (we will discuss this under “user interaction”). The use of data might suggest a controlled managerial approach to the design of a project, as opposed to an uncontrolled or chance-driven approach. The questions for the team quickly emerged: how could we allow this data, which we did not control, to exert its own control over the project? How could weather data produce a project in which final appearance or form is as controlled by the data as it is by our hands as designers? Our approach was to set up a system in which the data could produce its own environment, where we managed the infrastructure (Figures 2 and 3), but allowed the weather data itself, in its colors, patterns, and motions, to produce its own conditions. The nature of the animation, the patterns of color, the speed of change, the severity of change, were all outside of our control as designers. We likened this to an architect saying that he or she wants a building to be brick, but then allowing different people to pick the color, finish, texture, size, and clay type for each brick in the building. This idea likely sounds unappealing to most architects, however, this was precisely what we did (an approach that is, incidentally, being currently explored by a few critically-recognized architects, like Wang Shu).
Guiding our methodology and approach to using the collected weather data, our objective was to develop a mapping from data to balloons that would enable visualizing the entire 60-year, hour-by-hour historical weather dataset and that could be mirrored on both sides of the tunnel, with quantitative data visualized on one side and qualitative user data on the other. This was a major challenge, as it required depicting 525,600 data points (60 years x 365 days x 24 hours) each containing five data variables (temperature, rain, snow, wind, cloud cover) in just 432 “pixels” (the balloons are arranged in a 12 x 36 grid of “pixels”).

Figure 2: Weather Report elevation and section (Authors 2016)

Figure 3: Weather Report plan on Northern Spark Festival site (Authors 2016)
Our solution, illustrated in Figure 4, is like a weather clock—it uses animation to step through time at a rate of one half-second per one hour of historical weather data. The display is divided into four sections of increasingly fine time scale. From left to right, the balloons represent decades (columns 1–2), each month of each year in the currently highlighted decade (columns 3–12), each day of the currently highlighted month (columns 13–26), and each hour for the 5 days leading up the currently highlighted day (columns 27–36). The visualization always has exactly one hour of data highlighted (in Figure 4, it is 7pm on Tuesday, May 24, 2016), and the highlight moves from one hour to the next each half second. When the highlight reaches the end of the rightmost column, a new column of data (the next 12 hours) is paged in from the right and the display shifts one column to the left. If this brings the display to the next month, then the days–of–the–month display (columns 13–26) is updated accordingly, and so on. Colors are assigned to balloons using the mapping described in Figure 4 based on the historical data for temperature at the corresponding hour in the case of the rightmost section of the display or based on the average temperature in the case of days of the month, months of the year, and decades. The display enables comparison of multi-year trends. For example, change in average temperatures by month can be compared across a decade using columns 3–12.

On the quantitative side of the display, the additional data variables of rain, snow, wind, and cloud cover are visualized as ‘events’. When the display reaches an hour with high values for these variables, then an animated weather event effect is applied for 10 seconds as a semi-transparent overlay on the entire display. For example, if it snowed during the currently highlighted hour, semi-transparent white highlights will fall down like snowflakes across the whole balloon wall, subtly shifting the colors of the underlying temperature visualization. Similarly, high cloud cover introduces an animated overlay of pixelated clouds that drift across the display. Raindrops fall and darken the underlying temperature visualization, and high wind blows any of the other effects rapidly across the screen.
On the qualitative side of the display, the data are generated by visitors to the space who record values for all five data variables (temperature, rain, snow, wind, and cloud cover) at a specific hour in history using the interface pictured in Figure 5. This makes for a data set with many missing values, and the software fills these in by interpolating between consecutive entries in the subjective historical record. Temperature is visualized using the same mapping as for the quantitative side of the display. However, the animated overlay of weather events is replaced on the subjective side of the display by the visitors' own 10-second animation. This animation is created using a multi-touch sensitive display shown in Figure 6. Visitors simply draw or act out a weather-related memory directly on top of an image of the balloon wall almost as if they are playing it like an instrument. The resulting animation is displayed once on the wall immediately after it is drawn and then again, whenever the display advances to the hour of the viewer’s memory.

Upon reflection and critique of our use of the weather data in the Weather Report project, observations emerged to consider in future efforts. First, the legibility of the weather data could be improved. Most participants understood that the project was about weather, but few seemed to understand how time informed the display and that the system could actually be read with a high degree of accuracy. This clarity could be built into the system in a more intuitive way, through the use of a distributed communication strategy via the users' mobile phones, through cues like varying the sizes of the pixels or their distribution, and through auditory cues like a spoken didactic or sound feedback. Second, the scale or coverage area of the weather data could have been more tightly focused to the specific geography of the site. This would render the project more relevant to its location, and help participants connect more directly. Finally, the way the data were visualized could have been more experimental. In its current state, the data is rendered like a bar graph. However, since we were interested in exploring data spatialization, that is, how data can be expanded from its normative two-dimensional or quasi-three-dimensional expression and instead made truly spatial, we saw the reliance on two axes.
as limiting. Though visitors were able to occupy the data by placing themselves within and around the structure, the reading of the data was still mainly two-dimensional. How might we begin to occupy and understand data that is multidimensional from multiple vantage points?

![Weather Report balloon "pixels" (Authors 2016)](image)

**Figure 7:** Weather Report balloon “pixels” (Authors 2016)

### 1.2 DRIVER 02: User Interaction

The second of three primary drivers impacting Weather Report was user interaction. As was described in detail above, the two walls of the installation each communicated a specific kind of data: one, the actual recorded data from the MSP airport, the other, the weather from participants’ recollections. Participants occupied the space between these two data streams (Figure 8): one highly precise, the other intuitive/imprecise; one regular and predictable, the other erratic and unpredictable. In the case of user interaction, visitors to the art festival provided the project with data in the form of their memories of the weather on specific dates in the past. Beyond providing these memories, they also “acted out” their weather experiences through the gesture-drawings. Remembered and gestured information was then recorded and periodically replayed on the surface of the environment, as the data visualization cycled through their chosen date.

![Weather Report Interior (Authors 2016)](image)

**Figure 8:** Weather Report Interior (Authors 2016)

In contrast to the recorded weather data, this set of weather data was subjective, or qualitative. It was derived from the memories of participants, how they felt on a particular day, what their mood was, and how this was impacted by the events of the day. Perhaps a fond memory of a wedding skewed the memory of weather on that day as more pleasant than it actually was, whereas a sad event, like a funeral, was skewed towards occurring on a day they remember as less pleasant than it actually was. So, the challenge for the design team in the case of this subjective information, was not to determine how to relinquish control (we had no control over what was entered into the system), but rather to determine what we could control. Through the development of a standardized set of simple questions, a standard methodology for communicating the answers to those questions, then using a simple visualization strategy that matched the quantitative side of the piece, we achieved this goal. In presenting a system where quantitative information was clearly viewed in contrast to qualitative information, we set up a commentary on the nature of memory as it relates to time and environment. It was rewarding to observe how the participants interacted playfully with the piece throughout the night.
This was another influence beyond our control, and a completely unforeseen dynamic. By placing themselves between the projectors and the surface of the environment, participants created a dynamic, shifting reading of the surface where ghosted movement appeared and disappeared, organically blurring and unsettling the architecture (Figure 9). This produced a condition in which people could further influence the environment through their own, more tactile relationship with the data visualization.

Upon reflection, a number of changes might improve our approach to user interaction. First, the sample size of our user input was small. The input took place during the overnight Northern Spark festival that lasts 8.5 hours from 8:59pm to 5:26am. Because we only provided one touch display, and the queuing line for using it was long, only a small fraction of visitors were able to enter their memories. This might be improved through, again, developing a distributed, mobile-device-based user interface to provide input. In this democratization of data, the more people who can impact its formation and evolution over time, the less control we, as designers, have over it. Further, might the users be allowed, even encouraged, to more broadly impact other aspects of the piece? What if the users were able to change how the data was displayed, what kinds of data were displayed or how color was used? What if users could choose to associate themselves, their names, and where they are from, with their provided data? These questions, and specifically the question of the calculus between control by users versus control by the designers, are ones that this project is only beginning to ask.

1.3 DRIVER 03: Distributed Authorship

The third primary driver impacting Weather Report was its unique form of distributed authorship. In 2013, MINN_LAB was formed by a group of independent architects, designers, and landscape architects, to bring the design community into the annual Northern Spark Festival that was previously driven primarily by the art community. In 2015, the group expanded to include computer scientists through a research collaboration between the College of Design and Computer Science at the University of Minnesota. Weather Report was the third MINN_LAB installation and in response to the 2015 festival theme of Climate Rising, the team decided to address climate effects directly through the experience and spatialization of weather and its related data, and took a democratic approach to the project’s conception. It was not produced in the mold of any single team member’s previous work, but was instead driven by an approach that purposefully relinquishes design authority. By focusing on the development of a system and an attitude, rather than a specific esthetic character, the final outcome of the work was novel, surprising, responsive to its context, and continuously dynamic.

If weather data was a quantitative driver, and user interaction was a qualitative driver, then our distributed authorship could be described as a decentralized, or bottom-up driver. As designers and researchers, working in situations where we each typically enjoy exclusive authorship and decision-making privileges over our work, the idea that decisions within MINN_LAB would emerge from our collective voices was a challenge. To accomplish this, we have identified a set of ground-rules, outlined below, for working as a team. These rules have emerged organically, over time, but have become an unspoken (until now) set of guidelines to which we adhere.

First, ideas in MINN_LAB can come from anyone at any time. We work with student assistants, outside consultants, and a rotating roster of experts. If someone has an idea, they are free to express it. If it is a good idea, it will be incorporated. Second, we operate with trust and respect. Even when we disagree, we listen respectfully and wait for an opportunity to present a counter-argument. Third, we hold regularly scheduled meetings in which everyone presents prepared
drawings and sketches. Drawing and model making is an essential mode of communication (Nicolini, 2012). We draw in preparation for meetings and in meetings, and we find that drawing and modeling circumnavigates linguistic hurdles that emerge from our disparate disciplinary backgrounds. Fourth, the team is fluid and busy, and everyone cannot attend every meeting, so the group that attends a particular meeting is the group that makes important decisions. We do not backtrack or play catch-up, but rather move back and forth from working as a face-to-face to a distributed team (Warner, 2005). Fifth, every project has a leader or manager (Sonnenwald, 1996). This responsibility rotates, but it is important in such a distributed model of authorship that there is one person assigned to overseeing, scheduling, correspondence, and delegation of specific tasks. Lastly, we are driven by strong ideas; we do not move on with developing a project until we have come to a consensus around its central idea. This sometimes makes for slow progress, but good ideas, not speed, are our measure of success.

What is rewarding is that adherence to these rules results in work that no one could have predicted or produced had we authored the projects individually. The process of designing, while slow, messy, and sometimes frustrating, is ultimately rewarding. The work we produce is sophisticated and thoughtful on multiple levels because each of us brings varied priorities and expertise to the work. For example, the tightly choreographed management of the data visualization, with its precisely mapped projection strategy, would not have been present without the computer scientists on our team. The positioning of the piece in the landscape and its relationship to the water would not have been as carefully considered without the landscape architects on the team. The leveraging of everyday, throw-away materials to yield a cleverly crafted, inexpensive armature for the data projection would not have been successfully conceived without the architects on the team. In terms of a reflection or critique of this type of a distributed model, we admit that the MINN_LAB team has never overtly discussed the group’s methodology. Through collaborating on this paper, the team has reflected on its methods and outcomes. By its own estimation, the group could undergo more regular check-in’s on its established design processes and could more critically evaluate the extent to which these methods are working. Through a similar process by which we evaluate our design work, we could conduct a rigorous and critical analysis of our working process to determine where it is yielding positive results, and where it is not.

2.0 IMPLICATIONS
2.1 Architecture: Implications for the impact of data on architecture
The Internet of Things, an internetworking of physical devices, promises to bring the building industry data-driven intelligence to improve operation, but not necessarily user experience. Smart buildings, in their current state, allow for increased personalization, mobility, sustainability, efficiency, comfort, productivity, etc., through continual connection of local points to an exhaustive cloud. Development is led primarily by hardware and software development within computer science and engineering disciplines, focusing on controllers, gateways, and sensors that provide place-based nodes for inputs and outputs. However, as the number of interconnected components and systems grows, and intelligence is built into more architectural material, like lighting, surfaces, or even structure, there is exciting potential for data to take on a broader, more design-centric, role. And architects can lead this effort.

We explored this possibility with Weather Report. By starting with the individual pixel, a data point (in our case, a simple white balloon) that in its repetition produced a physical volume out of pure data, we were able explore the relationship between data, space, and perception. Data became physical and inhabitable. Our two walls of data straddled a pathway through which festival goers were encouraged to meander, thus inhabiting the space of the data. As such, the project asked the following broader architectural questions: how might data find its way into the surfaces and spaces of a built environment? How might data instrumentalize the Internet of Things in ways that extend beyond the hand-held digital displays and computer screens of our current time and into the material and spatial qualities of architecture itself?

For contemporary precedents of this we can look to a number of architectural projects that explore the potential of the analog building façade to spatialize the territory between the digital pixel, fenestration, light, volume, movement and animation. Solutions range from actual digital screens applied to facades, to more subtle, luminous surfaces incorporated into building skins that evolve and shift in color and intensity, to more spatial, three-dimensional expressions involving projection, volumetric lighting, or even sound. These examples hold the opportunity for open-source, user-generated data fields and other data streams to challenge the control architects typically enjoy over the more static versions of their work. With new bottom-up approaches to data and building appearance, the roles of architects, digital media designers and computer scientists will evolve. These traditionally stand-alone practitioners will collaborate in new ways as the territories of their disciplines continue to merge. The term "smart building" will take on new meaning, referring not just to utility and performance, but also to less measurable, more expressive and intangible qualities we desire in exceptional works of architecture.

2.2 Landscape Architecture: implications for the impact of data on landscape
Weather Report was strategically situated to draw in a larger set of forces within the site context. It was set on the bank of a side channel of the Mississippi within a pedestrian path, at a low point in the topography and infrastructure between a pedestrian bridge over the river and the base of a grassy hill leading up to the edge of a historic cultural
district within the downtown. The placement of the installation within this context catalyzed a normally inactive site through light, movement and exchange. The installation drew movement of thousands of people through the newly formed experiential channel, parallel to the Mississippi, capturing the dynamism and complexity of this storied river.

![Figure 10: Weather Report citing (Authors 2016)](image)

Weather Report represented an experiment in human interaction with landscape and weather. It deepened our understanding of environmental issues in relationship to people through offering an experience with an educational underlay. Some of the issues it foregrounded included the responsibility of landscapes to communicate and be experienced, the role of public space in the realm of experimentation, the capacity of user interface to confront issues of memory and time, and how landscape can produce new modalities of experience and communication. Weather Report reframes a temporal, indeterminate, and uncontrollable component of the landscape and weather into something both knowable and accessible. It deepens understanding an understanding of weather dynamics through an experience of temporality and flux, foregrounding larger questions around systems and data in landscape architecture.

### 2.3 Computer Science: implications for experiencing data through its physicalization

Data visualization, although an inherently interdisciplinary endeavor, has a strong academic home and tradition in computer science, where the first computer-mediated data visualizations grew out of the study of computer graphics. Research on data visualization is thriving and expanding, as evidenced by the IEEE VIS conference (ieeevis.org). Work in this community regularly makes use of virtual reality displays, multi-touch and 3D user interfaces, and other emerging forms of computing. Climate data is a frequent topic of exploration, with high-end supercomputer simulations and complex underlying scientific hypotheses driving the development of advanced interactive visualization and visual analytics tools and processes.

Weather Report is novel and exciting to this community for several reasons. First, the combination of human scale, public inhabited space, and outdoor venue for the display produce a radically different experience than what is possible via traditional and even recently emerging computer graphics displays. While many high-end data visualizations do utilize large (e.g., 30 foot) display walls, and virtual reality displays can enable viewers to experience data-driven environments at a human-scale, the ability to do this in a collaborative, public, outdoor setting is novel and exciting. It is a completely different take on scientific visualization. Second, Weather Report is an exciting example of data physicalization (http://dataphys.org), a topic that actually has a rather long history but has not been fully embraced. This is starting to change, at least within the visualization research community, with the widespread availability of 3D printers. The idea is that just as digital computer graphics has helped scientists and others to understand data, data-driven computation might also be used to explain data and/or move from data to insight but in a mode where the output of the computation is a physical, tangible object. To be sure, this is a concept that has been explored by artists for some time, but to do this with large, cutting-edge scientific datasets is an entirely different endeavor. To date, this has been explored almost exclusively at small scales (e.g., 3D printouts of medical data). By translating 60 years of weather data into a physical form that the public can walk through and touch, and by combining the physical representation into a hybrid system that also relies upon digital projection, Weather Report pushes the boundaries of this still-evolving concept of data physicalization.
CONCLUSION
As digital connectivity, robotics, and computation increasingly inform approaches to the design, fabrication, and construction of our built environment, our ability as designers to choreograph flows of information will similarly grow in importance. Just as automation has taken over the assembly of products, it will inevitably take over the assembly of our buildings. While architects have embraced this digitization of materials and assembly, we have barely begun to consider the digitization of space itself. In fact, it is even hard to visualize what the digitization of space, or data physicalization, might look like. With Weather Report, we endeavored to consider this provocative idea, and we call our approach spatio-data design. Far from a science fiction abstraction only accessible through movies like The Matrix, the idea that we might physically occupy and simultaneously affect our endless streams of collected data is now closer than ever to reality. Like many other disciplines, we as architects struggle to understand how to best capitalize on unlimited access to data. While the emergence of increasingly connected, or “smart,” buildings point to one strategy, this approach is narrowly utilitarian in nature. With Weather Report, we were interested in exploring the spatial qualities of data, in designing a system that might reveal the reflexive character of data. To do so, we focused on alternative approaches to design process. We purposefully yielded design agency over to the data, to the people who would occupy our work, and to a broad and diverse team of expert collaborators. In this way, the architecture emerged organically from the deftly and carefully crafted management of data flows, instead of from our preconceived attitudes about how we, as designers, thought the space should look and feel. This approach, rather than suggesting removal of control, for us, suggested a reallocation of control. Rather than crafting the physical appearance of our work, we crafted how its physical appearance emerged from the careful and thoughtful choreography of data.

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ABSTRACT: This paper explores the nature of knowledge through a history of knowledge production in society. It emphasizes the modes of knowledge including explicit and tacit and argues for knowledge management and knowledge transfer as strategies to both codify explicit knowledge and extract and transfer tacit knowledge. One method that has been identified to encourage tacit knowledge transfer is communities of practice (CoPs). Further, the paper argues for ways in which the university as an institution and network of institutions may serve as a CoP knowledge hub in specific regions to foster new modes of knowledge transfer beyond traditional scientific means. The paper concludes with a preliminary proposal for this type of CoP in the Built Environment Exchange (beX) as a model for international university–industry knowledge transfer in the construction sector.

KEYWORDS: epistemology, knowledge exchange, knowledge production, construction knowledge

INTRODUCTION
Construction in large measure, and multi-national global companies notwithstanding, is regionally specific – material, labor, and climate (Rhodes, 2015; McIntyre & Strischek, 2005). Although there is much explicit knowledge codified in codes, publications, and now video online, the majority of knowledge regarding construction is tacit or implicit, embedded within people and organizations (Chimay et al, 2007; Bigiardi, 2014). Therefore, the best practices in construction business, design & manufacture, and skills, to name a few, and its associated knowledge are held by individuals within universities, companies, governments and associations in discrete regions. This is perhaps one of the reasons why productivity continues to decline and presents a barrier to the advancement and innovation in the construction sector (CII, 1996; Latham, 1994; DTI, 1998; Barker, 2004; MMC Cross Industry Group, 2006; HM Government, 2025).

This study of knowledge in construction has been conducted through a robust literature review in order to: 1) identify the knowledge barriers in construction; and 2) create pathways to overcome these knowledge barriers. This literature review includes an epistemological analysis of construction and emphasizes types of knowledge including explicit and tacit. It argues for knowledge management and knowledge exchange through communities of practice (CoP) as strategies to both codify explicit knowledge and extract and transfer tacit knowledge in the construction sector.

1.0 KNOWLEDGE EXCHANGE
There are two primary types of knowledge. Explicit knowledge is representative, able to be codified and communicated. It is data, records, and documents. In academia, explicit knowledge may be journal publications, databases, books, websites and videos. Conversely, tacit knowledge is difficult to transfer by means of writing or speaking. It is embedded in people, organizations, societies and cultures (Lam, 2000). It is based on experience, thinking, competence and commitment (Polanyi, 1966). In academia, tacit knowledge is found in conference discussions, workshops, internships, and exchanges. Explicit knowledge, knowing that, what and why, constitutes an estimated 10% of our knowledge repository as humans, while tacit knowledge, knowing who and how, makes up 90% of our total knowledge base (Fig. 1) (Wah, 1999; Bonner, 2000; Lee, 2000).

Knowledge exchange is sometimes referred to as knowledge management, the process of creating, sharing, using, and managing the knowledge and information of an organization (Girard & Girard, 2015). Tacit knowledge is key to overall quality of knowledge exchange (Quinn et al., 1996; Wah, 1999; Goffee and Jones, 2000). Effective transfer of tacit knowledge generally requires extensive personal contact, regular interaction, and trust (Goffin & Koners, 2011). Researchers indicate that tacit knowledge is revealed through practice in a particular context and transmitted through social networks (Schmidt & Hunter, 1993). Therefore, tacit knowledge is exchanged through a network of individuals, organizations in a community of practice (Goffin & Koners, 2011). It relies on experience and without it, tacit knowledge is not able to be transferred effectively (Lam, 2000).
Explicit and tacit knowledge are often presented as divergent types. This is not the case however. Explicit and tacit are not separate modes of knowledge but in fact a continuum (Nonaka & von Krogh, 2009). Therefore, it is necessary to explore the concept of knowledge conversion, sometimes referred to as knowledge transfer, whereby knowledge is exchanged from one type to another.

Explicit knowledge may be transferred to another explicit form. This transfer is called combination. An example is academic archival research whereby texts are compared, synthesized and new explicit knowledge is developed, not unlike the function of this paper. Explicit knowledge to tacit conversion is called internalization. Knowledge is a human function; therefore, people internalize the knowledge making it part of their subconscious activity. An example of this transfer might include reading instructions to assemble furniture and then internalizing the operations after repeated activity. Tacit to explicit transfer is termed externalization, making that which is not easily explained or documented into a written or spoken form that is easy to communicate and disseminate. This transfer is the opposite of internalization. A worker for instance may have knowledge of how to assemble furniture, and then is asked to codify this knowledge in a training manual. Finally, tacit to tacit forms of transfer is called socialization. This transfer tends to be informal and often seen in apprenticeships. It is experienced in the very act of doing (Table 1).

Table 1. Knowledge conversion scenarios and terms

<table>
<thead>
<tr>
<th>Conversion Scenarios</th>
<th>Terms</th>
<th>(Nonaka et al 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit → Explicit</td>
<td>Combination</td>
<td></td>
</tr>
<tr>
<td>Explicit → Tacit</td>
<td>Internalization</td>
<td></td>
</tr>
<tr>
<td>Tacit → Explicit</td>
<td>Externalization</td>
<td></td>
</tr>
<tr>
<td>Tacit → Tacit</td>
<td>Socialization</td>
<td></td>
</tr>
</tbody>
</table>

2.0 KNOWLEDGE IN CONSTRUCTION
Knowledge management is a growing field not just because it explains how knowledge is produced and transferred, but also because it performs. A growing number of organizations are now implementing knowledge management in their planning because the results include business process efficiencies, better organization, and higher motivation.
among personnel and stakeholders (Nonaka & Takeuchi, 1995; Rezgui et al, 2010). The existing literature on knowledge exchange in construction is based on knowledge within specific architecture, engineering and construction firms, or project knowledge management and exchange between project stakeholders. It tends to focus on IT solutions for knowledge management whereby firms may codify explicit knowledge and exchange it across the firm and multiple office locations (Alvai & Leidner, 2001; Huysman & Wulf, 2006).

There are few references that cite the nature of construction knowledge more generally and theoretically. Of these sources, Patrirage et al (2007) claim that construction is tacit knowledge intensive, relying on experiential legacy knowledge embedded in people and organizations. In their research, the authors reveal that in construction valuable knowledge is wasted unless organizations make better use of tacit knowledge. Similarly, Woo et al (2004) explain that although construction firms are proficient at collecting and storing explicit information, they are poor at knowledge retrieval and exchange. The authors state that construction professionals find it difficult to reuse core experts’ knowledge for highly knowledge-intensive AEC activities. Therefore, there is an argument for a method of disseminating tacit knowledge from experts’ subconscious in the construction industry.

Further, Javernick-Will and Harmann (2011) point out that knowledge exchange in construction is a challenge because it is context specific. The authors explain that each region and country has unique explicit building code regulations, material and building system preferences, and labor skills availability. The authors utilize the theory of learning organizations – a concept coined by Garvin (1993) that refers to an organization whose personnel continuously increase in capability personally and collectively – and apply it to the field of construction. The basis for learning organizations includes proactive plans to engage people to gain new knowledge and exchange that knowledge through collaborative arrangements and networks (Kululanga et al, 1999).

3.0 KNOWLEDGE PRODUCTION
3.1 Mode 2
Gibbons et al (1994) in their seminal work The New Production of Knowledge, take the epistemological theory of two types of knowledge, explicit and tacit, further in proposing a new model for knowledge creation. The authors explain that historically traditional knowledge creation, called Mode 1, is the Newtonian model of inquiry that follows sound principles of scientific method. In this mode, the cognitive and social norms determine what counts as a significant problem and who is allowed to practice the solving of such problems (i.e. universities). Mode 1 is historically created and developed by and for the sciences. The method has now been adopted by the arts and humanities, architecture and engineering, law, business and seemingly every academic unit on campus by virtue of university massification in society. The authors point out at that these disciplines perhaps were never intended to be scientific in principle.

By contrast, Mode 2 knowledge production is created in the context of application. While Mode 1 is disciplinary and homogeneous, Mode 2 is transdisciplinary and heterogeneous. Organizationally, Mode 1 is hierarchical and self-preserving, while Mode 2 is flexible and transient. Mode 1 employs peer review based on standards of practice. On the other hand, Mode 2 is socially accountable and reflexive. It employs a temporary set of actors, collaborating on a problem defined in a specific context (Gibbons et al, 1994:1-16). Mode 1 excels in explicit knowledge exchange while Mode 2 thrives in tacit knowledge arenas (Gibbons et al, 1994:17,19,24-26,168).

Mode 2 is diffusing, characterized by closer interaction of scientific, technological and industrial modes of knowledge production (Gibbons et al, 1994:2-5). Mode 2 weakens the disciplinary and institutional boundaries through transient clusters of experts. It encourages market differentiation and international competition that is a result of Post WWII diffusion of mass production technologies based on economies of scale. Specific knowledge bases are localized and contingent on regional industry knowledge (Gibbons et al, 1994:68) (Table 2).

Table 2. Dimensions of knowledge production and attributes of knowledge production modes

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>MODE 1 ATTRIBUTES</th>
<th>MODE 2 ATTRIBUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge focus</td>
<td>Produced considering interest of</td>
<td>Produced considering the context of</td>
</tr>
<tr>
<td></td>
<td>academia</td>
<td>application</td>
</tr>
<tr>
<td>Mode of knowledge production</td>
<td>Expert-centred</td>
<td>Network of diverse stakeholders</td>
</tr>
<tr>
<td>Characteristics</td>
<td>Disciplinary and hierarchical</td>
<td>Transdisciplinary and horizontal</td>
</tr>
<tr>
<td>Relevance</td>
<td>Relevant to academics</td>
<td>Relevant to society</td>
</tr>
</tbody>
</table>
Dissemination

Through indexed journals

Diverse channels reaching a wider audience

Quality assurance

Peer reviewed publication

Quality review process and research uptake/impact

3.2 Knowledge Hub

Youtie and Shapira (2008) present an argument for the evolution and transformation of the role of universities to advance technological innovation and economic development. The authors document the transition of the university as a knowledge factory into a knowledge hub. Prior to the 19th century, the university was primarily a storehouse of knowledge. These medieval institutions, including Oxford and Cambridge, is where scholars housed in colleges lived and learned cloistered from the general craft producing public. Universities expanded beyond Europe during the late 19th and early 20th century. Shortly thereafter, WWII initiated government and industry funded research at universities expanding global R&D efforts. The university in this period through the end of the 20th century was a supplier of inputs and outputs, a technology developer, and a knowledge factory for research, training and commercialization.

In the later part of the 20th century until today Youtie and Shapira argue that the university is seeing another identity change. It continues to serve as a knowledge storehouse and a supplier to the economy. However, the university is also now a knowledge hub. In this new role, it seeks to animate indigenous development, new capabilities, and innovation, especially within its region (Shapira and Youtie, 2004; Newlands 2003) (Table 3). In this function, the university spans between industry, government and society. It is integrated in an intelligent region and promotes indigenous development and new capabilities. Youtie and Shapira (2008:1190) conjecture that “in an increasingly knowledge based environment, high-performing institutions are those which have capability not only to develop, acquire and use codified knowledge, but also to effectively advance, distribute, and recombine tacit knowledge”.

Table 3. Transformation of the university role in society.

<table>
<thead>
<tr>
<th>MODE</th>
<th>TIMEFRAME</th>
<th>CONTEXT</th>
<th>ROLE</th>
<th>PERSONA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>Prior to 19th C.</td>
<td>Craft production</td>
<td>Storehouse of existing historic knowledge</td>
<td>Elitist above society</td>
</tr>
<tr>
<td>Supplier</td>
<td>19th C – Late 20th C.</td>
<td>Industrial mass production</td>
<td>Knowledge factory for research, training and commercialization</td>
<td>Supplier of inputs and outputs, a technology developer</td>
</tr>
<tr>
<td>Hub</td>
<td>Late 20th C - present</td>
<td>Post-industrial knowledge economy</td>
<td>Integrated institution in intelligent region, promotes indigenous development and new capabilities</td>
<td>Spanning entity between industry, government and society</td>
</tr>
</tbody>
</table>

4.0 COMMUNITY OF PRACTICE

A community of practice (CoP) is group participation in an activity for which the participants share understandings that what they are doing means something in their lives and those for which they serve (Lave & Wenger, 1991:98). It is a set of relations among persons, activity, and world over time and in relations with other topically overlapping CoP groups. The critical element in CoP theory outlined by Lane and Wenger is that it is an intrinsic condition for the existence of knowledge (1991:98).

Rezgui & Miles (2011) outline a process of leveraging social capital in knowledge exchange via CoPs in the construction industry. In this way, communities are developing across organizational and project specific lines that share a common concern or have similar problems. Knowledge is shared through physical or virtual means synchronous and asynchronous on a continual basis (Rezgui & Miles, 2011:16; Wegner et al, 2002). The authors illustrate how these types of communities foster innovation in a particular sector or interest area (i.e. sustainability, building performance, lean construction, offsite construction, etc.) This has given way to additional organizations whose role is to provide a community of practice such as trade associations or advocacy institutes on behalf of these interests (i.e. National Institute of Building Sciences, American Institute of Architects, Modular Building Institute, etc.).

Li et al (2009) explain that CoPs require that the group exist for a duration of time amongst a changing participant
pool in order to develop its own culture and communication methods. The community learns as individuals observe and model one another. Bandura (1977) states that observing behavior allows for a more efficient way of acquiring tacit complex knowledge by way of skills than through personal trial and error. A learning community therefore must develop a high level of trust among its participants in order to be functional (Kling & Coutright, 2004). They can be located discretely or dispersed, but are linked by common interests and goals. Virtual learning communities are growing each year and offer many advantages to traditional communities. Learning communities must be monitored for effectiveness because they are susceptible to favoring sustaining relationships over learning (Wenger et al, 2002). In this way, there is a real risk of group-think (Turner & Pratkanis, 1998), and/or becoming dormant and dysfunctional (Leconi, 2002).

CoPs borrow from education, sociology and social theory with a focus on socialization and learning of the individual (Li et al, 2009). Wegner described CoPs as a group contained by three dimensions: mutual engagement, joint enterprise, and a shared repertoire. Mutual engagement represents the interaction between individuals; joint enterprise is the process in which people are engaged; and shared repertoire is the common resources members use to accomplish their work.

Wenger suggests that CoPs not only emerge spontaneously, but can also be intentionally fostered, structured, and created to cultivate the qualities of a CoP and thereby enhance their competitiveness and effectiveness (Wenger, 2002; Saint-Onge & Wallace, 2003). In this more mature approach to CoPs, the authors revised the 3 dimensions of mutual engagement, joint enterprise, and a shared repertoire and named them domain, community and practice (Wenger et al, 2002; Wenger, 2000). The domain is a common ground of minimal competence that differentiates members from non-members. Community is the social structure that facilitates learning through tacit interactions and relationships. And practice refers to shared repertories of resources that include explicit documentation (Li et al, 2009).

Wegner and colleagues claim that CoPs can optimize the creation and dissemination of knowledge when these three dimensions are present (Table 4). Li et al suggest two additional dimensions in order to realize a mature CoP. The first is a leader/champion, a person well respected in the organization who is responsible for spreading the word, recruiting, and providing resources for the group. The second is a facilitator that is responsible for the day-to-day activities of the CoP. It is suggested that this person understand the overall mission of the organization and is well connected with members (Li et al, 2009). In CoP studies, the facilitator role has been deemed the critical link, the absence of which or if the facilitator fatigues, most often leads to CoP failures (Lathelean & May, 2002; Gabby et al, 2003; Ardičišvi, 2002; Pereles et al, 2002). Sometimes the leader is the facilitator, while in other cases they are separate roles (Pereles et al, 2002; Chua, 2006). This decision is based on a number of factors including the size of the group, the geographical location of the members, the topic, and overarching goals of the CoP.

Table 4. Community of practice domains. (Wenger et al, 2002)

<table>
<thead>
<tr>
<th>COP Dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>Common ground of minimal competence differentiates members from non-members</td>
</tr>
<tr>
<td>Community</td>
<td>Social structure that facilitates learning through tacit interactions and relationships</td>
</tr>
<tr>
<td>Practice</td>
<td>Shared repertories of resources that include explicit documentation</td>
</tr>
<tr>
<td>Leader/Champion</td>
<td>Person or group that will advocate for the community and champion is vitality</td>
</tr>
<tr>
<td>Facilitator</td>
<td>Individual that facilitates the community interaction and structures the knowledge exchange</td>
</tr>
</tbody>
</table>

5.0 BUILT ENVIRONMENT EXCHANGE

The authors of this paper have created an international CoP focused on the topic of offsite construction called the Built Environment Exchange (beX). This progresses the concept of the university as a knowledge hub to the university as a CoP, working at the intersection of industry, government, and society. Instead of operating at a regional scale however, the beX CoP works at a global scale, exchanging knowledge across international contexts. This integrated institution is an intelligent global network that promotes international knowledge exchange in off-site construction. While many disciplines are represented in off-site construction (i.e. architecture, engineering, manufacturing, development, construction, etc.) the topic is unique and requires a particular knowledge base and knowledge growth to ensure the
The effective implementation of off-site and realize its potential is meeting the demand of the construction market broadly. The proposed beX is being tested for effectiveness and refined so that it is generalizable to other topics in construction and potentially provides a model that is replicable by disciplines outside of construction. The beX is a co-evolved, co-developed international research exchange program led by university champions (faculty) at the following 6 institutions that will initiate the pilot test of the start-up CoP: Edinburgh Napier University – UK, University of Utah – U.S., Lulea University – Sweden, University of Alberta – Canada, Hong Kong Polytechnic University, China, and University of Sydney – Australia. The beX is a partnership of researcher and students at the engaged universities and industry personnel to develop future skills and talent to modernize the construction sector and increase productivity. The aim is to create opportunities for graduates, employees and construction companies to design and collaborate on innovative projects, supervised by research leaders, with access to international partnerships and entrepreneurial training. The beX provides a pipeline of future talent for industry and academic partners (Table 5).

Table 5. Goals of the Built Environment Exchange (beX)

<table>
<thead>
<tr>
<th>GOAL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-site Construction Business Development</td>
<td>To develop the future technical and business leaders who will modernize the</td>
</tr>
<tr>
<td></td>
<td>built environment sector and spearhead the drive for sustainability and</td>
</tr>
<tr>
<td></td>
<td>efficiency, enabling the sector to deliver the sustainable communities of</td>
</tr>
<tr>
<td></td>
<td>tomorrow.</td>
</tr>
<tr>
<td>Workforce Development</td>
<td>To provide companies and industry lead organisations with opportunities</td>
</tr>
<tr>
<td></td>
<td>to engage talented graduates on innovation and development projects.</td>
</tr>
<tr>
<td>Student Development</td>
<td>To provide opportunities for graduates and talent in the built environment</td>
</tr>
<tr>
<td></td>
<td>to develop higher-level technical and business/entrepreneurship skills, and</td>
</tr>
<tr>
<td></td>
<td>to gain international experience.</td>
</tr>
<tr>
<td>Faculty Development</td>
<td>To develop academic practitioners who will integrate with industry to direct</td>
</tr>
<tr>
<td></td>
<td>future research and deliver long-term skills development.</td>
</tr>
<tr>
<td>Internationalization of Off-site Construction</td>
<td>To internationalize research collaborations and increase global industry</td>
</tr>
<tr>
<td></td>
<td>impact.</td>
</tr>
</tbody>
</table>

The beX provides unique opportunities for companies and graduates to grow and develop together through tacit exchange. The transfer of new knowledge and skills is enabled by:

1. **Sponsored Project**: sponsored by construction industry companies, student scholars are matched with companies to research and commercial activities via the host university partner, to work on paid projects delivering sector-defined innovation requirements while developing their enterprise skills. Students can work at the university, embedded within the company or from another location altogether, supported by faculty researchers and access to facilities at the partnering university institution.

2. **Entrepreneurship Training**: student scholars engage in a workshop series provided by the entrepreneurship training at respective university partnering institutions to hone business and enterprise skills oriented at the construction sector and the industry partner through the employability project. Entrepreneurship sessions include the industry partner(s) and faculty as appropriate to envision new products and processes aimed to transform and propel the construction sector into the future.

3. **International Exchange**: an internship available to penultimate year undergrad and graduate students from diverse disciplines. Scholars engage in an 8-10 week industry led research based project, supervised by academia and mentored by industry, with the opportunity for an international placement facilitated by the partnering universities.
CONCLUSION
Knowledge in the built environment is primarily tacit or embedded within individuals and organizations. Tacit knowledge represents up to 90% of the total knowledge repository in society and the disciplines of construction. As such it is imperative that the field of construction find ways to convert tacit knowledge to explicit knowledge through codification and dissemination, and transfer tacit to tacit knowledge through individual and organizational sharing. This research suggests that tacit knowledge production and management can best be fostered by means of communities of practice at the nexus of universities, government, industry and society. Further, value of the university serving as a knowledge hub and facilitator of a community of practice has been found in other disciplinary field outside of architecture, engineering and construction. We suggest that the built environment academic units may lead in a new mode of knowledge production that builds upon scientific method toward applied learning. Whereas this is not the traditional role of academia, in this way the university serves as a facilitator of emerging modes of learning, knowledge production and knowledge exchange. A specific international knowledge exchange program has been developed by the authors, called the built environment exchange. The model is based on this literature review and theoretical construct. Student researchers exchange internationally during the summer weeks, sponsored by industry companies, to engage in applied scholarship, then return to share this knowledge with their home context. BeX, concerned with off-site construction as a topic, is being piloted in the summer of 2017 and the results will be published at a later date for replicability by other topical CoPs in the built environment as well as disciplines outside of the construction sector.

ACKNOWLEDGEMENTS
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REFERENCES


ABSTRACT: Within the discourse of sustainability, two worlds collide. When translated cross culturally, sustainability does not hold the same meaning within different epistemologies, as demonstrated by anthropologist, Peter Rudiak-Gould in the Marshall Islands. Additionally, the use of terminology such as ‘sustainable development’, has a marginalizing effect – us versus them. Even within the context of urban renewal projects in the United States, development holds connotations of ‘minoritization’ (Laguerre), gentrification, and white-washing. Furthermore, the use of sustainability does not capture the complexity that is inherent in creating sustainable development. Ulrich Beck implements the term ‘reflexive modernity’ in his description of the ‘risk society’; perhaps if development is thought in terms of the inherent risks associated with ‘progress,’ then we can achieve more regenerative processes. What does sustainability actually mean in practice? Through a literature review on the implications of sustainable development in alternate epistemologies this paper builds a critique of the current practice. The view of sustainable development as a neocolonial agenda is carried forward into the case study of a series of sustainable development projects on Namdrik atoll, Republic of the Marshall Islands, which earned the ‘Equator Prize’ in 2012. The rising issue of human resettlement as the next embodiment of sustainable development is brought to light and the implication for the future resettlement of low lying atoll nations, such as the Marshall Islands, is discussed. Resilience is brought into the discussion in order to propose a way toward mitigating neocolonial agendas in development programs and leading toward the sustained role of social justice in policies and practice.

KEYWORDS: Sustainability, resilience, development, resettlement, displacement

INTRODUCTION

The meanings, practices and policies of sustainable development continue to be informed by colonial thought, resulting in disempowerment of a majority of the world’s populations, especially rural populations in the Third World (Banerjee 2003, 144).

The term ‘sustainable development’ has an inherent bias; the terminology is rooted in a western epistemology and could be construed to have a hidden agenda. There is an unconsciousness amongst those educated within a western epistemology that sustainable development implies progress. And to an extent, this carries over to all influenced by the western, scientific rationale of progress. However, this bias is based on a world view of the dominant, global, largely westernized culture. When translated cross culturally, sustainability does not hold the same meaning within different epistemologies, as demonstrated by Peter Rudiak-Gould (2013) in the Marshall Islands’. Additionally, the use of terminology such as ‘sustainable development’, or just ‘development’, has a marginalizing effect – us versus them. It is important to understand the ramifications of these western ideologies within the context of alternate epistemologies across the globe, or as Anaya Roy terms ‘subaltern realities’ (Roy and Crane 2015). Even within the context of urban renewal projects in the United States, development holds connotations of ‘minoritization’ (Laguerre 1999), gentrification, and white-washing. Furthermore, the use of sustainability does not capture the complexity that is inherent in creating sustainable development

An overarching technological approach has consumed the discourse of sustainability in architecture as demonstrated by Guy and Farmer (2001). If we take into consideration Ulrich Beck’s description of the “Risk Society”, the technological solutions produced by scientists leave the power in the hands of a few. Arguably, power and the reproduction of that power have led to the current crisis of global climate change. As Ulrich Beck (1992) demonstrates, technological advances have inherent risks that require technological knowledge to interpret – thus perpetuating the cycle of the risk society. Through interpreting Bourdieu’s theory of practice together with Beck’s theory of the risk society, it is apparent that the discourse of sustainability is promoted by the very power structures that have led to global climate change. The very definition of sustainability, as promulgated through the Brundtland report, demonstrates the extent of these power relations, and the reliance on a largely western, scientific approach. The World Commission on Environment and Development was commissioned by the United Nations to seek solutions that would reduce the negative impacts of industrialization in developing nations. The commission largely consisted of Western European delegates, who were
still rooted in an epistemology that saw the world as a binary; the developed and the undeveloped. Thus the solution to unsustainable practices became reliant on technocratic solutions, such as green technology. The post development discourse provides an extensive critique of issues inherent to sustainable development (refer to James Ferguson and Gupta (1997) and Arturo Escobar (2008)). In addition, Jacka (2015) argues that development fails in its bureaucratic processes; it simplifies complex local practices and ignores the contribution of local knowledge. Development practices concerned with rendering technical problems, separate the scientific knowledge from the indigenous or local knowledge. Within the overarching field of global climate change, the appropriation of sustainable development should be seen as a contentious matter if we are to approach the discourse through a critical lens. It is especially important to utilize and develop this critical lens in undertaking urban and rural development projects and resettlement programs that are in response to the outcomes of global climate change.

Sustainability needs to be viewed within the parameters of a complex system, taking into consideration latent potentials and their impacts on society. In considering resilience, the architectural discourse should be more inclusive of non-technological viewpoints, such as indigenous knowledge. Sustainability is in fact a cultural and a societal issue in need of approaches from both science and society. Perhaps, utilizing the term ‘resilience’ rather than ‘sustainability’ allows for a more productive method for continuing the development discourse.

1.0 A CASE STUDY OF SUSTAINABLE DEVELOPMENT ON NAMDRIK ATOLL

[Disciplinary power] is a mechanism of power that permits time and labor, rather than wealth and commodities, to be extracted from bodies...This new type of power, which can no longer be formulated in terms of sovereignty is one of the great inventions of bourgeois society, a fundamental instrument in the constitution of industrial capitalism and the type of society that is its accompaniment (Foucault 1980, 105).

In 2012, Namdrik, a small outer atoll of the Republic of the Marshall Islands with a population of approximately 600, received the UNDP Equator Prize, “awarded to outstanding community and indigenous initiatives that are advancing nature-based solutions for local sustainable development” (Perez 2017). Namdrik Senator Mattlan Zackhras, was instrumental in implementing sustainable development goals on his atoll. This objective is especially important since the atoll is facing the detrimental implications of rising sea levels and decreased habitability due to climate change. The goals were part of a larger national strategy aimed at fighting climate change and working on adaptive strategies for building community resilience. Through these sustainable development goals, largely designed by researchers from the United States, Australia, and New Zealand, steps had been taken to: establish gardens for diversification in agricultural production, including conservation of endemic producing plants; the Asian Development Bank provided support for an atoll-wide coconut replantation project to replace senile trees; and large portions of reef and land were designated as protected marine environments under Ramsar ("Mangrove Rehabilitation and Replanting Project for Namdrik and Jaluit Atolls Ramsar Sites, Marshall Islands | Ramsar” 2017). As part of the economic development goals in the larger sustainable development agenda for Namdrik, eighty-six acres of the lagoon were designated for the Pearl Oyster farm as part of the marine protected area and a lumber milling project was to be implemented as part of the coconut replanting project and broader sustainable forestry goals. Together these projects would provide more capacity for cash economies in the harvesting of black pearls, coconut lumber, and the production of copra and coconut oil.

1.1. Methodology
As part of a multi-sited case study of the Marshall Islands, I worked on Namdrik analyzing both the socio-spatial patterns of the community as well as the implications of sustainable land-use development practices on the atoll. In addition, I examined closely the desire for sustainable building practices. The community had recognized the need for more regulation on site selection along with the need for alternative building techniques that reduced the impact of construction on the environment. I spent four weeks on Namdrik, living with community members and engaging with daily life on the atoll, closely studying eleven family compounds using self-selected sampling. The data included site surveys of forty-two buildings and over fifty acres of land, eleven interviews with the heads of each of the eleven households, interviews with the mayor and senator, and participant observation. The interviews with households concerned climate change adaptation along with questions aimed at understanding life on the land and supporting socio-spatial patterns. Interviews with the mayor and senator covered these topics with the addition of questions concerning the sustainable development goals of Namdrik.

Through the participant observation of the study, I became very familiar with the pearl oyster project, helping with the pearl farmers often, and also became familiar with the other development projects through the eyes of several different community members. It became clear that many of the sustainability goals were not being met and it was not clear as to why (refer to Table 1). Some community members agreed that it was due to the lack of maintenance funds, while others alluded to the disinterest of the community as time went by. I observed that projects were not maintained because they did not fit within the daily pattern of life on Namdrik and were outside of socio-cultural norms. For example, the
A gardening project which took place behind the school was largely abandoned, and a pig pen that was constructed using the same funding was primarily used by the landowner rather than the larger community. When asked about it, several community members said it was used for school children to learn about horticulture, but as funding waned so did interest.

Table 1: Sustainable Development Projects on Namdrik

<table>
<thead>
<tr>
<th>Project</th>
<th>Support</th>
<th>Undecided</th>
<th>Negative Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Farm</td>
<td>Most supported the Pearl Farm</td>
<td></td>
<td>The viability of the project was questioned by community members and its implementers.</td>
</tr>
<tr>
<td>Coconut Felling and Planting</td>
<td>Copra is a significant portion of the cash economy. The project would benefit everyone.</td>
<td>Few understood the scope of the project.</td>
<td>Expert support had waned and little progress has been made.</td>
</tr>
<tr>
<td>Coconut lumber milling</td>
<td>When asked, community members were interested in the economic benefits as they saw the senile trees a waste otherwise.</td>
<td>Few knew of this project.</td>
<td>Lack of support for this project leaves the community feeling that such projects fall through.</td>
</tr>
<tr>
<td>Coconut Oil</td>
<td>Most supported.</td>
<td></td>
<td>The benefits from the oil extraction were not equal.</td>
</tr>
<tr>
<td>Gardening program</td>
<td></td>
<td>To most, the project was unsupported and undervalued.</td>
<td></td>
</tr>
<tr>
<td>Environmentally sensitive building siting</td>
<td>Some saw the benefits of re-siting housing away from the shoreline, but were more concerned with norms.</td>
<td></td>
<td>Without proper consensus between landowners, who define where housing can be built, and federal regulators it seems that proper land use zoning will be ineffectual.</td>
</tr>
<tr>
<td>Protection of Mangrove Forests</td>
<td>Many understand why it might be beneficial to protect the mangrove forest in order to protect shoreline erosion.</td>
<td></td>
<td>Most everyone see the designated protected zones as inhibiting cultural norms and believe these rules are not followed.</td>
</tr>
</tbody>
</table>

1.2 Analysis

This analysis shall focus on the pearl farm project, the coconut replanting program, and the designation of the mangrove forest as a natural reserve. As economic development projects, the pearl farm and coconut replanting projects are demonstrable of the commodification of local resources. The constant questioning of the pearl farm’s viability is representative of clashing epistemologies. The project had relied on the management from a British environmental scientist who had some managerial experience, but rather than building local capacity for the project to be fully operated by individuals in the community, the project entered a period of uncertainty when this agent left. Fortunately one of the head ‘farmers’ stepped up when offered training to become the new project manager.

The coconut replanting program and the designation of the mangrove forest as a natural reserve had interesting implications for the use of local resources in construction, handicrafts and other commodities. Based on interviews, it was clear that the preservation of the mangrove forests had an overall negative impact on the repair schedules of local housing and cookhouses because locals no longer had the freedom to select mangrove branches for repairs or construction. One individual expressed that even though the rules were not necessarily followed, it was irksome that they no longer had the freedom to do as they had done for generations. In conjunction with analysis from other interviews, it was clear that there was more of a burden on individual families to apply for the ‘Grants and Aid’ program in order to import lumber and hardware from the capital, Majuro, in order to carry out home repairs. This demonstrates
the devaluation and replacement of local knowledge by western knowledge. It was the coconut replanting project and removal of senile trees that provided promise for filling in the need for locally sourced wood products. However, with a lack of local capacity to run the milling machinery and a lack of training, the overall program has been at a standstill with the exception of attempting to season coconut lumber in saltwater. The design of these two programs could have formed a synergy that reduced the burden on locals, but arguably the western agenda took priority. In essence the individual deeming the natural preserve irksome is dependent on worldwide trends in resource consumption, trade policies of the World Trade Organization and funding interests of the Asian Development Bank and International Monetary Fund (Giddens 1990).

Land based resource management and sustainable development objectives demonstrated a lack of maintenance of early objectives, and a general burden was placed upon the community as outside funding slowed. As Deleuze and Guattari point out, there is a process at hand of deterritorializing and reterritorializing the flows of exchange (1987). In the case of the people of Namdrik, their local resources and local knowledge for maintenance of their resource base has been deterritorialized by UNDP development goals and reterritorialized for the benefit of global stakeholders.

Geertz (2000) demonstrates that a community forms local knowledge that is specific to their subsistence strategies, helping members to successfully attain viable livelihoods. The social structures and social practice adapt to these circumstances, sometimes subversively. The community on Namdrik carries on their everyday business based on their cultural context. Their local knowledge, which is ever evolving across time and space, is both in opposition to the imposition of development projects and part of it, “as a reflexive understanding of knowledge construction recognizes that it is always grounded in local, and western knowledge forms (Banerjee and Linstead 2001, 690). To a degree the local knowledge of the community is disempowered by the acculturation of their way of life through the globalizing power of western knowledge. It is difficult to resist something that may bring notoriety and progress and with these symbolic goods, monetary gain. It begs to ask, “are participatory processes being used to leverage certain agendas – implementing indoctrination?” Dangers lie within the mode of development to educate and instruct, as ulterior motivations can easily be hidden within our western aptitude for charity, perhaps a reason why Habermas (1991) defined authentic dialogue.

Working across multiple contexts, with alternate epistemologies, it is appropriate that sustainable development goals take into consideration the implications of western motives on non-western communities. Through operationalizing Bourdieu's theory of practice (1990) in dismantling a development project, it is possible to uncover ulterior motives, while analyzing contextual changes and syncretic systems developing in a community. Throsby (2014) utilizes Bourdieu's theory of cultural capital. By not sustaining cultural values that provide people with a sense of identity or invest in the enhancement of both tangible and intangible cultural capital, cultural systems may break down and lead to loss of welfare and economic output (Throsby, 2014). Cultural sustainability necessitates the long-term maintenance of cultural resources such that intergenerational and intra-generational equity are appropriately served.

The Reimaanlok Plan, the national framework for conservation, holds promise as a transformative approach to sustainable development in the Marshall Islands (Reimaanlok National Planning Team 2008). Developed as a conservation area planning framework, Reimaanlok puts the control in the hands of local communities to select and manage conservation areas. It has expanded beyond the constraints of conservation planning to include other development goals within its framework, and acts as a facilitator in building community capacity.

2.0. DISCUSSION: HUMAN RESETTLEMENT AND THE NEXT FRONTIER OF DEVELOPMENT'S AGENDA

Embedded within the cultural patterns of a community are two response mechanisms: adaptive strategies and coping mechanisms. Berkes and Jolly (2001) contribute adaptive strategies to mechanisms related to core cultural values of a group that are slow to change and contribute coping mechanisms to the individual/household and/or small spatial scope. Since these mechanisms are culturally embedded, it would be logical that a sustainable approach must invest in whatever possible models contribute to the mitigation of any possible vulnerabilities to cultural lifeways – such as ensuring that bottom-up processes are not inhibited. In theory processes that build resilience provide for sustainability as long as the system maintains the ability to adjust, reorganize, and rebound. Perhaps through leveraging cultural capital, development can work from the bottom-up in delivering agency to the marginalized society and overcoming the powers-to-be.

[C]ulture is a dynamic, interactive network of contingencies and possibilities...culture offers innumerable opportunities for variation, creativity, dialectical self-evaluation, and alteration (Wesson 2013, 101).

In considering cultural resilience as an approach to sustainability, change is inherent as an adaptive strategy to disturbance regimes; therefore, culture change does not necessarily mean the loss of culture, but “a creative space where new forms of cultural understanding (and practice) are developed” (Wesson 2013, 108). Based on Wesson's argument, investing in efforts to maintain cultural patterns to reduce the stresses on the health, well-being, and
security of the displaced populations will not sustain the pre-displacement culture, but will provide a mechanism for mitigating further vulnerability to greater stochastic events in the post-resettlement system. Cultural sustainability, therefore, does not maintain culture in the sense of static motion, but rather provides mechanisms that will most likely alleviate the shock and allow elements of the culture to persist – dependent on their desires in the evolution of their cultural identity. Understanding cultural patterns as elements that help support the continuity and enhancement of cultural capital, it is clear that ensuring the continuity is a necessity to create resilience and sustainable resettlement schemes.

![Conceptual diagram of cultural resilience](image.png)

**Figure 1:** Conceptual diagram of cultural resilience.

A common problem with resettlement programs is the tendency to dismantle the process into digestible components, disregarding the complexity of the system that these mechanisms operate within. Often operating on an outdated mode that utilizes principles of scientific management, governments and multi-national aid organization tend to dismantle resettlement programs, focusing primarily on the one issue, such as the economic problem and disregarding the inherent place-based, social and cultural issues (Oliver-Smith and de Sherbinin 2014; Scott 1998). This compounded by the notion that sustainable development means returning to a pre-resettlement state causes many of the issues apparent in resettlement programs. However, the dynamic processes within a system elude the possibility of returning to a state similar to pre-development or pre-resettlement.

Through a synthesis on the discourse of ecological and generative design, Du Plessis (2012) demonstrates that "ecological design and planning processes have four main characteristics: they are responsive to local conditions, adapt to changing conditions, employ decentralized approaches, and are developed through the contribution and collaboration of many simple entities through processes of bottom-up self-organization that follow certain generative rules" (p.16). These processes are inherently linked within social and cultural capital. Based on this systems approach to resettlement as regenerative development, social and cultural components may prove to be the most important factors in success.

**CONCLUSION**

Building upon Friedman's (1987) transformative approach to planning, I argue that sustainability should fall into a radical ethos of architecture: we must change the very structure that maintains the current world order. The current use of sustainability is a tool of the dominant, used to promote progress, but in reality the discourse of sustainability perpetuates control and systems of inequality. The ubiquitous approach to sustainability from a technocratic stance is demonstrative of this problem (see James Scott (1998)), we have a tendency to relate everything to numbers through scientific rational, and in the process we ‘fog’ the necessity of social systems and culture. Social and cultural factors are far more important than the technological factors. If we only consider sustainable architecture from the perspective of energy consumption, we might ignore the reasons why un-sustainable practices are perpetuated through the habitus (Bourdieu 2005). For example, May's (2008) case study on the sustainable development project in Huangbaiyu, China. May critiques the agenda of capitalist sustainable development goals, as off-setting their own carbon emissions, while negatively impacting the communities these projects are implemented in. While this brings to light the negative socio-economic effects of such programs, more emphasis could be drawn to the exploitive behavior of western ideologies, as demonstrated in Banerjee’s (2003) critique of sustainable development. If we can influence the habitus in a positive manner, that would lead to a regenerative change and is inherently more important than a simple technological solution.

The practical aspect of transformative theory is to empower people and move toward changing the system, in this case the exploitative agenda of western, capitalist development. These transformations take place through: 1) Politics of empowerment, through successful engagement of the political struggle; 2) Politics of redistribution of power; 3) Politics
of Place – defending people's life-space against capital and bureaucracy; contributing to life space of neighborhoods – protecting low-income areas from gentrification and displacement; and 4) Terrain of struggle. The goal of the radical architect in the design and development resettlement programs is to engage the community in a participatory process in order to draw their awareness of the political struggles as well as the dark-sides of the structural system. Through this participatory process, the radical architect develops an understanding of generative codes and verifies them with the community. These generative codes provide the basis for designing and developing a culturally supportive environment. Through a community-directed building process, the community ensures the correct implementation of the codes. The next objective of the radical architect is to work as a mediator between the community and the state in order to ensure that the cultural maintenance of the community is not hindered by land use and building codes.

ACKNOWLEDGEMENTS
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REFERENCES


ENDNOTES

1 Through his ethnolinguistic study of the Marshall Islands, Peter demonstrated that a clear translation or interpretation of sustainability did not exist because sustainability was a state of being amongst Marshallese up until the period of United States occupation following World War II (2013).

2 The following is an example based on a synthesis of arguments developed in Ulrich Beck’s discussion of the dark side of technological advancement that gives rise to wicked problems, such as global climate change, and Bourdieus’ theory of practice. The elite industrialists held the power at the turn of the 20th century and reproduced this power through capital gain, which put a tremendous tax on the environment. These power positions largely remain as privileged decedents hold onto the accrued capital, but rather than industrialists, they have taken on new vocations of power, such as a politician, who might lobby for continued resource exploitation. Here, this decedent might directly affect global climate change through petroleum extraction, release latent implications of drilling technology, and hold the knowledge to understand the negative consequences of such practice, thus truly holding onto the power.

3 The Convention on Wetlands of International Importance, called the Ramsar Convention, is the intergovernmental treaty that provides the framework for the conservation and wise use of wetlands and their resources.

4 The Marshallese family compound is defined by the weto, the piece of land that extends from the ocean to the lagoon which is passed down through matrilineal inheritance.

5 The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard. It involves a combination of factors that determine the degree to which someone’s life and livelihood is put at risk by a discrete and identifiable event in nature or society (Wisner et al. 2004).

6 Alexander et al. propose a new theory of urban design that attempts to capture the process of organic development. They argue that “towns grew as a whole, under its own laws of wholeness” (p. 1). Alexander and co-authors attempt to capture this process of creating wholeness and life-enriching environments throughout their subsequent works (The Nature of Order) and develop a process that deals
with the complexity of the urban system through collaborative strategies.

7 Transformative theory consists of five key characteristics: 1) It focuses on structural problems (within capitalist society), such as racism, patriarchy, class domination, resource degradation, impoverishment, exploitation, and alienation. 2) It provides a critical interpretation of reality, emphasizing relationship to the dark-side of systems and analyzing structural conditions. 3) It charts how the system reproduces itself without anyone doing something about it (in order to do so, one must understand the historical context). 4) It elaborates a preferred outcome based on emancipatory processes and holds a normative view. 5) Finally, transformative theory speculates that the best strategy for overcoming resistance requires political will (Friedman, 1987).
DESIGN CULTURE, SOCIETY, HEALTH, ECONOMIC, AND ENVIRONMENTAL NETWORKS
ABSTRACT: The combination of an increased value placed on quality of life and hospital satisfaction with the known health benefits of nature have fostered healing gardens to become a standard programmatic element in hospital design. Given the complex relationships between health and habitation, program and occupancy, healing gardens would benefit from greater study and research. This research observed use patterns of a healing garden located adjacent to the third-floor oncology unit of a pediatric hospital in Portland, OR. Use patterns recorded through observation and behavior mapping include user group, length of stay, and activity. Additionally, weather data taken onsite was correlated with use patterns to better understand the impact of temperature, relative humidity and light levels. Some findings in terms of healing garden use are concurrent with past research from literature reviews while other findings are not. While this particular healing garden is successfully used for longer durations than those found in the literature review (despite only being accessible from an upper floor), many aspects of this healing garden are not used as envisioned by the design team for a variety of reasons outlined in the paper. This research serves as an initial set of data to inform design decisions to improve the quality of life for patients, providers, and visitors.

KEYWORDS: Healing garden, Research-based design, Post occupancy evaluation, Design intent

INTRODUCTION
Roger Ulrich's study in 1984 found nature to have a direct benefit to the health and wellbeing of an individual primarily through the reduction of stress (Ulrich 1984). The realized benefits of nature subsequently coincide with a shift in hospital care. "Subjective domains of health outcomes... are becoming increasingly important in health and hospital culture, as the paradigm shifts from mobility and morality as primary outcomes of a hospital experience to a broader view that includes health-related quality of life and satisfaction (Sherman et al., 2005)." The combination of an increased value placed on quality of life and hospital satisfaction with the known health benefits of nature have fostered healing gardens to become a standard programmatic element in hospital design. Healing gardens are a natural space where physical symptom relief, stress reduction, and/or improvement in one's sense of well-being can occur through passive or quasi-passive activities, such as observing, listening, strolling, sitting, or exploring in that space (Marcus and Barnes, 1994). From a design perspective, healing gardens are unique as they are “both a process and a place. It is a concept at the meeting point of medicine and design (Marcus, 1994).” Given the complex relationships between health and habitation, program and occupancy, healing gardens would benefit from greater study and research. Specifically, documentation of occupancy use, environmental conditions, and a comparative analysis of design intent to evidenced use can solidify healing garden's role as an architectural space that contributes to occupant health and wellbeing.

1.0 LITERATURE REVIEW
1.1. User-group, duration, activity
Through observational findings in existing literature, three distinct user groups have been identified (patients, providers, and visitors) that utilize a healing garden. A 2005 observational study of 1400 healing garden users found patients to represent 4% of documented users while providers and visitors make up 45% and 46% respectively (Sherman et al., 2005). The averages of multiple case studies (Whitehouse, et al., 2001, Sherman et al., 2005, Abbas and Ghazali, 2010) reveal similar user percentages with 4% patients, 38% providers, 46% visitors, 7% non-patient non-hospital participants, and 4% with mixed/unknown user-group identifiers (Figure 1).
An average of past literature reveals 73% of users stay less than five (5) minutes inside a healing garden, 9% stay 6-10 minutes, 9.5% stay 11-20 minutes, and 6.8% stay over 20 minutes. These averages can be used as a base standard for comparison. For example, Sherman et al. (2005) showed a short length of stay in a particular healing garden. Of the 276 users in that study, almost two-thirds stayed less than one (1) minute in the healing garden studied (Figure 1).

Healing gardens accommodate a range of activities based upon the ability, physical and emotional health, and desire for each user group. Activities previously recognized in studies include: lunch, sit and talk, sit and relax, quick chat, structural interactions, work meeting, walking around, patient room, patient interaction, natural features, let children play, cell-phone, sit and wait, and play (Sherman et al., 2005). Figure 2 documents the frequency of activity as a color-coded bar collected from the literature review. Activities are organized by physical exertion; most exertion (play) is, therefore, on the far left while most stationary (sit and relax) is on the right. Activities from left to right are as follows: play (5%), structural interaction (10%), natural features (9%), patient interaction (7%), patient room (9%), walk around (13%), let children play (4%), work meeting (2%), lunch (2%), cell-phone (5%), sit and talk (19%), sit and wait (4%), and sit and relax (11%). Children's most frequent activity is "play" while both visitors and provider's most frequent activity is "sit and talk." Passive uses of a healing garden, such as viewing the healing garden from an interior space, are not recorded or documented for the purposes of this research.

1.2. Rationale
This research aims to record use patterns of a healing garden for comparison to design intent of a healing garden at a Portland, Oregon pediatric hospital. Documentation of use patterns is valuable as it has the potential to validate existing design approaches, reveal unanticipated uses, and inform future designs. The aspirational goal for this research project is to contribute to a body of knowledge where intent and use are reckoned for healing gardens to more fully impact the quality of life for patients, providers, and visitors.

This research also aims to establish an initial comparative data set between healing garden use and weather with an emphasis placed on occupancy. During the literature review, little documentation was found on weather during the observational period. The relationship between weather and healing garden use is, therefore, speculative and unknown, but it may have a direct impact on occupancy which would naturally influence design choices such as location, proportional shading devices, and feasibility. Incorporating a collection of technical weather data will provide additional insight to the occupancy and use patterns documented at the healing garden.

Finally, this research aims to provide knowledge on healing garden use specific to the Pacific Northwest. Healing gardens previously studied are clustered around regions with research on healing gardens is previously established. Without a collection of data on healing gardens throughout the United States, it is unknown how applicable existing research is outside of those documented regions. Furthermore, while healing gardens are becoming a standard programmatic element in hospital design, there is not enough published research on healing gardens to enable
comprehensive evidence-based design decisions to be made. This research will add knowledge of healing gardens in the Pacific Northwest to the existing set of research.

2.0. METHODOLOGY
In collaboration with the architecture firm Zimmer Gunsul Frasca Architects LLP (ZGF), a healing garden at a children's hospital (children 0-18 years of age) was selected for this research. Completed in 2012, Randall Children's Hospital (RCH) is a 165-bed hospital with a including neonatal intensive care unit, pediatric intensive care unit, a emergency department and a day surgery unit. RCH features many family friendly and child focused design elements such as animal cutouts within the wall of the lobby, soft material choices, and a vibrant color scheme. There are two outdoor spaces at RCH including a courtyard adjacent to the main lobby on the ground floor of RCH and a healing garden, known as the Terrace Garden, located on the third floor. ZGF was interested in studying the Terrace Garden as it has some unique circumstances. The programmatic elements on the third floor include the Children's Cancer and Blood Disorder Unit and an administrative wing; neither of which encourage accidental discovery or walk-by advertisement for the garden. Additionally, access to the garden is limited; only registered guests or patients of the hospital may enter the elevator at the lobby. There is only one entrance to Terrace Garden with alternate exits available for emergency egress only. For those with access, Terrace Garden is open from 6:00am until 11:00pm every day. The combination of these circumstances enable a uniquely controlled condition for research and study.

2.1. Design intent
The Terrace Garden is in the shape of an elongated rectangle. A four-foot high transparent wall runs along the east, south, and western sides of the garden with the exterior hospital wall to the north. There are a number of features and spatial arrangements, which are a direct response to ZGF’s design intent. For the purpose of this research, design intent is broken into (1) circulation, (2) spatial zones/areas, and (3) elements and features. When categorized in this way, design intent is aligned with spaces that incorporate biophilic patterns (Browning 2014).

Circulation, including surface material choices, is designed to accommodate patients regardless of mobility status (i.e.: access to the garden is provided to patients in wheelchairs, hospital beds, and with an IV pole). A specific design intent was to allow views from the infusion bay windows into the garden while still providing privacy for patients receiving treatment. ZGF designed a series of raised gardens in front of these windows, located on the north side of the garden, which distances garden users from the window surface thereby increasing privacy while still maintaining views to the garden.

Figure 3: RCH Terrace Garden Plan (based on ZGF drawings). Source: Author

Spatial zones/area are largely dictated by the raised (terraced) gardens in the Terrace (Figure 3). The far west area is intended primarily for providers as it is designed with a private door to/from the hospital and is farthest from the largest gathering area. The provider space was designed for activities such as lunch, sit and talk, sit and relax, and work meeting. Adjacent to the provider space is a space dedicated for children to play with special attention given to the design of surface materials. For example, a grass/turf material covers the ground so children may play on the ground comfortably. Three semi-private spaces are located between the play-space and large gathering area. These spaces accommodate a variety of activities and include fixed benches and natural features (ZGF, 2012). The main entrance to the Terrace Garden opens onto the main gathering area. The main gathering area includes a variety of movable seating and a large overhead canopy constructed of metal and translucent material overhead. This gathering area is intended to be an active area where all activities are encouraged. The last two intended spaces include a small niche appropriate for 1-4 people with direct exposure to the elements of weather and a secluded, privacy garden intended for respite and reflection (Barton, pers. comm.). The privacy garden had very specific goals in design to be a space dedicated for families experiencing extreme stress or loss.

Elements and features specifically designed/selected the Terrace Garden include seating, surface materials, plant
selection, and art. Seating (that is not a part of the raised gardens) is movable, and each piece has an intended location in plan drawing. Dark gray ground surfaces are made of a softer material and located where the intent was for children to play. Bamboo was selected to act as vertical privacy elements that can respond to climate and user needs. A local artist designed sculptures which act as playful elements in the landscape and are functional light wells for the neonatal unit below.

2.2. Weather and use observation
Research at RCH include two separate research periods. The first research period was conducted in March 2015 for approximately a week, and the second research period was from May 1, 2015 to May 31, 2015. HOBO meters were utilized to record weather and occupancy of Terrace Garden. Light, temperature, and humidity were collected every 15 minutes in the play-space, the privacy garden, the main gathering space, and the private respite area. An occupancy sensor was placed on the main entrance door of the garden to record each time the door was opened (subsequently referred to as an occupancy instance) throughout the duration of each research period.

Use observation data was collected by on-site observation done by one researcher, the primary author of the paper. Periods of data collection occurred from 9:00am to 5:00pm, Monday through Friday, in order to acquire a basic understanding of garden use during typical business hours. Use observation data collection includes recordings of user group, duration, and activity. User groups were categorized as either provider, adult visitor, or patient (child/adolescent). User group identification was determined through physical appearance and apparel. Duration is time passed (in minutes) from the onset of an event (enter garden) to the closure of that event (exit). An event can include multiple user groups and activities. Categories of activities include: quick chat, work meeting, cell-phone, sit and talk, sit and relax, sit and wait, walking around, natural features, struck interaction, play, let children play, patient interaction, patient room, and lunch. Activities were documented by visual observation on site. Behavior mapping was utilized for the recording of circulation, views, and sitting locations for each user.

3.0. RESULTS
A total of 2168 occupancy instances were recorded during the research periods. Data collected from occupancy sensors suggest occupancy for a typical week is varied and does not follow a day-of-the-week pattern. There are periods of several days with high use and periods of several days with low use. The data collected indicates an increase in occupancy use with higher recorded temperatures. There is also an increase in occupancy instance when recorded low humidity is within a range of 20–40%. Results also indicate occupancy is lower on days with an illuminance of 5,000 lux or less. As this paper specifically focuses on design intent compared to actual use, additional analysis done on relationships between temperature, humidity, light, and occupancy are not included within this paper but are a part of the larger study.

A total of 41 occupants were observed over 7 days of on-site observation. Three recognized user groups frequent Randall Children's Hospital Terrace Garden: patients (20%), and providers (33%), and visitors (48%) (Fig. 6). The mean average duration at the Terrace Garden was nine (9) minutes with a median duration of six (6) minutes. Of the 27 events recorded, 11.11% stayed 0-1 minute, 40.74% stayed 2-5 minutes, 29.63% stayed 6-10 minutes, 11.11% stayed 11-15 minutes, 11.11% stayed 16-20 minutes and 7.41% stayed over 20 minutes (Fig. 4).

Figure 4: User group, duration, and activities at RCH. Source: Author
During observation, eleven (11) of the thirteen (13) recognized activities were present: work meeting (2.38%), cell-phone (9.52%), sit and talk (4.75%), sit and relax (16.67%), walking around (28.57%), natural features (11.90%), let children play/play (2.38%), patient interaction (4.76%), and lunch (14.29%). A new observational category, view, was added in response to observed behavior. View was a purposeful recorded activity 4.76% of the time.

Behavior mapping was utilized to spatially track the circulation and movement of user groups during garden use. Each user group is distinguished by color with blue as visitor, red as provider, and purple as patient. Squares signify moments of pause greater than five (5) seconds, gradients indicate a purposeful viewing moment, and an “X” indicates sitting. As can be seen through the mapping, each user group circulates the garden differently. Providers primarily stay in the main gathering area (Figure 5). Patients and visitors walk through the garden in a similar fashion with visitors expressing a more exaggerated path of circulation. A loop or track motion is documented by both patients and visitors in which they move through the main gathering area, pass by the semi-private and play spaces, come to the provider space to then turn around and exit the garden.

Figure 5: Behavior mapping by user group. Source: Author
4.0. DISCUSSION
It appears occupancy increases with warmer temperatures, lower humidity, and higher illuminance. This can be perceived as a typical response to the onset of summer. However, there is at least one recorded day each week that does not reflect this pattern. These anomalies have no apparent relationship to weather conditions for that day. Anomalies do not occur on the same day of the week nor do they exhibit recurring scales (given the current set of data). The presence and behavior of anomalies ultimately suggest factors beyond weather influence occupancy for the Terrace Garden.

User group percentages are slightly unusual at the Terrace Garden with patients representing 20% of the users. This higher patient use could be contributed to several factors. First, the patients at RCH are children and therefore often follow the guidance/direction/desires of an adult, which in this case a visitor to the hospital. Visitors have a traditionally higher use percentage for gardens, which may lead visitors to more readily encourage patients to visit the garden than if the patient were an adult. Secondly, patients are easier to identify at Terrace Garden; they are children and, given the location of the garden, regularly have identifying apparel or medical equipment with them. Patients’ healthcare needs did not seem to influence frequency of use or activity level, as patients observed in the garden ranged in physical abilities, apparent health, and medical assistance required. Additionally, the restrictive nature of the garden could be contributing to patient presence. The unique circumstances of the garden, mainly its 3rd floor location and security protocol, provide a safe, secure space where patients can enjoy nature while still being near a patient's room. Other user groups at Terrace Garden are similar to past literature, with a slightly lower provider usage and a small increased usage by visitors.

A typical user stays longer at the Terrace Garden than the average duration found in past studies. The average length of stay at the Terrace Garden is nine minutes while the majority of users at other gardens stay for five minutes or less. Again, the Terrace Garden's location could be a driving factor in length of stay. Given the programmatic elements on the Terrace Garden floor, the Terrace Garden is likely a sought destination for users. This both encourages users to stay longer as they have invested more into the event and limits opportunistic passerbys that may be curious but would not linger.

The greatest activity recorded at the Terrace Garden is walking around. Other frequent activities include (in order of highest percentage) sit and relax, lunch, and natural features. Both visitors and providers are more active than their past study counterparts. An explanation for visitor's higher exertion could be the long rectangular form and design of the garden as it encourages visitors to walk along the stretch of the garden before returning indoors. Additionally, “views” have been added as a purposeful activity for the Terrace Garden. Views include an extensive forest park to the east and mountain range to the west, and to see both views, a user must walk the entire length of the garden.

There is a clear pattern found in behavior mapping based on user groups. Providers stay near the main entrance in the main gathering area. This could be due to the limited time providers have for break. It could also be because the main gathering area has an over head structure that provides shade and protects a user from rain. While visitors do stay in the main gathering area, they also walk along the southern wall of the garden.

4.1. Design intent
Design intent is discussed through (1) circulation, (2) spatial zones, and (3) elements and features. Circulation was both effective and engendered unanticipated uses. 62% of observed patients utilized a wheelchair or IV pole in the garden. These patients did not exhibit any noticeable difficulty in navigation or activity due to garden design which indicates chosen ground material and spatial circulation effectively satisfy design intent. Additionally, a track-like motion was regularly exhibited by users as can be seen in behavior mapping (Figure 6). This track-like motion was not an original design intent, but it is an effective way for users to experience the garden. Additionally, the track-like motion lasts approximately four minutes, exceeding the minimum duration required for stress reduction benefits (Ulrich 1984). If the track-like motion is incorporated into design intent, rather than an unanticipated result, a looped path could be designed for garden users to continue the track-like motion. A looped path has the potential to increase longer stays, more exercise, and additional engagement with nature, thereby increasing effectiveness of the healing garden.
Most of the spatial zones do not function as intended (Figure 7). The far west area intended for providers is not used by providers as can clearly be seen in behavior mapping. Part of this may be due to the lack of accessibility to the door located in the provider space. This door, originally envisioned as a provider door for this space, is inaccessible as it proved to be a source of potential contamination for children receiving chemotherapy. Additionally, the provider space has full exposure to weather. Instead, providers stay near the main entrance where there is shade, an overhead canopy, and tables.

During observation, no children played in the play-space which indicates the play-space is not used as intended. Two observed interactions occurred in the play-space. Both interactions were visiting adults without children curious about the artistic sculpture in the space. The semi-private spaces, located between the play-space and large gathering area, were also not used with the exception of one walk through during observation periods. These smaller, semi-private spaces would greatly benefit from the addition of mystery elements as they would both reward visitors that walk through those spaces and draw new users into those spaces.

The large gathering area appears to be used as intended. Seating is arranged by the user to accommodate different group sizes and preferred views. The overhead structure makes the large gathering area an ideal place to eat or read as it prevents direct sun from landing on a visually focused surface. 85.7% of observed activities recorded as lunch were located in this area. The south-east corner of the Terrace Garden is also used as intended. The small niche is regularly frequented by one (1) visitor with one (1) patient. The combination of direct sun, a small semi-private space that is close to the main entrance are likely driver for frequent use of this space.

The north-east corner of Terrace Garden is not used as intended. The doorway to the north-east corner was closed off to the public due to administrative hospital expansion. As this doorway was the only access point for this portion of the garden, users must now walk through a garden bed to gain access to that space. As such, the north-east corner receives very little occupancy use even though it is perhaps the most visually stimulating area.

Seating is not kept in the locations laid out in the plan drawing, but they do allow users of the garden to interact with the garden by personalizing the space through chair motion. The dark gray ground surfaces were not noticed by users during observational periods. As such, it is unlikely children congregate in those areas for play, even though
the gray material is softer and more suitable for such activities. Bamboo has been successful in acting as a vertical privacy element. However, the maintenance bamboo requires is greater than the available resources, and it has become overgrown. As such, it was removed from the garden entirely in summer of 2015 due to high maintenance requirements. Lastly, the sculptures designed by an artist are not sources of play as they were intended to be. Users asked questions such as, “What is this? Why is it in the garden?” As answers to these questions are unknown to the user, other artistic elements in the garden are typically avoided.

CONCLUSION
This research provides post occupancy insight on a healing garden in a hospital facility. While larger contextual relationships (such as floor location and adjacent program) are important, they do not necessarily negatively impact the potential use of a healing garden. In fact, factors that may limit occupancy may also increase duration and patient presence both of which increase healing garden effectiveness to improve health and wellbeing.

To answer the initial question which prompted this research, “who actually uses a healing garden anyways?” the simple answer is everyone. Everyone does not infer a high occupancy count but rather an established presence of each type of user group at a hospital facility. Percentages vary, but healing gardens are not primarily used by one user group, nor are they used in predominantly one way. Design decisions can be informed by research to increase the effectiveness of healing garden design. While seeking as many occupants is ideal, a healing garden is most effective when users stay a minimum of three minutes in the healing garden. This, rather than shear occupancy or specifically chosen features, should be a primary design intent for healing gardens in the future.

5.1. Next steps
The relationship between weather conditions and occupancy use would greatly benefit from additional study. Through this initial collection of weather conditions with occupancy use, it appears healing gardens have a higher frequency of use with an increase in temperature, illuminance and lower humidity as can be seen in the transition from spring to summer for Portland, Oregon. This trend does not, however, explain the frequent anomalies where occupancy does not respond to weather conditions. A full year of documented occupancy and weather at RCH would solidify the correlation of weather and occupancy.

Additional research at RCH should include an incorporation of surveys and interviews. Data gathered from these qualitative research methods can then be further compared to weather, occupancy, and observation in order to more fully understand (1) the behaviour of occupants in the garden (2) why this particular garden encourages extended duration and (3) opportunities for optimization.

Lastly, more healing gardens need to be observed to understand the relationship between location, duration and general use. Healing gardens are typically seen as most beneficial if they are located in a central, easily accessible area of the hospital. The Terrace Garden at Randall Children’s Hospital is not central nor easily accessible, yet it has a significantly higher duration than past research. This indicates healing garden duration may be influenced by location, and centrality may not be the most effective design decision. To compare location and duration, a massive collection of healing garden data, including their location within a hospital should be collected. Documenting context such as geographic location, user group, and hospital information is critical to decipher what use patterns are unique to location and what use patterns are consistent. This data can also be used to establish both place-specific design strategies and general use patterns across the United States, enabling designers to make informed decisions when designing healing gardens.

ACKNOWLEDGEMENTS
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REFERENCES


ABSTRACT: Tokyo is one of the planet’s largest, most complex and most successful cities. With a population exceeding that of Canada, the Tokyo Metropolitan Region embraces a rich array of features key to a well-crafted, well-designed and highly-functioning city. Consistently Tokyo ranks among the world’s top cities, based on a wide array of metrics/measures. From a world-class multi-modal transportation system and vibrant mixed-use neighborhoods to walkable streets and planning innovations, Tokyo demonstrates how an urban centre can be colossal and complex while proving demonstrably dynamic, accessible and livable. For those looking from outside Tokyo proves a paradox – massive in size, and incomprehensible in scope while functioning at high levels, running smoothly and being relatively free from serious problems. Amenity is high, crime is low, efficiency is unprecedented, design is pervasive and a sense of community is ubiquitous. Tokyo’s success is worth critical examination, not only to cull out reasons for achievement but also to better grasp facets of the city than contribute to its Gestalt. An approach overarching the research critically considers the vehicle of ‘urban typology’. Using typology as a lens for investigation, the work imaginatively identifies/delineates unique typologies that define, shape and characterize Tokyo’s rich fabric. Case studies embrace conventional awareness of typology while charting new ground in conceiving exceptionally Japanese types. Creative typologies include: Gate-Threshold; Spiritual Spark; Arcade Street; Optimize Leftovers; Extreme Parking; Koban; Palimpsest Remnants; Folded + Compressed; Thin Landscapes; Vending Ethos; and Love Zones. The approach taken to Tokyo Typologies is original, bold and in keeping with the pulse, energy and uniqueness of this leading global city. The author invokes an existing holistic framework for design + planning to better illuminate compelling reasons for Tokyo’s ongoing progress despite intense pressures on economic, environmental, social, cultural & spiritual fronts. Application of findings, beyond Tokyo, is postulated.

Keywords: systems, holism, typologies, urban design, place-making

BACKGROUND

“The Japanese society approaches much of life with a respect for space and a critical eye to efficiency. Take clothing, for example: kimonos are designed to be folded then stored flatly, tightly, and efficiently. The bento box for food is another example where the focus is on space: attention to delivery, designed presentation, concern for aesthetics, and no waste. Cemeteries are another example of high efficiency, effective use of room, and the appreciation for scale, mass, surface, and space. As regards design and space, Japanese culture so often places tremendous value on beautiful functionality, on quality, on keeping, on maintaining, on preserving, on innovating, and on appreciating.”

Sinclair (2015)

Tokyo is a remarkable urban conurbation, with intense population, compact development, extraordinary character and an exceptionally high quality of life. With an urban population exceeding that of Canada, the Tokyo Metropolitan Region embraces a rich array of features key to a well-crafted, well-designed and highly-functioning city. Tokyo is regularly acknowledged as a leading global city, with metrics underscoring rich amenities, walkable streets, diverse neighborhoods and extraordinary attention to design + planning. From a world-class multi-modal transportation system and vibrant mixed-use communities to pedestrian-oriented fabric and design innovations, Tokyo demonstrates how an urban centre can be colossal and complex while proving demonstrably dynamic, accessible and livable. For those looking from outside the city Tokyo proves a paradox – it is massive in size, and incomprehensible in scope while functioning at high levels, running smoothly and relatively free from serious problems. Amenity is high, crime is low, efficiency is unprecedented, design is pervasive and a sense of community is ubiquitous. Tokyo’s success is in many regards without parallel. As an urban phenomenon it is worth critical examination, not only to cull out reasons for such achievement but also to better grasp the features and facets of the city than contribute to its Gestalt. In many regards Tokyo affords environmental design theoreticians and practitioners an outstanding exemplar for study, for experimentation, for inspiration and for best practices. While without question the context and culture of Tokyo and Japan is unique and nuanced, the author contends that many lessons learned are of demonstrable value and potential application well beyond the present geographical boundaries.
Considering Complexity, Context and Culture in Contemporary Tokyo: Sinclair

In examining Tokyo as an urban model for managing complexity and achieving livability, the researcher cast the study within, and deployed assessment through lenses respecting, the explicit context, conditions and culture of Japan. The present paper builds from the author's long-standing connections to and extensive immersion in Tokyo, including pedagogical explorations and urban investigations conducted within the ethos of an annual study-abroad studio. The research is structured, methodologically, upon three aspects: literature review, logical argumentation, and case studies selected from within the confines of Tokyo. An approach overarching the research critically considers the vehicle of 'urban typology'. Using typologies as a lens for investigation, the research innovatively identified and delineated a series of unique typologies that define, shape and characterize the rich fabric of the city. Review of historic and prevailing approaches to urban design, urban analysis and urban typologies, such as Cullen's *Townscape* (1961) and Mikoleit + Purckhauer's *Urban Code* (2011), was undertaken in order to underpin the current research. Context matters. Sandalack and Ulribe (2010) wrote “Public space typology must also be considered within the morphology of the city. A space or street by itself is meaningless – it must be conceptualized and designed in relation to its physical and spatial context.” Also considered vital are cultural and spiritual parameters that influence, inform and inspire the shaping of the city. The pivotal force of Metabolism, evidenced in projects by Tange, Kurokawa and Isozaki for example, is of relevance within a broader perspective of utopian vision and post-WW2 rebuilding of Japan. It is important to highlight that an understanding of Tokyo's order despite complexity and chaos is tightly intertwined with a mindset arising from and informed by historical forces fundamental to the soul of Japan, including bushido (way of the warrior), chado (way of tea) and kendo (way of the sword). Within frenzied environments, whether physical, social, political or spiritual, decorum and calm is pursued with such forces underpinning perception, attitude and action. The author has previously written about these pervasive cultural influences and their weighty impacts upon topics ranging from homelessness (Sinclair, 2010) to current architectural theory & practice (Sinclair, 2016) in Japan.

It is valuable to explore some dimensions of Japanese culture, with a particular emphasis on spiritual qualities, in an effort to better contextualize urban typologies and design gestures evident in Tokyo. In Japan architecture and planning historically and conventionally blurs and dissolves boundaries between inside and outside. For example, buildings visually and often physically interconnect with surrounding landscapes. The natural and the built purposefully interlace. We see this in many cases where mutability of space and form affords users the opportunity to change their environments in ways that enhance connection, conditions and comfort. In a ryokan (type of hotel) (Figure 1) residents can readily adapt their room to suit their needs, whether physical (such as room layout), social (such as converting a room for sleeping into a room for conversing), or spiritual (such as shifting a solid wall into a transparent wall that draws in the landscape beyond) (Figure 2). In Japan many spaces and places tend to be multi-purpose, capable of accommodating shifting needs. Walls move via shoji screens. Floors embrace the modularity of tatami mats. Much of contemporary planning and design in Japan draws influence and guidance through such historical practices and principles.

Figure 1: Ryokan outside Kanazawa

Figure 2: Shoji Screens + Tatami Mats

Spirituality also assumes a key role in Japan's planning and design, including of course approaches and strategies to deal with its largest cities. Shintoism and Buddhism coexist, with each contributing guidance to the conduct of design. Several Buddhist constructs are especially apropos to the design and planning of architectural and urban environments. Mushin translates as 'no mind'. It is about having freedom to act and react. It is a state of flowing where one pursues complete awareness. Three tenets of Buddhism warrant further exploration with regard to design and planning.
Ephemerality is the opposite of being concrete, of being fixed and of being set. It is characterized by a lightness of existence and an ethereal quality. Noted Japanese novelist Junichiro Tanizaki potently captured and conveyed such realms of ephemerality in his classic book *In Praise of Shadows* (1933). Impermanence suggests all of reality is in a state of constant flux. Life is an ever-changing ethos, where situations rise and fall and uncertainty is a certainty. We see this tenet manifest if Japanese designs that celebrate open building and capacities for disassembly and reassembly. Non-attachment is the ability to distance ourselves from the material world. It weakens notions of objects as precious, primary and unchangeable. This construct is powerfully illustrated with the Japanese obsession with *goraiko* (sunrise) – a fleeting moment that is to be relished but not held. It is a mere moment in a much greater sea of moments. These spiritual dimensions serve to influence the thinking and acting of Japanese designers, planners, builders and users of the city.

**TOKYO TYPOLOGIES**

“*The essential difference between life and a machine is that a machine eliminates all idleness and ambiguity. It is constructed entirely on the basis of physical connection, functional, rational principles, and efficiency. In contrast, life includes such elements as uselessness, ambiguity, the unknown and idleness. It is a flowing interrelation continuously creating a dynamic balance.*” Kisho Kurokawa (1995)

Without doubt urban typologies serve as powerful moments that shape our cities and influence our experiences. In a Western sense we understand typologies such as streets, parks and plazas. In terms of Tokyo these typologies, while at times present, are arguably not pivotal. Rather, there are in the view of the author distinct typologies that have arisen in response to the unique pressures and parameters present in the city. The case studies developed in the present paper embrace conventional awareness of typology while concurrently charting new ground in conceiving of exceptionally Japanese types. Creative typologies invented and examined in the paper include: Gate-Threshold; Spiritual Spark; Arcade Street; Optimize Leftovers; Extreme Parking; Koban; Palimpsest Remnants; Folded + Compressed; Thin Landscapes; Vending Ethos; and Love Zones. These typologies are found across the Tokyo region and often enjoy inter-relationships and associations.

**Gate -Threshold:**

Thresholds and gates are key elements in the Tokyo landscape. They signal change in an urban or architectural realm – for example, a shift from a profane zone to a sacred space (Figure 3). They also celebrate arrival and entry, such as seen in the demarcation of the notable Ameyoko Market (Figure 4) in the Ueno district of Tokyo. In compact, at times messy, fabric gates and thresholds introduce welcomed clarity.

*Figure 3: Nezu Shrine*  
*Figure 4: Ameyoko Market*
Spiritual Spark:

Another typology concerns spiritual moments, or points, in the urban fabric. Spirituality is pervasive in the city – Buddhist temples and Shinto shrines punctuate and activate the urban landscape. Scales of activation vary widely (Figures 5-6), from major temple complexes of deep cultural importance to modest neighborhood shrines. In all cases they focus attention away from the everyday and towards the sacred.

Arcade Street:

A very pervasive and special typology in Tokyo is the arcade street (Figures 7-8). A good illustration of this type are the omnipresent shopping zones, covered and protected, that envelope public streets (i.e., ginza streets) that remain public and fully accessible. Unlike the privatization of ‘public’ space in North American malls, these Tokyo developments find a rich and healthy balance of the public realm and private enterprise.

Optimize Leftovers:

As noted previously in the paper, Japanese phenomena, such as bento boxes and cemeteries, illustrate and emphasize an attitude towards the precious nature of space and the efficient utilization of resources. A typology that extends such thinking at the urban scale concerns optimizing leftover space. In many cases we see high quality space (e.g., retail functions) realized in tight, difficult and unruly conditions – such as marginal areas within historic buildings (Figures 9-10) or under active rail lines (Figure 11). Such spaces, in North America, would typically be deemed orphan spaces that prove unreasonable and unworkable.
Extreme Parking:

Again responding to the tightness of space on the relatively small islands of Japan, and the overwhelming spatial pressures in the mega-city of Tokyo, the typology of extreme parking has serious ramifications in the urban ethos. There is limited on-street parking. Home-owners need to provide proof of space within their property in order to receive a vehicle permit (Figures 12-13). In response to a demanding regulatory regime in the city, Tokyo has witnessed an incredible proliferation of high-technology-based high-density robotic parking structures. These windowless soaring parking towers (Figure 14) dot the landscapes across Tokyo.

Koban:

A very special and impressive typology of Tokyo, with both physical and social implications, is the Koban (i.e., community policing kiosks). Every neighborhood has a distinct and readily identifiable koban. Police are seen as vital and welcomed members of the community – readily accessed and always willing to assist. Each koban has a unique architectural quality and character that is intentionally in keeping with its community setting and urban context (Figures 15-16).
Palimpsest Remnants:

The typology of palimpsest remnants acknowledges the fact that modern Tokyo is built and layered upon a city with centuries of history and generations of complicated land division. Buildings, as a result, are often thin, tall and irregularly shaped – being constructed on impossible sites, with intriguing geometry, using structural gymnastics and open-minded and somewhat flexible regulatory concessions (Figures 17-19).

Folded + Compressed:

Land in Tokyo is extremely precious with building sites tight and demanding. In response design and planning practices have adapted. Often design is intentionally aimed at accentuating experience and optimizing perception – for example, conveying a feeling that a space is far bigger than its reality would dictate. In spaces, such as residential developments, the movement of visitors is carefully choreographed to unfold the experience – to reveal slowly the environmental conditions at hand and to heighten perception despite any spatial limitations (Figures 20-21).

Thin Landscapes:

Again underscoring the scarcity of land and finiteness of resources, the typology of thin landscapes is a clever
reaction to a need to customize, to personalize and to humanize space and territory. In Tokyo even the most modest and seemingly insignificant spaces are brought to life and given meaning. The insertion of nature into the cracks and crevices of the urban fabric (Figures 22-23) serve to enrich the city and bring down the vastness of Tokyo to a manageable and comprehensible level.

Figure 22: Vertical Garden

Figure 23: Interstitial Garden

Vending Ethos:

Another typology that capitalizes on slender and awkward interstitial (or in-between) spaces is the ethos of vending machines. Mechanized automated commerce of convenience (e.g., hot + cold drinks, food items of all varieties, cigarettes, electronics, etc.) finds its place along building edges, in nooks and crannies, and in found spaces throughout Tokyo. These machines afford punctuation, variety and relief to the streetscape while proffering moments to slow down, to connect and to recharge. (Figures 24-25)

Figure 24: Interstitial Vending

Figure 25: Edge Vending

Love Zones:

The last typology is one that is uniquely Japanese – that is, the love hotel regions of Tokyo. Japan is particularly liberal and permissive when it comes to sex and associated activities + industries. Love hotels, and the zones in which they are located, relate again to scarcity of space in the city. These hotels, rented commonly by the hour, populate urban ethos along rail lines in sub-cities of Tokyo (e.g., Ugiusudani). They tend to optimize difficult land, portray a character all their own, and afford islands of distinctiveness, relief and release in the vastness of the metropolitan region. (Figures 26-27). It is important to note that these areas are not problematic from an everyday citizen perspective. Rather such zones are typically and uneventfully interwoven into surrounding neighborhoods with community members, regardless of gender, comfortable moving in and around them on their daily commutes to and from local transit stations.
Returning to the matter of complexity, it is important to underscore that despite Tokyo's intensity and diversity the city works exceptionally well. The city is perhaps best grasped in its holism and through the dramatic integration of its parts. Tokyo is a city influenced deeply by tradition and spirituality yet committed to progress, innovation and experimentation. It is an urban milieu comfortable with uncertainty and accepting of indeterminacy. In many ways the city illustrates with potency the success that can surface when a richness of consideration and a multiplicity of needs is addressed in city building. The author has written widely on the need for systems thinking and holistic posturing in the execution of architectural design and city planning (Sinclair 2009, 2015). The author’s Holistic Framework for Design + Planning was inspired in part through his longstanding relationship with and engagement in Tokyo. Agility is about an ability to mutate, to accommodate, to adapt and to respond as circumstances shift. Fitness concerns the appropriateness of environments and their resonance with user needs and situational purposes. Diversity celebrates the inclusion of uses/users into the equations of urbanity and city dwelling. And perhaps most critically, Delight underscores essential yet largely immeasurable qualities of our environments that cause us to be joyful, enlightened and inspired. Synergies with Japanese spirituality & culture are not accidental.

To understand Tokyo's success we must push hard to grasp the bigger picture. Over 37 million people in an urban environment characterized by high amenity, strong order, efficient transit, low crime, exceptional walkability and arguably unequalled livability. The success story of Tokyo is in part driven by a population with strong societal norms and pressures concerning behavior. In part by strong connections to nature that dictate a blurring and blending of otherwise distinct boundaries. And in part informed by sensibilities and sensitivities drawn from firmly held spiritual tenets and widely subscribed cultural parameters.

No doubt the typologies imagined and invented in the present paper shape experience and environment while concurrently reflecting/capturing/conveying zeitgeist. The particular approach taken to the development of Tokyo Typologies is inventive, bold and in keeping with the pulse, energy and originality of this leading global city. The prevalence of the typologies, and their demonstrable influence on civic life, is supported via governance, regulatory regimes and approaches to resiliency that factor into the city's extraordinary means of managing complexity. The author argues that such strategies, including relevance to an existing holistic framework for design and planning, serve to illustrate and explain the compelling reasons for Tokyo's ongoing progress and triumph despite intense pressures on economic, environmental, social, cultural & spiritual fronts.

CONCLUSIONS | IMPLICATIONS

“Nothing is harder, yet nothing is more necessary, than to speak of certain things whose existence is neither demonstrable nor probable. The very fact that serious and conscientious men treat them as existing things brings them a step closer to existence and to the possibility of being born.”

Hermann Hesse, The Glass Bead Game (1972)

So what can designers and planners from outside Japan learn from the principles, processes and practices of urban Tokyo? From the author’s vantage point there are many lessons to be learned about city building, meeting user needs, space shaping and place making. In the West we commonly rely on expertise, experience and traditions when approaching design and planning. While these often work well and have positive outcomes, increasingly we are called upon to innovate in response to changing & challenging conditions (at local, regional, national and international levels). For certain Tokyo presents many unique and intriguing dimensions from urban planning and urban design perspectives.
The novel typologies in Tokyo, delineated in the present paper, arise through sundry and distinct forces of people and place. Seeing through the eyes of others, studying different approaches to problem solving, and being far more open to creativity, boldness and innovation – such as witnessed in the Tokyo Metropolitan Region – is vital to our ongoing advancement as environmental designers and to our continued development of our planet’s growing urban ethos. Yuki Sumner (2010), in the *Residue of Japan-ness*, wrote “Japanese spatial renderings, whether contemporary or historical, are inherently performative; that is to say, they are incomplete without people.” Tokyo Typologies can provide us with new ways of executing spatial renderings, with alternative means of viewing urban life and with different means of achieving greater walkability and improved livability for our cities and their inhabitants.

**REFERENCES**


ABSTRACT: Changing weather patterns, combined with population growth and demographic shifts, have begun to impact the shape and structure of India's traditional water landscapes. Water scarcity as well as superabundance can be linked to natural weather events such as cloudbursts, glacial lake outburst floods (GLOFs), and drought, as well as to human causes such as development pressures. Considering as a backdrop the intertwined issues of urban development and climate change, this paper establishes a taxonomy of water management systems found in India and charts each system's capacity for change. Both traditional and current systems are identified, in an effort to better understand the varied tools and techniques used for harnessing, regulating, and conserving water in South Asia. Water management systems featured in this paper include the talaab, the ghat, the canal, bunds and tanks, the stepwell, the artificial glacier, the ice stupa and the snow barrier band. This research draws upon a combination of field study and archival document studies, conducted in India from 2012-2016. As a survey of water management strategies, this paper makes a connection between design practice and water husbandry, acknowledging the need for reference material that could support adaptive design thinking in the face of environmental change.

KEYWORDS: Water management, India, infrastructure design, landscape architecture, design for climate change adaptation.

INTRODUCTION
India is a country in South Asia known for its sheer size and diverse geography (Figure 1). The subcontinent has a long history of human-centered development, with unique site-specific approaches to irrigation infrastructure stretching back to ancient times. Because of this history, as well as the country's rich cultural and spatial influences, water management practices are both varied and time-tested (Briscoe & Malik, 2006). India's breadth of design thinking around water husbandry, as well as experience with a wide variety of design strategies, offers landscape architects and urban designers an important reference collection of proven lessons and ideas.

Figure 1: Map of India. Source: Author

This paper surveys just eight of these water management strategies, all of which are currently found in India. Included in this study are the talaab, the ghat, the stepwell, the canal, bunds and tanks, the artificial glacier, the ice stupa and
the snow barrier band. In so doing, the survey provides a taxonomy of different types of designs for water management in India, links each strategy to a series of attributes and design conditions, and highlights opportunities for change or adaptation. This comparative organization helps to make the opportunities and constraints associated with these different water management approaches clear, and could potentially help designers to adopt components of such systems as they work in other contexts.

BACKGROUND

The ‘improved’ water management system used in Western contexts consists of a wide variety of design responses, many of which are entirely invisible to the people who rely upon that water (Kinkade-Levario 2007). By placing water catchment, drainage, and delivery mechanisms below ground, and sourcing water from enclosed or otherwise secured sites, municipalities can effectively control, maintain and regulate water resources. But this concealed infrastructure also has the concomitant effect of severing people’s physical and psychological ties to their own water resources (ibid). Without a visual appreciation for the processes of water collection, purification, conveyance, and disposal, people served by underground municipal water services lack strong connections to hydrological landscapes and processes (Rossano 2015). In obscuring hydrological systems there is a missed opportunity for improved water literacy and environmental stewardship; in these situations people are more likely to overuse, undervalue, and pollute water held in the commons (Ostrom et al. 1999, Orff 2016).

The disconnect between resource stewardship and environmental visibility may even be exacerbated by the twin pressures of climate change and urban development (Sarté & Stipisic 2016). In this context, opportunities for additional co-benefits, especially, may be unrealized. According to architectural educator Ila Berman, “By insisting on the clear legibility of our infrastructural systems, while simultaneously assuming the limitless of the environments we have exploited, we have largely disregarded the vast impacts of these systems on a broader and more nuanced ecology” (2014). As water becomes a scarcity in some places, and a flooding threat in others, the visibility of this resource could serve as an ever-present reminder, helping humans to both mitigate and adapt to changing conditions (Clouse & Lamb, 2017). Invisible hydrological processes, on the other hand, may effectively camouflage environmental risk while decoupling human behavior from associated hydrological impacts.

In India, many villages, towns, and even cities have a vibrant physical relationship with their own water husbandry. Water in this context is a form of the commons, and the spaces of water management may also serve as valuable sites for social, cultural, and religious engagement, as well as recreation (Nawre 2013). These multifunctional spaces reveal co-benefits that help residents develop personal relationships with their hydrological landscapes, in turn potentially improving environmental awareness as well as quality of life factors (Silveirinha de Oliveira, & Ward Thompson, 2015).

By making water management processes visible, people can easily see the effects of pollution, or track drought, or recognize relative risk conditions (Ludy & Kondolf 2012, Rohrmann 1994). Also, when individuals participate in the governance of a shared space, such as water management infrastructure held in the commons, they are more likely to also assert some ownership over that space, which may benefit long-term maintenance and land stewardship (Ostrom et al. 1999). The shared water resources of a community can be held underground---invisible---or above ground---in full view---and the outcomes of this decision have far-reaching implications for both environmental health and human experience. The water management strategies explored in this paper help to demonstrate that visibility and accessibility are central features of the adaptive and multifunctional co-benefits found in Indian water spaces.

METHODS

This paper began as a survey of water management strategies in India, with expansive if not comprehensive representation of different approaches from across the subcontinent. Strategies were specifically selected because of their potential to inform the topics of climate adaptation and a multi-functional design approach. In addition, it was important to find examples that addressed both conditions of drought and flood, scarcity and surfeit. While most of the systems studied contribute primarily to agricultural irrigation, design strategies were also selected to represent other types of water use.

Field research was conducted during the course of the past four years, which included visits to many of these water management sites, and where photographs, drawings and maps helped to produce an understanding of the characteristics and working components of each system. In addition to this work, historical photographs and records relating to some of the water management strategies helped to fill in additional information, particularly for the classification structure that was developed. In this initial research phase, the tables of attributes, co-benefits, adaptive potential and operational qualities were constructed in such a way as to compare widely divergent case studies under a common system of terms, areas of impact, and features. In so doing, the composite pieces of each water management type begin to show similarities and differences in a readable and succinct format. Additional studies might address more nuanced design responses in this manner, or perhaps conduct interviews for a better understanding of human responses to these design ideas.
WATER MANAGEMENT STRATEGIES
The following water management strategies highlight just eight of the many different hydrological landscapes currently in use in India. These eight examples come from several different cultural, social and environmental contexts, despite sharing the same national boundaries. In an effort to better display the different approaches and characteristics of these systems, the following table of attributes has been produced. (Table 1)

Table 1: Design Attributes for each Water Management Strategy. Source: Author

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Location</th>
<th>Material</th>
<th>Size</th>
<th>Cost</th>
<th>Scalable? Description</th>
<th>Machinery</th>
<th>Energy Description</th>
<th>Longevity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talaab</td>
<td>Village centers with water</td>
<td>Stone or concrete</td>
<td>+/- 50,000 sf</td>
<td>Labor only</td>
<td>Yes. But one can serve a village</td>
<td>Digging equipment only</td>
<td>Passive</td>
<td>Permanent</td>
</tr>
<tr>
<td>Ghat</td>
<td>River edges</td>
<td>Stone or concrete</td>
<td>+/- 10,000 sf</td>
<td>&gt;$10,000</td>
<td>Yes</td>
<td>Needed for stonework</td>
<td>Passive</td>
<td>Permanent</td>
</tr>
<tr>
<td>Stepwells</td>
<td>Urban centers</td>
<td>Stone</td>
<td>+/- 50,000 sf</td>
<td>No longer built</td>
<td>Yes, as individual wells</td>
<td>Needed for stonework</td>
<td>Passive</td>
<td>Permanent</td>
</tr>
<tr>
<td>Canals</td>
<td>Connecting villages and farms</td>
<td>Earthen banks</td>
<td>+/- 900 linear km</td>
<td>Labor only</td>
<td>Yes, across many farms</td>
<td>For digging and dredging</td>
<td>Passive</td>
<td>Semi-Permanent</td>
</tr>
<tr>
<td>Bunds &amp; Tanks</td>
<td>Individual rural farms</td>
<td>Stone and earth</td>
<td>Walls up to 9’ tall, any length</td>
<td>Labor only</td>
<td>Yes, across many farms</td>
<td>For digging only</td>
<td>Passive but pumps can be used in tanks</td>
<td>Semi-permanent</td>
</tr>
<tr>
<td>Artificial Glaciers</td>
<td>Between glaciers and pipes</td>
<td>Stone and pipe</td>
<td>Up to 1 mile in length</td>
<td>$6,000 per major pool</td>
<td>Yes, within one watershed</td>
<td>Human labor</td>
<td>Passive but some maintenance is needed</td>
<td>Permanent</td>
</tr>
<tr>
<td>Ice Stupas</td>
<td>Between glaciers &amp; households</td>
<td>Plastic Pipes</td>
<td>+/- 1,000 sf</td>
<td>&lt;$1,000 per system</td>
<td>Yes</td>
<td>Human labor</td>
<td>Active effort during construction</td>
<td>Annual Construction</td>
</tr>
<tr>
<td>Snow Barrier Bands</td>
<td>High mountain passes</td>
<td>Stone</td>
<td>+/- 1,000 linear feet</td>
<td>Labor only</td>
<td>Yes</td>
<td>Human labor</td>
<td>Passive</td>
<td>Permanent</td>
</tr>
</tbody>
</table>

In addition to this table, each design strategy is described below, individually. A brief description of the type of intervention is followed by the adaptive response of each design solution.
Talaab
The talaab is a human-made depression, much like a pond, meant to hold monsoonal water for use across the entire year. These communal water access points serve as multifunctional landscapes, places for people to collect water for household use, but also a space to bathe, wash clothing, and commune. More than 1.3 million talaab are known to exist in India (Nawre 2013). Where water scarcity is a potential problem, talaab can help to extend water resources across the entire year. The catchment ponds hold water when it is abundant (during the monsoon) for drier times. (Figure 2)

Ghat
India’s ghat line river edges, as a series of steps, to both enable human access to the water and to minimize flooding. The stepped edge of the river promotes communal space and interaction, where humans gather to perform personal tasks as well as to gather for cultural, social and religious functions. Moreover, this hardened edge also effectively holds the water in the river, minimizing flooding by creating a stepped zone that can also carry additional loads. This edge therefore acts as a dynamic edge, populated by human activities and occasional flooding events (Samant 2004). Ghat function like public parks, and each ghat may take on its own identity, defined by the activities it hosts: laundry, yoga, basketry, boat making, puja, etc. (Figure 3)

Stepwells
India’s stepwells are mostly out of use, now, having been replaced by smaller wells and municipal water systems. However, many of the old stone stepwell structures still exist, where they are venerated for their craftsmanship, used as a communal meeting space, and often host active shrines. When the stepwell was used for water management, it was an elaborate, stone structure built into the earth, shaped like an inverted pyramid that enabled individuals to reach well water via a series of steps. Because these steps funnel down into the far reaches of the bottom of the well, water was made available to citizens during both high and low well levels. When not holding water, the stone steps served as space for socialization and reprieve from the heat, thanks to the shade and cooling breezes afforded by the well. (Figure 4)

Canals
The canal is used to move water throughout India, but it is most clearly expressed as a spine, edge, and movement corridor in the state of Kerala. Here more than 900 km of canals move water throughout the low-lying landscape, effectively transporting and equitably distributing water. This system enables water access more uniformly across the land, while also reducing the risk of flood and drought events. (Figure 5)

Bunds and Tanks
On the Deccan Plateau, bunds are the earthen embankments that extend across swales to trap rainwater, and tanks serve to collect that runoff (Mathur & De Cuna 2014). Bunds typically slow and retain monsoonal rainwater on a site, so that it might recharge the groundwater, or be collected to serve as irrigation later in the year. However, bunds are also used in India to manage mud and retain topsoil, as well as to deter saltwater intrusion. Combined with storage tanks, bunds can help to direct and hold rainwater for human use.

Much like the practice of contour bunding, which is a strategy typically employed in mountain or hillside agricultural contexts, India’s bunds promote water retention and reduce soil erosion. Bunds are made from locally-harvested stone, which is piled up above the ground to form bermed walls. Stone bunds also typically enter into the ground, and they can be dug into the ground up to 9 feet. While bunds are challenging to build, they remain as landscape features, and continue to work passively, with minimal additional management over the years. (Figure 6)

Artificial Glaciers
In northern India, water is collected as it cascades down a mountain slope and stockpiled, as ice, for agricultural use in the spring. These formations are called artificial glaciers, as the ice masses share similar shape, form and function as the natural glaciers in this region. Artificial glaciers represent one of the many ways in which farmers have begun to extend the water resources issued from larger, parent glaciers, by trapping water in the winter months that otherwise would
move into the Indus watershed below (Clouse 2014). Artificial glaciers can extend up to a mile in length, and once built they require very little oversight, aside from the seasonal manipulation of regulator gates. (Figure 7)

**Ice Stupas**
Similar to the artificial glacier, ice stupas redirect and collect winter snowfield meltwater to a site located above a village, where it is stored, as ice, until the spring planting months. Ice stupas are smaller than artificial glaciers in terms of footprint, but they can grow to 60' in height. Interior pipes shoot water up into the cold air from the center of the stupa; when it freezes on the surface it builds a larger ice mass. Buddhist monks from monasteries visit and bless these stupas, connecting the process of water management to the religious fabric of Ladakh. (Figure 8)

**Snow Barrier Bands**
Also found in northern India are snow barrier bands: the long, linear walls that have been erected to funnel snow into drainages with village settlements. In this high-Himalayan rainshadow context, water is extremely scarce, and yet critical for subsistence agricultural purposes. By pushing water into specific drainages with farms below, snow barrier bands increase the water resources available to village farmers.

Snow barrier bands are constructed from site-harvested stone, and once built, may serve a community for many decades. A recent snow barrier band build, at Warila Pass in Ladakh, effectively enlarged and improved an existing 100-year old snow barrier band. These constructs rely on gravity and wind, and once created, can serve their purpose without human management or oversight. (Figure 9)

**DISCUSSION**
In India, water is a resource that is typically understood as a form of the commons. It is a shared resource, a basic human right, and a critical component of efficient and effective agricultural landscapes. The eight examples highlighted in this paper have developed over time to reflect specific site constraints, as well as physical features and social responses that connect to the place in which they perform. Still, all eight examples also feature a shared set of qualities: they are multifunctional landscapes, with deeply intertwined ecosystem services, and in many instances they also overlay social and cultural spaces. Together they suggest the breadth of ways that Indians have historically managed, regulated and conserved water for public use.

Vernacular hydrological landscapes suggest a number of important design attributes. They tend to be visible structures, with clear, decipherable organization and components. They are often built by the people who will rely upon the system, using inexpensive local materials. Such connections to the construction process enable ongoing maintenance while also allowing for low-tech, incremental adaptation. While many of these solutions are often labor intensive, in India they have been extraordinarily affordable.

In acknowledging the diverse array of attributes and contextual responses that characterize water management strategies in India, designers can better understand potential opportunities for improvement and adoption. Moreover, by distilling each water management strategy into discrete components, we can better understand each design in relation to its broader urban planning relevance. (Table 2)

**Table 2: Adaptive Potential. Source: author**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Primary Use</th>
<th>Adaptive Application</th>
<th>Improves Husbandry</th>
<th>Downstream Impacts</th>
<th>Could this intervention scale up, or be applied in other contexts?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talaab</td>
<td>Storage</td>
<td>Drought</td>
<td>Yes, through awareness</td>
<td>Possible pollution</td>
<td>Yes, these depressions would work in any flood-prone landscape. New Orleans, for example.</td>
</tr>
<tr>
<td>Ghat</td>
<td>Access</td>
<td>Flooding</td>
<td>Yes, through awareness</td>
<td>People access waterway, possibly polluting the river</td>
<td>Yes, these access points help to minimize bank erosion and improve people’s connection to river edges.</td>
</tr>
<tr>
<td>Stepwells</td>
<td>Access</td>
<td>Drought</td>
<td>Yes, through veneration</td>
<td>Aquifer is drawn down</td>
<td>Perhaps. This is an enlarged, communal well. It could transfer to other areas without pump technology.</td>
</tr>
</tbody>
</table>
Canals | Movement | Flooding | NA | Water is dispersed across landscape | Yes. These canals are ubiquitous, and when combined with barrages, help to provide fresh water access in low-lying coastal areas.

Tanks and bunds | Retention and Storage | Drought | Yes, through soil retention | Less water leaves site | Yes. These are useful in places where sheet runoff removes soil, and water from farming landscapes.

Artificial Glaciers | Storage | Drought | NA | Less water volume runs into rivers | Yes. These require high mountain sites and drainages that feed communities.

Ice Stupa | Storage | GLOF reduction | Yes, through blessings | Less water volume runs into rivers | Yes. These may be used to help purge backed-up glacial lakes, while holding the water for future use.

Snow Barrier Bands | Deflection Increasing capacity | Drought | NA | Watershed on the other side of a pass is deprived of water | Yes. These bands may help to stop and funnel water into the appropriate drainages.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Talaab</td>
<td>Storage</td>
<td>Water source for wildlife</td>
<td>Watering hole</td>
<td>Swimming</td>
<td>Shrine site</td>
<td>Site for community events</td>
<td>Affordable water distribution</td>
</tr>
<tr>
<td>Ghat</td>
<td>Access</td>
<td>Reduction of river bank erosion</td>
<td>Watering hole</td>
<td>Access to swimming</td>
<td>Place for riverine offerings</td>
<td>Site for community events</td>
<td>Place for entrepreneurship</td>
</tr>
<tr>
<td>Stepwells</td>
<td>Access</td>
<td>Water source for wildlife</td>
<td>Watering hole</td>
<td>NA</td>
<td>Temple associated</td>
<td>Ornate stone carvings</td>
<td>Shared well, Affordable water distribution</td>
</tr>
<tr>
<td>Canals</td>
<td>Movement</td>
<td>Dispersal of water across a much larger landscape</td>
<td>Access to others via boat</td>
<td>Boating</td>
<td>NA</td>
<td>NA</td>
<td>Enables the cultivation of additional farmland</td>
</tr>
<tr>
<td>Artificial Glaciers</td>
<td>Storage</td>
<td>Retention of water on site</td>
<td>Built by people together</td>
<td>Ice Skating</td>
<td>NA</td>
<td>NA</td>
<td>Enables larger crops</td>
</tr>
<tr>
<td>Ice Stupa</td>
<td>Storage</td>
<td>Retention of water on site, Emergent vegetation</td>
<td>Built by people together</td>
<td>NA</td>
<td>Blessed by monks and a sacred site</td>
<td>Site for community events</td>
<td>Enables larger crops</td>
</tr>
<tr>
<td>Snow Barrier Bands</td>
<td>Deflection Increasing capacity</td>
<td>Retention of water on site</td>
<td>Built by people together</td>
<td>NA</td>
<td>Prayer flag sites</td>
<td>NA</td>
<td>Enables larger crops</td>
</tr>
</tbody>
</table>
There are a number of limitations to this study. First, in scope and range, the paper broadly addresses several different water management solutions in India, and therefore cannot offer a detailed assessment of each option. While eight different design solutions for water husbandry were selected for study, many more exist in India alone, and this paper would benefit from a more exhaustive survey of water management landscapes in the future. This is particularly important in the context of the shifts to water management systems in India and abroad: in the context of both climate change and the rural-to-urban demographic shifts that have become critical development pressures impacting water resources.

Finally, the topics of climate change adaptation and shifting population pressures on water security are in and of themselves complex, multifaceted issues (Sarté & Stipisic 2016). The paper acknowledges the nuanced approaches to contending with these major challenges without fully articulating those disparities. In gaining a better understanding of extant water management practices, and gleaning insight for future development challenges, this taxonometric approach is perhaps useful. However, next steps for this research include a more comprehensive approach to data collection and interrogation, revealing more explicit research outcomes.

CONCLUSION
As climate change threatens to change many of the weather conditions that have enabled stable water resources and sustainable water management in places across the globe, change will become the new normal. Also, as global water use increases with an increasing population and with new standards for water usage, water will likely become ever scarcer or more risky (Sarté & Stipisic 2016). In this context, communities will need to adapt or improve upon their longstanding water management practices.

Designers occupy an important role in this shifting water landscape (De Waegemaeker et al. 2016). Landscape architects, planners and architects are well equipped to envision future water systems. They are skilled in managing many different stakeholders, in representation and visualization, and in problem-solving. But designers are also adept at referencing historical precedents, and integrating old wisdom and knowledge into new design schemes. It is for this reason that designers would do well to consider the vernacular water management landscapes of India.

India is an important country to reference in the study of vernacular water management strategies, because the country has a broad range of climatic and weather conditions, irrigation approaches, and intact examples. Moreover, because the country has a history of managing water for more than 2,600 years, it is a rich repository for a wide variety of approaches and time-tested solutions.

Each of these eight design strategies for water management respond to, and will be impacted by, increasing population pressures and the shifting weather patterns caused by climate change (Gosain et al. 2006, Mall et al. 2006). In this context, it is worthwhile to examine the existing components of India's water management in an effort to better understand opportunities for adaptation in the future. For instance, attributes of systems may need to adjust to continue to be effective in the face of ongoing development pressures, and a clear understanding of these disparate elements may ease that transition.

Moreover, the considerable knowledge and experience found in India's current water management landscapes may be useful for other people, places and conditions. Alternate or hybrid systems could have applications for other contexts, and components or approaches taken from these systems may be useful when applied to other areas (De Waegemaeker et al 2016). As the swift changes in climate and urban living necessitate new forms of water infrastructure, the diverse approaches explored in India could become useful and valued contributions to the design field.

ACKNOWLEDGEMENTS
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REFERENCES


ABSTRACT: In this paper, I consider two approaches to the analysis of photographic practices carried out as part of the federally-funded Urban Renewal program. Using the case study of the Pruitt-Igoe housing project in St. Louis, Missouri, I map photographers' points of view and fields of view into a digital model to produce representations of the space of photography, and I map photographic fragments into a digital model to highlight photographers' biases and omissions. The work discussed here is characteristic of ways in which photographic practices were used in other cities engaged in the Urban Renewal program.

KEYWORDS: photography, Urban Renewal, Pruitt-Igoe

INTRODUCTION
As a topical subject for a case study in “the architecture of complexity,” few contemporary phenomena constitute as rich a field for inquiry as the federally-funded Urban Renewal program carried out in the United States largely in the latter half of the twentieth century. This program leveraged federal sponsorship to identify, study, and document “blighted” urban areas – i.e., districts and neighborhoods disproportionately inhabited by marginalized populations – and to clear those areas of existing buildings and people, allowing the properties to be resold or deeded to private developers. The deeply contested program, affecting as it did a constellation of diverse interests and populations (e.g., entrenched populations, racial and community identities, business interests, politicians, champions of historic preservation, etc.), was characteristically subject to complex, diverse and often contradictory practices of mapping, documentation, and propaganda.

As a specific case study condensing both the fleeting successes and the enduring failures of the Urban Renewal program, the Pruitt-Igoe project in St. Louis, Missouri, is at once one of the most recognizable icons of Modernism and Urban Renewal and – per Charles Jencks’ oft-cited and controversial remark – the enduring image of Modernism’s death. Yet, as later research has convincingly shown, Pruitt-Igoe does not easily sustain reduction to iconic image, irrespective of deeply-held partisan desires to promote the project as representative of either the best or worst of Modernist design. Its status as an icon notwithstanding, Pruitt-Igoe constitutes a highly charged case study for Urban Renewal research, due in no small part to the wide dissemination of photographic images of the project at various stages in its life.

1.0 THE SPACE OF PHOTOGRAPHY
1.1. Photography in the Urban Renewal program
Urban Renewal, as a federally-subsidized program in the United States, formally began with the passage of the Housing Act of 1937. The act effectively targeted for demolition those areas of cities which “by reason of dilapidation, overcrowding, faulty arrangement or design, lack of ventilation, light or sanitation facilities, or any combination of these factors, are detrimental to safety, health, or morals.” Until the 1949 Housing Act was passed, the responsibility for removing such areas belonged to municipalities; with its passage, federal help was made available to cities for the purchase and clearance of so-called “blighted” areas. The Housing Act of 1954 formalized the term “Urban Renewal” for the expanding program.

In pursuance of Urban Renewal goals, photography was an indispensable, constituent practice precisely because photographs could be selectively framed to highlight existing conditions and patterns of use, and to promote new possibilities for development; photography permitted “blighted” conditions to be foregrounded and brought to the attention of decision-makers. Conversely, opponents of the program mobilized photography to make a case for preservation of landmark buildings. As I have discussed elsewhere, such inherently selective approaches to photography could be used with respect either to individual buildings or to districts.

Consistent with contemporary discourse, Pruitt-Igoe was a politically charged and contentious project existing at the intersection of racial segregation, government involvement in public housing, architectural design, and urban planning. Considered as a subject environment for this research, Pruitt-Igoe constitutes a deep and rich source of photographic
material. The project, completed in 1954, was formerly located north and west of downtown St. Louis in an area generally bounded on the north side by Cass Avenue, on the south side by Carr Street, on the west by Jefferson Avenue, and on the east by North 20th Street. Prior to the project’s construction, this was a predominantly African-American neighborhood containing mixed-use buildings (e.g., two- and three-story multi-family apartments, single-family detached and semi-detached houses, retail, warehousing, and some light industrial structures). The neighborhood – with the notable exception of two churches – was almost completely razed in the early 1950s in order to make way for the Pruitt-Igoe project. Pruitt-Igoe was originally intended as a mixed-race project, although residents were kept racially segregated among the project’s buildings. As is well documented, over a period of fifteen to twenty years, the Pruitt-Igoe project deteriorated and it was eventually demolished in the early 1970s. The site remains almost entirely vacant today.

Absent the promise of resolving the multiple, intertwined layers of politically charged questions surrounding the Pruitt-Igoe project, yet in the hope of finding ways to highlight and foreground those questions to the extent that they remain latent within a photographic record, this research specifically seeks to test the potential of new analytical tools upon old photographs. While the history of Pruitt-Igoe – including the history of the neighborhood prior to its construction, and the contemporary history of the project’s site – constitutes a complex situation variously susceptible to analysis, this research is guided by the expectation that new technologies could potentially be brought to bear on that history.

Tactically, the work discussed in this research consists of two approaches. First, the points of view and fields of view of photographers within a defined urban environment are mapped into a model of Pruitt-Igoe to represent the space of photography, i.e., the collective space made visible through a set of photographs. When considered as representative of the collective behavior of photographers, a space of photography uniquely reveals biases, omissions, predilections, and intents. Secondly, sampled historical photographs are mapped into a digital model, enabling the construction of views from any arbitrary point within the environment, as well as to deconstruct biases inherent in individual photographs. In these ways, the latent capabilities and limitations of photography as a practice are foregrounded, and their relevance to the study of Pruitt-Igoe is newly examined.

1.2. Production of POV/FOV maps
Given one or more photographs of a subject site (i.e., a building, or an urban district), and a digital model of the site, the model can be populated with data registering the photographers’ positions, fields of view and directions of view. The resulting three-dimensional dataset is specific to the photograph or photographs under consideration, and is here termed the space of photography of those photographs.

A space of photography can be made visible in several ways, of which the point-of-view/field-of-view map (or POV/FOV map) is perhaps the simplest (Figure 1). A POV/FOV map takes the form of a plan or a section, and together with conventional plan- or section-based annotations representing built features, also records photographers’ points of view and fields of view.

Clearly, a given site can host an arbitrary number of spaces of photography, each corresponding to an individual photograph, or to groups or collections of photographs. Moreover, a given space of photography can register the practices of photographers. For example, given a specific building or site, a space of photography corresponding to a set of professional documentary photographs should be expected to differ from a space of photography corresponding to a set of photographs taken by tourists. Furthermore, a set of images resulting from an internet search (e.g., by means of Google or Flickr) should be expected to exhibit its own unique characteristics, with “popular” images arising earlier or more often in the search results.

1.3. Pruitt-Igoe and St. Stanislaus Kostka Church
Consider the Catholic church of St. Stanislaus Kostka located on the eastern edge of the Pruitt-Igoe site. The late nineteenth-century church was one of the few structures in the Pruitt-Igoe project area to escape the wholesale demolition of the neighborhood in the early 1950s. An online image search for photographs of St. Stanislaus returns several contemporary photographic images of the building (of which the first ten are mapped in Figure 1). Through the use of a simple digital model of the building, the photographs can be mapped into a space of photography to make the photographers’ vantage points and fields of view apparent.
This map (i.e., a POV/FOV map of a particular space of photography) reflects the inherent bias of the images resulting from the Google search: i.e., that photographs of the church from the east and south are more prevalent than photographs from other vantage points. Indeed, based only on the photographs available through a Google search, it would seem that photographs of the west side of the church are uninteresting, unpopular, or simply non-existent. The bias is simply explained by the fact that the contemporary condition of the site makes it difficult to take photographs of the west side of the church from any significant distance.

Historical photographs of St. Stanislaus are, in general, reflective of a different set of practices. When the building was photographed in the context of the Pruitt-Igoe project, evidence suggests that it was addressed either as a building marginalized from the photographer's focus of attention, perhaps important for establishing context, or for the purpose of establishing difference between what constituted the Pruitt-Igoe project and what did not; or as a kind of reference for locating or orienting a particular view of the project to a known and easily-distinguishable landmark structure. Again, a selection of historic photographs can be mapped into a space of photography to emphasize this point. Although the sample size as currently constituted is small, the initial mapping is suggestive: when St. Stanislaus was photographed within the context of the Pruitt-Igoe project, it was rarely identified as a focal point.
Figure 2: A point-of-view/field-of-view map of St. Stanislaus Kostka in the context of selected Pruitt-Igoe photographs.

A pair of photographs consistent with this interpretation is reproduced in Figure 3. The image on the left is a contemporary photograph of the church resulting from the Google search cited above, while the image on the right is a historical photograph of the Pruitt-Igoe complex within which St. Stanislaus (circled) can be observed.

Figure 3: At left, a contemporary photograph of St. Stanislaus Kostka church; at right, a historical photograph of Pruitt-Igoe with St. Stanislaus Kostka circled.

The photographic collections mapped in Figure 1 and Figure 2 are drawn from different times and contain radically different subject matter. Figure 1 illustrates the result of Google's search algorithms, which clearly indicate a bias toward contemporary photographs of the publicly accessible sides of the church, and moreover, toward photographs which are centered on the church and tend to exclude other content. The collection in Figure 2 is a “curated” collection, selected from publicly available, digitized archival photographs of Pruitt-Igoe, on the basis of whether the church appeared in the image, even marginally.

In particular, the comparison between the spaces of photography mapped in Figures 1 and 2 demonstrate two distinct ways in which such a space can function. First, a map of the space of photography can emphasize practices of photographers' behavior, i.e., the difference between using photography as a practice of drawing attention as distinct from using it as a practice of marginalization. In contemporary practices, the church stands out as a landmark building...
representing a tangible, documentable connection to a past state otherwise preserved only in records. By comparison, practices at the time of Pruitt-Igoe tend to treat the building marginally, admitting it to attention primarily for the reason of providing a counterpoint to the documentation of the then-new housing complex.

Secondly, the space of photography functions as a mechanism for disclosing practices of orientation. Seen in this way, the church constitutes a stable reference making it possible to ground the photographs across spans of time. The mechanism provided by St. Stanislaus in this way is exactly analogous to that provided by St. Bridget of Erin Church on the opposite corner of the Pruitt-Igoe complex (demolished in 2016), or the Gateway Arch on the Mississippi River in downtown St. Louis, both of which are visible in several historic photographs of the Pruitt-Igoe project.

**1.4. Implications for the Study of Urban Renewal**

As I have remarked elsewhere, photography is a set of politically charged practices implicating buildings' capacity to operate as mechanisms for producing images. The images “produced” by buildings are shown here not to be neutral with respect to photographic practices, i.e., in relation to the particular agendas and motivations of photographers. The implications of this work to future study of the Urban Renewal program are profound, insofar as photographs were key components of (a) local agency applications for federal funding to study and clear sites for renewal, and (b) preservationists’ efforts to identify sites for protection against demolition. In other Urban Renewal projects, conditions as documented through photography have been shown to be neither typical nor representative of as-built conditions. The method for producing POV/FOV maps is therefore a potentially important component of the future study of such situations.

**2.0. MAPPING PHOTOGRAPHS INTO DIGITAL SPACE**

**2.1. Pruitt-Igoe Opening Day**

Mapping photographic images into a three-dimensional digital model makes it possible to view those images from arbitrary angles, in particular from simulated vantage points external to the associated spaces of photography. Stated differently, when mapped into a three-dimensional model, a photographic image can be displayed in three-dimensional space together with a diagrammatic representation of the image’s point of view and field of view. This ability has the apparent effect of disassociating the pixel-based content of a photograph from the locus of the original photographer’s practice.

Figure 4 reproduces a photograph taken on the opening day of the Pruitt-Igoe project, with a large crowd in seated and standing positions, occupying a grade-level plaza along Dickson Street. Three newly-completed Pruitt-Igoe buildings are visible behind the crowd, and St. Stanislaus Church is just visible at the left margin of the photograph.

![Figure 4: Photograph taken on opening day, Pruitt-Igoe project.](image-url)
Figure 5: Photographic imagery from Figure 4 mapped into a three-dimensional digital model of the Pruitt-Igoe project, diagramming the photograph’s point of view and field of view. St. Stanislaus church is at left.

Figure 5 shows that the photograph’s content is in some sense typical of the imagery made possible by the construction of the Pruitt-Igoe project, all but three buildings of which are not present in the photograph. Furthermore, the marginal presence of St. Stanislaus Church, on the eastern edge of the Pruitt-Igoe project, functions as an orientation device as discussed in this paper’s previous section. Arguably, photographs such as the one reproduced as Figure 4 served an important function in the marketing and promotion of Pruitt-Igoe, emphasizing the project’s apparently eager clientele in the context of modern, “purist” architectural design. (Although not considered in detail here, later photographs of the project served a similar function with regard to the deterioration and vandalism experienced by the project in the years prior to its demolition.)

2.2. Photograph of Mixed-Use Buildings at Jefferson-Biddle
Consider a historic photograph of a neighborhood store with apartments above, on the southeast corner of Jefferson Avenue and Biddle Street, along the western edge of the Pruitt-Igoe site (Figure 6). The buildings in this photograph were demolished to make way for the Pruitt-Igoe project. The photograph was taken by renowned St. Louis photographer Arthur Witman, and is one of several photographs taken of the demolition of buildings in the area.

Figure 6: Historic photograph of mixed-use buildings at the corner of Jefferson and Biddle.
Sampled imagery from the historic photograph is mapped into a three-dimensional digital model depicting the neighborhood demolished to make way for Pruitt-Igoe, and the photographer's point of view and field of view are diagrammed within the model (Figure 7). The diagrammatic representation of Witman's point of view and field of view suggests he was positioned on the opposite side of Jefferson Avenue, outside of the boundaries of what was to become the Pruitt-Igoe site. The surfaces documented in his photograph conceal a hidden depth which the model makes clear: this is not simply the depth of the buildings directly photographed but the depth of the extended neighborhood behind the buildings.

On first inspection, photographs such as the one reproduced as Figure 6 are useful to the study of Urban Renewal simply because they provide a kind of documentary record of historic buildings. But the possibility of mapping such photographs into a digital model, as shown in Figure 7, extends the usefulness of the photographs into a realm of speculation – why, for example, was a specific point of view chosen, rather than other apparently possible viewpoints? In mapping photographs into models, we are better equipped to ask about a photographer’s conscious or unconscious biases: was a photographer acting under his or her own discretion, or in pursuit of someone else’s agenda? What was excluded, what was highlighted, what was concealed? While more work is required to explore these questions in depth, the research shows promise, as it begins to outline a method for opening up historic photographs to a new discussion of latent motivations and biases.

2.3. Summary
Digitally modeling a space of photography in three dimensions, whether the space is associated with a specific photograph, or with a collection of photographs, constitutes a representation of the space significantly distinct from a map-based representation as discussed in this paper’s first section. The digital modeling of the space of photography suggests new avenues for disclosing bias present in single photographs or collections of photographs, specifically insofar as the model makes it possible to visualize how specifically-framed photographic subject matter relates to its immediate and distant context.

3.0. FUTURE WORK
This work is proceeding on several fronts. Additional online photographs from several archival sources are being assessed as candidate members of a large image set for purposes of visualization and analysis. Where appropriate to the investigation, large-scale reproductions of selected photographs may be requested from sources. Additionally, the digital model of the Pruitt-Igoe site continues to be refined with additional detail and metadata. These two efforts (photograph assessment and model refinement) are complementary: even as photographs are mapped into the model,
the detail in the model is being refined in response, enabling future work to be carried out with greater accuracy.

In the broadest sense, this work contributes to the larger project of architectural epistemology, i.e., the study of how information about architecture is produced, structured and disseminated. The project is a primary motivator for an upcoming monograph, in which the Pruitt-Igoe project will be discussed at length alongside other illustrative examples.

CONCLUSION
Although the work described here is purposefully narrow in scope, focusing on questions which are susceptible to digital modeling, photographic compositing, and spatial geometry, it has clear implications in other areas. In particular, the work is potentially relevant to – but does not yet explore in depth – issues of racial identity and segregation, government involvement in public housing policy, and the persistence of culturally significant practices and constructs. Pruitt-Igoe’s rich history condenses political and governmental issues, as well as questions of race and segregation, and any serious effort to explore this history from an architectural perspective will benefit from an expanded toolset.

Yet, despite its purposefully narrow scope, the work described in this paper supports the larger contention that photography, taken as a whole, is a politically charged set of practices with implications and repercussions across many realms. For example, as I have discussed elsewhere, photography is complicit in the canonization of buildings, as suggested by Charles Jencks’ well-known use of photographs depicting the demolition of Pruitt-Igoe.” In its wider applicability, the research could be brought to bear upon the criteria used by the federal Urban Renewal Agency to approve local and state requests for funding the clearance of urban areas targeted for redevelopment. In particular, as local and state agencies worked to demonstrate the existence of “blight” to the satisfaction of federal authorities, as a precondition to receiving federal funding, photographs played a central role and were used strategically to emphasize a renewal area’s “worst” conditions.

In summary, this research aims to provide a tool for identifying potential biases within photographs, which necessarily constituted a small though significant factor within the constellation of forces comprising the Urban Renewal program. Even as its own historical power to frame content and to orient interpretations is diminished through the use of digital models allowing the production of images from arbitrary viewpoints, photography and photographs are shown here to be susceptible to analytical methods brought about by new technologies and toolsets. In this way, photography’s relevance extends beyond the purposes and motivations of its originators.

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REFERENCES


Photography in the Urban Renewal Toolkit: The Case of Pruitt-Igoe: Christenson


ENDNOTES

1 Jencks' remark, published in several editions of his seminal book originally titled The Language of Post-modern Architecture, is as follows: "Modern Architecture died in St. Louis, Missouri on July 15, 1972 at 3:32 p. m. (or thereabouts) when the infamous Pruitt-Igoe scheme, or rather several of its slab blocks, were given the final coup de grace by dynamite ... Boom, boom, boom." Charles Jencks, The Language of Post-Modern Architecture (New York: Rizzoli, 1977), 9.


8 See Christenson, “Research Notes.”

9 See, for example, Richard Cahan, They All Fall Down: Richard Nickel's Struggle to Save America's Architecture (Washington, D.C.: Preservation Press, National Trust for Historic Preservation, 1994); or With Heritage So Rich: A Report of a Special Committee on Historic Preservation (New York: Random House, 1966) – a seminal and influential document in the development of the historic preservation movement, one that relies extensively on photography and that was published in the year of passage of the National Historic Preservation Act.


12 See Christenson, “Research Notes.”
**ABSTRACT:** In 2006, China's central authority released a new policy calling for “Building a New Socialist Countryside.” This policy embraces a set of ideas that aim to boost modern agriculture, increase rural affluence, advance infrastructure construction, and improve public services and democracy. The local practice, however, turns this broad concept into a ground up rebuilding of a new countryside where rows of identical apartment buildings rapidly emerge in rural China. Meanwhile, rural residents are relocated to new settlements and historical and vernacular houses are demolished. Using Yanxia village in Zhejiang Province as a case study, this paper examines the local deployment of this policy. Drawing upon archival research and ethnographic fieldwork, this paper argues that the newly constructed settlement fails to provide a satisfactory home environment for the local residents because of its detachment from the existing cultural landscape. This detachment fundamentally breaches the place-bound relationship between the residents and the vernacular settlement, which is essential in constructing the meaning of home for residents of Yanxia.

**KEYWORDS:** Home, Vernacular Architecture, Tradition, Modern Development, Rural China

**INTRODUCTION**

In February 2006, China's central authority released a new policy that called for “Building a New Socialist Countryside,” which became the base for an ongoing political and social movement in rural China. This document identifies a broad set of economic and social goals that are highlighted in its official slogan: agricultural development, affluent life, civil society, clean and ordered built environment, and regulated democracy. These five goals are carefully laid out in a hierarchical order. The first and foremost goal of the policy is to boost modern agricultural development. It then focuses on the farmers, including improving their living standard and welfare; finally, it touches upon the built environment. Nevertheless, this document does not advocate the necessity nor the importance of building a new rural environment. However, the underlying intent of this policy has been misinterpreted by some Chinese scholars, who advocate creating a “clean and ordered built environment” as the key in constructing a new socialist countryside (Li 2006; Yang et al. 2009; Liu, Cheng, and Zhang 2009; Liu and Zhuang 2009). Specifically, Qiu (2006) argues that creating a clean and ordered built environment is the foundation for the other four goals, because a clean and ordered built environment is the prerequisite for agricultural development, the essence for affluent life, the medium to realize a civil society, and the physical carrier for democratic practices. Supported by scholarly arguments, constructing a “clean and ordered built environment” gradually became the priority of the local deployment of this policy, especially after 2008 when the overall political context in China started to focus on housing, land transfers, and urbanization (Looney 2015). As a result, newly planned settlements with rows of nearly identical houses or apartment buildings that are detached from the existing cultural landscape have rapidly emerged in rural China since 2006. Meanwhile, rural residents are forced to move out of the vernacular settlements that have been their homes for generations.

Using Yanxia village in Zhejiang Province as a case study, this paper examines the local deployment of the policy of “Building a New Socialist Countryside.” Through examining the planning and the design of the new settlement, this paper argues that the newly constructed settlement, although claims to provide a better residential environment such as a larger living area and indoor plumbing, fails to become a satisfactory home environment for the local residents because of its detachment from the cultural landscape of Yanxia. This detachment fundamentally breaches the place-bound relationship between the residents and their vernacular settlement, which is essential in constructing the meaning of home for residents of Yanxia (Zhao 2015).

This paper draws upon archival research and ethnographic fieldwork conducted in three phases between 2007 and 2016. The first phase, between 2007 and 2008, focused on the history and cultural traditions of Yanxia. The second phase, between 2010 and 2015, focused on the meaning of home as understood by residents of Yanxia. During this phase of the research, single-use cameras were distributed to the participants, who were asked to photograph meaningful aspects of their homes. This process was followed by semi-structured and in-depth interviews focusing on the contents of the photographs. The third phase of the research was carried out in October 2016, which followed up with the participants on their living conditions and collected some basic data regarding the new settlement.
1.0 LOCATING YANXIA

Yanxia, a small settlement of about 2,000 residents, is located in the middle of Zhejiang Province and is about 350 kilometers to the south of Shanghai. The Cheng family moved to Yanxia in the middle of the fourteenth century and soon turned this once multi-family settlement into a lineage-based settlement with many collectively owned public spaces, including ancestral halls, ponds, and open spaces (Zhao 2015). These public spaces were the center for social activities and cultural performances, through which the bond among members of the lineage were strengthened and the intimate social relations among residents were built. In the 1850s, members of the Cheng family started hosting pilgrims, who came from afar during the pilgrimage season to worship the local deity that was enshrined on the top of Fangyan Mountain, the rocky landscape located at the western side of Yanxia. Since then, this family-based hospitality business provided the major source of income for most of the residents. Meanwhile, residents developed a strong attachment to the local deity and the cultural landscape that nurtured this religious practice.

In 2006, the local government of Yanxia announced the plan to relocate all residents to new settlement area as a way to clean up the vernacular build environment. This plan received great resistance from the local residents (Zhao 2013). It was not until the end of 2014 that residents finally started to slowly move out. Meanwhile, some residents started to construct their new houses, in the style of four- or five-story townhouse, in the new settlement that is a few kilometers away from Yanxia. As of October 2016, while the new settlement was still under construction (Fig. 1), Yanxia was largely razed to the ground with a few remaining families struggling to live their lives (Fig. 2).

Figure 1: The new settlement as being constructed in October 2016. Photo by the author.
2.0 THE VERNACULAR PLACE AND THE MEANING OF HOME

In addition to being a contextual, relational, and cultural construct (Appadurai 1995; Gupta and Ferguson 1992; Massey 1994; Rodman 2003), vernacular place covers what Rapoport (2005, 20) defines as the “system of settings,” within which daily activities take place outside the physical boundary of a house and at locations collectively shared by all residents, such as the places to get water. In addition, Fei (1992) argues that lineage-based vernacular settlements in rural China are highly socialized spaces and rests on social relations established upon consanguineous coordinates. In addition, the consanguinity is also a social force that not only stabilizes and sustains rural societies, but also results in an attachment to place.

Based on this understanding of place and certain aspects of Chinese culture, Zhao’s (2015) dissertation argues that the meaning of home, as it is understood by residents in Yanxia, goes beyond the physical boundary of house or the legal boundary of homestead and is attached to cultural traditions recognized by the local residents. These traditions include the lineage structure and its associated kinship affairs established in the early fourteenth century, family-based economic practices started in the 1850s, and, most importantly, the land in which their residential spaces have been situated for generations.

This understanding of home is well illustrated in the case of participant C23 as shown in Figure 3. This diagram illustrates the locations and perspectives of the 16 (out of a total of 27) photographs that participant C23 took outside the boundary of the courtyard house he shared with his sister’s family. In addition to these 16 photographs, four photographs participant C23 took inside the courtyard house focused on objects and sceneries directly associated with local cultural traditions. Overall, 49 percent of all 610 identifiable photographs focused on things outside the physical boundary of the homestead and on traditions that were either treasured by an individual family or collectively shared by all the residents of Yanxia (Zhao 2015).
As the most important set of traditions in constructing the meaning of home for residents of Yanxia, the place-bound relationship can be best illustrated through participant C25’s words:

At our place here, we have the mountains, have the water, have the land, and I have my private plot. If I move down there, won’t I then become a city dweller, who can only eat? The water from the mountains is very good, and it is free. There are not even any ponds down there. How could I wash my clothes? How could I live my life? And they say that it will be better than my present life?

Participant C25’s comments contains four messages. First of all, he felt a strong place-bound relationship to his village, Yanxia, which provided fundamental resources for living, such as water and firewood, land to grow grains and vegetables, and ponds to do laundry. Secondly, this place-bound relationship was the means by which he identified himself, as well as other residents living in Yanxia and even the entire population living in rural China, as being different from city dwellers, who, in his view, were detached from the land and the raw materials and could only enjoy the finished and final products. In addition, he did not want to lose his identity and live like a city dweller where the living environment would require what he considered a fundamentally different lifestyle. Lastly, the better lifestyle defined by the local government officials and professionally trained planners and architects was quite different from the desired rural lifestyle described by participant C25. In other words, participant 25 did not yet accept the new identity associated with the lifestyle of city dwellers or acknowledge its compatibility with who he was.

3.0 THE MISSING COMPONENTS IN THE NEW SETTLEMENT
The new settlement is located a few kilometers outside the valley in which Yanxia is located; it used to be a large piece of agricultural land belonged to villages of the surrounding area. The local government acquired the land and turned it into the new settlement for Yanxia and other seven villages, as well as the site for the new government building.

Since the new settlement is still in construction, an in-depth study on whether or how the new settlement, as part of the new socialist countryside, affects people's lives and their understandings of home cannot be carried out yet. However, a few findings can be revealed from examining the planning and the design of the new settlement with the understanding of the place-bound relationship in constructing the meaning of home for residents of Yanxia. The following analysis focus on the role of public space, the importance of lineage structure, the sense of ownership, and the economic challenges.

3.1. The Lack of Integrated Public Space
The vernacular built environment of Yanxia was integrated with collectively owned buildings, such as ancestral halls and the ancestral house named Degeng-Ju, and various kinds of open spaces, including ponds, creeks, small plazas, and even private courtyards (Fig. 4). These spaces, easily accessible by the residents, acted as a large and shared living space, where daily activities, social interactions, and cultural performances took place. The availability of shared public space is a fundamental difference between rural vernacular landscape and urban built environment. In addition, these integrated open and accessible spaces also nurtured a close social relation between neighbors. As summarized by participant C34 when he compared his life experiences living in Yanxia and the nearby city, “In the city, you close the door immediately..."
after you enter the door!” In other words, these open spaces and the public places were the core of an extended nexus that connected all the adjacent homes with open doors (Fig. 5). As a result, the residents living in those homes formed an intimate social relationship that crossed the boundaries of homestead and family.

**Figure 4:** The southern section of Yanxia with the indication of all the open spaces and collectively owned buildings (“A.H.” stands for Ancestral Hall. “Xi” means brook. “Tang” means pond). Drawing by the author.

In comparison, the new settlement is modelled after development projects of urban China and is not integrated with the kinds of open spaces or collectively owned buildings that served local residents as in Yanxia (Fig 6). Designed to prioritize automobile transportation, the new settlement is dominated by wide and straight driveways. As a result, the buildings, as well as the little patch of green space, are surrounded and defined by driveways and parking spaces. In contrast to the extended nexus of open spaces in Yanxia, this extended network of driveways seem to hinder the interactions, as well as the establishment of social relations, between neighbors (Fig 7).

**Figure 5:** Residents were socializing at the open space in front of Degeng-Ju. Photo by the author.
3.2. The Breakdown of Lineage Structure

Cohen (2005) argues that the examination of any matters of social life in rural China needs to be based on the understanding of lineage structure and kinship affairs. As a lineage-based settlement, the built environment of Yanxia evolved and grew as the lineage proliferated. The lineage not only organized ritual activities throughout the year, which continually strengthened the lineage and the bond among family members, but also helped its members in times of difficulty. Participant C3’s personal story demonstrated the importance of lineage in rural China. His family, who were not descendants of the Cheng lineage, used to be a well-established family in Yanxia running a very successful family-hotel in the early twentieth century. However, after a fire destroying the building, his family collapsed financially and then physically. Without the help from the lineage, they could not rebuild the building nor find an alternative way to make a living. To survive, they had to give up one of their sons, participant C3, and let an older single male from the Cheng family to adopt him, so the family could become associated with the Cheng family and then have a place to live with the help of the lineage.

In comparison, the new settlement was designed without the consideration of the role and the importance of lineage in rural China. Not only was it designed to have no integrated spaces that support kinship affairs, the new settlement also dismantled the existing lineage structure. During the relocation process, the residents from eight villages were assigned the locations of their new houses through a lottery system. In other words, the members of the Cheng family, as well as residents from other lineage-based settlements, are dispersed throughout the entire settlement and away from each other. As participant C29 believes: “the breaking down the existing bond within the lineage enabled the local government to do their jobs.”
3.3. The Loss of Sense of Ownership
Land ownership in China is a limited concept in the way that the complete ownership is dissected into three segments. These are legally defined ownership, use rights, and the rights of ultimate disposition, which, in most cases, belong to farmers of the same village collectively, the individual farmer and their families, and the government respectively (Yan 2014). In the case of Yanxia, all residents collectively owned all the land, while an individual or a family had the use rights to a specific piece of land for the purposes of constructing a house or farming. As a lineage-based settlement, when most of the residents belonged to the Cheng lineage, collective ownership and lineage ownership large overlapped. In addition, according to Fei (1992), the concept of family in Chinese culture has a flexible boundary and an extended family can be as large as the entire lineage. Therefore, in the case of Yanxia, this overlapping blurred the distinctions between what was my property, what was your property, and what were our properties; it also enabled residents to have a strong sense of ownership towards things they collectively owned, which helped strengthen the place-bound relationship. As participant C20 expressed her concern about moving to the new settlement, “If I go there, everything belongs to others. Even if I walk a little bit, the road belongs to others! In my village, we own everything together. Even if they build the house for me, I won't feel I own it.”

In contrast, the local government owns the land underneath the new settlement, while individuals or family only have the use rights to the lot where they build their new houses. This new model assigns the legally defined land ownership and use rights to different entities. Without having the land ownership, the sense of ownership residents have towards their new houses weakened. Without this sense of ownership, the meaning of home will start to crumble. As participant C33 believed, “neither a golden nest nor a silver nest is as good as my own muddy nest.” Participant C16 expressed a similar feeling, “it is hard to say which style of housing is good, which style of housing is worse. The best is the one that belongs to you!”

3.4. The Economic Challenges
As explained earlier, this family-based hospitality business had been the major source of income for most of the residents living in Yanxia. The emergence of this economic practice was due to Yanxia’s unique location: at the end of the pilgrim path and the foot of Fangyan Mountain. In other words, this practice was deeply rooted in place and was an essential part of the local cultural landscape. However, being away from the pilgrim path and the temple, the location of the new settlement can no longer supports such economic practice. In addition, as part of the rural lifestyle as described by participant C25 and quoted in section 2.0, when living in Yanxia, most residents grew vegetables in their private plots, did laundry and washed vegetable in the ponds, and collected firewood from the mountains. All these place-bound activates helped to lower the cost of living dramatically. In contrast, living in the new settlement as urban dwellers requires residents to pay for all their food and utilities. As participant C39 described, “if I move to the new house, I will start to spend money from the moment I wake up, because I have to pay for the water to flush the toilet.” When considering both factors, one can understand the reason for the strong resistance from the residents regarding for the relocation plan, because, for most residents, moving to the new settlement means not only leaving the home environment that their ancestor established in the fourteenth century, but also having unbearable economic challenges for the family.

CONCLUSION
The fundamental issue in the planning and the design of the new settlement for Yanxia, as well as for other seven villages, is its detachment from the local cultural landscape—the place—in which residents’ homes were rooted and nurtured. This detachment destructs the place-bound relationship between residents and the vernacular environment that their family had been living for centuries. Specifically, the new settlement is designed without integrated public spaces and collectively shared buildings that can serve as the center for daily activities, social interactions, and cultural performances. Instead of trying to maintain and protect the existing social relations within the lineage, the relocation process breaks down the intimate bond between neighbors and family members by scattering them throughout a large area. In addition, the division between the legally defined land ownership and the use rights for the residential buildings in the settlement diminishes the sense of ownership that residents have towards their new houses. Finally, the relocation causes many residents losing their way of living, which was the family-based hospitality business rooted in the place that marked the end of the pilgrim path. With the high cost of living in the new settlement, e.g. unable to continue agricultural practice and higher utility bills, residents will face great economic challenges after they move into the new settlement. Overall, the breaching of the place-bound relationship weakens the meaning of home as it was understood by residents of Yanxia. In other words, although providing better and modern houses judging from local government and design professionals’ perspective, the new settlement might fail to become a satisfactory home environment for the local residents.

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ENDNOTES

1 This paper is largely based on my dissertation that was completed in May 2015 at the University of Illinois at Urbana Champaign with the guidance of Professor Lynne Dearborn, Professor John Stallmeyer, Professor Helaine Silverman, and Professor Carla Santos. The title of the dissertation is “Home Beyond the House: The Meaning of Home for People Living in Yanxia Village, Zhejiang Province, China.”
EXPANDING INCLUSIVENESS-
INTEGRATING STUDENTS WITH ASD

Ulrike Altenmüller-Lewis, Dr.-Ing., AIA

INTRODUCTION

Autism spectrum disorder (ASD) and autism are broad terms for a group of multifaceted and complex neuro-developmental disabilities, often characterized by a range of autism-related conditions that occur in a continuum of different forms and gradations. According to estimates from the U.S. Centers for Disease Control and Prevention's Autism and Developmental Disabilities Monitoring (ADDM) Network, in 2012 about 1 in 68 children had been identified with autism spectrum disorder (ASD), an increase from 1 in 150 a decade earlier (Christensen, 2012). The disorder occurs in every racial and ethnic group and across all social and economic levels, but boys are 4.5 times more likely to develop ASD than girls. While some children and adults with ASD are able to participate in all or most every-day activities, others require substantial support to perform essential activities. Scientists believe that both genetics and environmental influences likely play a role in ASD, however to date no specific environmental causes or triggers have been identified with certainty. ASD is today often diagnosed in children between the ages of 1 and 4. Thorough neurological assessment and in-depth cognitive, behavioral and language testing is available and comprehensive evaluations with multidisciplinary clinical teams including psychologists, neurologists, psychiatrists, speech therapists and other professionals can provide guidance and help (NIH, 2016). The rapid rise in diagnosed children can be attributed to a better awareness and thus more frequent diagnosis of ASD. However, it also means that as a society we must better understand and appropriately consider the needs of people with ASD, needs that may vary widely. A broadening of the requirements and attributes of inclusive design is necessary. A new understanding of diversity is a key principle in the development of theories, tools and techniques of design for inclusion (Baumers, 2010).

While people at every age suffer from autism, supporting children on the spectrum and helping them to develop to their best potential should be of priority for our society. There is no cure for ASD, but behavioral interventions and coordinated therapy can remedy and significantly improve specific symptoms. Early behavioral/educational interventions with the use of highly structured and intensive skill-oriented training sessions can help children to develop social and language skills. Applied behavioral analysis can encourage positive and discourage negative behaviors (NIH, 2016). Typically, early detection and intervention gives children the most positive prognosis to attend regular school and participate in a typical classroom with the goal to eventually—while usually still faced with certain impairments—live independently or semi-independently in community settings. Engaged caretakers and health professionals can provide helpful environments, but regular educational setting too often still fall short of providing autism-friendly spaces that address the distinct needs of this specific user group. On the contrary, many well-intended “child-friendly” designs actually have unsettling or irritating effects on autistic people.

1.0 THE AUTISTIC USER AND THE BUILT ENVIRONMENT

While embarking on this research, we found contradicting studies and publications that lead to inconclusive results
and not always empirically support design recommendations. While an increasing number of researchers work toward producing better and more rigorous autism design studies, at this point data often is based on anecdotal evidence that is easily influenced by cognitive biases and usually lacks necessary controls (Henry, 2011). This paper gives a general perspective on the perception by people on the autism spectrum of the built environment. It outlines initial recommendations for environments that consider the needs of children with autism, with the hope of raising awareness to the cognitive styles and challenges of people and especially children with autism. While more rigorous studies have to be designed to obtain more objective data to fully underpin any design recommendations, we hope to raise an awareness that designing autism-friendly spaces can play an important role in providing environments that have the potential to improve the life of children and adults with autism; and as a result of anyone around them.

1.1 Sensory sensitive approach or neuro-typical approach
An examination of recent publications on autism-friendly design reveals two widely and competing disparate attitudes to designing for autism. We are presented with plausible arguments for a sensory sensitive approach and a competing neuro-typical approach.

Leo Kanner, who first described the disorder, implied in his earliest reports that autistic people process sensory information in a special way. At times this leads to unusual reactions to stimuli including hypersensitivity, hyposensitivity or inability to distinguish certain stimuli (Kanner, 1968). The sensory sensitive approach maintains that adjustments to the multi-sensory environment can be beneficial for individuals with autism and lead to positive and constructive behavior. ‘Sensory Design Theory’ presents a flexible and adjustable tool that can help generate architectural design criteria for environments based on their sensory qualities, while considering the needs of autistic users (Mostafa, 2003, 2008 & 2014; Henry, 2011 & 2012). While more prescriptive than descriptive, it can be applied in different ways and adjusted to the skill levels of the autistic user, which is especially important in learning environments that must be zoned for various activities (Mostafa, 2014). Similar to the neuro-typical approach, the sensory sensitive approach addresses the concern of generalization of skill by “using graduated sensory spaces, from the highly adapted to the typical, to allow for gradual skill development (Mostafa, 2008, p. 204)” (Mostafa, 2014). According to sensory sensitive theory, difficulties in processing and integrating stimuli from the surrounding physical environment, especially when faced with multi-sensory experiences, disturbs the ability to make sense of the environment and underlie the atypical behavior in autism (Iarocci, 2006).

The neuro-typical approach “proposes the immersion of the autistic user in as typical and stimulating an environment as possible, in order to encourage adaptation to the overstimulation so typical of the disorder and to replicate the level of stimulation found in the real world. The conceptual basis behind this design approach is that it would best prepare the autistic user for the generalization of his or her skills, particularly those acquired in a learning environment, to the outside world” (Mostafa, 2014). Supporters of this theory suggest that best help can be given if generalization rather than sensory sensitivities are addressed first. However, Mostafa warns that “it assumes that the user has received a certain quality of care and a consequent minimum level of baseline skill, whereby the autistic user is able to adapt to a degree that allows them to even use such environments. This, however is not always the case, particularly in the more severe instances of the disorder, in the early stages of intervention and in cases where intervention has been delayed or not been made available to the autistic individual, as is the case in most of the developing world. A further limitation of this approach is that it has not been empirically investigated and is based on a hypothesis rather than evidence based research (Marion, 2006)” (Mostafa, 2014).

1.2 Key markers and symptoms of the disorder
Autism, as a group of pervasive, multifaceted developmental disabilities, shapes every part of life for the people affected. One of the key characteristics of autism spectrum disorder and autism is that no two (or ten or twenty) people with autism will be completely alike and that autism-related conditions in different combinations occur in a continuum of different forms and gradations. Thus, every autistic person has a distinctive set of abilities and disabilities and as such, “every [autistic] child will be at a different point on the spectrum. And, just as importantly, every parent, teacher and caregiver will be at a different point on the spectrum. Child or adult, each will have a unique set of needs” (Notbohm, 2002). Known as a ‘spectrum disorder’, autism can become noticeable through a variety of symptoms that may range from a mild form of learning disorder or a barely noticeable social disability to a gamut of severe impairments and highly unusual behaviors. These conditions include, for example, intellectual disability, difficulties in motor coordination, attention and physical health issues that can lead to significant communication and behavioral challenges, and great difficulties in social interaction or isolated interests (US Centers for Disease Control Prevention, 2016). Often autism manifests itself with difficulties to interact or communicate verbally as well as non-verbally with others. Many people with autism exhibit restricted mental flexibility that reveals itself in overly rigid adherence to daily activities or routines.

1.3 The effect of ASD on perception and experience of space
Autistic people are often either highly sensitive or under-responsive to sensory experiences like sound, light or touch. Mostafa notes that...
The key to designing for autism seems to revolve around the issue of the sensory environment and its relationship to autistic behavior. [...] Simply stated this dialogue hypothesizes that autistic behavior [...] may be a result of a malfunction in sensory perception. This malfunction may take the form of hyper-sensitivity or hypo-sensitivity, in its various degrees and across the scope of all the senses, leaving individuals with autism with an altered sensitivity to touch, sound, smell, light, color, texture etc. In other words, this leaves them with an altered sense of the world around them (Mostafa, 2014).

Mostafa, who also developed a sensory design matrix in an attempt to track sensory impulses within the built environment, further notes that “autism is a spectrum with each individual exhibiting a different sensory profile with variant response to stimuli (Anderson, 1998) (her) matrix generating different, and sometimes conflicting, design guidelines for each sensory profile examined” (Mostafa, 2014). Mostafa then warns that, while a customized design may work exceedingly well in environments that only cater to the needs of one autistic user, would be much more difficult to transfer to group settings where users may have greatly varying needs (Mostafa, 2014).

Besides the many deficits there are also significant differences in perception of senses associated with autism that impairs the way of thinking and perceiving the world. Stijn Baumers and Ann Heylighen (2010), who analyzed written reflections of spatial experiences and challenges of people with autism, maintain that characteristic behavior is tied to these different spatial experience, which is based on a special way of sense-making or organizing spaces or spatial environments in the autistic mind. This in return also influences the way the autistic adult or child interacts with or is able to de-code their environment. They note:

Different theories confirm that people with autism are characterized by a particular view on the environment, be it restricted to what is directly perceptible (Lawson, 2003) or just fragmentary (Happé, 1999). Due to a fundamentally different way of information processing, adequate sense-making needs to be consciously constructed step by step (Noens & van Berckelaer-Onnes, 2004). The conscious experiences of people with autism show that bringing a space into use can signify much more than only performing a certain action on a given place. Even the smallest details of the built environment can attract the attention, and in this way, using space includes seeing, hearing, feeling, smelling, ... and thoroughly experiencing different dimensions of that space (Baumers, 2010).

Further the authors report that an acute awareness of detail and heightened sensory awareness that exceeded the perception of the average person must be considered when designing spaces.

A term used to characterize the appropriateness of a particular person-behavior-environment transaction is “congruence” or “fit”. Fit is a state of equilibrium where an individual’s capabilities are in balance with the demands of the environment. Equilibrium may not be a specific pivot point but rather “zones of adaptation” within which individuals are sufficiently challenged yet not so challenged or deprived that they are under pathological stress. Perception of users plays a role in “fit.” Enabling environments, designed to achieve the best fit, should be congruent with the functional requirements of users (Baumers, 2010).

Through their analysis of written ‘auti-biographies,’ Baumers and Heylighen (2010) also uncover ways autistic people have found for dealing with the built environment and better understanding the importance of the physical surroundings to their user. They state:

In the study of the world of experience of people with autism, the attention was attracted by the grip offered by physical space and the sense of certainty and confidence this can bring about. The predictability and regularity of the physical space even turn out to cause objects, as immovable entities, to qualify the spatial behavior of people with autism. This notion of grip, offered by physical space in an autistic perspective on the world, can value the physical entity of objects. Even banal objects are essentially physical anchor points of the built environment, which can draw attention to what is undeniably here (Baumers, 2010).

2.0 DESIGN CRITERIA AND RECOMMENDATIONS

Despite the obvious opportunities, the consideration of specific design features may bring, autism and other cognitive disabilities have generally been excluded from architectural design codes and universal design guidelines (Mostafa, 2014). After considering perception with its various sensory triggers as exercised by the built environment, and equipped with the knowledge about two competing approaches to autism-friendly design and an awareness of the imperfect nature of any recommendations that have not yet been able to be studied in an empirical setting, we can now better gauge how responses to this input from the environment and architectural design are linked to autistic behavior. Many considerations need to be made when designing environments for people with ASD. The recommendations listed below lean on but expand those suggested by Magda Mostafa with her Autism ASPECTSTM. They should, however, not be considered an exhaustive list but rather provide initial guidance for designers and educators to help them design and/
or adjust educational environments for school and day-care spaces. They are meant to help better integrate children on the spectrum into the learning environment so that they may reach maximal independence, a sense of security, and their fullest integration into society. The following parameters are particularly relevant when designing or adapting spaces for autistic users (National Autistic Society: Environments & Surroundings, 2016). They are listed briefly and shall contribute to enhancing well-being and ensuring the safety of residents and staff (National Autistic Society: Building Design Factors, 2016).

2.1 Safety
Safety may be the biggest concern for children with autism who may have an altered sense of their environment and little or no awareness of danger. So, the key focus is to provide a low-risk and safe environment that is also proofed against escapes. In general, the layout and organization of the facilities and the intent of the design should be to allow the greatest possible freedom and independence for all users while minimizing hazards, security risks or behavioral triggers for those with ASD.

2.2 Context and Community
Inclusion and respect in society gains importance with rising numbers of diagnosis of children with ASD. The necessity to provide community-linked services to support families and individuals but also to afford the opportunity for student interaction with society should be considered. Including services for people on the autism spectrum within neighborhoods helps develop social and vocational skills in the students as well as promote a positive productive image of autism to the community at large (Mostafa, 2014).

2.3 Zoning and Compartmentalization
The clear organization of functions with respect to one another is of surpassing importance as it has great impact on the comfort of the user, the conducive quality of the learning environment and the possible independence enjoyed by students within a building (Beaver, 2003, Whitehurst, 2012; Mostafa, 2008, 2014; et al.). The sensory environment should be clearly defined and limited so that each activity, within shared spaces, a classroom or even an entire building, is organized into discrete compartments, each housing a single and clearly defined function and consequent sensory quality. It is vitally important that functions are visually and spatially separate and organized.

2.4 Spatial Sequencing
Considering the affinity of individuals with ASD to routine and predictability it is sensible to organize spaces in a logical order and involve sensorial compatible function. Ideally the spatial sequence is based on the typical scheduled use of spaces and allow a seamless transition from one activity to the next through one-way circulation. This can alleviate disruption and distraction throughout the day. Areas that require a high level of alertness but provide low stimulus, can be grouped together. Services, which are usually high-stimulus, including bathrooms, kitchens, staff-rooms and administration, should be separated from the student areas. Buffer areas such as gardens, free-play, sensory curriculum rooms and some other open spaces may act as transitional areas between the low-stimulus “focus” zones and the high-stimulus “alertness” zones (Mostafa, 2014).

2.5 Thresholds
The separation between individual zones or compartments does not need to be abrupt but must still clear transitions are preferable. It has been found helpful to clearly distinguish the sensory qualities of each space. This will help provide sensory cues as to what is expected of the user in each space, with minimal ambiguity (Mostafa, 2014). These thresholds or transition zones help the user adjust their senses as they move from one level of stimulus to the next and are especially important as users transition from high-stimulus areas to those of low stimulus.

2.6 Way-finding, Navigation & Circulation
The lack of a comprehensive organization and anticipated logic behind the organization of space can easily cause confusion and distress when autistic users lose their spatial orientation, either within buildings or in the outside environment (Baumers, 2010). Mostafa and others stress the importance of conducive wayfinding and navigation that can assist the special needs user when coupled with sensory zoning in gaining various skills and independence while freeing staff and faculty. Some researchers have gained positive experiences with transition zones such as gardens and sensory curriculum rooms may assist when this one-way circulation is not possible. Others (Assirelli; Beaver (2003); Whitehurst (2006, 2012) further suggests to steer away of corridors but rather develop well designed circulation space that afford opportunities for socializing or being to themselves and a range of other activities such as various types of play or story-telling. These inviting but more open-ended spaces can foster a sense of independence (Assirelli, 2016).

2.7 Escape Spaces & Sensory Rooms
Secluded retreats are important features in educational facilities to provide relief for the autistic user in case of overstimulation through their environment. (Mostafa, 2008, 2014; Whitehurst, 2006, 2012). When no separate rooms are available, small partitioned areas and corners throughout the building can provide these quiet escape spaces.
Provisions of distraction-free, generally neutral sensory rooms as leisure facilities and possible retreat areas are further recommended. These rooms should per se provide only minimal stimulation to provide an important respite but can be equipped with adaptable and flexible equipment that can be changed to be either stimulating or calming to meet the needs of individual users.

2.8 Control of Sensory Stimuli
A tight control of all sensory stimuli is necessary throughout learning environments for children with ASD. These include aspects of acoustics (Mostafa, 2008, 2014; Beaver, 2006), lighting (Mostafa, 2008, 2014; Beaver, 2006) and also the use of color (Beaver, 2006, Whitehurst, 2006), heating, ventilation and the control of scents (Whitehurst, 2014, Clements and Zarkowska, 2000).

Acoustics
Among the sensory stimuli within the built environment, acoustics is the most influential factor on autistic behavior (Mostafa, 2014, Beaver, 2006). Mostafa reports on significant improvements to attention spans, response time, self-regulation and behavioral temperament, if children with autism learn in environments that strictly control noise levels, reverberation and echo (Mostafa, 2008). She recommends further adjusting acoustical control in response to the level of focus and activity in the respective zones and to consider “the skill level and consequently severity of the autism of its users. For example, activities of higher focus, or according to Sensory Design Theory, those taking place in “low stimulus zones”, should be allowed a higher level of acoustical control to keep background noise, echo and reverberation to a minimum” (Mostafa, 2014).

Lighting
Similar to acoustic stimuli, visual stimuli and adjusted lighting levels can create active and calm zones throughout the schools and should be designed appropriately to their activities. Access to natural daylight for both people with ASD and their caretakers have proven beneficial. However, careful control of reflections, glare and shadow patterns is necessary. Artificial lighting should be equipped with dimming controls to allow for adjustments or designed as indirect light source to create a glowing interior (National Autistic Society: Building Design Factors, 2016). The use of harsh fluorescent fittings is strongly discouraged.

Color
Neutral and calming colors and the use of natural materials are best suited for autism-friendly learning environments. Disturbing and overly stimulating colors should be avoided. Beaver (2006) recommends careful choices to ensure a good balance between the shared and private spaces.

CONCLUSION
This paper summarizes first explorations of research in the field of autism-friendly environments and uncovers the need and the possibilities of further investigation that will be necessary to better understand the complexity of issues related to the perception of and interaction with the built environment by people on the autism spectrum in general and the implications for educational environments specifically. At this moment though we feel that we have raised more questions than we are able to answer. More rigorous studies have to be designed to obtain objective data to underpin possible design recommendations. As Henry (2011) states concerning any design parameters, “the effectiveness of any of the aforementioned measures remains unknown” (Henry, 2011). We also want to add that the success of architecture always requires us to look at the building as a whole and not only the sum of its individual parts. Especially, when tackling a complex and sensitive challenge as autism, one must look both at the individual elements and the building, its context and the pedagogy as a whole. While we are aware that our research is in its infancy, we believe that designing autism friendly spaces can play an important role in providing buildings, spaces, furnishings and technologies that have the potential to improve the life of children and adults with autism, and as a by-product anyone in their environment. Failing to consider the needs of this user group can easily result in more frequent episodes of behavioral incidents and social insulation (Henry, 2011). We do not claim to give a complete and empirically grounded assessment or all-inclusive design guidelines but want to inspire designers, to engage in the challenge of dealing with the profound complexity that the design process for autism-friendly spaces implies. We hope to create awareness that to design these environments and consider the needs of all users, architects and designers must surrender their own notions on the built environment and be open to other ways of perceiving and interacting with space.

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ABSTRACT: This paper investigates the origins and the cultural development of the 19th century German country schools of Gillespie County, Texas focusing on three selected school sites which have been preserved and maintained to the present day by the descendants of the original builders and students. By 1900, there were over forty rural schools thriving in close-knit rural communities which eventually would close through consolidation in the 1950s. Today, less than twenty remain standing preserved through private support as cultural heritage centers concurrently maintained to accommodate a wide variety of community activities. This study begins with an overview of rural education in Gillespie county followed by the analysis of three surviving schools evidenced by archival materials, oral histories, and on-site field documentation. The central thesis of this paper is the architectural qualities, functional purposes, and building technologies found in the rural schools of Gillespie County represents a contextual cultural response to social and physical needs, and delineates a syncretic method for merging embedded social traditions from the German source regions of the original colonists with the cultural and environmental conditions of the Texas Hill Country region. The sustainability of the schools as historical sites and active community centers is highly dependent upon the physical support of the living descendants of the families who attended the schools, and as their numbers diminish the future of the schools is uncertain.

KEYWORDS: Material Culture, Vernacular Building, Historic Preservation, Cultural Landscapes

In the introduction to his book Poststructuralism and the Politics of Method, Andrew Koch contends that knowledge is “a reflection of the conditions of human life. Our claims to knowledge are the products of our social and physical needs, environmental necessity, and conceptual ordering of reality.” (Koch, viii) Are distinctive and sustainable cultural landscapes, such as the one founded by the Germans of the Texas Hill Country, the result of “contextually contingent” knowledge? A term Koch uses to describe a poststructuralist view which negates any assumption of universally accepted standards for knowledge. To answer this question, it is necessary to understand the origins of the German immigrants and their founding of Gillespie County. Located in the west central area of Texas, Gillespie County was situated in the vast expanse of territory north of the Rio Grande won from Mexico by the Republic of Texas in 1836. In 1846, one year after Texas became a state, a group of around 120 Germans settled permanently in the area establishing the town of Fredericksburg. They belonged to an organized mass immigration movement directed by German noblemen seeking social, economic, and political freedom who hoped to recreate an independent “New German” community in the remote unsettled territory of central Texas.

Although the search for religious freedom motivated some Germans in the 1700’s, it was seldom an active consideration for the majority of German immigrants who reached Texas in the 1800’s. Social and economic improvement, along with political idealism, were the primary goals of these Texas settlers. (Lich, 16)

Seeking free land grants, the Germans endured exceptionally hard times according to Ferdinand Roemer who joined the colony in 1847. He described the living conditions as deplorable with colonists living on “a diet of bear meat, corn meal, and coffee.” (Morganthaler,58-64) The first public building erected in Fredericksburg in 1847 was the Vereins Kirche (People’s Church) which also served as the first school. Over time, land was settled in the outlying county as it became apparent that the traditional farming methods widely practiced in Europe were not possible in the thin rocky soils of the Texas Hill Country. Ranching and grazing soon eclipsed garden crop farming as the main source of income, and numerous small communities sprang up throughout the county as the Germans relinquished European farm village settlement patterns and spread far into the countryside. Early buildings were small in scale and were often first log cabins copied from American settlers rather than the substantial farm estate homes of landed German farmers from the immigrant’s source regions in central and northern Germany. The modest means of the early settlers necessitated an expedient and affordable means of habitation and this approach to building carried forward in the country schools.

Though log houses were popular especially in the initial years of settlement, within a few years some German Texans began to choose to use the traditional German fachwerk, a heavy frame carefully fitted together with mortise and tenon joinery and infilled with stone, brick, or— in Texas— adobe. Those who chose to build in
The founding of schools very early in the establishment of the town of Fredericksburg and the surrounding county of Gillespie underscores the cultural importance of formal learning which was highly valued in the source regions of Germany which provided the bulk of the immigrants to Gillespie County during the years between 1840-1870.

A sense of community and social responsibility was very important to the Germans of Gillespie County, who placed great emphasis on the traditional values of church and school. (Kohout)

As the town of Fredericksburg grew during the 1850s the Germans operated rudimentary private schools. In 1854, the State of Texas passed laws which formed the foundation of a public education system laying out a framework for the establishment of “common Schools” which received state money and were further supplemented with local revenues managed by locally elected trustees.

The 1854 law was a major commitment to establishing secular education in Texas, but for the most part, private schools continued as few places were ready or able to organize a public education system. In Central Texas, however, counties with predominantly German populations were successful in starting commons schools. The Germans who emigrated to Central Texas in the 1840s had come with the enlightened and progressive ideals of 19th century Europe and were adamant in their desire for free public schools. Gillespie County, with impetus from the 1854 school law, converted its rudimentary semi-private school, and starting with six common districts, established a public education system. (Fisher 1986, 23)

Numerous small rural communities through Gillespie county formed common schools and by 1900 there were over 40 country school districts. At first, basic instruction was conducted in the homes of individual settlers and often the teacher would take up residence with a family, especially if the teacher was unmarried. Eventually, permanent school buildings were built on donated property, often constructed by the community members themselves, at locations which were benefited by proximity to water, accessible to existing roads, and within practical distances to settlements where the students resided. A location defensible from Indian attack was often a high priority in the selection of site and the disposition of the buildings in the mid-1800s. The Gillespie County common schools flourished during the first half of the 20th century until the passage of the Gilmer Aikin Law in 1949. This law consolidated 4,500 loosely structured public school systems throughout Texas into 2,900 state administered units and by 1960 forced the closing of the original German common country schools.

As a result of the district mergers, countless rural schools-houses became obsolete in short order, and without a systematic plan for their continued use, many of them disappeared from the cultural landscape. Given the prevailing concept of local control, most school boards simply sold the structures. (Utley 2013, 117)

After the “consolidation” the country schools’ students were transferred into the Fredericksburg ISD. However, many of the former common school buildings throughout Gillespie county remained active community centers for 4H Clubs, community gatherings, polling places, family reunions, and weddings. More than places for regular school activities, the rural school locations continued to be useful places of gathering for the extended family groups who had attended the schools and shared a strong bond of kinship associated with the historical significance of each small school. By the 1970s, less than 20 schoolhouses remained intact and although owned by the Fredericksburg Independent School District, cooperation within the local communities associated with the schools insured the survival of some of the structures. In 1999, citizens became concerned that the school buildings would be lost if the district sold the land upon which 12 historic schools stood to private buyers. Working with legislators, the newly formed Friends of the Gillespie County Country Schools instigated the signing of Texas Senate Bill 116 which changed state laws allowing school properties to be donated to governmental or non-profit organizations at no cost. Today, the Friends oversee 12 historic German country school sites which are accessible on the Gillespie County Country Schools Trail. Three of these school sites are presented showing how the architectural qualities, functional purposes, and building technologies found in the rural schools of Gillespie County represent a contextual cultural response to social and physical needs demonstrating what Koch described as a “conceptual ordering of reality.”

**Distinctive Features of the Gillespie County Country Schools**

Several innovative local conventions or typologies in country school design and construction emerged in the late 19th and early 20th century. Apart from the schoolhouse proper, a second structure known as the “teacherage” was often constructed, either as an addition to the one room schoolhouse or a separate structure, which became the permanent residence of the teachers who were hired by the school trustees. Records of the various county school districts show a high turn-over rate in teachers during the early years. Rural teaching was often an itinerant profession and the teacherage better accommodated a married teacher with a family, reduced the time of travel to the school location each
day, and afforded the teacher in residence the opportunity to maintain the building and the grounds.

Professionally trained administrators and better educated teachers brought with them to the rural areas different expectations for living quarters. The “teacherage” was proposed as a solution to the problem of housing teachers and also as a model home for the edification of farm families. (Maxcy 1979, 267)

Schools closer to towns were less likely to have a teacherage as boarding places were close enough to reach by horse and wagon each day. Often a saddle barn and fenced areas for horses were built as many students rode them to school. Wells were dug and cisterns were installed to collect rainwater from the building roofs, a necessity for clean drinking water in times of drought.

A unique building type developed at many of the German country school compounds. Known as the “pavilion”, these covered gathering areas were originally built as large open air “pole structures” and were at first covered with tree limbs and foliage until shingles and tin roofs were applied.

The permanently constructed wood framed pavilions began to appear in the early 1930s at various school complexes in Gillespie County and were most likely inspired by the open air “tabernacles” common throughout the rural areas of the United States originating in the years following the Second Great Awakening to accommodate worshippers attending outdoor revival camp meetings. As with the adoption of the American log cabin and the teacherage, the tabernacle, introduced to the Texas Hill Country by settlers from Arkansas, Georgia, and Tennessee, would have been known to the Germans of Gillespie County as many were constructed in nearby counties including McCulloch, Mills, and San Saba.

Beginning with temporary stages erected for May festival celebrations, the permanent pavilion structures were built with a stage specifically designed for performances of singing, dramatic plays, and musical concerts by both students and parents at the onset of spring planting as classes concluded for the year. At some schools, elaborately painted stage curtains were created featuring a scenic landscape surrounded on the borders by the names of sponsoring businesses. Known as “school closings” each community used the pavilion, as well as the other school buildings for elaborate community celebrations at the end of the school year when students went to work on family farms and ranches.

The ending of a school year was an occasion for a big all day celebration. School closings were celebrated with BBQ, plays, and dances. BBQ, at one time, was prepared in three foot deep x four foot wide pits dug out of the ground. Meat was donated by members. The trimmings were brought by the women. The meat and drinks and other items were sold during the day. Admissions was charged for the plays and dances. Students were treated by local merchants. The students would be given two to three tickets for free refreshments, drinks, ice cream, etc. The money raised at these school closings was used for improvements and repairs of the school grounds and building. If not enough money was raised parents paid a certain amount per child to meet expenses. (GCPBC 1983, 10)

An important aspect of the country schools was to function as places of community gathering and social interaction beyond regular classroom activities, a concept uniquely associated with the German country schools. Still used today, the outdoor barbeque “pit”, which was often covered with a pole supported roof, was designed to prepare enough meat to feed a sizable group of people. The southern barbequing tradition, which dates to antebellum times, was also borrowed by the Germans to feed large gatherings of people during holidays and festivals becoming an enduring social tradition up to the present day. The common country school districts were populated by tightknit communities of extended family enclaves that over time developed each school site into multiple-use social centers which reflected the communal spirit of each group. Baseball fields were constructed for contests with rival schools, and shooting matches, singing festivals, and literature clubs, all social traditions highly prized in the German communities, were organized and held at the school sites. Gatherings at the rural churches and schools constituted the only social interaction many people had beyond the isolated daily life on the family farm or ranch. As populations grew and shifted, new roads were built, and creeks ran dry, many of the historic country schools were torn down and rebuilt, and disassembled and moved to other locations. Once established, the schoolhouses were enlarged and new buildings were added over time creating a spontaneous eclecticism of styles, materials, and configurations to accommodate an ever-increasing complexity in use and social meaning.

Cave Creek School: Figures 1-3
The first structure erected at Cave Creek in 1881 is a one-room wood building measuring 12’ x 16’. Shortly thereafter, a stage and a pole frame “pavilion”, 24’ x 66’, was added to this building. “The roof consisted of cedar and tree limbs for shade.” (GCPBC 1983, 10) The present schoolhouse (Fig. 1,2) was built in 1896 and consists of a wood frame structure measuring 20’ x 36’. Most likely, the original exterior was wood shingles and board siding but it is now re-covered in embossed tin siding panels and a tin roof, as were many buildings of the late 1800s in the region. More resilient and requiring less maintenance than wood, metal building cladding insured the long-term survival of many of the country schoolhouses. Typical of the era, water was collected in an underground cistern, heating was provided by a wood stove,
and gas or kerosene lanterns were used for lighting until electricity was installed in 1942. School began in mid-October and ended in May. Classes ran from 9:00 am to 4:00 pm, students walked or rode horseback or buggies to school, fenced pastures and corrals for animals were part of the school site as were outhouses, saddle barns, and outdoor cooking pits. “In 1932 or 1933, the pole frame structure was improved with a tin roof and concrete floor.” (GCPBC 1983, 10) (see Fig. 1, 3)

Figure 1: Cave Creek School Site Plan (Shacklette, 2016) & Aerial Photograph (Google Earth 2015)

The teacherage dates to the early 1930s replacing the original 1881 structure and it provided living quarters until 1944. Modern restroom buildings (Fig. 1:7) and additional storage buildings (Fig. 1:6) have been added to most of the surviving rural school complexes. Except for the teacherage-stage area (Fig. 1:2&3) all buildings conform to a NW axis unlike other school sites that generally feature more S-SW exposure. (see Fig. 1,4,7)

Figure 2: Cave Creek School Looking South-West (Shacklette, 2016)
Crabapple School: Figures 4-6

The Crabapple community is one of the earliest settlements founded by the original immigrants of 1845. “That there was a school as early as 1867 is evident from the commissioners’ court minutes which lists Crabapple one of the ten schools of the county then in existence.” (Gold 1945, 81) The first schoolhouse (Fig. 4:3) was constructed in 1878 from limestone quarried at nearby home sites and wood hauled from Austin by mule train. It was comprised of a large room and a smaller room with a fireplace. After the second year of school the teacher married and moved into the larger room and classes were taught in the smaller room. As enrollment grew a second larger one-room schoolhouse, 18’ x 26’, was built in 1882 west of the original school and it too was constructed of local limestone. (Fig.4:1) “After the second building was erected, the first building was used as a teacherage.” (GCPBC 1983, 31) The teacherage also served as the Crabapple post office from 1887 to 1910. The second school building was also used as a Lutheran church until 1897. In 1910, enrollment at Crabapple peaked at 60 pupils attending grades 1 through 7. Water was drawn from the nearby church well until a cistern was dug in 1936. The teacherage was expanded with a 10’ x 17’ wood framed kitchen addition extending eastward. This addition is clad in embossed tin siding panels like the schoolhouse at Cave Creek. (Fig. 6) This metal siding is seen throughout Fredericksburg in buildings dating from the 1880s onward and it was a cost effective and yet aesthetically compatible alternative to the preferred random coursed ashlar limestone common to the Hill Country of Texas.

It is not known exactly when the current pavilion structure was added to the original schoolhouse but the methods of wood joinery used would indicate the early part of the 20th century. (Fig. 4:2) A similar pavilion at Pecan Creek school was built in 1935 and it too is enclosed so this may help to date its construction. It is also likely that an earlier structure similar to the pavilion at Cave Creek may have existed. Sometime after its construction the open-air pavilion...
was encased with board and batten siding featuring operable hopper style openings which would allow light and ventilation during warmer months. (Fig. 5) Enclosing the pavilion made it suitable for additional overflow class space and community activities during fall and winter months. Some of the other country schools in the area adopted this approach as fluctuating enrollments and funds for new buildings were often scarce. A saddle barn of galvanized steel cladding over wood frame, and a structural clay tile restroom facility date to later years. When Crabapple consolidated with the Fredericksburg ISD in 1957 enrolment was then less than 25 students. Since then, community clubs continue to meet regularly in the buildings, and space is rented out for weddings, reunions, graduations, and birthday parties.

The Crabapple School shows an architectural typology first created by the Germans of Gillespie County in the 1870s which continues to remain a viable and sustainable place for community activities 60 years after the schools were shut down. The second limestone schoolhouse was constructed in 1882 for $600, which is equivalent to about $13,500 in 2017, suggesting a remarkable rate of return for a structure that has remained in continual use for 145 years, even when considering maintenance and upkeep.

**Figure 5:** Crabapple School North Elevation of Enclosed Pavilion and Schoolhouse (Shacklette, 2016)

**Rheingold School: Figures 7-10**
The Rheingold community was established in 1859 on North Grape Creek 14 miles northeast of Fredericksburg. The first school building was a 12’ x 14’ square log cabin built in 1873 and it is typical of early German buildings in the mid-19th century. (Fig. 7&9) The 22’ x 40’ wood frame schoolhouse existing today was constructed in 1900 and the original log cabin was converted to the teacherage and was enlarged with a matching wood frame addition in 1881 extending to the west and doubling the size of the original cabin. A second addition of limestone, estimated to be from the 1920s, measuring 10 feet wide was added to the north running the full length of the first two structures. (Fig. 10) At one time, the wood frame schoolhouse had a south facing porch and center door which has since been removed and the door rebuilt as a window. The pavilion, was “started in 1936 and finished in 1938” (Shacklette, Dec. 30, 2016) with materials

**Figure 6:** Crabapple School North Elevation of Teacherage, Pavilion, & Schoolhouse (Shacklette, 2016)
and labor donated by the community. As in the case of many of the school pavilions of the era, it may have had a dirt floor and hand hewn wood shingles before the additions of tin roofing sheets. “The school building, teacherage, and a later pavilion, were all built with materials and labor donated by the families of the community.” (Pue, D8) Enrollment at Rheingold peaked in the 1934 with 78 students and attendance eventually dwindled to less than 20 by 1949 when the school consolidated.

Figure 7: Rheingold School Site Plan (Shacklette, 2016) & Aerial Photograph (Google Earth 2015)

Of all the remaining 12 schools under the jurisdiction of the Friends of the Gillespie County Country Schools, Rheingold represents the fullest range of building technologies used by the trustees and community members during the common school era in Gillespie County. The original log cabin school was stuccoed on the south side and sided over with vertical wood boards perhaps to downplay the rustic origins of the school. The log cabin was sometimes seen as a crude type of building necessitated by the hardscrabble conditions in the early years of settlement. The wood frame addition uses manufactured wood siding on the south and west façades as does the 1900 second schoolhouse, (Fig. 8) and the limestone addition on the north side of the teacherage conveys an appreciation for the permanence and regional prestige associated with masonry construction. (Fig. 9&10) Wood framed buildings of milled lumber were easier to transport as roads improved and fast to erect onsite. An inherent advantage is larger glazed openings, less practical in either log or stone construction, increasing the amount of daylight to the interior rooms which is logical in the era before electricity became available. Within the last few years, the original red oxidized tin roofs on both the schoolhouse and teacherage have been replaced with galvanized steel, and modern restroom buildings have been added for convenience. (Fig. 7:1)

Figure 8: Rheingold School Pavilion & Schoolhouse (Shacklette, 2016)
The continued care given to Rheingold School in preservation and modernization call attention to the pivotal role volunteers and supporters have played in ensuring its survival over the past 68 years following the closing of the school. Community attention to maintaining adequate roofs, which prevent the inevitable destruction of structures, has contributed significantly to the survival of the schools and the schools will continue to remain viable community centers into the foreseeable future so long as local private support remains strong. The three case studies examined in this study, like many of the 42 common rural country schools of Gillespie county known to have existed, each began in the mid to late 1800s as single-room rural schoolhouses which necessitated an incremental process of adaptation, addition, and expansion eventually creating an aggregate complex of structures including teacherages, saddle barns, cisterns,
communal cooking pits, and the “pavilion” for public gatherings which are all unique elements only found in the German country settlement schools of Gillespie County. The process of adaptation and addition charts an ever-increasing complexity in a broadly conceived system for rural education which resulted from a local “knowledge” for building which formed a contextual cultural method for making places for social and physical needs. The modest rural school locations incrementally evolved into multifunctional centers for community celebrations and social interaction that lived well beyond the closing of the schools. The German tradition of compulsory education carried from the homeland was maintained in a difficult setting by borrowing American building forms and methods which were uniquely combined to create a system for rural education largely independent from external governmental, religious, and cultural influences. Incrementally evolving into multifunctional compounds for community celebrations and social interaction, the schools remained useful and important after closing as public schools in the 1950s because of volunteerism on the part of the descendants of the school attendees who value the utility of the structures, and have deep consanguineous attachments which have been forged between the schools and their respective communities for several generations. When asked about the future of the country schools Helen Birck, a school supporter and descendant who attended Crabapple and Cherry Spring Schools from 1955-1964, said “When we are no longer able to function as a club we worry.” (Shacklette, Dec. 29, 2016)) Each of the three case study schools are an example of how sustainably designed places result as much from human contexts as from special construction technologies. Today, each German rural school is a preserved cultural center contingent upon a complex network of community support which may become less certain as descendants move away and family lines die out.

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HEALTH IMPACTS OF MICROENVIRONMENTS IN THE SUMMER

Pravin Bhiwapurkar
University of Cincinnati, Cincinnati, Ohio

ABSTRACT: Economically deprived communities in urban areas face disproportionately significant health risks; children and the elderly are particularly affected. While socioeconomic factors are commonly associated with health disparities, the role of the outdoor environment, especially during extreme heat events, has been less frequently studied. This research investigates the heat stress index (HSI) and ultrafine particle (UFP) exposure in 24 microenvironments. The data were recorded during an extreme heat event in 2016; the goal was to better understand how residents experience environmental exposure as a part of their daily routine when the boundaries between microenvironments are repeatedly crossed. Additionally, a statistical analysis of such exposure along both spatial and temporal scales is presented here, in order to assess the dual roles of development patterns and overlapping loci of social interactions within these microenvironments. The results of this study shows that HSI and UFP exposure varies in space and time. The HSI in 54% of the microenvironments tested was within the danger zone identified by the National Weather Service (104°F to 124°F), while the remaining 46% of the microenvironments fell within the extreme caution zone (91°F to 103°F). The average five minute walk among these microenvironments indicated that 70% of the time, residents would be subjected to a danger zone, and the remaining 30% of the time they would fall within extreme caution conditions. The average UFP exposure varied from 7,633 to 34,751 particles/cm³. Microenvironments with a high percentage of sealant surfaces and lack of vegetation showed increased HSI values; close proximity to traffic and the freeway further elevated HSI and UFP exposure. These results are useful in understanding the health outcomes previously recorded by a community health survey in which heat and respiratory illnesses were substantial. The evidences presented here provide crucial context-specific information for re/designing urban communities to minimize health disparities.

KEYWORDS: microenvironment, development pattern, heat stress index, ultrafine particle exposure, low-income communities

INTRODUCTION
Economically deprived communities in urban areas face disproportionately high health risks. Children and the elderly are particularly affected (CDC). In addition, due to increased heat and high precipitation/flash flooding, the general urban landscape and built environment make low-income communities particularly vulnerable to heat-related illnesses such as heat stress and stroke, and respiratory afflictions like asthma (D’Amato et al. 2015). Demographic factors such as race, gender, age, and income are frequently-cited denominators for negative health outcomes in socio-economically impoverished communities (Claudio, Stingone, and Godbold 2006, O’Neill 2005). However, the responses of such communities to these health outcomes are not consistent (Beck et al. 2014) and vary per geographic location and the associated context-specific impact (e.g., proximity to industry, freeways, brownfields, etc.). Conversely, the role of the urban landscape and built environment has been less frequently addressed in medical literature, particularly in terms of how these issues intertwine with the design of buildings and complexes, as well as their interaction with the environment and society as a whole.

If communities hope to improve upon this situation, then documenting such dis/associations is crucial and green buildings and the new urbanism movement (i.e., form-based zoning) that claim to improve health can be adopted. However, the financial hardship faced by the residents of low-income communities, as well as decades of ignorance regarding appropriate development by their political leadership, make it challenging to implement such strategies, mostly when it is a top-down approach. While there are examples of successful reform, the resulting inner-city gentrification (Checker 2011) is a major concern. For instance, when Cincinnati economically developed the Over the Rhine community, it gravelly underestimated the displacement of local residents that would result (Addie 2008). Alternatively, bottom-up approaches such as do-it-yourself urbanism show promise (Kinder 2016); however, their success depends on occupants being provided with the necessary tools and support to implement resident-led change. Further, such efforts are gaining popularity in urban communities, the role of urban microenvironments within which the residents of low-income communities live, learn, play, and work continue to be poorly understood.

This study focuses on microclimates (Erell, Pearlmutter, and Williamson 2011), spaces between buildings and along sidewalks, green areas, street intersections, parking areas, and playgrounds within public housing complexes that
are modified by development patterns such as land use, land cover, tree canopy, street network, building typology, or development density. Environmental exposure within such microenvironments varies, due to urban processes and infrastructure systems. Residents overlap with them as a part of their daily lives, but are unaware of how such interactions affect their health. A health survey conducted in a South Cumminsville community (Cincinnati 2016) reported that 61% of residents felt irritable in summer due to heat exposure where 60% residents spent less than nine hours indoors and 42% of local children used parking lots and vacant lots as play areas. Thus, understanding how microenvironments act as a context for design interventions is essential to successfully improving the quality of residents’ health.

The overall goal of this research is to examine how low-income residents’ health is affected by their urban landscape, built environment, system infrastructure, and social patterns. In service of this goal, this study seeks answers to questions such as: How does the urban landscape and built environment contribute to local health risks? What are residents’ levels of environmental exposure within certain microenvironments during extreme heat events, in terms of the heat stress index and air pollution? How do social patterns affect environmental exposure? How do the data on microenvironments relate to and compare with the demographics and mental health records established in the case-study health survey?

1.0 THE CASE-STUDY COMMUNITY

The low-income community of South Cumminsville, located in the heart of Cincinnati, Ohio, was selected for this study because of its health concerns related to its increased exposure to heat, air pollution, and combined sewer overflow for the past 30 years. The existing urban landscape and built environment, which includes brownfields, empty warehouses, large parking lots, and facilities for the trucking industry, as well as proximity to a freeway and vacant buildings and lots, makes this location uniquely appropriate for this research. The study area was annexed by Cincinnati in 1873; at that time, it was known as Cumminsville. Subsequently, it was split into North and South Cumminsville by the construction of Interstate 74 in 1970. The east side of the study area is bounded by Mill Creek, certain areas of which are protected by the Mill Creek Conservatory. The west side of the study area is bounded by a hill and dense vegetation. The southwest is populated by low-income communities facing a fairly uniform level of development and health problems. Since construction of the freeway, the study area and vicinity have been adversely affected by flash flooding and traffic-related air pollution (TRAP). These phenomenon associated with health issues including heat stress, respiratory allergies and asthma guides the focus on outdoor environmental exposure.

South Cumminsville is one of the smallest of Cincinnati’s 52 neighborhoods, with a population of 801 in 2010 (Census Bureau). The majority of the population is African American (93.5%); White (3.9%) and other races are marginal. The average household income is $15,357, which is less than a third of Hamilton County’s median household income. Approximately 64% of the residents live at or below the poverty line. The majority of the households in South Cumminsville are headed by working class, single mothers. The majority of the population is female (53%) rather than male (47%). A study conducted by Cincinnati’s Health Department reported that the residents of South Cumminsville had a life expectancy of 71.2 years, which is nearly 16 years less than residents of more affluent Cincinnati neighborhoods.

2.0 HEALTH SURVEY

Due to a lack of timely health data on the area, a health survey of randomly selected residents was conducted in 2015 (n=118, including children), in an effort to better understand the health issues faced by the community. This effort was a subset of the City of Cincinnati’s “Project Cool It,” funded by the Center for Disease Control and Prevention’s Agency for Toxic Substance and Disease Registry (Cincinnati 2016). The survey collected neighborhood data and demographics such as gender, race/ethnicity, and age. In addition, respondents were asked to report their occupancy status (rent/own) and perceptions of their indoor and outdoor environments, so that researchers could investigate how self-perception of the environment might affect reported health outcomes. Respondents’ average length of residency was 18.8 years; moreover, 52.2% (n=64) owned their own homes, 48.8% (n=52) rented, and the remaining data (from two residents) were missing. This trend is consistent with the 2010 Census data.

This work was an important first step towards creating a baseline health condition for perceived physical and mental health. Complementing above health survey, this research examines how development patterns create microenvironments that modify both actual and perceived health concerns; in service of this goal, researcher recorded the heat stress index (HSI) and ultrafine particulate (UFP) exposure levels. Based on the survey results, 61.5% (n=72) reported feeling irritable in the summer due to the heat, and 41.9% (n=56) and 42.1% (n=48) of the residents cited summer heat as the cause of changes to their mood and general health, respectively. Approximately 30.8% reported having asthma or another lung disease; while 75.4% (n=89) described owning an air conditioner, only 69.5% (n=82) indicated that they used their air conditioner in the summer months. Four residents cited the cost of electricity as their reason for non-use. The majority, 60.3% (n=70), reported spending less than nine hours a day indoors during the summer months. Importantly, 42.7% of the children (n=50) described using parking lots as a playground; this was followed in frequency by vacant lots, which were used by 35.7% (n=41) of the responding children. The majority of
residents reported living within a one-block radius of a vacant building or lot and/or spilled chemicals. There was a greater level of variability in the respondents’ self-perception of the outdoor environment; in particular, 56.8% (n=67) reported that greenspace was available to them, and 87.1% felt safe walking in their neighborhood during daylight hours.

3.0 DEVELOPMENT PATTERN
South Cumminsville was developed as an industrial corridor in the 1880s, due to its proximity to water and rail. The combination of light industry and residences allowed workers to live in close proximity to their jobs. Prior to this industrial development, the adjacent waterways of Mill Creek and West Fork Creek created a flood plain; in 1937, flooding destroyed so many businesses and residences that the land use pattern was indefinitely altered. Several flood control projects were subsequently implemented, and the current risk of flooding is significantly lower. However, the community continues to be impacted by small-scale flooding. Beyond the economic, social, and environmental consequences of urban flooding, the chronically wet houses are linked to increased respiratory problems (Reponen et al. 2013).

To investigate the role of the built environment on occupant health, the community development pattern of the study site was analyzed using a Geographical Information System (GIS). The 2015 dataset was made available by the City of Cincinnati’s GIS department (CAGIS). Another element of the dataset, the physical attributes of the area’s buildings, were available from the Hamilton County Auditor’s records. Combining this information allowed the researcher to study development patterns such as land use, land cover, tree canopies, sealant surfaces, street networks, building typology and occupancy, and development density, among others. The intersection of development patterns with related urban systems such as traffic, sewer, and vegetation is also discussed below.

South Cumminsville covers 325.7 acres and is distributed across nine land uses: public service (43.7%), residential (11.47%), institutional (0.3%), mixed-use (0.13%), commercial (1.4%), public utility (1.6%), parks and recreation (7.8%), light industry (11.5%), and vacant (17.4%), as shown in Figure 1. The industrial zoning along the creek lacks vegetation and has a high number of impervious surfaces (roofs and parking lots) that increase the likelihood of flash-flooding. Approximately 42% of the land cover is impervious; it is concentrated near the creek on the east side of the study area (see Figure 1(a)), whereas a majority of the tree canopy (29%) is concentrated on the hillside, away from the creek (see Figure 1(b)). The topographical conditions, including the hills on the west side that slope towards the creek to the east, serve to increase the surface runoff. In addition, the combined sewer overflow (CSO) on the hillside releases surplus water from other areas into South Cumminsville. The result is that the land-use land-cover LULC, tree canopy, topographical conditions, and combined sewer overflow in the floodplain are creating hazardous conditions, resulting in a disproportionately high level of chronic illness in this community.

![Figure 1. (a) Land-use and (b) Land-cover properties of South Cumminsville, Cincinnati, OH (2015).](image)

3.1 Vacant lots and buildings
At the time of the 2010 Census, there were 422 total housing units, 110 of which were vacant. Fifty of these units were abandoned. Figure 2 illustrates the (a) vacant land, (b) vacant buildings, and (c) building uses in the community. The vacant lot and buildings map is regularly updated in response to foreclosures and demolition. Currently, the majority of independent residential development is located on the north side, on either side of Beekman Street. The south side...
hosts public housing projects and a few independent residences. The data also indicate that at the time of collection, 54% (n=168) were owner occupied, and 46% (n=144) were occupied by renters. Most residents were children under the age of 20 or middle-aged (45 to 49 for males and 50 to 54 for females).

The east side of Beekman Street, a prominent North-South street, hosts several industrial buildings. To date, approximately 30 sites have been identified as potential brownfields or appropriate for land reuse, including 58 acres of industrial land, three former oil refineries or oil warehouses, 15 acres of city-owned land (including one incinerator), two industrial properties on the city’s demolition list, a former gas station adjacent to an elementary school, and other industrial structures used for metalworking, metal plating, chemical manufacturing, oil refining, and printing. One of the most prominent business is a trucking company, which has significantly increased truck traffic in the community.

As might be expected given the proximity of residential areas to vacant lots and industrial spaces, 59% of residents reported living within a ½ block proximity to vacant properties, and 23% lived within a 1 to 3 block radius of the same (11% within one block, 8% within two, and 4% within three). Approximately 7% of the respondents indicated that they did not live close to a vacant property, and 7% reported no knowledge of the topic. At the same time, 51% and 39% of the residents felt that they had “very easy” and “easy” access to greenspace, whereas only 11% indicated that greenspace was either not easy or very difficult to access.

Figure 2: (a) Vacant land, (b) Vacant buildings, and (c) Building use.

3.2 Social Patterns
The use of impervious surfaces (such as parking lots, brownfields, and vacant lots) as playgrounds and areas to gather socially was a very common part of respondents’ daily routine, even though 90% reported easy access to the greenspaces. The majority of children indicated that they walked to the school, and that while doing so, they were on paved surfaces for between 5 and 20 minutes. To walk to school, students must travel along a major thoroughfare (Beekman Street), cross several street junctions (at Elmore St, Dreman St, and Millville Court), and wait near a number of parking lots (at residential, institutional, and commercial locations) at which TRAP levels are high. When not in school, a local non-profit organization, Working In Neighborhood (WIN), hosts a daycare center and uses their parking area for outdoor activities. Similarly, adults and children alike frequently use locally-owned shops, recreational areas, and open spaces along the Beekman corridor as sites for social gatherings. Youths, mostly unemployed, prefer to spend their recreational time in the industrial areas. According to the health survey, more than 60% of the residents reported spending less than nine hours a day indoors during the summer months. Home ownership, use of an air conditioner, and extremely hot indoor conditions during the summer months may all affect such behavior. Staying outside, however, increases exposure to heat stress and air pollution, depending on a resident’s location in the community. Therefore, understanding environmental exposure in terms of both space and time is critical to improving the health quality of the residents of this community. The following section examines environmental exposure in various microenvironments and its association with health stressors.

4.0 HEALTH STRESSORS
As suggested by the National Weather Service, the HSI and UFP exposure (Brandt et al. 2015, Brunst et al. 2015) were recorded as indicators of the heat and asthma-related diseases prevalent in the community. The data were collected on August 12, during the hottest week of 2016; air temperature and relative humidity were above 80°F and 40%,
respectively. The second-by-second data were collected by walking around the selected community spaces in two loops; a total of 24 microenvironments were covered (see Figures 3(a) and 3(b)). The first loop was completed in the northern section of the community, where a majority of the single and multi-family residences are located. This area is closer to the freeway and consists of light and heavy industrial use. The data were recorded for a total of 45 minutes, beginning at 11:00 am. The second loop was completed in the southern part of the community, where an elementary school, recreation center, and several public housing projects are located. These neighborhoods are closer to the industrial land use spaces, empty warehouses, and vacant lots. The data were recorded for 15 minutes, beginning at 12:15 pm. Figure 3(c) illustrates the combined loops; the analysis of the recorded data is divided into two categories: space and time.

The HSI was measured using a Kestrel 5400 Heat Stress Meter (NWS 2017). A state-of-the-art portable ultrafine particle (PUFP) meter, developed by researchers at the University of Cincinnati, was used to record particles smaller than 0.1µm that could have a significant impact on respiratory health (Ryan et al. 2015). Currently, UFP levels are not recorded at any of the EPA's monitoring stations; often, particulate matter (PM) is used as a surrogate. Importantly, the lack of location-specific measurements prevents a thorough investigation of how this type of exposure is entangled with development, social, and infrastructure patterns. Without a thorough knowledge of HSI and UFP exposure in low-income communities, future designs for health-promoting environments will be unlikely to achieve their goal.

![Figure 3](image)

**Figure 3:** (a) Path traversed in Loop 1, (b) Path traversed in Loop 2, and (c) The combined loops.

### 4.1 Heat Stress Index

The average HSI on a spatial scale is shown in Figure 4(a). The HSI in 54% (n=13) of the microenvironments fell within the danger zone (104°F to 124°F), according to the heat index scale provided by the National Weather Service (NWS 2017); the remaining 46% (n=11) of the microenvironments were within the extreme caution range (91°F to 103°F). HSI levels in this range can cause heat stroke, dehydration, and exhaustion, the primary causes of heat-related admissions to hospital emergency rooms and heat-related deaths (Hess, Saha, and Luber 2014, Klinenberg 1999, Sheridan and Lin 2014). In the study area, microenvironments such as street intersections, parking lots, and sidewalks along busy streets were all found to fall within the danger zone; such areas have a high percentage of surfaces covered in sealant, are in close proximity to anthropogenic heat (such as traffic), and lack a tree canopy. For example, the intersection of Beekman Street and Millville Court had the highest recorded HSI at 115.78°F, whereas a parking lot near the elementary school and public housing, almost empty at the time of data collection, was at just above 108°F. The HSI values along the sidewalks close to parking lots and industrial areas, and along streets with frequent traffic, were also high (i.e., within the range of 104°F to 108°F).
Figure 4: Heat stress indices: (a) Spatial distribution of HSI, and (b) Temporal distribution of HSI, averaged over 5-minute intervals (Outdoor Spaces - 1: Parking lot at WIN, 2: Dreman Avenue (WIN-Beekman), 3: Intersection of Beekman and Dreman, 4: Dreman Avenue (green zone), 5: Cass Avenue (single-family residential zone), 6: Hoffner Avenue (single-family residential zone), 7: Heron Avenue (green zone), 8: Powers Street (single-family residential zone), 9: Sylven Avenue (next to playground), 10: Intersection of Beekman and Elmore, 11: Llewellyn Avenue (single-family residential zone near freeway), 12: Borden Street (single-family residential zone near freeway), 13: Elmore Street, 14: Dirr Street (in industrial zone), 15: Dreman Avenue (in industrial zone between Dirr and Dawson), 16: Dreman Avenue (single-family residential zone between Dawson and Llewellyn), 17: Llewellyn Avenue (residential zone, near parking lot), 18: Parking lot of elementary school, 19: Beekman Street, 20: Intersection of Beekman and Millville Court, 21: Parking lot of a public housing project on Bellevue Street, 22: Millville Court, 23: Parking lot of a recreation center, 24: Playground between a recreation center and the elementary school).

It was also observed that a transition space between land use and land cover on the same sidewalk showed major variations in HSI. A sidewalk on Dreman Avenue that transitioned from an industrial zone (Outdoor Space 15) to a residential zone located near industry (Outdoor Space 16) and then to a residential zone away from any industrial zones showed average HSI changes from 106.97°F to 104.4°F to 98.81°F, respectively. Mature tree canopies in the residential zone likely contributed to this change, making a strong case for shaded sidewalks. At the same time, the sidewalk on Dreman Avenue that runs along a playground where shading is minimal showed an HSI of 103.01°F.

The average HSI values along a temporal scale are presented in Figure 4(b). It was observed that 70% of residents’ time-averaged HSI exposure estimated in five minute increments (described herein as Periods) fell within the danger zone, and 30% were within the extreme caution range. The highest HSI (109.74°F) was recorded during Period 10, which covered most of the school’s parking lot and part of Beekman Street. This period also showed the maximum amount of variation in HSI values, as the locations in which the data were recorded changed from the center of a parking lot, to a shaded space near buildings, to shade under a tree. Period 7, which was recorded along the Elmore Street sidewalk, had an HSI value of 107.65°F; this area was closer to industry and the freeway, and the tree canopy cover was minimal. This period indicated only a minimum of variation between the high and low HSI values, making extended periods of walking a concern. Also, Elmore is a busy street, and traffic affects the HSI values of sidewalks and intersections. Similarly, sidewalks without any tree canopy in industrial land use areas like parts of Dreman Avenue (Period 9) tend to have higher HSI values (Dreman Avenue had a value of 105.91°F) than do sidewalks in high-canopy areas (in this study, 102.08°F).

4.2 Ultrafine particulate exposure

The UFP concentration varied by both space and time (see Figure 5). Figure 5(a) shows the spatial variations in UFP exposure. The highest values were recorded at the intersection of Beekman and Millville (34,751 particles/cm³); this was followed closely by the sidewalk along Dirr Street (34,677 particles/cm³). The lowest UFP exposure (7,633 particles/cm³) was recorded along the sidewalk of Powers Street. Thus, the average UFP concentrations along the 24 microenvironments varied up to 78%. Such variations may have occurred due to traffic exposure, as this can instantly cause a spike in exposure levels. Therefore, the data presented in Figure 5(b) was averaged at five minute intervals. The parking lots (Period 10) and sidewalks along the major streets (Period 7) were the most susceptible to high pollution exposure. Street intersections were the microenvironments most susceptible to short-term exposure, such as what
was observed at the intersection of Beekman and Millville Court (Periods I and II). Areas near public housing, such as parking lots and sidewalks, were also among the spaces with the highest UFP concentrations.

Figure 5: Ultrafine particulate exposure. (a) Spatial distribution of UFP concentrations, and (b) Temporal distribution of UFP concentrations averaged over 5-minute intervals.

Distance from the freeway also affected the collected UFP exposure values, due to migrating pollution; areas within 500 feet of the throughway were the most affected (Ryan et al. 2005). In this research, however, the UFP concentrations were recorded during off-peak hours, and consequently, no such influence was observed. For example, sidewalks on Llewellyn (Outdoor Space II) and Borden (Outdoor Space II) located within 500 feet of the freeway actually had lower UFP concentrations than other microenvironments. However, the minimum UFP concentrations observed within the range of 10,000 to 15,000 particles/cm³ represented the effects of indirect pollution, since there was no traffic at the time of recording. One possible reason for this could be that UFP tend to be very light in weight and can stay in the air for up to 30 days before settling down. In such cases, UFP movement depends upon wind direction and speed. Consequently, it can be difficult to predict its actual contribution and thus was not attempted in this research. UFP concentrations during rush hour were higher than during non-peak hours, which was as expected; this finding also agrees with the literature (Ryan et al. 2005, Brunst et al. 2015), emphasizing the role of urban transportation systems in microclimatic conditions and their health impacts.

Vegetation plays an important role in reducing UFP concentration. Sidewalks along Cass, Hoffner, Herron, and Powers Street (Periods 2 through 6) are located in the greenest part of the community, distant from the freeway; consequently, they showed lower UFP exposure levels than the sidewalks along Beekman, Elmore, and Dreman Street (Periods 7 through 9), which are closer to the freeway and serve as major streets for through traffic. Existing land uses such as light and heavy industry are major UFP contributors because of the resulting truck traffic. The lack of vegetation and minimal freeway buffer were evident in the high concentration levels recorded. For example, a sidewalk on Dreman Avenue that runs east-west through the community and connects an industrial area on the west side with residential spaces to the east showed a mean UFP concentration of 37,847 particles/cm³ near the industrial areas; this was reduced to 11,909 particles/cm³ near the residential neighborhoods, where the tree canopy is denser.

DISCUSSION
The heat-related mortality rate in the US has decreased in the last decade, due to improved access to air conditioning, better forecasting, and a general increase in preparedness. However, heat-related mental health impacts and certain long-term illnesses are on the rise, and extreme heat remains a prominent public health threat (CDC); the built environment plays a significant role in this. The health survey report examined in this research and a cross sectional HSI and UFP exposure confirmed this in the study area. It is undeniable that a long-term investigation of the relationships among the physical attributes of the built environment and health outcomes is needed; however, the above analysis presents a preliminary results of the combined effects of development patterns, urban infrastructure systems, and socioeconomic factors on microenvironments.

There are several questions that must be answered as the city continues to search for ways to improve the environment.
These include: How can the pilot data regarding the health survey and environmental exposure be used to inform the design process? What type of designs provide hope for improved health in the community? Could resident-led changes be engaged to develop small-scale ventures using a bottom-up urbanism approach? And, How to integrate small-scale projects in holistic plan? Importantly, how to avoid gentrification as nearly half of the current residents are renters.

The evidences presented in this research provides crucial context-specific information that can be used to design and redesign the built environment in ways that stimulate improved living conditions and minimize health-related disparities in economically deprived communities. Health surveys and community science projects can provide support for resident-led changes geared towards lowering the public health burden caused by land reuse and brownfields. A survey instrument developed to document current health and place-based issues would provide an evidence-based platform for requesting changes to policies and funding for projects. Finally, this research's analysis of existing development patterns and processes and on-site environmental data offer meaningful opportunities for infill development and resident-led bottom-up urbanism projects that will include urban greening.

CONCLUSION
The findings of a study conducted during an extreme heat event are presented here to understand urban landscapes and the built environment's relationship to heat and asthma-related illnesses, as reported in an earlier health survey.

Urban landscape and the built environment: Existing urban development patterns with a high percentage of sealant surfaces (42%) and tree canopies (29%) are creating a wide variety of microenvironments in the low-income community examined in this research. It was observed that an uneven distribution of tree canopies located very high on a hillside and far from the industrial areas is creating a significant gradient in overall environmental exposure. Also, the presence of industry and the resulting heavy track traffic is a major source of anthropogenic heat and air pollution. Finally, close proximity to the freeway further intensifies this type of exposure.

Environmental exposure in microclimates: The heat and air pollution varied across space and time. Among the 24 microenvironments in the study community, 54% had HSI values in the danger zone (104°F to 124°F); the remaining 46% had HSI values within the extreme caution zone (91°F to 103°F), per the scale provided by the National Weather Service. The high HSI values were complemented by UFP exposure, particularly in industrial zones, at street intersections, and in parking lots. HSI values based on an average five minute walk among these microclimates showed that 70% of the time, residents would be in the danger zone and 30% of the time they would be in the extreme caution zone during extreme heat events. The UFP exposure based on averaged five minute walk varied from 7,633 to 34,751 particles/cm³, between high-canopy streets and low-canopy streets with greater traffic exposure.

Environmental exposure and mental health: The outdoor spaces commonly used for social gatherings and children's playgrounds, such as parking lots and spaces near street intersections, had high HSI values and health-damaging environments that could result in heat-related irritation and mood swings. The evidence presented in this study provides clues to understanding how and why reported heat-related mental health issues (irritation, mood swings, and negative perceptions of health) are emerging in the community. A need for long-term data is evident if the relationships among the built environment and negative mental health outcomes are to be fully explored.

Demographics and microclimates: The demographic parameters of gender, race, age, and home occupancy were all found to be significantly associated with negative health outcomes, as was argued in the health survey. The evidence presented in this research are useful in understanding how microclimatic environmental exposure may affect health outcomes, and highlight potential directions for future research.

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ABSTRACT: This paper reports a series of research and design activities that explore an innovative model of healthcare delivery in rural areas. In spring 2016, a group of researchers in the School of Architecture, Design, and Urban Planning and School of Engineering at the University of Kansas organized a think tank titled “Innovations in Rural Healthcare Environments.” The symposium brought together more than 100 healthcare providers, policy makers, and designers to outline specific research issues about how innovative design solutions can improve the efficiency and effectiveness of rural healthcare systems. Several major themes emerged from the panel discussions: 1. Rural healthcare facilities will need to adapt to changing practice models and constricted economic conditions by blending themselves into the fabric of the surrounding communities they serve and partner with local communities; 2. “Community Outpatient Hospitals” (COH), a new type of facilities that concentrate on primary and outpatient services, community-based health maintenance programs, and information technology rather than bricks and mortar will replace the obsolete “Critical Access Hospitals” (CAH) model; 3. Future rural healthcare designs should recognize the root causes of community health issues and also address individual uniqueness; 4. One size doesn’t fit all.

These key themes were used in a research-based design in the Health and Wellness graduate capstone studio. Students explored a range of design options that addressed the ways that traditional rural inpatient hospitals could be repurposed and refocused using Philips and Harper counties in Kansas as examples. In addition to in-depth analysis of socio-economic status, community health, and physical infrastructures of these two typical rural communities, students also conducted onsite observations, workflow mapping using spaghetti diagrams, and focus group interviews to inform innovative prototypical solutions for rural hospitals. The inter-disciplinary evidence-based design approach has been proven to be effective for student engagement and deeper understanding of rural conditions.

KEYWORDS: Rural Healthcare, Critical Access Hospital (CAH), Community Outpatient Hospitals (COH), Research-based design, Design Education

INTRODUCTION

Rural hospitals provide health services to a large portion of the US population, especially in the Midwest. Based on a 2017 survey conducted by American Hospital Association Hospital Statistics, there are 1,829 rural community hospitals, which account for 37.6% of total community hospitals (American Hospital Association 2017). In Kansas, the 95 small rural hospitals represent 75% of the 127 community hospitals in the state (Flex Monitoring Team 2017). However, as the United States becomes more urbanized, and the healthcare systems become focused on specialized and centralized delivery modalities, populations in remote rural settings are being underserved and marginalized. Meanwhile, the increasing elderly population keeps adding pressure to the existing healthcare system. More than 16.5% of rural Americans are aged 65 and older, which is a higher proportion than in the rest of the country (Coburn and Bolda 2001).

The traditional methods and practice models of healthcare delivery based on Critical Access Hospitals (CAH) that have served rural America for the past few decades have become strained. Most rural CAHs, which were built after World War II under the Hill-Burton programs, have reached the end of their useful lives. These outdated facilities cannot support new outpatient and preventive care based models. The state of Kansas – similar to the states throughout the Great Plains and agricultural Midwest – is facing a crisis in maintaining, upgrading, and replacing aging healthcare facilities. The rural healthcare environment is at the crossroad for innovative solutions. Currently, there is very limited research on rural healthcare from the perspective of facilities. This paper explores an alternative to CAH to provide more efficient rural health care. It presents a research-based design model that integrates expert opinions and evidence-based design research as an integral design process in informing innovative design solutions for the rural healthcare environment.

1.0 LITERATURE REVIEW

1.1. Rural-urban health disparity

Evidence exists that, compared with non-rural residents, rural residents experience health disparities on many indicators of population health. According to existing research, rural areas have higher death rates from unintentional injuries and chronic obstructive pulmonary disease (Eberhardt, Ingram, and Makuc 2001). Infant mortality rates are
higher in rural areas (Eberhardt and Pamuk 2004). According to the 2014 update of the rural-urban chartbook (Meit et al. 2014), there are a higher teen birth rate, children who are overweight, diabetes incidence, and more preventable hospital stays in rural areas compared to metro urban areas.

The health disparities are driven by demographic and social economic factors. Rural residents are older, with lower income, and higher unemployment rate. In addition, rural areas have fewer physicians, nurse practitioners, and even fewer specialists per 100,000 inhabitants than urban areas (Meit et al. 2014, Merwin, Snyder, and Katz 2006). Health behavior and risk factors also contribute to health differences among rural and non–rural residents. Rural adults are more likely than their urban counterparts to be physically inactive, overweight(Fig.1) and have poorer access to healthy food (Rural Health Information Hub 2014).

1.2. Historical Development of CAH
Several approaches have been undertaken to address the urban–rural health disparity issue. CAH is one of the attempts. CAH is a designation given to certain rural hospitals by the Centers for Medicare and Medicaid Services (CMS). This designation was created by Congress in the 1997 Balanced Budget Act (BBA) through the Medicare Rural Hospital Flexibility program (Flex Program) in response to a string of hospital closures in the 1980s and early 1990s. CAHs must be located in a rural area and be more than 35 miles from another hospital (15 miles by secondary roads or in mountain terrain) or have been certified before January 1, 2006, by the State as being a necessary provider of health care services. Additionally, to be considered a CAH, the hospital must have an emergency room that operates 24 hours per day and 7 days per week using either on–site or on–call staff. A CAH is normally limited to 25 inpatient beds used for either inpatient or swing bed services. CAHs are also subject to a 96-hour (4-day) limit on the average length of stay. As of October 12, 2016 there are 1,337 CAHs in the United States, which account for 73.1% of rural hospitals (Flex Monitoring Team 2017).

However, CAHs are at a critical time as a result of rapid changes in economics, rural demographics, and healthcare policies. Many CAHs are suffering from maintaining bottom line and retaining health care workforce. In addition, there are concerns with regards to hospital care quality in CAHs. Compared with non–CAHs, CAHs have fewer clinical capabilities and worse measured processes of care (Joynt et al. 2011). When compared using quality indicators of acute myocardial infarction, heart failure, and pneumonia, CAH have a lower satisfactory performance on most of these indicators compared to non–CAH, urban acute care hospitals. In addition, through a pooled time-series, cross-sectional data analysis from 34 states for the period 1997 – 2004, average estimated cost inefficiency was greater in CAHs (15.9%) than in non–converting rural hospitals (10.3%) (Rosko and Mutter 2010).

Moreover, since 2010, there has been a steadily increasing of CAH closures across the nation as a result of proposed cost cutting under health reform and the lack of Medicaid expansion in some states (Kaufman et al. 2016). According to the NC Rural Health Research program's (2017) real–time tracking, there have been 80 CAH closures to-date. Approximately 673 rural hospitals are vulnerable to closure and 68% of these hospitals critical access hospitals. The CAH closures will make the rural–urban health disparities more severe. The vulnerable rural populations will have no timely access to care, which can be life threatening in emergency cases. More importantly, rural hospitals play a major role in the economic vitality of small cities and towns. They serve as critical sources of employment and act as economic engines within their communities (Brooks and Whitacre 2011, Holmes et al. 2006). The closure of rural CAHs can lead to the decay of the entire rural community.
1.3. “Save Rural Hospitals Act” and Community Outpatient Hospital (COH)

The rising rate of closures suggests that existing model and policy support may no longer be sufficient to maintain the financial health of rural hospitals. A bill (H.R. 3225) introduced by Reps. Sam Graves (R-Mo.) and Dave Loebsack (D-Iowa) in July 2015 aimed to provide financial and regulatory relief to rural hospitals. The Save Rural Hospitals Act would create a new classification – Community Outpatient Hospitals – that would include a 24-hour emergency room and observation care (not to exceed an annual average of 24 hours), 24 hours per day, 7 days per week, coupled with outpatient services and primary care. There would be no inpatient beds, but the hospital would be required to have a transfer agreement with another facility to transfer patients who require a higher level of care (NRHA 2015). Even though there have been discussions regarding the new COH classification and the implications on financial model and policy, no research has been conducted to investigate its impacts, considerations, and constraints posed on the built environment. It is unclear where the future of rural health facilities is heading.

2.0 METHODS

This is the context that formed a multi-phase research/design project to explore innovative rural healthcare environment of the future. The project was developed in three phases: 1. gathering expert opinions to inform new delivery models; 2. conducting onsite empirical study; 3. translating research to design.

2.1. Gather expert opinion through “innovations in rural healthcare environment” think tank

To bridge the rural health policy, new health delivery model and facility design, a group of researchers in the School of Architecture, Design, and Urban Planning and School of Engineering organized a one-day think tank titled “Innovations in Rural Healthcare Environments” at the University of Kansas in Lawrence in spring 2016. The think tank brought together more than 100 healthcare providers, policy makers, and designers to outline specific research issues about how innovative design solutions can improve the efficiency and effectiveness of rural healthcare systems.

The panel discussions during the day focused on three topic areas: healthcare system challenges and opportunities; policy implications for rural healthcare; and the role of innovation and technology in rural healthcare. The first panel session discussed the ways that rural healthcare providers will need to adapt to changing practice models and constricted economic conditions in rural settings in the future. Decreases in service lines of care and in the number of solo practices will continue to put pressure on rural providers in isolated and remote healthcare environments. The concept of “stealth–health facilities” was presented by Michael Pulido, chief administrative officer of Mosaic Life Care, as a possible way to blend traditional medical environments into the fabric of the surrounding communities they serve. In this model, the local gas station—not the critical access hospital—may be the appropriate rural setting to initiate primary care healthcare discussions. A major theme that emerged from the second panel on policy was the likelihood that the traditional critical-access hospital model would be replaced in the near future by a facility type that concentrated on primary and outpatient services, community-based health maintenance programs, and information technology rather than bricks and mortar. This new rural healthcare environment has been called by several names including “community outpatient hospital,” “primary health center,” and “integrated rural clinic.” Rural healthcare environments will likely be viewed as “community organizers” rather than freestanding and independent institutions in this new model, and medical services will be delivered outside the confines of traditional settings. Brock Slabach, senior vice president for member services at the National Rural Healthcare Association (NRHA), reminded designers to be much more attuned to the realities of “form follows finance” in an era that includes Medicaid expansion, results-based reimbursements, and financial rewards for improving population health. The final panel discussed the roles of technology and design innovation in rural healthcare environments. Building on the panel discussions, the narrative of this session focused on finding ways to use environmental quality to improve the rural community’s well-being. A common theme shared by the panel was the concept of the healthy village, where the hospital was only part of the equation for community health. “Eat well, stay well, get well” was proposed as an approach for the continuum of healthy living. The panelists also highlighted the importance of population health and partnerships with the local community. Future rural healthcare designs should recognize the root causes of community health issues and also address individual uniqueness. Big data could support the understanding of the holistic patient profile, but Erik Gallimore, director of rural health at Cerner Corporation, also stressed the importance of designers listening to the individual stories within rural communities.

The keynote address was delivered by Marci Nielsen, chief executive officer of the Patient-Centered Primary Care Collaborative. She focused on the shifting emphases in American medicine from illness to health, from the provider to the patient and family, and from inpatient to outpatient services. She challenged the audience to conceive of a rural healthcare system that sustains itself through local community values and strength, and to recognize that there was not a uniform definition of “rural healthcare,” but rather a continuum of healthcare needs in rural settings. In short, four major themes emerged from the panel discussions: 1. Rural healthcare facilities will need to adapt to changing practice models and constricted economic conditions by blending themselves into the fabric of the surrounding communities they serve and partner with local communities; 2. “Community Outpatient Hospital” (COH), as a new facility type that concentrates on primary and outpatient services, community-based health maintenance programs, and information technology rather than bricks and mortar will replace the obsolete CAH model; 3. Future rural healthcare designs should...
recognize the root causes of community health issues and also address individual uniqueness. Big data could support the understanding of the population health and the holistic patient profile; 4. One size doesn't fit all, which addressed applying a modular design that can adapt to various rural community needs.

These key themes were used in a research-based design in the Health and Wellness graduate capstone studio. Students were charged to explore a range of design options that reflect future rural health models and address community needs, using Philips and Harper counties in Kansas as examples. In addition to in-depth analysis of socio-economic status, community health, and physical infrastructures of these two typical rural communities, students also conducted an onsite empirical study in Philips County Hospital, KS to gain a comprehensive understanding and tangible experience of the current state of CAH, especially in the Midwest region.

2.2. Onsite evaluation: Philips County Hospital (PCH)
Philips County Hospital is a typical run-down CAH with a building from the 1950s. It has gone through several additions and small partial interior remodels. The facility is exemplary of many CAHs that have not fully updated or replaced their built environment to reflect the state-of-the-art technologies. The case study was conducted using multiple methods, including focus group interview with hospital staff, post-occupancy evaluation (POE) of clinics and medical surgical nursing unit design using standardized toolkits, and spaghetti diagram to map patient and staff flow.

2.2.1. Focus group interview
A focus group interview was conducted with 12 key clinical staff and administrators of PCH, including CEO, nursing director, director of rehabilitation, operating room manager, director of radiology, lab director, director of maintenance, director of material management, director of food service, clinic administrator, registration, and community coordinator. The interview had three components: the hospital's relationship with the local community, the workflow and departmental adjacencies, and the financial and operational aspects of the hospital. Regarding community relationship, despite many community outreach efforts and community health promotion events, the strong bond between the community hospital and the local community is difficult to maintain. Several deficiencies of existing spaces were identified: multiple entrances, unclear wayfinding system, non-ideal adjacencies of functions within the hospitals, large distance between clinics and hospital, and in compliance with handicap accessibility and HIPPA. For the financial performance, the outpatient services, especially rehabilitation services were identified as revenue generators, while inpatient bed occupation rate is as low as seven patients per day and out of the seven patients usually around two are acute care patients. New facilities are viewed as a mechanism to attract local patients and quality providers.

2.2.2. POE
Students were divided into three teams and conducted POE for the rural outpatient clinic, specialty clinic, and inpatient units. A standardized POE toolkit from the Center for Healthcare Design (CHD) was adopted to evaluate the quality of the physical environment in both clinics (The Center for Healthcare Design 2015a). This audit tool provides a rating system for a set of design features at major clinic spaces. The inpatient unit POE was conducted using the CHD design medical-surgical patient room POE tool (The Center for Healthcare Design 2015b). The POE tool is organized around 23 Evidence-Based Design (EBD) goals that link design with desirable healthcare outcomes. Students walked through spaces together with clinical staff where each rated how well the features meet certain criteria. On a scale of 1 to 5 (with 5 indicating the highest evaluation rating), the PCH outpatient clinic received an average score of 2.20, specialty clinic received an average score of 2.11, and the inpatient room received a score of 1.91 (Fig. 2). All POE ratings were on the unsatisfactory side, which demonstrates that existing facilities cannot support high-quality patient care experience and staff work experience.
2.2.3. Patient flow and staff workflow mapping
In addition, students worked in four teams alongside the clinical staff to create spaghetti diagrams of patient flow and staff workflow in outpatient rural primary care clinic, specialty clinic, surgical department, and inpatient unit. The mapping results demonstrated that the outdated facility had several issues regarding departmental adjacencies, which caused inefficient staff workflow and unnecessary patient trips to get services (Fig. 3).

Figure 3: Specialty clinic patient flow

2.3. Translate Research to Design Proposals
Students later synthesized expert opinions and empirical research and translated them to healthcare facilities prototypes for Phillips and Harper counties. They provided a range of design options that addressed the ways that traditional inpatient hospitals could be repurposed and refocused. For instance, Erin Hoffman, Erica Hernly, and Connor Crist’s design explored the alternative model of “community outpatient hospital” (COH) that eliminated the inpatient unit of a critical-access hospital. The COH focuses on the role of the rural hospital as a community hub and
an education center for healthy living and preventive care. Many spaces such as café, demo kitchen, and multi-function community space were designed to host community events and bring in community partners for improving population health (Fig. 4).

**Figure 4:** Philips County Replacement Hospital Lobby and Café (Erin Hoffman, Erica Hernly, and Connor Crist, 2016)

In another project, Rachael Wotawa and Briana Sorensen developed a master plan for Cerner Harper County Healthy Village with a full range of health and wellness services, including hospital, nursing home, assisted living, independent living, retail, apartments, educational building, intergenerational activity space, and community center (Fig. 5). They also proposed a universal care room to replace the traditional medical-surgical inpatient room, which could serve as an observation bed for the emergency department and a transitional care bed (Fig. 6). Their design considered the implementation of health IT and telehealth throughout the health village, which would support holistic care and the family involvement and bring state-of-the-art care close to home.

**Figure 5:** Cerner Harper County Healthy Village Master Plan (Rachael Wotawa and Briana Sorensen, 2016)
CONCLUSIONS AND FUTURE WORK
The study on rural hospitals highlighted the urgency of exploring an alternative to critical access hospitals to provide more efficient rural health care. The elimination of health disparities among rural populations will require a population approach that is sensitive to local variations in physical and cultural realities (Harney, 2004). The transition to a population-based, outpatient driven healthcare has implications in physical environments. Traditionally, the discussion on rural healthcare has focused on policy, care delivery, and financial model, but not on facilities. The think tank and the research-based design studio are one of the early attempts to explore the impacts of new rural health model on the physical environment. The inter-disciplinary evidence-based design approach has been proven to be effective for students' engagement and deeper understanding of rural conditions. More research is warranted to further explore the impact of alternative rural health care models on healthcare facilities and patient outcomes.

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ABSTRACT: Increasing interest is seen at the intersection of architecture and health. The built environment has become associated with health outcomes including obesity, cancers, and diabetes (Sallis, J. F., et al. 2012). Engaging our students in these inquiries surrounding health is important in preparing them for future practice, regardless of the specific building type on which they ultimately focus. This paper reviews the implementation of one such course focusing on the well-being and overall health of the occupant, using the frameworks of the WELL Building Standard and the Living Building Challenge (LBC). The reviewed course engages interdisciplinary teams composed of students from the School of Architecture, the College of Engineering, and the College of Natural Resources, with private practice. Through these partnerships, students focus on real-world projects as case studies to conceptually assess health and well-being implementation strategies, lending prominence to wider sociocultural influences surrounding the topic of health in the built environment (Kahu 2013). The course, rooted in the theoretical perspective of Constructionism, puts forth an effort to break out of the conventional assumptions and meanings commonly associated with an object (Crotty 1998), such as the built environment's neutral impact on health. The course has been specifically designed to: (1) establish a framework for common content relating to health in the built environment across disciplinary boundaries; (2) build meaningful partnerships between a variety of student focus areas through intentional exercises; and (3) establish a common vocabulary between architectural education and aligned disciplines regarding health and the built environment. The course structure, activities, and assessments are reviewed, proposing a solid template for including integrated design and themes of health in architectural education, and providing methods for sharing the value of the architectural education process across campus.

KEYWORDS: health and well-being; built environment; interdisciplinary; sustainability; course development

INTRODUCTION
While the conversation around sustainability and green building still includes a heavy emphasis on energy use, resource consumption, and material selection, there is an increasingly strong thread of discussions swelling around the health and well-being of building users. Though this topic is not new, the vitality around it is growing, and quickly (Vanette 2016; Brammer 2016; Alter 2016; Welker 2016). Contemporary health issues abound, including concerns with sedentary activity (Chae, Kim, Park & Hwang 2015; Jackson, Lewis, Conner, Lawton & McEachan 2014), obesity (Barkin, Heerman, Warren, et al. 2010; Finkelstein 2010; Kowlessar 2011), nutrition (Kahn-Marshall & Gallant 2012), and mental health (Addley, et al. 2014; Wang, et al. 2014). Literature at the intersection of health and the built environment primarily focuses on associations between the built environment and health behaviors and/or outcomes, largely at the planning scale (Frank & Engelke 2001; Frumkin, Frank & Jackson 2004; Koohsari, Kaczynski 2013; Besenyi, et al. 2014). Little literature addresses how to begin to incorporate these complex themes into architectural education. Issues of health and the built environment can and should be addressed in the design of all of our spaces, and should therefore be addressed somewhere in our design curriculum. This article describes the development of such a course, which has been hosted twice with equal success. The course is listed as a seminar course, but functions more as an inquiry-based lab, designed around the formation of interdisciplinary groups and engagement with architectural practice to address these complex issues.

1.0 BACKGROUND
Building owners are increasingly interested in the health and well-being of their employees (Horwitz, Kelly & DiNardo 2013). Though this is a fairly simple statement, there issues of complexity buried in the concept of well-being including both mind and body considerations. These issues far exceed the scope of an architect's expertise, but should not land outside the professional architect's sphere of influence. The increasing popularity of systems such as the WELL Building Standard and FitWel indicate the growing importance of health concerns in the built environment. Leading firms such as Perkins + Will (perkinswill.com/purpose/wellness) are adopting these issues as priorities in their design processes. Given this interest, these multifaceted topics should be addressed somewhere in architectural education to better prepare students for future practice. Because of the complexity inherent in the topic, interdisciplinary groups should be addressing these challenges, puncturing holes in disciplinary boundaries.
This study focuses on the two-time execution of a seminar course, hosted out of the School of Architecture at North Carolina State University, addressing the review and assessment of health and wellness in the built environment. The questions reflect on the implementation of the course, without research intent during the design of the course. As such, the primary research interest of this paper is to establish a better understanding of how health and wellness considerations can be incorporated into architectural education outside of the studio setting by critically assessing the success of the course.

2.0 RESEARCH AND COURSE GOALS
Because of the specific focus on including standards relating to wellness, and availability of the course information, this review is structured methodologically as a case study rooted in a constructionist epistemology. As noted by Crotty, “[Constructionism] is the view that all knowledge, and therefore all meaningful reality as such, is contingent upon human practices, being constructed in and out of interaction between human beings and their world, and developed and transmitted within an essentially social context.” (1998) This way of knowing translates into the case study methodology. Case study research promotes an in-depth understanding of a single or small number of “cases” set in real-world contexts (Bromley 1986; Yin 2015), embracing socially constructed knowledge. It is important to study specific cases in depth focusing on the questions of How and Why. Yin has argued that a case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context” focusing on questions framed in How and Why (Yin 2015). Groat and Wang (2015) suggest that case studies can be used to “explain causal links.”(Yin 2015) Similarly, Yin believes that case studies can “explain the presumed causal links in real life interventions that are too complex for the survey or experimental strategies.” This article seeks to explore possible causal links between elements of the designed course and course outcomes.

2.1. Establishing a Supportive Course Structure
The seminar course has been held twice in subsequent spring semesters, structured in a three-hour timeframe meeting once per week. Twenty-seven students participated the first time the course was held, and thirty enrolled in the second offering. The distribution of students can be seen in Figure 1.

![Figure 1](image)

Both years, this distribution allowed at least one student in each of six groups to provide perspective and expertise from outside of the design field. In the second year, the number of engineers increased, allowing the ratio other fields to architects to increase, with at least one student from Natural Resources and one from Civil Engineering in each group. This shift in student population initially indicates a growing interest in these areas outside the architecture field, though additional semesters would be needed to confirm this trend.

The course is divided into three modules across the sixteen weeks of the semester. During the first module, content is shared by the instructor to provide a foundation of knowledge about the state of green building in the built environment professions. While many of the students are familiar with the concept of the LEED Rating System, few have had courses on it or have been involved in a LEED project directly. Because this course is not focusing on LEED as a strategy or an end goal, the review of the system is basic. However, it is included, understanding that the system is the current and most accepted measuring stick for green building in the design and construction industries. A member of USGBC leadership has participated in both years to discuss the origins and evolution of the LEED Rating System, including thoughts on how the two systems that the course will focus on (WELL and LBC) compare and contrast with LEED. Representatives from the WELL Building Standard and the Living Building Challenge have also been brought in, both in person and remotely, to share the larger goals and approaches of the two systems. At the end of this first module in the course, the students begin to compare and contrast the systems, using case studies of award-winning green buildings for conceptual, basic assessments.

The second module of the course focuses on digging deeply into the different categories of the two systems, WELL and LBC. This allows the students to understand particular strategies as well as required thresholds and measurements to work toward achieving certification in the two systems. The students are arranged into interdisciplinary groups and are tasked with researching and presenting one or two of the systems categories, or petals, and their requirements.
For example, with the differing perspectives in the teams from interdisciplinary team members, a more holistic representation of the issues are provided to the class to help deepen their understanding of opportunities and challenges.

Also during the second module, we strive to engage industry experts. For example, during the class session dedicated to Energy, the assigned student group is tasked with giving their presentation for the first half of class, with the same expectations and timeframe as the other groups. Then, during the second half of the class period, an engineering firm that specializes in net-zero design comes in for a presentation and discussion about their strategies, opportunities and challenges in the real-world context. Similarly, for the class dedicated to Materials, the group gives their presentation for one half of the class, while a local expert with Cradle-to-Cradle shares insight on processes and considerations in material selection. These guest speakers, along with the detailed presentations on the topics and credits from the two systems, provide all students with more in-depth information that will serve them well for the rest of the semester.

By the end of the second module, the students have at least a basic understanding of the different considerations and possible strategies to achieve credits through each of the rating systems, from various perspectives.

The third module of the semester focuses on the conceptual application of the two systems to real-world projects. The students remain in their interdisciplinary groups from the second module, each partnered with a local firm to explore a project in process. The final deliverable for the semester is a public presentation about the feasibility of each project to achieve some type of WELL or LBC certification. Throughout third module, students are charged with assessing the inclusion of specific strategies in their projects, looking conceptually at challenges and opportunities with the design and operations of the facility in question. Issues including air filtration, urban agriculture, occupant fitness, and material content are only some of the complex issues addressed by the student teams.

The goal of this phased course structure was threefold. First, establish a foundation of knowledge that the students across disciplines could appreciate and understand. Second, empower interdisciplinary partnerships to build upon that knowledge. And third, apply this new knowledge to a real-world project from a variety of interdisciplinary perspectives. These goals were achieved in great part due to the scaffolding of the information and partnership development across the phased semester.

2.2. Interdisciplinary Engagement
Because of the complexity of health issues in the built environment, one of the primary goals of the course is to engage the students meaningfully in interdisciplinary activities and partnerships, supported by the previously reviewed structure. Education of sustainability themes should be viewed as an exchange acknowledging multiple viewpoints and differing perspectives to be both voiced and validated within the classroom (Coops, et al., 2015). Within this dialogical environment, the intention is that the open learning environment itself promotes meaningful interaction, partnerships and “positive appreciation of diversity.”(Coops, et al., 2015; Misanchuk, Schwier & Boling, 2000). This was the overarching goal of a group arrangement for the students.

While architecture practice is rooted in collaborations and interactions with professionals from other disciplines, there is rarely an opportunity for students to participate in these types of meaningful activities during their university education. In design education, as well as in Engineering and Natural Resources, most of the required classes and disciplinary electives are insular. Many of the electives outside of the majors are either large classes in lecture format that offer no opportunity for interaction, or are seminar classes that can facilitate potentially valuable discussions, but do not include interactive group work. The phased modules and group structure was designed to address this.

To ensure interdisciplinary teams, students were grouped in their home departments, and then numbered off into groups of six. This method resulted in evenly distributed expertise for each group, though the majority of group members has been from architecture both semesters, given the overall distribution of the disciplines in the class. Observations of team work during class periods showed that most teams worked well together and were eager for input and insight from other fields.

2.3. Engagement of Practice
Another primary goal for the class is to apply the newly formed knowledge in a real-world project. This structured collaboration with professional practice allows for an element of service learning in the class and, in most cases, flips the role of expert from the practitioner to the student. Thus far, the practitioners are not well-versed in either the WELL or LBC systems, allowing the student groups the opportunity to share knowledge of the system and bring enrichment to the profession.

Student groups were assigned randomly to partner firms as the class moved into the final module. Firm profiles were
printed and put into blank envelopes and student groups each picked one to determine their partner and project. One student was assigned to be in charge of communication with the firms so as not to overwhelm the contacts with numerous emails and queries. Both students and professionals expressed value in this interaction. Students were excited to participate in a real-world design project, many not having internship with a design firm experience prior to the course. In addition to getting exposure to a new perspective of the built environment, the students felt that this project could be an element of their portfolio, providing a notable distinction between their application package and other job seekers. Lastly, students valued the personal relationships developed with practicing professionals at the different firms. Professionals agreeing to participate were eager to engage students, and happy to discuss opportunities for design strategies with the teams, as well as entertain larger questions about the profession, providing valuable insight for future practitioners. Similarly, the owners that were directly engaged were also exceptionally interested, and happy to request engagement in the course from their project teams.

3.0. ASSESSMENT
There are a number of ways to begin to assess the success of the course in reference to the stated goals, through different perspectives. Perspectives of the course could be offered from the students themselves addressing: (1) the perceived shift in their knowledge across the duration of the course; (2) the success of the interdisciplinary teams; and (3) their overall opinion of the value of the course itself. Assessments could also come from the practice partners, providing insight on the process, engagement of students, and deliverables and insights provided. And lastly, the goals of the course could be addressed by both observation and through reflection on each of these other feedback methods. Each of these techniques were addressed in both semesters.

3.1. Pre- and Post-tests
Assessment of the course goals is primarily based on self-reported pre-test and post-test data. The initial goal of the pre-test and post-test was to better understand the perceived level of knowledge gained during the course. The pre-test is given on the first day of class, immediately after review of the syllabus and expectations for the course. The post-test is given on the very last day of class, after all content has been reviewed and all presentations have been given. The statements were provided with a Likert scale from 1-10, addressing different measures of knowledge about health and the environment. The statements covered perceived understanding of strategies, thresholds and resources. Directions were, Please rate your perceived current level of knowledge in each of the following on a scale from 1 to 10. Statements included: How buildings impact human health; Rating systems available beyond LEED to measure the impacts of the built environment; Possibilities for a design project to have a positive environmental impact on a community; and Leveraging interdisciplinary partners to address project challenges and opportunities. No names were provided on the sheets, ensuring anonymity of respondents. The self-assessments were collected at the end of each class, students delivering the individual papers or small groups of papers to the instructor.

As shown below in Figure 2, the pre-test and post-tests from both semesters indicate that the students believe there to be significant growth in understanding between the beginning of the semester and the conclusion of the course, as well as in the appreciation of interdisciplinary perspectives. Total completions of the survey are noted.

| Spring 2016 Pre-Tests (27 completions) |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 |
| 4.10 | 3.45 | 5.07 | 5.55 | 4.00 | 4.17 | 5.03 | 4.62 | 5.97 | 3.97 | 5.86 |

| Spring 2016 Post-Test (22 completions) |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 |
| 8.00 | 8.59 | 7.86 | 8.45 | 8.05 | 7.36 | 8.36 | 7.00 | 8.32 | 7.59 | 8.86 |

| Spring 2017 Pre-Test (26 completions) |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 |
| 5.19 | 4.68 | 5.50 | 6.12 | 4.92 | 4.92 | 5.81 | 4.85 | 5.62 | 4.54 | 6.31 |

| Spring 2017 Post-Test (27 completions) |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 |
| 8.11 | 8.59 | 8.11 | 8.56 | 8.11 | 7.70 | 8.37 | 7.81 | 8.37 | 7.81 | 8.89 |

Figure 2

3.2. Course Goals
A second way to assess the course is to reflect on the course goals. The course has been successful in the three overarching goals of: (1) establishing a framework for common content relating to health in the built environment across disciplinary boundaries; (2) engaging students in meaningful interdisciplinary experiences; and (3) establishing a
common vocabulary for discussion of these topics between student disciplines. A discussion of each follows.

Goal 1: Establish a framework for common content relating to health in the built environment across disciplinary boundaries. In an effort to create common knowledge between students from different disciplines, the course uses two established assessment frameworks as a way to structure complex topics across expertise: the WELL Building Standard and the Living Building Challenge (LBC). The decision to use established frameworks was based on the success of a similarly formatted course at North Carolina State University, hosted by the same faculty member, structured around the LEED rating system for Building Operations and Maintenance. The two courses (LEED and WELL/LBC) both have the primary goal of engaging interdisciplinary teams and facilitating meaningful group work. The use of established frameworks facilitated unbiased conversations among group members, not catering to one field over another. Students were happy to engage these systems, and discuss their goals and strategies through different discipline perspectives.

Similarly, while not all students had previously participated in a real-world design process prior to the course, they were all excited at the prospect of collaborating with a firm. The involvement of practicing professionals seemed to heighten the quality of deliverables. Likewise, firms that participated in the first semester of the course proactively asked to be able to participate in the second semester.

Goal 2: Build meaningful interdisciplinary partnerships through intentional exercises. Exercises given to the class throughout the semester were all interdisciplinary and targeted at increasing understanding across discipline boundaries. Strategically designed exercises included case studies where different discipline perspectives were articulated, and conceptual assessments of the two systems were reviewed in class. Other examples include a Myths and Stereotypes exercise where students were sectioned into college groups and asked to identify three myths and stereotypes about each group, including themselves. Upon the out-loud sharing of obviously ridiculous statements such as, “Engineers all play World of Warcraft,” “College of Natural Resources students all study grass or something,” and “Design students never shower,” the groups became much more comfortable around each other and the class became something of a safe space; no judgment would be helpful or tolerated. These new partnerships were strengthened through the group work.

Goal 3: Establish a common vocabulary between architectural education and aligned disciplines regarding health and the built environment. Collaborative, interdisciplinary presentations during the second module of the course helped to position specific topics of interest and possible strategies in a common framework for the entire class. This interdisciplinary approach enables students from different backgrounds to see the value of a concept from other perspectives. The resulting multifaceted understanding helps to enrich every student’s appreciation of the goals and approaches for different strategies and thresholds in the systems, providing a better understanding of possibilities and realistic options for strategies.

4.0. OPPORTUNITIES
There are many opportunities for improvement and modification in the course as it matures. The most significant areas for improvement revolve around project selection by the firms, and increased participation across disciplines.

4.1. Project Selection
Over the course of two semesters, one opportunity consistently found to enrich the conceptual assessment of real-world projects would be to create criteria for both project types and phases of projects. Because it is necessary that we have six firms participating, with one team for each project, the instructor simply asked for participation from local firms without giving criteria for project selection. Most firms approached were happy to participate, though one was unable to participate at the last minute in the first iteration because there was a problem with the project they had in mind. The projects selected for the first semester were across the board and included a sorority house; a primary school; a guard house for a laboratory facility; a higher education classroom building; a large biotech facility; and a new city market.

In the second semester, owners were approached in addition to design firms, targeting two local school systems and the home university. The design firms that were approached were eager to participate and brought forth the following projects: a university lab building; university classroom and research building; and a new wing addition to a local hospital. The owners that were approached were even more excited to join and brought forward their own undertakings, as well as engaged their associated design teams. The larger local school system was interested in exploring a prototype that had been operating for a year in one location, and is scheduled to be rebuilt in the few next years. The smaller local school system, who is a leader in sustainability themes in both facilities management and integrating education, wanted to look at a major renovation of their high school. The university, who served at the third client, was interested in looking at the major renovation and construction of the student recreation and wellness center. Each of the projects identified by the firms and owners alike provided a rich context for student engagement.
The results of the different approaches to real-world engagement across the two semesters indicates that it may be better to seek to engage owners, particularly those interested and invested in the population health of their buildings, such as K-12 and the university student population.

4.2. Increased Participation
While it could be argued that the basics are covered with the mix of students currently in the class, including architecture, civil engineering and environmental sciences, the interdisciplinary interactions could be enriched by having additional perspectives in the class. Disciplines such as Landscape Architecture, Psychology, Policy, and Mechanical Engineering are only a few that would lend valuable insight to assessing the opportunities for these rating systems. It will take considerable effort to begin to engage these populations, but one they are involved, as with Civil Engineering, it is anticipated that there is a swell in significant interest and class enrolment.

5.0. DISCUSSION
This analysis indicates that the course achieves success in each of its primary goals. The use of established frameworks has shown to be a valid tool for integrating different disciplines meaningfully toward a common understanding of a complex issue. Exercises given to the class helped to establish meaningful partnerships between disciplines, fostering relationships and trust between allied fields. The three-phase structure and delivery of the course helped to establish a sense of community among the participating students. Overall, peer reviews of team members were overwhelmingly positive, despite notations of different strengths and traditional ways of processing information.

Common presentations, reviews of content, and engagement in a somewhat standardized design process with design firms help to establish common vocabularies around concepts in the intersection of health and the built environment. By engaging established frameworks that address different disciplines equally, while simultaneously positioning students in interdisciplinary teams, complex issues of health and sustainability in the built environment can be successfully incorporated into design education.

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ABSTRACT:
Our research identifies purposeful uses for multi-sensory responsive surfaces. The premise of our research explores spatial typologies which we believe would benefit from such surfaces. Digital fabrication tools and technology, as well as material characteristics and mechanisms, provide a strategic means for navigating the multitude of forces at play.

Serving as the activating link between material research and design innovation, the relationship between the designed object and the forces surrounding that object are always present, perceivable, and tactile. Both Programmatic as well as physical complexities guide the methodology of our design process, which progresses through a series of focused strategies. Through a specific disposition, we evaluate each responsive surface for performance potentials.

Our goal is to study the effects on how human behavior positively changes as a result of our multi-sensory responsive surfaces. Our responsive surfaces seek to reduce fatigue and distraction in both office environments -- daylighting, as well as educational multi-use spaces -- noise.

For interior performance and comfort in office environments, our responsive surface optimizes interior lighting levels by constant actuation. Each individual module is set with parameters controlling a mechanical curl ratio mandated by true material allowance uncovered through performative weather data and real-time lighting metrics. For educational multi-use spaces, our responsive surface optimizes interior environments by adapting to the changing reverberation rhythms of voices and footsteps. It can also be parametrically calibrated to a desired acoustic setting, which allows for increasing or decreasing acoustic dampening depending on the needs of the interior space and its occupants.

Additionally, our research is testing the capabilities of an augmented reality design tool, for real-time, immersive data visualization experiences within a virtual space. Through an immersive digital environment, we are able to view a digital prototype in a space at full size. The information visualized and collected assists in the design refinement of our digital prototype. The virtual environment provides a strategic understanding of how the responsive surface responds to multi-sensory input (proximity, light, and sound), as well as how it performs in various spaces.

KEYWORDS: responsive surfaces, multi-sensory, material performance, digital fabrication, immersive environments

INTRODUCTION
The purpose of our responsive surface research begins with the question of whether or not interior spaces can contextually and autonomously respond to its occupants. Artificial intelligence is changing the way many industries function and perform, from information gathering, to self-driving cars. Algorithmic approaches to informed and autonomous decision making is becoming the new normal, and what we should expect for the future (Stanford University 2016). We want to understand how these principles can lead to better scenarios in buildings and spatial typologies. While artificial intelligence doesn’t have much of a presence in architecture and interior design, the fundamental ideas of smart building systems are perhaps the building industry’s equivalent. Mainstream interests in energy efficiency, renewable energy, and environmental design have been brought to the forefront of architecture. As a result, building control systems leverage the use of environmental data, informing new architectural approaches and outcomes. By responding to environmental factors, this form of autonomous architecture has established a new baseline for energy performance (International Energy Agency 2011).

The aim of our work is not to focus on how to further optimize buildings for energy performance, but how to optimize buildings for occupant performance. We take a creative design approach to contextualizing interior elements that can become autonomous systems. By responding to their immediate interior environment, self-regulating surfaces have the ability to increase occupant performance and overall well-being (The WELL Building Standard v1 2015). With this framework in mind, our research began with responsive surfaces designed to mitigate workplace distractions. As office cultures trend toward collaborative working environments with mobile workstations, office space designs are becoming increasingly open. There is a growing need to mitigate distractions such as solar glare and interrupting noise. Our
research demonstrates efforts to generate examples of potential solutions to these distractions through the use of responsive design elements. Naturally for us, we are just as much problem-makers as we are problem-solvers. Our means to conceptualize autonomous methods to optimize occupant performance has re-informed our overall design process. As a parallel research effort, we have reasoned with the idea that a data-driven design process will result in a more informed, and overall, a more effective approach to realizing prototypes.

Our early prototypes used parametric software to assist in visualizing our digital assumptions of what distractions might occur, and how to represent our response through design. With the emergence of well-developed virtual reality and augmented reality tools, we are taking our visualization techniques from parametric assumptions, to mixed reality realizations. This method streamlines the prototyping process by evaluating the effectiveness of a digital prototype through multi-sensory experiences and real-time data visualization. By evaluating the specific design parameters needed to visualize responsive data on changing surfaces, a more informed prototype design can be digitally optimized and approved for empirical testing. This paper describes the process we designed to yield efficient and more accurate results.

1.0. USEFUL PURPOSES FOR MULTI-SENSORY RESPONSIVE SURFACES

1.1. Daylight mitigation: FlowerWall
Conceptualized as a response to the sun, FlowerWall (Figure 1) is a responsive surface that optimizes interior environments by adapting to changing outdoor environments. While exploring the physical space that exists between building and nature, the design for this responsive surface was informed by the natural response of phototropic flowers.

For interior performance and comfort, the responsive surface optimizes interior lighting levels by constant actuation. Each individual module is set with parameters controlling a mechanical curl ratio mandated by true material allowance uncovered through performative weather data and real-time lighting metrics.

FlowerWall's array responds to commands from an automated control system based on outdoor weather conditions and interior lighting levels. It can be operated manually by occupants with a smartphone or tablet interface. It can also be seen as an aesthetically pixelized scratch pad where users can doodle with various visual arrangements and consequently a desired privacy level.

For an experiential effect, flowers can be programmed to create dynamic patterns across one single module or an entire surface. Programmed arrays can also provide an interactive response to human proximity, maintaining a one to one scale interface of human and system interaction.

The FlowerWall concept is a prototype that was the springboard for our research. This surface which is activated mechanically with light cables and computer controlled motor actuators, allows unique folding panels to be separately controlled. The panels can be "arranged" to control views and privacy, ventilation, air flow, and strategic sun-shading from morning to afternoon (Figure 2). The tune-able facade optimizes interior environments by adapting to changing outdoor environments. An automated system responds to commands from a smart building control system based on outside weather conditions; it can also be operated manually by the homeowner with a smartphone, or tablet interface.

Figure 1: FlowerWall, photograph. Source: (Wagner 2012)
1.2. Noise mitigation: AuralSurface

AuralSurface (Figure 3) is inspired by the need to control ambient noise created from everyday life in the office, while also serving as an adjustable separator that maintains a sense of open space. For workplace performance and comfort, the responsive interior surface optimizes interior environments by adapting to the changing reverberation rhythms of voices and footsteps. AuralSurface can also be parametrically calibrated to a desired acoustic setting, which would allow for increasing or decreasing acoustic dampening depending on the needs of the interior space and its occupants.

The WELL Building Institute writes in The WELL Building Standard, “Built environments can harbor sounds that are distracting and disruptive to work or relaxation. Employee surveys show that acoustic problems are a leading source of dissatisfaction within the environmental conditions of an office” (The WELL Building Standard v1 2015, 119).

There is a growing need to mitigate distracting and interrupting noise. Studies show that exposure to noise generated within the building can lead to reduced concentration and mental arithmetic performance, and increased distraction due to reduced speech privacy (The WELL Building Standard v1 2015, 124).

The proposed AuralSurface is an innovative multipurpose intelligent modular tile system designed to dynamically adjust space acoustics, privacy, as well as serve as an adaptable visual enhancement.

AuralSurface seeks to reduce fatigue and stress in the workplace by controlling ambient noise disturbances. Employee fatigue affects their well-being, productivity, and their propensity to commit errors; in addition, one study showed that a three-hour exposure to low-intensity office noise induced a small increase in adrenaline level (Jahncke 2012). AuralSurface’s design allows it to autonomously deploy an acoustic material at specific locations when the perceived decibel levels are higher than normal. In addition to a physical response, the acoustic material may be seen as a visual cue once deployed. Those holding conversations may recognize this as a subtle sign to speak more softly or to take a conversation to another area. AuralSurface, a panelized surface, is an otherwise seemingly typical modular system.

AuralSurface’s array can respond to commands from an automated control system based on various noise levels, or can be operated manually by occupants with a smartphone or tablet interface. Like the FlowerWall, AuralSurface can also be seen as an aesthetically pixelized scratch pad where users can doodle with various visual arrangements and consequently a desired privacy level, both visually and aurally.
2.0. IMMERSIVE DATA VISUALIZATION

2.1. Re-informing the design process
With the emergence of our parallel research, the use of immersive data visualization along with the development of a responsive surface, gained traction through the idea that we will end up with a more informed design to take into the prototyping phase. Early design iterations were hit or miss when built prototypes, particularly with the FlowerWall project. Our assumptions about the effectiveness of the surface design, as well as the materials, mechanisms, and sensors used, were not evaluated until we had a completed prototype. While each new prototype was fully functional and served a purpose as another proof of concept iteration, our process was not efficient and lacked pre-evaluation assessment. Further elaboration on this is in the following chapter, 3.0. Design Methodology.

2.2. Multi-sensory data channels
Through immersive data visualization, we will be able to evaluate the effectiveness of several design parameters through multi-sensory environmental channels prior to prototyping. For AuralSurface, such parameters include material effectiveness, acoustic properties, surface module design and form optimization, structural framework design, mechanical response time, and scale. Each of these parameters is a factor that influences the outcome of the next one.

One of our design options is evaluating the acoustic absorption impact that felt has. The felt sheet will deploy by unrolling when digital sensors respond to real-time people and voices in the space trigger environmental acoustic decibel sensors (Figure 4). The responsive function of the modular surface will pinpoint the origin point of sound through proximity sensors (Figure 5), and each adjacent panel will have a gradient association: the loudest location will have fully deployed panels, each panel adjacent will be slightly less deployed, etc.

These multi-sensory data channels are both viewed and heard through the augmented reality headset. By adding a graphic layer of data visualization seen through the augmented reality headset, we will be able to not only hear acoustic differences, but also verify the material effectiveness visually with acoustic data. For material effectiveness, we will have the ability to test multiple thicknesses of the felt. We will be able to virtually evaluate 1/8” felt to visualize and experience its effectiveness, and then be able to immediately swap the virtual material data asset to evaluate 1/4” felt.

The study of the responsive surface through an augmented reality headset is only valid for our research when it is calibrated and synchronized with real-time environmental sensors in the space being evaluated.

Figure 4: AuralSurface, digital representation of decibel data parameters per panel. Source: (Wagner 2017)

Figure 5: AuralSurface, digital representation of proximity data parameters per surface. Source: (Wagner 2017)
3.0. DESIGN METHODOLOGY

3.1. Parametric analysis
Parametric software was used in early design stages to inform decisions based on assumptions for both conceptual idea and material tolerances. For the FlowerWall, we relied on this method of visualization to understand the curl ratio of spring steel, a material that will maintain its original form without deformation (Figure 6). For AuralSurface, we simulated wavelengths (Figure 7) that represented sound waves to visualize how the surface would respond. With the visual outcome being much of an assumption, we recognized the importance to move forward with the new process of using data visualization in immersive environments.

![Figure 6: FlowerWall, digital process in Grasshopper. Source: (Wagner 2012)](image1)

![Figure 7: AuralSurface, digital process in Grasshopper. Source: (Wagner 2016)](image2)

3.2. Material characteristics
Through performance and evaluation, material characteristics shaped each iteration by revealing tolerances and limitations. As a result, design criteria had to evolve with each prototype. The FlowerWall design adapted to a unique mechanical movement that accommodates solar shading and interior lighting levels by curling an array of flowers CNC laser cut from shape memory spring steel (Figure 8). Each flower consists of petals that are activated mechanically with light cables and electronically controlled motor actuators.

A common research continuum within the design and prototyping stages will be material exploration. We can rely on a variety of materials to each provide different results within our performance criteria. It is our goal as educators, and stewards of this earth, to choose materials that not only help to optimize our research results, but that also come from safe resources. Whether rapidly renewable or recycled and reclaimed, we will strive to make decisions that are best for our environment and promote sustainability (Figure 9).

![Figure 8: FlowerWall, photographs: material studies // spring steel. Source: (Wagner 2012)](image3)
3.3. Sensors and mechanisms
Digital fabrication tools and technology provided a strategic means for navigating the multitude of forces at play. Serving as the activating link between material research and design innovation, the relationship between the designed object and the forces surrounding that object are always present, perceivable, and tactile. The methodology of this design progressed through a series of focused strategies. Each prototype was created by simple operations, undertaken through a specific disposition, and evaluated for performance potentials. Prior to our re-designed process through the use of immersive environments, early steps were taken to develop various functions of the FlowerWall (Figures 10-15).

Figure 9: AuralSurface, photographs: material studies // felt. Source: (Wagner 2016)

Figure 10: FlowerWall, elevation study: tuning potential // array variation. Source: (Wagner 2014)

Figure 11: FlowerWall, photographs: opening sequence. Source: (Wagner 2012)

Figure 12: FlowerWall, elevation study: tuning potential // column variation. Source: (Wagner 2014)
The AuralSurface system is prototyped using the Raspberry Pi computer in conjunction with the Pd-L2Ork (Bukvic 2014) rapid prototyping visual programming environment. This setup offers unique affordances in terms of comprehensive monitoring, adequate computational power, and ability to create an intelligent network of sensors. In order to adjust the audio-visual “porousness” of the AuralSurface, the Raspberry Pi is coupled by an efficient low noise servo motor responsible for coiling the AuralSurface’s insulating material. In addition, the system relies on a photoresistor to measure the amount of light and more importantly a two microphones to monitor noise levels in the immediate vicinity on each side of the individual panel. The ensuing system inherently supports WiFi and Bluetooth connectivity that allows for users to actively partake in designing an optimal environment.

There are three modes of interaction: the default autonomous mode, the manual/collaborative mode, and the artistic/installation mode. The autonomous mode allows panels to fold and expand the dampening material based on the observed noise in the immediate vicinity of each individual panel. Based on the default settings, each panel can further respond to provide the desired amount of lighting, as observed by the photoresistors. Inevitably, the two sensory stimuli need to be ordered in terms of precedence to avoid stale-mate-like configurations where the two inputs are at odds and as a result the AuralSurface fails to satisfy either condition.

The manual mode is optional and can be enabled and coordinated through a centralized Raspberry Pi server or a dispatch. Such a node is networked with all the other panels and is capable of providing overriding states. As a result, users can intentionally change the current state of the AuralSurface array by either selecting one of the built-in presets, or by individually and/or collaboratively by altering individual panel states. Lastly, the installation mode focuses on using the environmental data to create a dynamic collage of possible panel arrangements, resulting in an interactive and responsive environment and an architectural space. The ensuing system is low cost, low power, and inherently malleable, including remotely administered software updates and configuration through a custom centralized client that can be run on a remote computer or in a form of a mobile app (Figure 16).
After initial AuralSurface conceptual models were decided upon, the production process moved from a parametric modeling environment into software more conducive to animation and real-time rendering in a virtual environment. A reduced polygon versions of the parametric curtain was modeled in Autodesk's Maya (Figure 17). Deformation of the curtain surface was achieved with the use of a simple joint chain running down the long axis. Nested inverse kinematics handles were used to simplify the animation process while still giving the impression of a folding curtain. Given the limitations of polygon counts for objects used in a game engine like Unity, the animations aim only to be approximations that allow for rapid prototyping of the larger systems. Further version will look to refine the simulation fidelity of the cloth surface within the virtual environment.

4.0. EVALUATION OF EFFECTIVENESS

4.1. Immersive environments

Our work-in-progress research will be testing the capabilities of a multi-sensory responsive surface (AuralSurface) in existing spaces. We have pinned down two typologies: open office environments, as well as mixed-use educational spaces. We believe there is potential to visit case study environments to understand human interactions and behavior patterns prior to the implementation of AuralSurface. Once we are in location, we hope to find success in studying interactions while viewing the space as an immersive environment through an augmented reality tool such as Microsoft’s HoloLens. We are working to program responsive sensors within the digital model that will respond to both human proximity as well as any sound generated from human interactions (Figure 18). The aspect ratio of 16:9 (Kreylos 2015) can be somewhat limiting, but we expect to visualize our results without issue. The immersive environment should provide a better understanding of how the responsive surface responds to multi-sensory input (proximity and sound), as well as how it performs in various spaces.
4.2. Real-time data visualization

We are working to implement an augmented reality design tool for real-time immersive data visualization experiences within existing spaces. Through the immersive environment, we will be able to view a digital prototype in a space at full scale. The data visualized and collected will contribute to the evaluation of our design, which we see as a step toward refinement with our digital prototype that did not previously exist. This approach should streamline the prototyping process by evaluating the effectiveness of a digital prototype through multi-sensory experiences, leading us to a more informed prototype design (Figure 19).

5.0. RESULTS

5.1. Redefined design process

The use of immersive environments will be critical to visualize the effectiveness of AuralSurface as a responsive surface. While the process is still a work-in-progress, the method provides promise for the future of AuralSurface’s development. By involving people in real-time behaviour, we are able to see our digital model respond to their actions.
5.2. **Empirical testing**
Technical feasibility will focus on answering whether it is possible to implement a proof of concept that is capable of scaling. We will assess this based on system's reliability and sturdiness. Something we intend to explore iteratively through the development cycle. Efficacy will focus on prototype's ability to perceptibly alter room acoustics. We will measure this by conducting a series of preliminary audio tests to ascertain the potential impact on the room acoustics. Marketability will focus primarily on the prototype's potential cost overhead in small, medium, and large scale deployments. This data will be used to determine next steps, including potential pursuit of technology transfer opportunities.

5.3. **Positive effects on human behavior**
This section is reserved for future studies of the AuralSurface prototype implemented in both office environments as well as mixed-use educational spaces.

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**REFERENCES**


RESILIENT DESIGN FOR HUMAN CAPITAL/HUMAN DEVELOPMENT-BASED BUILDINGS

Joseph Bilello

Ball State University, Muncie, Indiana

ABSTRACT: From case studies of architect and non-architect-designed buildings confronted by natural and manmade disasters of the recent past, where human capital restoration was a greater determinant in courses of design action rather than financial capital, this paper extracts exemplary cases of mitigation, adaptation, and transformation design responses to disaster instances in first and third world sites at building and town scales. Testing the relevance of resilience attributes from biology and complexity theories (Zolli and Healy 2012), cases prepared with graduate students in courses on resilience and research methods, studied these tenets of resilience that readily mapped onto architecture (i.e., simple cores/complex edges, modularity, etc.). Further, the case method pedagogy challenged students to make architectural decisions before, during and after disasters. Selected disaster mitigation strategies for (a) post-earthquake school design in Port au Prince, Haiti, (b) future disaster adaptation designs in New Orleans 9th Ward housing post-Hurricane Katrina, and (c) post-tornado transformative building designs that changed the identity of small town Greensburg, Kansas, are abbreviated. In contrast to well-understood roles before and after disasters, architects roles during disasters are absent from the literature and mainstream practice of architecture. Efforts to better ascertain critical roles for architects during relatively predictable disaster events (i.e. hurricanes, flood, wildfire, storm surge, sea level rise, etc.) are explored and a precedent illuminated.

KEYWORDS: Resilience theory, human development, case method pedagogy for decision-making

Resilient design for human capital/human development-based buildings

This inquiry turns to answer this subject’s questions that have emerged for the convergence of sources:

1. Wealth on planet earth defined by Buckminster Fuller (1968) in terms of human metaphysical energy, thus directly related to human development.
2. A former graduate student’s compelling argument that my research focus and case development on resilient design for highly capitalized buildings should address human capital as well as financial capital preservation. Her case concerning Haitian school design and construction for third world human development was compelling (Goffinay 2012).
3. Concrete masonry unit innovation for post-earthquake Port au Prince field test results from an architect colleague working on the rebuilding of a Haitian orphanage.
4. Attempting to comprehend the horrific loss of human capital/development that refugee camps and other forms of dislocation resulting from man-made disasters, in many cases, have caused. Current estimates of 65 million refugees globally (UN Refugee Agency 2015), a “fourth world,” subpopulation socially excluded from global society (Hall 2003);
5. Addressing a substantial previously unfulfilled pedagogical interest in case method teaching as a modality to accelerate design decision-making capability for students to work effectively before, during, and after disasters in practice.

In the paper, the terms human capital development and human development are used interchangeably despite different origins. The concept, human capital, dates back to economic theorist Adam Smith’s work (1776). Smith conceived human capital:

“...of the acquired and useful abilities of all the inhabitants or members of the society. The acquisition of such talents, by the maintenance of the acquirer during his education, study, or apprenticeship, always costs a real expense, which is a capital fixed and realized, as it were, in his person. Those talents, as they make a part of his fortune, so do they likewise that of the society to which he belongs. The improved dexterity of a workman may be considered in the same light as a machine or instrument of trade which facilitates and abridges labor, and which, though it costs a certain expense, repays that expense with a profit.”

Relative to human capital formation, architects’ designs range from concerns that dwellings elevate human potential, spirit or psyche (self-actualization is optimal), to designing institutional and civic space that envision enhancement
of similar intent (morale/values elevation, productive capacity, retention, etc.). In both cases, resilient buildings/environments attendant to human capital development aspire to enhance the best of what it means to be human at this time and anticipate a better future that the built work intends to foster.

In the wake of increasingly obfuscating definitions of sustainability, those of resilience are expanding to similar detriment; fetishized, au currant, or just plain market savvy to enter the “resilience business.” The definition adopted herein for resilience springs from Zolli and Healy’s thesis (2012), distinctive in the literature, citing biological and complexity theory foundations for the term, and offering ten principle tenets. (See Appendix 1). Some tenets/attributes have readily mapped onto architectural design. To achieve reasonable simplicity and redundancy in works of complexity or large scale, nature takes on modularity. Architects frequently design modules in resilient works that benefit from repetitiveness. Similarly, other complex and large-scale works have designs with simple cores and complex edges to address performance demands of their respective functions and place within and at their perimeters. Other biologically-based tenets do not readily fit, but have become the source of substantive investigation for the potentials they infer. Bird and fish populations’ capacities to flock and swarm seeking the collective safety found in numbers needed to preserve themselves, is notable (Balonso 2011).

Building designs that programmatically address aforementioned resilience tenets, as well as human capital development resources are not entirely new. Indeed, in seismic, windstorm, and flood prone areas of the developed world, safety attributes are frequently mandated and their regulation enforced. Now, comprehensive resilient design emphases are companion to strategic shifts in the design of human development-centered works and communities distressed by disasters globally. Indeed, 21st century sustainability and resilience-based meanings of human welfare in the health, safety, and welfare (HSW) licensed professions are becoming codified (Bilello and Rosenman 1997) and mandated. The State of California will require zero net energy for all residential buildings in 2020. With increasing frequency, architects built works illuminate human development concern in hospitals, churches, schools, affordable housing, and townscapes. This paper offers examples in the latter three types in three phases—before, during and after disaster. Further, briefs from the pedagogical strategy, case method, end each case. The discourse seeks to empower graduate architecture students to make effective design decisions when resilience-related response is essential. Finally, the author/instructor shares the widely shared concern that this Anthropocene Era will be characterized by a period of increased catastrophic events, climate change and seemingly incontrovertible sea level rise consequences to both the built environment and human development.

THE CASES

Case 1. Post-disaster Port au Prince, Haiti schools
Before this catastrophic seismic disaster (2010), poorly crafted, humbly furnished spaces aggregated children in schools that were, at best, simple shelters. As such, from human development perspective, they contributed to advancing life prospects in the most rudimentary of ways, rather ineffectively building human capital in this hemisphere’s poorest country. Nonetheless, Haitians have believed that education is among the only promises for opportunities in the future for their people. (Goffiney 2012). Notably, almost half of the Haitian population is under the age of fifteen, with a strong demand for schools. At the time of the earthquake, nearly every block of Port-au-Prince had a school building.

During the disaster, schools became unwitting agents of harm. Buildings of non-existent or unenforced building codes collapsed on children as shear forces exceeded minimal range of building responsiveness to the safety needs of this most vulnerable population. (Booth and Wilson 2010). As a result, Haitians witnessed the near destruction of their entire school system. Eighty percent of Port-au-Prince's schools were leveled and sixty percent of the schools nationally became unusable. (Esnard and Sapat 2014). Schools had been constructed with limited funding and without the skills and expertise required to do the job properly. No building code had been enforced. (Goffiney 2012). Part of the multi-dimensional human tragedy (that included a cholera outbreak, violence, etc.) resulted from a lack of construction knowledge, a problem solved by improving the education system, which is ironically housed in buildings that failed.

After the disaster, when schools reopened in April 2010, school classes were frequently held under aid-provided tents from entities like UNICEF, provider of one hundred fifty tents for classrooms and a number of prefabricated offices for the Ministry of Education. Over time, several important post-disaster design and construction decisions were made by humanitarian architecture foundations to build contextually responsible schools to not only resist natural disasters, but promote sustainable living with features such as cisterns, photovoltaics, and community gardens. Some international agencies have remained working with the Haitian Ministry on a model for earthquake-proof schools using innovative building technologies, including environmentally-friendly compressed earth blocks. (Costello 2010)

A particularly noteworthy construction remedy has taken debris and re-appropriated it in building material for schools. (Gregory 2011). Stacked wire-frame cage modules, gabion baskets, became walls that should prove considerably more resistant to future earthquake and windstorm disaster forces than their unreinforced masonry forebears. Rubble-based, the walls also continually remind of the disaster, “lest we forget.” In addition to concrete/rubble, salvaged rebar, scrap
metal, wood scraps, earth, cars, and fabric have been similarly collected and reused in debris-based designs. Further, available natural materials—sugar cane, bamboo, cornstalks, and water—have been allocated to reconstruction ends. Even refuse from first responders’ provisions: plastic bottles shipping pallets, shipping boxes, and tents have been adaptively reused.

These resilient design responses relate to the aforementioned Zolli and Healy cited attributes. The gabion baskets provide beneficial modularity with components that fit one another. They effectively cluster resources (the hybridity of debris and gabion), and turn the failure represented by debris into part of the solution to greater human development assurance.

Pedagogically, architecture students were challenged to address situation-based architect's decision-making questions/topics (before, during, and after disaster) including:

1. **Before disaster:** Architect's responsibility to work to affirm international building codes and their enforcement
2. **During:** Are architects as first responders? Second responders? Non-responders? First responders' contribution to life safety assistance was manifested in informal network formation, as Ushahidi Haiti (Tufts University students and friends globally). With cell phone connectivity globally, they real-time mapped emergency routes through the city in ways governmental entities could not, and ways architects did not. (Meier 2010)
3. **After:** How can architects better understand that cascading effects may hold solutions in addition to problematizing the disaster environment? Debris design, a hybrid solution of disaster and available technology, illuminates directions and ways of thinking in other disaster settings.

**Case 2: New Orleans Lower 9th Ward housing post-Hurricane Katrina**

Numerous resilience scholars have documented the Lower 9th Ward before, during, and after Hurricane Katrina (Hartman 2010; Kirby 2010; Klein 2008; LaRose 2014; Lohr 2016). In brief, before the Hurricane Katrina disaster, the largely residential district was home to a predominantly low income African American residential community, occupied by the poorest of the poor in New Orleans. (Giple 2013). What human development potential prospects existed were found in the community, access to institutional infrastructure and technology beyond the neighborhood (exceeding that of its Haitian counterpart in what one scholar terms the American “fourth world,” a subpopulation socially excluded from global society (Hall 2003, Dotson 2011)). During the hurricane's cascading effect, the flooding part of the disaster, water up to twelve feet deep filled the 9th Ward and stayed there for weeks. More lives were lost there than any other place on the Gulf Coast during the disaster. Initially forsaken, the place became abandoned. Over time, however, it was re-inhabited by a percentage of the community either committed to its place as home and those with nowhere else to go. After the disaster, the 9th Ward became the subject of deep architectural reflection and speculation on our professional subculture's humanity, its commitment to human development and its capacity to contribute to rebuilding in this context. Choices to rebuild challenged environmental rationality favoring the culture's other less rational attributes. They connect deeply to the human need to find home as a critical part of human development (Hartman 2015, LaRose 2016, Lohr 2016).

Responding to the need, Make It Right Foundation built more than one hundred houses for 9th Ward families otherwise unable to afford a home. Many have photovoltaic and other eco-friendly features. At least forty more are planned. Thom Mayne (Float House), Shigeru Ban, and Frank Gehry contributed innovative prototypes. Mayne and Ban designs proved unable to meet the project’s $150,000 budget per prototype. The Gehry design team's duplex prototype came close ($350,000). Foundation officials consider moving beyond the prototype, but Lower 9th Ward would-be recipients have sought single-family homes more like those lost. Notably, the majority of the homes meeting budget, successfully built and that lend themselves to replication came from lesser-known regional and local architects. (Hartman 2015).

These resilient design responses also positively correlate to Zolli/Healy attributes. With assistance, the Lower 9th Ward is ensuring neighborhood continuity by dynamically reorganizing with housing prototypes both culturally and environmentally responsive. In the Lower 9th Ward, resilience is not robustness, redundancy, or attempting to recover to original state. Rather, translational leaders, some of whom are local architects, have collaborated in a noteworthy effort to promote cultural sustainability with resilience-centered prototypes.

Pedagogically, the case’s situation-based decision-making questions/topics (before, during, and after disaster) for architecture students included:

1. **Before disaster:** how can architects best address divergent culture, sustainability, and resilience vectors in site selection and occupation and building design?
2. **During:** architects roles during disasters of long duration: informed decision-making on evacuation and
roles as first responders, and assessing building suitability for re-habitation.

3. After: re-engaging questions of cultural sustainability and resilience and expectations of socially responsive design by signature and lesser-known architecture firms.

Case 3. Transformative design strategies that changed the identity of Greensburg, Kansas
Greensburg, Kansas, population 1,574, 96% Caucasian, $28,348 median household income, 45-year old average was a small town remnant of the twentieth century American Midwest. Small, conservative, surrounded by farms, most buildings in town were built in the early to mid 1900’s: a 95-year old county courthouse, a movie theatre built in 1915, and a schoolhouse built in 1903. Downtown was a one block row of buildings whose notable architectural feature was tin ceilings. A social vulnerability index with eleven composite factors that differentiates counties according to measures akin to levels of human development--personal wealth, age, density of the built environment, single-sector economic dependence, housing stock and tenancy, race, ethnicity, occupation, and infrastructure dependence--gave Greensburg a medium-high ranking for vulnerability (ATSDR 2007). Measured for hazard risk, the State of Kansas ranking entity gave Greensburg 3.4 on a 4.0 point scale, a calculated priority risk index of high planning significance, meaning creating preparedness for tornadoes was essential.

On the evening of May 4, 2007, an F5 tornado destroyed 95% of the town: most dwellings and mobile homes, city hall, two schools, the business district, and its only tourist attraction, the world’s largest hand dug well. Residents reportedly staggered out of shelters to find their town gone. Eleven people were killed by the Greensburg tornado and smaller tornadoes from the same storm system, most a result of debris (falling roofs and walls when seeking shelter in basements, flying debris, and trees). In addition, nearby oil storage tanks were damaged and caused large-scale environmental damage.

In the immediate aftermath, FEMA was delayed almost 48 hours delivering temporary housing shelters because there wasn’t a place to put them. The National Guard was sent in initially but was under-manned due to troops being overseas. The Governor issued a statement saying, “When the troops get deployed the equipment goes with them. So here about 50% of our trucks are gone. We need trucks. We are missing Humvees. We’re missing all kinds of essential equipment that would help us respond in this kind of emergency.” Most city and county trucks were inoperable and weren’t able to respond. Residents with operable vehicles and traversable roads left town for shelter and family elsewhere in the region. The National Guard issued a statement about being short on front-end loaders and equipment that could help move debris. Aid agencies rushed in as post-disaster responders: 39,172 meals were served by American Red Cross; 7604 volunteers were sent by Americorps alone; 57,786 work hours were logged by volunteers. The Kansas Department of Transportation removed 40,000 truckloads of debris in the first four days. The majority of main roads were cleared and useable in the first two days of cleanup. Eventually, $12.7 million was paid by FEMA to agencies and volunteers. No architect received mention.

Weeks after the disaster, the town’s re-emergence from debris clearance was followed by considering the merits of abandonment versus rebuilding. Less than half of the residents returned. The eventual decision to rebuild came with the inducements of considerable state and federal aid. Heated discourse on how to rebuild ensued—reconstruct as the town had been? Or another alternative? Kansas City architects, BNIM, were called in to create a new comprehensive plan. In their design response, they noted,

“as one of few communities with the opportunity to do a complete overhaul of its infrastructure, buildings, and government, Greensburg is uniquely positioned to be a laboratory for research on sustainable design and community development. In addition, Greensburg is the first rural municipality to take on these aggressive goals, making it a one of a kind sustainable community. It is recommended that every entity involved in rebuilding take extra care to record successes and understand failures. In the coming years as Greensburg’s rebuild becomes more and more substantial, there will be an opportunity to attract research entities in the way of resident programs, university partnerships, and even scientific studies. (BNIM Comprehensive Plan 2008).”

Emergence of the new town was captured by a Planet Green network television series. With the architects input, the decision to rebuild moved from making Greensburg whole again to making it wholly different. Greensburg became a small town committed to rebuilding with LEED Platinum buildings: Arts Center, John Deere Dealership, Centera Bank, Kiowa County Courthouse, Kiowa County Memorial Hospital, Kiowa County Schools, Prairie Pointe Townhomes, and SunChips Business Incubator. Greensburg’s identity was transformed. In so doing, widespread interest in seeing the re-created town was spurred. Newly conceived, Greensburg has now become a tourist destination and a sustainability model for the twenty-first century small American towns.

As in the previous two cases, Greensburg’s resilient design responses relate to Zolli/Healy’s tenets. The town’s destruction, its failure, was an essential part of its resilience. The town did not attempt to recover to original state; it moved toward a new state that has thereby catalyzed human development. The town ensured its continuity by
dynamically reorganizing into a new sustainability paradigm that would not have otherwise occurred. In the wake of the disaster, the clustering of human development needs brought the town's resources into close proximity with one another. Despite heated discourse, under supportive conditions internal and external to the community, residents exercised their capacity for trust and collaboration. In similar fashion, translational leaders became manifest inside and outside the community.

Again, pedagogically, Greensburg's story affords other professional practice decision-making questions/topics related to resilience:

1. Before disaster: what are the roles of architects in small towns distant from cities where architects typically practice? Similarly, what is the place/role of architecture in small towns? The design of buildings that protect the public's health, safety, and welfare (HSW)?
2. During: Are there roles for architects in rapid onset disasters? Can architects ameliorate cascading effects in the immediate aftermath of a disaster?
3. After: is architectural design potential for changing community identity predictable? Is the transformation of place into new identity the direct or indirect result of architecture?

The architect in resilient design for human capital/human development-based buildings

Architects' roles before and after disasters are enduring and well understood. Building codes and standards creators address the health, safety and welfare design needs of individuals and groups of all sizes and levels of vulnerability. Architects participate in the development of those codes. They adopt new building knowledge as it emerges, is popularized, and is legislated within the design and building industries. Works by architects meet or exceed HSW needs and the standards that enshrine them. In conforming jurisdictions, they are inspected and regulated for adherence. Those roles expand in scope as architects increasingly engage themselves in resilience work.

In contrast to architects' engagement before and after disasters, roles during disasters are largely absent. Efforts that occur are difficult to find in the profession's literature and equally hard to find in nearly all practices of architecture. Perhaps this is why, they become misrepresented. (Figure below. Can an architect do anything helpful with hands on hips as portrayed?).

The effort to better ascertain critical roles for architects may most readily begin with relatively predictable, longer duration disaster events like flooding (others include hurricanes, wildfire, storm surge, sea level rise, etc.). A case in a nearby Indiana community may illuminate directions.

In 2008, Columbus, Indiana experienced a flood that enveloped the regional hospital, Columbus Regional Health, a distinguished Robert Stern design adjacent to Haw Creek, the flood's source. As creek floodwaters rapidly rose above the hospital's ground floor level, all power, including backup generator power, was lost. The hospital became powerless jeopardizing the lives of patients on mechanical life support. The hospital facilities manager contacted the building's architect for ongoing other projects, Gary Vance, FAIA, BSA Lifestructures Principal in Charge at the time. In response to a call, Vance rapidly converted a significant segment of his Indianapolis team into an architectural SWAT team, shifted personnel from other projects to assist. First, they planned to stabilize conditions at the hospital, then create a temporary hospital facility that served as a transitional care unit, and design/organize a means to evacuate patients from the hospital to requisite life support beyond. Concerning his roles during the disaster, he asserted “assisting in saving lives during the Haw Creek flood has been the most significant professional experience in my life.” The event revealed to the firm serious shortcomings in its adaptability to radically changing circumstances in practice but expanded the firm's scope of services thereafter. The search for other examples in other forms of disasters continues.
In summary, the cases show that failures in the built environment can be more substantial hazards to people than natural/man-made disasters themselves. Though lagging well behind engineering counterparts, these challenges/opportunities are becoming normalized in architectural practice in the United States. In terms of human development and human capital development, the cascading effects of disaster have PTSD type equivalence for victims, especially among the most vulnerable populations—children, the elderly, the impoverished, and the infirm. Despite protracted abandonment in communities following disasters, critical masses of people return out of necessity or desire with human development prospects hanging in the balance.

The challenges of providing forms of architecture that promote human development in a world of inequitable resource distribution, and varying degrees of compassion to address that increasingly problematic circumstance are profound. Resilience theories emerging from biology and complexity science affirm some existing design directions and open new possibilities.

Can architects help create places in which realizing the potential of all human development becomes central to humankind's aspirations and reflected in their works? Architect, inventor, and comprehensive anticipatory design scientist, Bucky Fuller, wondered aloud about humanity's prospect for human development in a world in which everyone could spend their time doing the things each loved doing most of all. The likelihood of invention frequency, now 1:250,000 people, he estimated (Fuller 1968), would increase many-fold. Redefining the meaning of wealth on the planet from its current accounting systems to the combined total of all the physical and metaphysical energy on the planet would be required, he further speculated. Design for resilience in ways that focus on the development of human capital must accelerate lest this era of increasing disaster brought about by climate change's devastating effects render us perilously bifurcated. Reasons for optimism, Fuller also points out, reside in our human ability to channel our thinking in ways that energize the potential for emerging new paradigms in times of profound crisis.

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APPENDICES

Appendix 1. Attributes of Resiliency
From Resilience: why things bounce back, Zolli and Healy 2012.

Patterns (tenets) of resilience:
1. Feedback mechanisms to determine when an abrupt change is nearing
2. Ensure continuity by dynamically reorganizing
3. Decouple the system from underlying material requirements
4. Beneficial modularity: simple internal modular structure with components that plug into one another
5. Diverse at the edges but simple at their core
6. Flock or swarm when time is right and to break into islands when under duress
7. Clustering—bringing resources into close proximity with one another
8. Resilience is not robustness, not redundancy, nor attempting to recover to original state
9. Failure may be essential part of resilience
10. Resilient people have (a) capacity for trust and collaboration, (b) form informal networks, manifest translational leaders
Appendix 2. Characteristics Of A Safe And Resilient Community. ARUP report to the U.N.

A safe and resilient community:

1. is knowledgeable and healthy. It has the ability to assess, manage and monitor its risks. It can learn new skills and build on past experiences.
2. is organized. It has the capacity to identify problems, establish priorities and act.
3. is connected. It has relationships with external actors who provide a wider supportive environment, and supply goods and services when needed.
4. has infrastructure and services. It has strong housing, transport, power, water and sanitation systems. It has the ability to maintain, repair and renovate them.
5. has economic opportunities. It has a diverse range of employment opportunities, income and financial services. It is flexible, resourceful and has the capacity to accept uncertainty and respond (proactively) to change.
6. can manage its natural assets. It recognizes their value and has the ability to protect, enhance and maintain them.
ABSTRACT: This paper examines the history of municipal annexation as a mechanism for suburban expansion in San Antonio, Texas between 1939 and 2014. Annexation, which permits municipalities to enlarge jurisdictional boundaries by absorbing adjacent, unincorporated areas, emerged as a powerful governmental apparatus to grow Sunbelt cities across the postwar United States. Political elites in San Antonio began leveraging annexation with remarkable efficiency after World War II and continue the practice today. During the period under study, the city council executed 461 annexations and boundary adjustments, adding 497 square miles to the metropolitan footprint (List of Annexation Ordinances, 2014). The same time frame saw San Antonio grow to become the seventh most populous city in the United States, adding 430,000 people in the last decade alone, with another 1.1 million expected by 2040 (Rivard, 2016). The continued use of municipal annexation as a way to grow the city has generated a wide array of responses among citizenry, ranging from strong support within development communities eager to access emerging markets, to opposition from historically disenfranchised neighborhoods where people contend that annexation further consolidates resources in middle- and upper-income areas of the city. This paper examines the historical roots of such positions in an attempt to clarify today's contentious discourse on annexation in San Antonio.

KEYWORDS: Municipal Annexation, Metropolitan Expansion, Metropolitan Fragmentation, Suburbanization

INTRODUCTION

The origins of municipal annexation, the territorial and municipal services expansion that it authorizes, and its far-reaching impacts date to the early postwar period. In 1940, the year that San Antonio undertook its first annexation, the city’s population of 253,854 remained confined within San Antonio’s original 36-square mile grid (San Antonio, Texas Population History 1880-2015, 2017; List of Annexation Ordinances, 2014). By 2016, San Antonio had grown to become the second largest city in the United States, with a population of 1,469,845, and a municipal boundary covering 465 square miles (United States Census Bureau, 2016). The primary mechanism for San Antonio’s demographic and geographic explosion has been annexation, which the City of San Antonio defines as “...the process by which cities extend municipal services, voting privileges, full regulatory authority and taxing authority to new territory” (Annexation, 2014).

In Texas, the legal authority to annex territories resides in the 1912 Home Rule Amendment to the Texas Constitution, which provides cities with a population above 5,000 the right to annex adjoining territory. The Municipal Annexation Act of 1963 clarified the required annexation procedures, adding the concept of extraterritorial jurisdiction, which provides a city with limited control over land that extends beyond current city limits. In 1999, the Texas Senate introduced Senate Bill 89, which obliged municipalities to announce annexation plans three years in advance. It also compelled cities to publish service plans providing future residents with a description of municipal services that would occur under annexation (Tyson, 2012).

In 2017, the conversation surrounding annexation remains as contentious as ever. The City of San Antonio is currently pursuing the annexation of five priority areas totaling 66.47 square miles, which would increase the city’s population by approximately 117,517 residents. Among the five areas under consideration are a 15 square-mile addition of mixed-use property northwest of downtown along Interstate Highway 10 West; 9 square miles of residential property northeast of downtown along U.S. 281 North; and another 1.9 square miles of commercial and vacant property northeast of downtown along U.S. 281 North (Annexation Program, 2017). The proposed annexations are generating a wide range of reactions from residents, developers, and city officials.

Historically, arguments for and against annexation break down in a relatively consistent pattern. The following positions represent four common justifications for annexation:

1. Annexation as progressive municipal-governance strategy. This position is often taken up by urban planners and city officials who view annexation as a tool to maximize the efficiency of land-use planning, particularly as it relates to the delivery of infrastructure and utilities. Proponents of this
position sometimes emphasize the added benefit of extending environmental regulations to larger portions of the metropolitan area.

2. Annexation as means to consolidate tax revenues. This position is predictably held by city officials who are concerned about the negative impact that suburban growth can have on tax revenue, particularly as large portions of middle- and upper-income residents and businesses relocate beyond established municipal boundaries.

3. Annexation as tool for economic development. This position is most often espoused by developers who are looking to enter new markets and need a reliable municipal authority to guarantee the delivery of services.

4. Annexation as mechanism to acquire access to political representation or municipal services. This position is taken up by homeowners who occupy the periphery of a municipality and are looking to either improve political representation or acquire access to critical services such as water, fire, and police protection.

The following arguments represent four common objections to annexation:

5. Annexation as abuse of tax authority. This perspective is most often expressed by two distinct groups of people: The first includes people who leave cities in order to minimize their financial and regulatory obligation to public institutions. Tyson refers to this phenomenon as the “secession of the successful,” as it often involves wealthy individuals who do not wish to pay taxes that may subsidize the government services of others (Tyson, 2012). A second group includes less-affluent residents of unincorporated areas who share a similar aversion to potential tax hikes, though the latter group’s opposition is likely rooted in financial vulnerability to the negative impacts of gentrification such as rising property taxes.

6. Annexation as perpetuation of political status quo. Many politically or economically disenfranchised communities believe that annexation consolidates resources in middle- and upper-income communities, often at the continued expense of underserved neighborhoods.

7. Annexation as threat to localism. Residents who espouse this position believe that representative government works best at the smallest possible scale and with the least amount of regulation.

8. Annexation as an empty promise. Residents in some districts argue that the supposed benefits of annexation rarely come to fruition, as the process fails to deliver promised goods and services.

The next section considers the historical origins of these positions as they relate to the growth of San Antonio.

1.0 CONSOLIDATION: ANNEXATION AS A METROPOLITAN POLITICAL WEAPON, 1939-1952

Prior to World War II, municipal governments mainly in the Northeast and Midwest relied on annexation to expand the influence and economies of major metropolitan centers. In the postwar period, however, annexation as a growth strategy waned in those regions, but remained a potent force in the Sunbelt and Western regions of the U.S. (Nicolaides and Wiese, 2006). Postwar San Antonio, Texas expanded its city boundaries by annexing outlying areas. Suburbs that resisted annexation often turned to incorporation as a means to preserve home rule. This meant that the suburb assumed responsibility for sustaining municipal services such as police and fire protection, streets, sewers, drainage, parks, libraries, and schools (Edwards, 2008).

A combination of factors accelerated San Antonio’s push for annexation. Postwar population growth, industrial and residential suburbanization, and economic development opportunities prompted the city council in the 1940s to begin reining in the emerging metropolis. Suburbanization, especially, forced the city of San Antonio to act affirmatively in order to preserve coherence and influence on the region as hastily planned suburbs vied for services, and siphoned off potential sources of tax revenue (see Figure 1).

This last factor likely drove Mayor Maury Maverick’s decision to annex the South Side neighborhood of Harlandale in 1940. His plan marks the first example of what would soon become a continuing pattern of annexation in San Antonio. It also provoked fierce resistance by local home-owners. Led by Thurman Barrett, the community of nine thousand residents opposed annexation. However, rather than take the concerns of property owners seriously, Maverick and committee members mocked Harlandale residents, and Barret in particular. Maverick promised to prepare a “fancy document” signed by all the council members declaring Barret the “Duke of Harlandale” (Harlandale Annexatino Studied,
This incident characterized the city's disdain for opponents of annexation, an attitude that would endure for the remainder of the decade.

As World War II came to a close, metropolitan regions across the United States experienced a postwar boom in regional development. In anticipation of the boom, and in an effort to protect future assets, the city again initiated a series of sweeping annexation drives. Led by Mayor Gus B. Mauerman, the city used land acquisition as both a tool and a weapon against metropolitan fragmentation, thereby inaugurating San Antonio's first dedicated annexation regime. “I kept on my toes and never let any new suburbs grow,” he explained, “I took them in[to the city] before they had a chance to grow.” In 1944, the city approved a group of ordinances permitting the annexation of more than six thousand acres of unincorporated territory (Fleischmann, 1977) New territory permitted larger scale growth. During this decade, the city added 29,500 residents by annexation, in addition to 124,900 new residents by migration and natural increase (Fleischmann, 1977).

By 1952, Suburban incorporation drives continued to threaten San Antonio's future growth and tax base. Under a
newly reformed city government running a council-manager system, San Antonio annexed 80 square miles of land and 32,000 new residents, more than doubling the size of the city (Booth and Johnson, 1983; Rosales, 2000). Acquiring and consolidating new territory into the existing political structure while stamping out resistance, the city's growth leaders found in annexation the power to shape a metropolitan region while avoiding political balkanization. Yet, the methods the city employed to achieve these ends provoked further resistance and ensured that the debates around annexation would only intensify as population numbers climbed, demographics shifted, and tax revenues and expenditures ballooned.

City reformers swept the 1955 council elections. This self-identified Good Government League (GGL), a group of businessmen, politicians, social elites, and ethnic middlemen, dominated local politics for the next eighteen years. To secure their power the GGL depended on ethnic patronage and the promise of government backing for the growth of private enterprise. In doing so, the GGL further established the use of annexation as a tool for economic development. To be sure, the GGL's growth agenda created opportunities for homeownership and small business entrepreneurship. Still, the GGL's continued neglect of social problems provoked grassroots movements for actual urban reform coming out of Chicano and African-American neighborhoods across the city. During this time, disenfranchised groups became more convinced than ever that annexation represented a tool to consolidate power in the hands of elites, thereby perpetuating the economic and social status quo in the city. Continued annexations only exacerbated these tensions. Under the GGL, San Antonio developed a growth pattern dubbed "spoke annexation." It allowed for the annexation of thin tracts of land that emanated out of the city boundaries, and in effect became a way of claiming territory in advance of official procedures. The areas located within the "spokes" became fertile development zones as builders anticipated annexation at a later date. These seemingly small annexations produced far less public rancor and enabled city officials to go about the business of growth unencumbered. Using this model, the city annexed more than 1,300 acres of territory between 1967 and 1970, with designs to fill in the gaps during subsequent waves of development (Fleischmann, 1977).

An example of this came at the beginning of April 1970, as Mayor McCallister announced a city plan to study annexation sites on the periphery of the city. The pause in annexation efforts in the previous year began to frustrate the mayor as he pushed for action in city growth (San Antonio Light, 1970). As a result, City Manager Gerald C. Henckel, Jr., announced in June that the city planned to annex a large tract of territory between the northern reach of Culebra Road and Interstate Highway 10. This area included the 600-acre site for the University of Texas at San Antonio to the outer loop 1604. The city justified the cost by pointing to a recently adopted gas connection fee that charged developers one hundred-fifty dollars to tap into city resources if the development was outside the city boundary, compared to thirty dollars if the development was sited inside city boundaries (San Antonio Light, 1970).

Yet, the annexation of this particular tract of land touched off a series of debates and a major legal challenge to San Antonio's spoke method of annexation. Bexar County Commissioner Albert Pena was among the most vocal critics of this plan. As an outspoken advocate for working-class ethnic Mexicans, as well as a keen opponent to the GGL agenda, Pena served an important role in local government to speak on behalf of those who had no civic voice (Rosales, 2000). From Pena's perspective, the University of Texas Board of Regents received a sweetheart deal from the city to site the university on the far northwest side. Instead he argued that the university would better serve students and taxpayers if it were located on the south side (Pena, 1970). Meanwhile, property owners in the community of Hills and Dales adjacent to the proposed UTSA site pushed for municipal incorporation in an effort to stave off annexation by the city. Simultaneously they filed a lawsuit challenging the city's annexation methods. Following a ruling in favor of the city in the Court of Civil Appeals, the case went for review at the Texas State Supreme Court (San Antonio Express, 1971). Ultimately, efforts by residents of Hills and Dales to establish and protect their autonomy failed as they became residents of the City of San Antonio.

3.0 MASSIVE GROWTH, MASSIVE RESISTANCE IN THE POST GOOD GOVERNMENT LEAGUE PERIOD 1971-1981
Repeated annexations, migrations, and natural increases combined with outmigration to far-flung suburbs began to shift the racial demographics of the city. Between 1960 and 1970, San Antonio transformed from a majority Anglo-city to a majority Latino-city. In the span of a decade, Latina/os went from 41.5 percent of the population to 52.2 percent of the population. Likewise, the percentage of Anglo population fell from 51.2 percent to 39.2 percent. And, African-Americans remained steady at 7 percent and 7.6 percent, respectively.
The city rolled out ambitious annexation plans in 1972, but faced resistance from local homeowners, small developers, and grassroots organization. A lawsuit brought by Ray Ellison Industries in May of that year prompted the city to shift their course of action from grabbing one large tract of land to taking smaller pieces of territory over an extended period of time (Reed, 1972). Likewise, the Mexican American Legal Defense and Education Fund (MALDEF) argued that the proposed north side annexations would only deepen the unequal quality of city services to the west and south sides. Additionally, the group feared that the city council, which was already overrepresented by Anglos from the north side, would remain out of reach for Mexican-American candidates (Rosales, 2000).

As pressure mounted, the GGL’s foundation began to crack. Expansive territorial additions introduced backlogs in the delivery of water and efficient trash collection, and the police department also scrambled to cover new areas. Residents, unsurprisingly, complained of increased taxes despite receiving inferior services (Robinson, 1973). However, inefficient city services would prove to be the least of the city’s problems related to the 1972 annexations. Several years later, the United States Justice Department determined that the city was in violation of the 1975 Voting Rights Act, which mandated fair government representation for all citizens.

San Antonio’s at-large election format came under fire because, in the ruling of the Justice Department, newly acquired suburban tracts with majority Anglo residents held the potential to dilute the electoral representation of the city’s Mexican-American communities, just as MALDEF had feared. Initially, the city challenged the judgment while the first female mayor in the city’s history, Lila Cockrell, announced plans to sue the federal government. However, councilman

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**Figure 2**: San Antonio annexations by mayoral administration. Source: (Maps by Authors, Data from City of San Antonio, 2017)
Henry G. Cisneros sought a more conciliatory path as he led an effort to re-write the city charter (Weser, 1976). Ultimately, the city opted for charter reform and agreed to abolish the at-large council elections and instead introduced a single-district format that would offer a fairer electoral process across the city (Cottrell and Stevens, 1978). More than any previous set of annexations, the 1972 annexations changed the political and social landscape of the city. Still, historical patterns of growth and the accompanying debates over annexation continued.

In October 1979, hundreds of protesters stormed a city council meeting to register their opposition to an annexation plan for a group of subdivisions in the southeast part of the metropolis near Lackland Air Force Base. The mix of Anglo, suburban home owners, and members of the predominantly Mexican-American grassroots organization Communities Organized for Public Service (COPS) represented a cross-section of the area. The former constituency charged that they would face prohibitive city taxes should the annexation plan succeed, whereas the latter group argued that sections of town comprised of working-class communities of color suffered neglect and stood to experience further alienation with each successive land grab. Despite the vigorous resistance, Mayor Lila Cockrell guided the council to a 6-4 vote in favor of annexation (Martin, 1979). Cockrell's determination to annex territory was driven by a commitment to keep San Antonio among the top ten most populous cities in the U.S. “It meant a great deal to be in the top ten,” she declared, “you never hear about the top eleven or the top twelve.” Perhaps even more importantly, she noted, there were one hundred federal grant programs up for grabs, all of which used population as one criterion for award (Annexation Called 'Must', 1979). This brought an end to a tumultuous decade of growth politics. Even as local opposition grew more intense, the city consolidated its power by adding formerly unincorporated districts, thereby avoiding the political problems of a fragmented metropolis. However, the demographic shift that saw ethnic Mexicans overtake Anglos as the majority population for the first time since the nineteenth century upended established growth-by-annexation strategies. In doing so, it also paved the way for a restyled vision of metropolitan expansion championed by one of the city's brightest stars.

### 4.0 CISNEROS ADMINISTRATION AND SAN ANTONIO'S EMERGENCE ONTO THE NATIONAL STAGE, 1980'S - PRESENT

In 1981, voters elected Henry Cisneros as mayor, the first Latino in that position since 1842. He began a decade long tenure that saw the city expand its territorial boundaries, principally because of his uncanny ability to negotiate consensus between competing factions. This skill enabled him to draw popular support while maintaining a business-friendly agenda (Rosales, 2000). On the heels of the 1970s when Latinos emerged as the majority population and dissent from working-class areas registered with greater force, Cisneros represented the voice of compromise. “What the population distribution means is that the cultures have to come to understand each other,” he declared, “And that is what is happening. This is a city that has had to learn to accommodate different points of view” (King, 1983). In many ways, Cisneros was the perfect figure to restore the trust of everyday residents in their city government, while promoting growth consistent with entrenched patterns. This did not mean he went unchallenged.

In January of 1985, fresh off a series of annexations that drew large swaths of the northwest side into the municipal boundaries, Cisneros and William Jovanovich, chairman of Harcourt Brace Jovanovich, Inc., together announced plans to build a Sea World theme park on sites along the 151 corridor (King, 1983). The announcement yielded a great deal of excitement among the business community, as Sea World promised to instantly make San Antonio an important national tourist destination while providing further opportunities for investment. Still, skepticism quickly surfaced, like that expressed by councilman Bernardo Eureste, a fearless critic of growth politics. Eureste charged that the city gave land speculators inside information, thereby creating an unfair advantage for developers with knowledge of the impending project. One local real estate broker admitted that prior to the public announcement, “the area where Sea World is [had] been hotter than a rock for the [previous] three months” (Rosales, 2000; Hawkins, 1985) The secrecy surrounding the deal damaged Cisneros's reputation, but did not break it. In subsequent years, he was able to attract a 15-million-dollar donation from Ross Perot to build a biotechnology park, arrange a papal visit, and secure an annual Professional Golf Association tournament (Rosales, 1986).

In many ways, the Sea World deal confirmed the core motivation for annexation politics in San Antonio since the end of World War II: suburban development. For decades, city leaders had tirelessly pursued land on the outskirts of town for economic opportunities, often securing benefits for friends and business partners along the way. This modus operandi assured that city government would continue to dominate San Antonio's political and economic landscape. Cisneros, despite the mayor's popular appeal among the local Latino population, guaranteed that the patterns established by GGL leadership would continue relatively intact. During the Cisneros Administration, the City completed 99 annexations, adding 52,104 acres (81.4 square miles) to San Antonio's municipal footprint (see Figure 2).

More recently, political progressives have come to view annexation as a vital strategy to extend environmental regulations to ecologically threatened areas. Specifically, two of the current annexation targets, Interstate Highway 10 West and US 281 North, are located over the fragile and critical recharge zone of the Edwards Aquifer in the northern part of the city. In theory, these areas would benefit from municipal restrictions that limit the amount of new
impervious groundcover that accompanies new buildings, streets, and parking lots. Such restrictions are intended to reduce the amount of water runoff that ends up in the storm sewer, while minimizing the amount of polluted water that flows into the aquifer. However, in a surprising twist, environmentalists—including representatives from the Greater Edwards Aquifer Alliance—have come to oppose the annexations, pointing out that the legal limits on impervious cover within the extraterritorial jurisdiction (ETJ) are more restrictive than San Antonio’s current guidelines (Davila, 2016). Presumably the end-game of such environmental groups is to convince the city to increase its own restrictions on impervious ground cover. Meanwhile, additional opposition to the latest annexation targets is coming from residents who see the entire process as a threat to their local political autonomy. State Representative Lyle Larson (R–San Antonio) of Leon Springs is championing this position most loudly, not surprising given that in August 2016 the City Council voted to annex his district. Lyle last year introduced legislation that would require an affirmative vote from residents in order to annex an area with more than 200 people (1200 News Radio WOAI, 2017).

CONCLUSION
The history of annexation in San Antonio reveals that, where urban growth was concerned, the enduring competition between multiple, often diverging political interests produced a consistent outcome: the expansion of municipal boundaries. The city’s 461 annexations and boundary adjustments since 1940 testify to the formative role that annexation played in the political and geographic growth of the city (List of Annexation Ordinances, 2014). This is not to say that proponents of annexation were motivated by singular ambitions, or that the practice has yielded a predictable result. To the contrary, the practice of annexation has generated a wide variety of impacts and opinions: what began as a way for municipal government to consolidate tax revenue has become a rallying cry for anti-tax groups; where progressive elites tout annexation as a tool for coordinated growth, proponents of localism instead see a threat to political autonomy; while the San Antonio business community enthusiastically leverages annexation to expand economic opportunity, disenfranchised groups claim that it simply allows political and economic elites to consolidate power; and while some peripheral communities hold the hope that annexation can help them acquire increased political access and municipal services, others see it as an empty promise, guaranteed only to raise taxes.

Nevertheless, we can make several critical observations about the historical impact of annexation on San Antonio’s urban growth. First, while elites used the mechanism for decades to consolidate and extend their own political power, the Charter reform of the 1970s unquestionably spread the benefits of annexation more evenly across city populations. Today, City Council and council districts represent voices that decades ago did not enjoy access to power. Still, the larger impact of the council system turned out to be more political than economic, as the vast majority of economic growth continues to appear on the north side of the city, which is disproportionately Anglo.

Second, the practice of annexation allowed San Antonio’s city government to capture a growing regional population and tax base that would have otherwise been lost to neighboring municipalities. It is no accident that San Antonio today boasts the seventh largest population among U.S. cities, despite its location within the twenty-fifth largest metropolitan statistical area in the country (United State Census Bureau, 2017). San Antonio’s standing as one of the ten most populous cities in the U.S. continues to enhance the city’s national profile, helping it to attract new businesses and investment—a fact not lost on Mayor Cockrell over four decades ago. Annexation additionally prevented the political fragmentation seen in so many other U.S. cities, allowing the city to maintain a relatively cohesive—if often contentious—public discourse.

Third, the practice of annexation in San Antonio accelerated the centrifugal expansion of population and investment. Massive decentralization resulted in the dispersion of industrial and residential program away from the city center and towards the suburban periphery. With the pattern of northward growth firmly established by the 1970s, annexation did more than stretch the political boundaries of the city. The integration of existing and self-sustaining neighborhoods exacerbated suburban isolation and increased overall wariness of centralized planning processes.

Finally, despite the positive overall impact of the city council system, the patience of working-class San Antonians wore thin as their communities continued to suffer infrastructural and representational neglect. In this regard, annexation intensified tensions up and down the class spectrum, and across racial lines. When the Justice Department found the city in violation of the 1975 amendments to the Civil Rights Act that guaranteed representative government, the city was forced to redesign its charter. Despite such signal achievements, the business of growth persists and is accelerating. Slow-growth NIMBYism has since become a steady companion to municipal expansion. This tension continues to produce fierce public debates over the limits of homeownership, environmental degradation, class privilege, and the integration of underrepresented people into civic life.

Against this complex and evolving backdrop, annexation continues to define spatial politics in San Antonio today. The long history of annexation has resulted in a widespread—at times fatalistic—acceptance of the practice. As local Council member Mike Gallagher recently concluded, “[w]e’re going to grow, no matter what. Either we are going to control it or someone else will” (Ortiz, 2015). So it is that the residents of San Antonio, like so many other Sunbelt denizens, can
expect to contend with the continued costs and benefits of municipal annexation in the decades to come.

ACKNOWLEDGEMENTS
The Authors would like to acknowledge the efforts of UTSA student Monica Martinez, B.S. Architecture 2017, who made significant contributions to the mapping and data visualization.

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ABSTRACT: Like many American cities, Charlotte, NC is undergoing a flood of in-town apartment construction that saturates the market with repetitive, single-use housing stock. This phenomenon is exacerbated as emerging professionals seek metropolitan living in the city center only to move out of the city once lifestyles mature, expanding suburbanization. Based on historical research of urban renewal in Charlotte and studies in recent demographic changes and current housing trends, locally and nationally, this paper presents R.A.W. or Residents at Work, a complex model of mixed-use, mixed-income and income-generating urban housing that responds as an antidote to the rampant quantities of large-scale, single-use, monolithic housing construction recently built in Charlotte, North Carolina.

KEYWORDS: housing, live/work, affordable housing, gentrification

Figure 1: R.A.W.: Residents at Work Proposal, Mint Street, viewing north. Source: (Authors 2016)

1.0 INTRODUCTION
In 1914, developer F. C. Abbott established the Wilmore Neighborhood in Charlotte, North Carolina. Farmland originally owned by the Wilson and Moore families was combined to create a residential neighborhood to help support the activities of industries in Charlotte’s South End. These companies included Atherton Textiles, Mecklenburg Flour Mill, Charlotte Trouser Co. and Charlotte Pipe and Foundry. Historians have called this sector of town the city’s first industrial park. Its rise as a production corridor featuring locally-owned businesses established a strong identity for
Wilmore. A vibrant and local social and economic complexity evolved to the benefit of those who lived and worked there.

Social complexity is the study of the phenomena of human existence and the many possible arrangements of relationships (Simon 1962 and Hayak 1964). A change in neighborhood demographics in the mid to late-1960s as a result of urban renewal, blockbusting, and white flight brought African-Americans to the area. Today, the forces of market-rate economic development near Center City are driving the next phase of change, resulting in rampant real estate speculation with the associative ill-effects of gentrification and homogenization. A phenomenon of alienation between the inhabitants and their environment has set in. Like other growing American cities, Charlotte is undergoing a flood of in-town apartment construction that saturates the market with repetitive, single-use housing stock. This phenomenon is exacerbated as emerging professionals seek metropolitan living only to move out of the city once lifestyles mature, expanding suburbanization.

R.A.W. or Residents at Work (Fig. 1) proposes a mixed-use residential-industrial urban community that re-inscribes the legacy of the Wilmore neighborhood. It attempts to offer an alternative form of development by introducing a new model of permanent, leased, and mixed-use living and work space that offer a more comprehensive, complex and sustainable urban option. The project aims to provide flexible economics that permit families to lease backyard micro-units, creating a small-scale affordable “alley urbanism.” It also permits business owners to lease live/work spaces as part of an inclusive “maker network” along Mint Street, transforming a former industrial corridor into an incubator zone for small business development. The single-family housing with accessory structures west of the site inspired the idea for affordable alley micro-units. These units are intended to be low-cost rentals of the single-family houses above that support housing for a diverse neighborhood workforce. This combination of live/work, market-rate, and affordable housing promotes diversity at both an economic and social level.

Architecture has the capacity to engender social and economic complexity in the places people inhabit. Social and economic complexity is central to an emergent urbanism driving the health and life of the city. The dynamic relation between buildings, streets, sidewalks, alleys, trees and street furniture and neighbors of different socio-economic backgrounds is the source of the vitality of the places we inhabit. This paper will present a study of the salient characteristics of social and economic complexity in the urban environment with the goal of engendering complexity in the everyday lives of fifty residents.

2.0 URBAN RENEWAL HISTORY: DOWNTOWN CHARLOTTE

Charlotte's identity as a “New South City” originates from its regional location as a trading hub during the 19th and early-20th century. Unlike Charleston, South Carolina or Atlanta, Georgia, the focus on commerce rather than agriculture is one of the identifying traits of towns in the Southeast following the establishment of industries such as mining but more importantly the textile production that lasted until the 1960s. In addition, a major factor in Charlotte's urban growth can be attributed to its role as a railroad transportation center, expanding the city's capabilities as a distribution axis from north to south as well as from the Atlantic coast westward. The growth of these industries, aligned with the flow of transportation, made a suitable place for financial institutions to take root, becoming a part of the contemporary workforce in the city today (Bank of America and Wells Fargo).

For much of its early development before the 20th century, Charlotte was an integrated city. Home ownership in the City’s four wards created a diverse urban core that was occupied by white and black families. After the turn of the century, new segregation laws and the physical separation of the public services under Jim Crow orders created a new hierarchy in the urban fabric. This continued with the New Deal in the 1930s and also suffered under the mandates of urban renewal in the 1960s (Hanchett, 1998). Arguably, the current day dilemma of affordability in Charlotte is connected to these complex series of events that stratified wealth and led to the physical and social division of Charlotte's housing opportunities. This pattern continues today in the wake of lucrative business transactions and the pro-developer atmosphere of the City.

3.0 CHARLOTTE DEMOGRAPHICS

With a population of 827,097 (U.S. Census Bureau, July, 2015), Charlotte is the 17th largest city in the United States. To the surprise of many, the city of Charlotte is twice the size of the city of Atlanta (463,878). The county seat of Mecklenburg County, Charlotte is the second largest city in the southeastern United States, just behind Jacksonville, FL, and the largest city in the State of North Carolina. The percentage change in population between 2010 and 2015 is 12.4%. 66.5% of the population is under the age of 18 and 8.5% of the population is over the age of 65. 50% of the population is White, 35% is Black or African-American, 13% is Hispanic or Latino, and 5% is Asian. The female population is 52% and the male population is 48%.

Table 1: Top 20 Incorporated Cities by Population Estimates. Source: (U.S. Census Bureau, July, 2015)
City | Population | City | Population
---|---|---|---
(1) New York, NY | 8,550,405 | (11) Austin, TX | 931,830
(2) Los Angeles, CA | 3,971,883 | (12) Jacksonville, FL | 868,031
(3) Chicago, IL | 2,720,546 | (13) San Francisco, CA | 864,816
(4) Houston, TX | 2,296,224 | (14) Indianapolis, IN | 853,173
(5) Philadelphia, PA | 1,567,442 | (15) Columbus, OH | 850,106
(6) Phoenix, AZ | 1,563,025 | (16) Fort Worth, TX | 833,319
(7) San Antonio, TX | 1,469,845 | (17) Charlotte, NC | 827,097
(8) San Diego, CA | 1,394,928 | (18) Seattle, WA | 684,451
(9) Dallas, TX | 1,300,092 | (19) Denver, CO | 682,545
(10) San Jose, CA | 1,026,908 | (20) El Paso, TX | 681,124

Between 2011–2015, 88.4% of the population in the city of Charlotte was a high school graduate. During this same period, 41.3% of the population held a Bachelor’s degree or higher. In 2015, there were 305,488 family households with 2.55 persons per household. 20.5% of the population in Charlotte speaks a language other than English at home. The median household income is $53,637 and per capita income in 2015 was $32,254. The percentage of persons in poverty is 16.8%.

In analyzing the top 100 most populous cities in the U.S. by comparing quality of life, value, job market, desirability and net migration, Charlotte was recently ranked one of the Top 20 Livable Places in the U.S. (4). In 2017, Charlotte received an overall score of 7.1 out of 10, up from 6.9 in 2016.

**Table 2:** 2017 Top 20 Livable Places Criteria. Source: (US News and World Report, February 2017)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Category Weighting</th>
</tr>
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<tbody>
<tr>
<td>Job Market Index</td>
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<tr>
<td>Value Index</td>
<td>25%</td>
</tr>
<tr>
<td>Quality of Life Index</td>
<td>30%</td>
</tr>
<tr>
<td>Desirability Index</td>
<td>15%</td>
</tr>
<tr>
<td>Net Migration Index</td>
<td>10%</td>
</tr>
</tbody>
</table>

**4.0 IN-TOWN CHARLOTTE APARTMENT CONSTRUCTION**

According to Real Data which tracks multi-family apartment markets, more than 12,300 units are currently under construction in Charlotte with about 13,500 more planned. As of September 2016, the apartment vacancy rate in the city of Charlotte is 5.9% with an average rent of $1,052 and a Market Rank of 97 (5).
Table 3: Vacancy and Market Rate. Source: (Real Data 2016)

<table>
<thead>
<tr>
<th>City</th>
<th>Vacancy Rate</th>
<th>Average Rent</th>
<th>Market Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charlotte, NC</td>
<td>5.9%</td>
<td>$1,052</td>
<td>97</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>5.6%</td>
<td>$1,113</td>
<td>93</td>
</tr>
<tr>
<td>Greensboro, NC</td>
<td>5.6%</td>
<td>$796</td>
<td>91</td>
</tr>
<tr>
<td>Greenville, SC</td>
<td>7.9%</td>
<td>$905</td>
<td>92</td>
</tr>
<tr>
<td>Nashville, TN</td>
<td>5.7%</td>
<td>$1,110</td>
<td>96</td>
</tr>
<tr>
<td>Norfolk, VA</td>
<td>5.7%</td>
<td>$1,010</td>
<td>91</td>
</tr>
<tr>
<td>Richmond, VA</td>
<td>6.5%</td>
<td>$987</td>
<td>89</td>
</tr>
</tbody>
</table>

Despite the flood of new supply, vacancy rates in Charlotte remain low due to strong demand. As a result, for the past two years, owners or landlords have been in a position to raise rents. The average apartment rent in Charlotte hit $1,000 in 2015 for the first time since 2008, straining affordability. This is particularly true closer to downtown, when the average rent for an apartment is $1,694.

According to the forecast of the 2016 Greater Charlotte Apartment Association, Charlotte’s apartment boom is not expected to slow down. The factors behind the acceleration of apartment construction aren’t cooling off, and developers plan to keep building. The share of renters in Mecklenburg County is about 43 percent of current households, according to the U.S. Census Bureau. Ken Szymanski, the association’s executive director reports that’s a major shift, up from 36 percent in 2005. He tells us:

That’s unprecedented ... [i]t was always in the 30 [percent range]. In case you’ve missed the forest of cranes and new construction: Charlotte is in the middle of a record-breaking boom in apartment construction.

Seven features of the 2016 apartment boom in Charlotte include:

1) Rising Demand, Rising Rent
As thousands of new apartments enter the market between 2017-2018, rents will trend higher, powered by an increasing number of renters. 

2) Amenities Expand
The amenities expected by renters in new apartments increases yearly. Pet washing stations, dog walkers, dry cleaning and laundry delivery, package storage and polished demonstration kitchens were all cited as important features.

3) Financial Flow
Institutional investors and private equity firms with billions of dollars to spend are increasingly looking to acquire and finance apartment buildings, as many other assets are more volatile with lower returns on investment.

4) Global Markets
While North Carolina’s population growth was ranked 4th in the U.S. in 2016, with much of the growth is streaming to Charlotte, developers are more concerned about external market risks: stock and oil price declines, an economic slowdown in China, political turmoil.

5) Design Demand
With a plethora of new 4-5 story wood-framed apartment buildings constructed around a parking deck, there have been calls for better urban and architectural design.

6) Technological Change
Like other sectors of the economy, apartment developers are managing increasing amounts of technological change. How apartments adapt or fail to adapt to changing technology will determine which projects succeed, from social media to Google Fiber to Airbnb.

7) Aging Population
While much of the focus of new multi-family housing has been on millennials, downsizing baby boomers are seen as another major source of demand. Projections show about 20 percent of renters nationwide will be 50 or older by 2020.
5.0 AFFORDABLE HOUSING IN CHARLOTTE

Charlotte’s housing stock has really declined in affordability in recent years.

- Dionne Nelson, CEO, Laurel Street Residential, Affordable Housing Developer

The city of Charlotte is working to create or preserve 5,000 affordable housing units over the next three years. Selling city-owned land to affordable housing developers is one of their strategies. The key to growth and long-term viability is diversity of housing options. Unlike other metropolitan centers, Charlotte does not mandate that new multi-family housing projects maintain a percentage of affordable units. Though city leaders like Hugh McColl (former CEO of Bank of America) and Harvey Gantt (the City’s first African-American mayor and professional architect) have called for such plans, the State of North Carolina, rather than its municipalities, have established laws restricting integrated affordable units within market-rate projects.

Beyond the typical 300+ unit single-use apartment complex – a formula that is the profit threshold for developers – Charlotte must provide incentives for smaller and more diverse housing morphology, including duplexes, granny flats, four-plexes, townhouses, and 1-2 story six-to-eight unit courtyard housing. While multi-family construction continues to expand in and around Charlotte, only a slight percentage of new rental properties fall within the affordable housing category. In Charlotte just 4.2% of new apartments built between 2014-2016 have median rents in the least-expensive third of rental properties. That’s the lowest percentage of the nation’s 15 major housing markets. Denver and Seattle follow Charlotte in that measure. High-end rental units built during that same time span in Charlotte account for 71.3% of overall new apartment construction.

The year-over-year rental increase for low-end properties in Charlotte is 12% versus a 3.4% bump in the entire rental market. However, Charlotte's costlier properties saw rents rise the highest, at 14% annually. “There’s a growing divide in the rental market right now,” reports Zillow Chief Economist Svenja Gudell. “Very high demand at the low end of the market is being met with more supply at the high end, an imbalance that will only contribute to growing affordability concerns for all renters.” Jenna Martin of the Charlotte Business Journal concurs, reporting that:

We're simply not building enough at the bottom and middle of the rental market to keep up with demand. As a result, these segments are becoming very competitive, as both new renters look to find their first place and existing renters get shut out of homeownership because of extremely limited for-sale inventory. Apartment construction at the low end needs to start ramping up, and soon, in order to see real improvement.” Sacramento had the greatest rental cost disparity in low-end apartments (32.7%) when compared to the overall market (7.4%) (Martin, 2016).

6.0 PARKING PLANS AND IMPEDIMENTS

In the “Texas Doughnut” model (Fig. 2), apartments wrap around a central parking garage where residents live near their cars, with dedicated parking places, hidden from view, requiring a minimal additional outlay of land. The problem is that most Texas doughnuts are single-use massive structures that require at least two acres of land for above ground parking with no infrastructure for people to walk around and interact with one another. In the "Podium" model (Fig. 3), apartments are stacked above ground floor parking and as a result are immediately unfriendly to the pedestrian and passerby, deadening “life on the street.”

Figure 2: Texas Doughnut Diagram. Source: (Authors 2016)
One of the biggest impediments to affordable housing is the cost of parking requirements associated with the construction of multi-family housing. According to a 2012 affordable housing study by the Bureau of Planning and Sustainability in the city of Portland, Oregon,

... a low-end rental unit in a building with no parking is $800 a month. Rent in the same unit in a building with podium parking is $950 a month and with surface parking is $1,200 a month, a 50% rise in cost. In a building with underground parking, the low-end rent is $1,300 a month.”

One can draw the conclusion then that replacing the construction cost of parking spaces with transit passes makes multi-family housing significantly more affordable.

7.0 R.A.W.: RESIDENTS AT WORK PROPOSAL

R.A.W. proposes a different model upon which affordable residences coexist with the history of the industrial roots of the Wilmore neighborhood and the mixed use structures in this the area’s commercial corridor. The approach embraces a new “alley urbanism” that layers in a miniature residential corridor separate from the main street. While the latter harbors commercial and retail in the traditional manner, alley life is built upon the existing service lane typically found in Charlotte’s inner blocks with the hopes of creating a more complex and public use of these small streets (Fig. 4).
The proposal provides a complex mix of leasable and/or affordable micro housing within the communal alley lane. Renters and/or owners would qualify for reduced costs based on income level, with sales or lease expenses controlled at a rate different than the normal market rate (Fig. 5).

Figure 5: R.A.W.: Residents at Work Proposal, Alleyway of Affordable Units. Source: (Authors 2016)

The commercial side of the site would retain an existing auto repair building that would be emptied and hollowed (the roof removed and turned inside-out). The repurposed space would serve as a landscaped entrance to a sub-level parking area. The ground surrounding this reused structure is lofted to establish a new landscaped podium (Fig. 6). This platform is constructed in post-tension concrete similar to today's typical podium apartment model but subverted as a semi-public space with a planted green surface. The varying heights and levels of this surface differentiate degrees of privacy and ownership for the market-rate housing on the inner block and the perimeter live/work studio units that are built over the maker spaces and retail/studio fronts that line the main street corridor (Fig. 7 and Fig. 8).

The northern end of the project supports retail businesses, a local produce market, a beer garden and other public amenities. This area is shaded by a hovering solar and evaporative cooling parasol that alters the microclimate of the site.

Figure 6: R.A.W.: Residents at Work Proposal, Podium Level. Source: (Authors 2016)
Figure 7: R.A.W.: Residents at Work Proposal, Diagram from alley (left) to main street (right). Source: (Authors 2016)

Figure 8: R.A.W.: Residents at Work Proposal, Section Drawing through Three Housing Types. Source: (Authors 2016)

Figure 9: R.A.W.: Residents at Work Proposal, Mint Street Elevation. Source: (Authors 2016)

Figure 10: R.A.W.: Residents at Work Proposal, Plans of Live/Work Studios along Mint Street. Source: (Authors 2016)
8.0 CONCLUSIONS
Charlotte, like other growing American cities, is witnessing the pressures of near-town apartment construction, saturating the market with homogenous housing stock that does not support affordable options or a long-term solution to permanent residential options in the urban core. At face value this form of development tends to answer to the trend of recharging our urban centers and creating a more sustainable and walkable living environment. However, this development model forces those who are on limited incomes to seek housing at the edges of the city where rents are generally lower. Moreover, center city millennials who enter leases in these urban apartments are more likely to transition in three to five years to the city outskirts in search of single-family options as they settle into suburban lifestyles. This speculative and short-term developer’s model is not sustainable and is simply a catalyst for continued suburbanization.

R.A.W. is merely the first look at how design research and urban awareness might provide some relief to the problem of 21st century affordable in-town housing strategies. The complexities inherent within this problem are many and further definition of appropriate rubrics and solutions are rich with potential.

REFERENCES


ENDNOTES
1 According to Simon, social complexity reflects human behavior as it is exercised in ongoing and increasingly broader and more complicated circumstances of individual and collective existence. Social complexity has emerged as the conceptual and practical framework wherein these phenomena and their relationships can be studied.

2 Real Data tracks multi-family apartment markets in major metro markets of the Southeast. Apartment statistics are based on 100% market survey versus sample data, tracking statistics on over 1,000,000 multi-family units in North Carolina, South Carolina, Florida, Virginia, Georgia and Tennessee.

3 Market Rank score is based on a city’s occupancy rate, employment growth, development pipeline, demand and rent growth. A higher score is more favorable with scores typically ranging from 90–95.

4 Market Rank score is based on a city’s occupancy rate, employment growth, development pipeline, demand and rent growth. A higher score is more favorable with scores typically ranging from 90–95.

5 Charlotte City Council is considering a plan to sell 11.6 acres on West Tyvola Road to a developer who would build affordable housing on the site. Located across from the City Park development at the former Charlotte Coliseum site, the land would accommodate up to 200 units. Laurel Street Residential, a Charlotte-based developer is offering $1.2 million for the site, currently vacant. Laurel Street Residential plans to build a “mixed-income” development, which typically include market-rate units and some units reserved for people making less than the area’s median income. “The property on West Tyvola Road is located in an area experiencing new market rate developments with little to no affordable housing,” the city of Charlotte said in a news release. City Council will be asked to approve the sale to Laurel Street on Feb. 13, 2017.

6 Greystar, an apartment management company, recently built a 33-story residential tower at Third and Poplar streets in downtown Charlotte. Rents increased by 6.3 percent in 2016.

7 According to Malcolm McComb, vice chairman of brokerage CBRE, federal tax rules changed in 2015, making it easier for foreign investors to invest in the U.S. apartment market.

8 Ben Collins, VP at Crescent Communities, reports that an unexpected shock could lead to “the R word,” or another recession, and pressure apartment developers with loans coming due.

9 According to Crescent Communities, there is a lot of media attention on multi-family design in Charlotte, challenging developers and designers for more innovative, creative and distinct design.
Although many of the new apartments under development are studio and one-bedroom units with reduced square footage geared toward young renters, a bigger supply of larger units with multiple bedrooms and more square footage could be needed to meet older renters’ demands (Crescent Communities).

Seattle-based online real estate firm Zillow, Housing Report 2016. The rise in rent among low-end apartments is outpacing the overall rental markets in 15 major metro areas.
ECOLOGY OF THE BUILT ENVIRONMENT
ANALYSIS OF A NEURAL NETWORK MODEL FOR BUILDING
ENERGY HYBRID CONTROLS FOR IN-BETWEEN SEASON

Jonhoon Ahn, PH.D., Soolyeon Cho, PH.D., Associate Professor
'North Carolina State University, Raleigh, North Carolina

ABSTRACT: In residential and commercial buildings, programmable thermostats have been practically used to provide appropriate heating and cooling energy to satisfy the thermal conditions. With the help of rapid development of computing technology, recent controllers were able to adopt advanced algorithms such as Fuzzy Inference System (FIS) and Artificial Neural Network (ANN). Several studies for the algorithms were tested to improve the performance of conventional controllers through the large scaled databases associated with hidden interactions between parameters. However, most models focused on the optimization of fuel use for boilers or motor speed for fans, which have some disadvantages to provide sensitive control signals responding to thermal demands in zone scale level.

The advanced FIS and ANN controllers, which deal with simultaneous control of supply air mass and temperature, are tested to optimize supply air conditions for in-between seasons that require both moderate heating and cooling. The controllers are compared with a thermostat on/off model by means of the total control errors and thermal energy consumption. To verify the effectiveness of the controllers, the measures of Integral of Absolute Errors (IAE) and energy consumption results are compared with conventional thermostat on/off controller. The IAE describes the difference between desired and measured room temperature reflects control accuracy, and hourly thermal gain from the system reflects energy efficiency. The ANN mass and temperature simultaneous control algorithm indicates high efficiency for control errors by 5.59% and effectively mitigates energy increase by 3.95% in comparison with thermostat on/off controller. Even though the ANN model can effectively reduce control errors for thermal comfort, it consumes quite less energy than FIS model, and similar amount of energy for thermostat on/off controller. Under building’s conditions requiring more sensitive controls and consuming large amount of energy, the ANN controller can be used to effectively optimize the supply air conditions.

KEYWORDS: Building Control, Neural Network Model, Mass & Temperature Control, In-between Season, Energy and Control Efficiency

INTRODUCTION

1. Control model
To improve the performance of building energy supply systems, the fuel amount into the boiler and fan motor speed was commonly adapted as major control factors. Many studies improved the mathematical thermal models to optimize fuel use or distribution for boiler and its turbine by using control algorithms like Proportional – Integral – Derivative (PID) algorithm (Rossiter, Kouvaritakis, & Dunnett, 1991; Zhuang & Atherton, 1993; Wang, Zou, Lee, & Bi, 1997; BNP media, 2001; Tan, Liu, Fang, & Chen, 2004). The rapid development of computing technologies made many researchers improve the models with large amount of data and complex calculations, and the Fuzzy Inference System (FIS) and Artificial Neural Network (ANN) were preferred. Several studies for the algorithms were adopted to improve the performance of conventional controllers through the network-based approaches which can effectively deal with large scaled databases and parameters interactions. Some researchers developed hybrid models which combined PID and FIS models in one distribution network. By changing nodes and locations within distribution network, energy consumption was compared through the various models combining the PID and FIS models for a boiler fuel and turbine speed control or wind power systems, and integrated thermal control systems were developed through the comparison of the conventional control theory and FIS genetic algorithm (Fraisse, Virgone, & Rous, 1997; Alcala, 2003; Anderson et al, 2007; Somsai, Oonsivilai, Srikaew, & Kulworawanichpong, 2007). The signal control efficiency of the FIS model was developed by using multi-dimensional genetic algorithm or matrix for HVAC control model of buildings for specific use (Zhang, Ou, & Sun, 2003; Fazzolari, Alcala, Nojima, Ishibuchi, & Herrera, 2013). Energy efficiency from the various scenarios for locations of FIS models associating with PID controller was compared to improve the performance of boiler control (Hamdi & Lachiver, 1998; Lianzhong & Zaheeruddin, 2007; Beinarts, 2013). Also, amount of fuel for boiler or fan motor speed control models adopting refined FIS algorithm were tested to compare conventional PID tuning rule (Malhotra & Sodhi, 2011; Soyguder, Karakose, & Alli, 2009). Still others developed control models, such as damper control by combining the FIS and ANN models (Soyguder & Alli, 2010). Multi-layered genetic algorithm was used to improve the performance of ANN model which might cause overshooting or reduce level of generalization, and the control combining fan motor and damper angle were tested to meet thermal demands of several thermal zones using various weather data (Dounis & Caraiscos, 2009; Dounis Koulani, Hviid, & Terkildsen, 2014; Jovanovic, Sretenovic, & Zivkovic, 2015; Ji, Xu, Duan & Lu, 2016).
### 1.2. Problem statement

However, most PID and FIS models which dealt with controlling fuel amount or fan motor speed were not appropriate to immediate response to the thermal demand of zone scale level. Also, most control models for damper and valve were utilized to define time collapse to satisfy thermal demands or optimize amount of supply heating water into thermal zones, respectively. These approaches had some disadvantages that controllers cannot operate sensitively and promptly corresponding to outdoor temperature conditions.

In this research, network-based control models for supply air mass and temperature are proposed by using FIS and ANN algorithms. Design strategy section describes the structures of the HVAC model, equations, and FIS and ANN algorithms used. Result and discussion sections indicate the advantages and disadvantages of FIS and ANN models in comparison with typical thermostat equipped in most buildings in the US.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>area (m²)</td>
</tr>
<tr>
<td>D</td>
<td>depth of envelope components (m)</td>
</tr>
<tr>
<td>m_{in}</td>
<td>mass flow-rate into room (kg/h)</td>
</tr>
<tr>
<td>m_{out}</td>
<td>mass flow-rate out from room (kg/h)</td>
</tr>
<tr>
<td>m_{heater}</td>
<td>mass flow-rate of heater (kg/h)</td>
</tr>
<tr>
<td>m_{roomair}</td>
<td>mass of room air (kg)</td>
</tr>
<tr>
<td>Q_{loss}</td>
<td>convection and transmission heat loss (J)</td>
</tr>
<tr>
<td>Q_{gain}</td>
<td>convection and transmission heat gain (J)</td>
</tr>
<tr>
<td>T_{in}</td>
<td>air temperature entered into room (°C)</td>
</tr>
<tr>
<td>T_{room}</td>
<td>room temperature (°C)</td>
</tr>
<tr>
<td>T_{out}</td>
<td>outdoor temperature (°C)</td>
</tr>
<tr>
<td>T_{set}</td>
<td>set-point temperature (°C)</td>
</tr>
<tr>
<td>h_{in}</td>
<td>specific enthalpy (J/kg)</td>
</tr>
<tr>
<td>h_{out}</td>
<td>specific enthalpy (J/kg)</td>
</tr>
<tr>
<td>h</td>
<td>convection heat transfer coefficient (J/m²·°C)</td>
</tr>
<tr>
<td>k</td>
<td>transmission coefficient (J/m²·°C)</td>
</tr>
<tr>
<td>r</td>
<td>thermal resistivity (m·h·°C/J)</td>
</tr>
<tr>
<td>R</td>
<td>thermal resistance (h·°C/J)</td>
</tr>
<tr>
<td>Cv</td>
<td>specific heat capacity at constant volume (J/kg·°C)</td>
</tr>
<tr>
<td>Cp</td>
<td>specific heat capacity at constant pressure (J/kg·°C)</td>
</tr>
<tr>
<td>W</td>
<td>work (J)</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>E</td>
<td>error (°C)</td>
</tr>
<tr>
<td>ΔE</td>
<td>derivative of error</td>
</tr>
<tr>
<td>R2</td>
<td>fraction of variance</td>
</tr>
</tbody>
</table>

### 2.0. DESIGN STRATEGY

#### 2.1. HVAC model

Figure 1 describes the diagrammatic flow for the HVAC model used in this research. This room is an independent module equipped with one heating system with a single duct. The pressure variations of indoor air speed are neglected, as well as air leakage between envelopes and duct systems, and also, airflows in the zone are de-stratified.

![Diagrammatic flow of HVAC model](image-url)

**Figure 1**: Diagrammatic flow of HVAC model
The heating system describes a heating system and its relationship to a room for thermal characteristics of a house and a heater, and outdoor and indoor temperature. Total thermal energy is contained within any objects is defined by temperature, mass, and characteristics of materials. From the thermodynamic first law, the thermal energy transfer is given by:

\[ Q_{\text{loss}} + Q_{\text{gain}} = \frac{\Delta U}{\Delta t} \]  

(1)

where \( Q_{\text{loss}} \) is heat transfer from room to outside and \( Q_{\text{gain}} \) is heat transfer from heater to room. \( U \) is internal energy, and \( t \) is time.

From the conduction through the walls and windows, thermal energy loss of room, \( Q_{\text{loss}} \) is given by:

\[ Q_{\text{loss}} = \frac{(T_{\text{room}} - T_{\text{out}})}{R} \]

(2)

\[ R = \frac{1}{h_{\text{out}}A} + \frac{\rho}{kA} + \frac{1}{k_{\text{in}}A} \]

(3)

where \( h_{\text{out}} \) and \( h_{\text{in}} \) are heat transfer coefficients, \( k \) is transmission coefficient, \( A \) is area, \( D \) is depth of envelope. From the mass flow rate and enthalpy, assuming that there is no work in the system, thermal energy gain of room, \( Q_{\text{gain}} \) is given by:

\[ Q_{\text{gain}} = \dot{m}_{\text{in}} * h_{\text{in}} - \dot{m}_{\text{out}} * h_{\text{out}} \]

(4)

From the law of conservation of mass and the assumption of no change in the flow rate:

\[ \dot{m}_{\text{in}} = \dot{m}_{\text{out}} = \dot{m}_{\text{ht}} \]

(5)

From Eq. (4) and (5), \( Q_{\text{gain}} \) is transformed:

\[ Q_{\text{gain}} = \dot{m}_{\text{ht}} * C_p * (T_{\text{heater}} - T_{\text{room}}) \]

(6)

The rate of internal energy is given by:

\[ \frac{\Delta U}{\Delta t} = \dot{n}_{\text{room}} * C_p * \frac{dT_{\text{room}}}{\Delta t} \]

(7)

From the equations above, Eq. (8) for simulation is obtained:

\[ \frac{dT_{\text{room}}}{\Delta t} = \frac{1}{\dot{n}_{\text{room}}C_p} * \left( \frac{T_{\text{room}} - T_{\text{out}}}{h_{\text{out}}A} + (\dot{m}_{\text{ht}} * C_p * (T_{\text{heater}} - T_{\text{room}})) \right) \]

(8)

Based on the equations and scenarios, initial input parameters are assigned, and Table 1 summarizes the factors and
assigned values used in the simulation test (ASHRAE TC9.9, 2011; Steinbrecher & Schmidt, 2011; Mathworks, 2016).

Table 1: Design factors and values

<table>
<thead>
<tr>
<th>No.</th>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Set-point temperature ($T_{set}$)</td>
<td>20 °C for Heating, 25.5 °C for Cooling</td>
</tr>
<tr>
<td>2</td>
<td>Wall width x height</td>
<td>19.5 m x 4.4 m</td>
</tr>
<tr>
<td>3</td>
<td>Wall thickness ($D_{wall}$)</td>
<td>0.15 m</td>
</tr>
<tr>
<td>4</td>
<td>Wall thermal conductivity ($k_{wall}$)</td>
<td>136.8 J/m·h·ºC</td>
</tr>
<tr>
<td>5</td>
<td>Window width x height</td>
<td>1.5 m x 1.0 m</td>
</tr>
<tr>
<td>6</td>
<td>Window thickness ($D_{window}$)</td>
<td>0.02 m</td>
</tr>
<tr>
<td>7</td>
<td>Number of windows</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>Window thermal conductivity ($k_{window}$)</td>
<td>2,808.0 J/m·h·ºC</td>
</tr>
<tr>
<td>9</td>
<td>Mass flow rate into room</td>
<td>3,600 kg/h</td>
</tr>
<tr>
<td>10</td>
<td>Weather data</td>
<td>Incheon Int’l Airport in South Korea</td>
</tr>
</tbody>
</table>

2.2. Thermostat on/off model
The thermostat on/off controller operates within the dead-band setup. If the difference between $T_{set}$ and $T_{room}$ is larger than a specified value, the control model sends the run or stop signal to the heater. As a reference to compare to other control models, the initial values of deadband are +1ºC and -1ºC. For instance, $T_{set}$ and $T_{room}$ are 20°C and 18°C, respectively, wherein the heater turns on and starts to supply hot air into room because the difference is 2ºC.

2.3. Fuzzy Inference System (FIS) model
The purpose of the FIS models used in the three cases is to determine the optimal values of the mass and the temperature of the supply heating air, which depends on the difference between the $T_{set}$ and $T_{room}$. Figure 2 shows the FIS membership rule with two input variables: wherein the temperature differences between $T_{set}$ and $T_{room}$ ($E$) are derivative of the $T$ difference ($\Delta E$).

![Figure 2: FIS membership graphs for mass and temperature control signals](image)

In this research, the new method uses five membership functions for each input variable with universal of discourse 0 to 0.5 and -10 to 10; respectively, Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS), and Positive Big (PB). The method also uses an output of control signal of 0 (0% output) to 1 (100% output).

2.4. Artificial Neural Network (ANN) model
The ANN consists of a large class of several structures, and the appropriate selections of a nonlinear mapping function with a network are required (Politechnika Wroclawska, 2016). Figure 3 indicates diagram for typical multiple nodes within the neural network function (Politechnika Wroclawska, 2016). The function in the network used in this research consists of two input layers, 10 hidden layers, and an output layer.
The inputs of \(x_1, \ldots, x_k\) to the neuron are multiplied by weights and summed up with the constant bias. The resulting is the input to the activation function. Then, results from activation function were summed up goes to output \(y_k\). The ANN models in this research are performed through the two inputs: Error (E) is temperature difference between \(T_{\text{set}}\) and \(T_{\text{room}}\), and \(\Delta E\) is derivative of the error. Table 2 describes the configuration used for ANN simulation in this research.

Table 2: ANN configuration

<table>
<thead>
<tr>
<th>No.</th>
<th>Configuration</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td># of training set</td>
<td>60,480</td>
</tr>
<tr>
<td>2</td>
<td># of testing and validating sets</td>
<td>25,920</td>
</tr>
<tr>
<td>3</td>
<td># of hidden layers</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Algorithm</td>
<td>Scaled conjugated gradient</td>
</tr>
<tr>
<td>5</td>
<td>Max # of iterations in 1 Epoch</td>
<td>1,000</td>
</tr>
</tbody>
</table>

2.5. Simulation model

By using the assumptions and design strategy, one reference model and two controllers are tested. The reference model is a typical thermostat on/off controller. By using fuzzy logic, the FIS controls for mass and temperature simultaneously are tested. Also, the results from the FIS are trained by the ANN regression fitting model, which generates the ANN controller. Figure 4 describes the diagrammatic structure of the MATLAB simulation model. In the case of the FIS and ANN models, when the difference between the lower limit temperature of cooling \(T_{\text{set}}\) setting and the upper limit of heating \(T_{\text{set}}\) is +1 °C, a switch for automatically limiting the supply is activated like the thermostat on/off model.
RESULT AND DISCUSSION

Table 3 shows the performance of ANN fitting model trained by inputs of $E$ and $\Delta E$, and a target of FIS output signals to respond to changes in $T_{out}$. As indicated in the $R^2$ values for training and validating, the regression of ANN for mass and temperature controls is significant.

Table 3: ANN fitting results and regressions

<table>
<thead>
<tr>
<th>No.</th>
<th>Results</th>
<th>Mass Control</th>
<th>Temp Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td># of iterations (maximum 1000)</td>
<td>138</td>
<td>587</td>
</tr>
<tr>
<td>2</td>
<td>Gradient</td>
<td>0.001</td>
<td>0.214</td>
</tr>
<tr>
<td>3</td>
<td>Validation checks</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>$R^2$ of training set</td>
<td>0.9954</td>
<td>0.9975</td>
</tr>
<tr>
<td>5</td>
<td>$R^2$ of validating set</td>
<td>0.9951</td>
<td>0.9975</td>
</tr>
<tr>
<td>6</td>
<td>$R^2$ of testing set</td>
<td>0.9951</td>
<td>0.9974</td>
</tr>
<tr>
<td>7</td>
<td>$R^2$ of all data set</td>
<td>0.9953</td>
<td>0.9975</td>
</tr>
</tbody>
</table>

Figure 5 describes the results of three control strategies. From 10:00 to 14:00 and from 19:00 to 24:00, the $T_{out}$ is in between the upper and lower dead-bands of $T_{set}$. This confirms the fact that $T_{room}$ follows $T_{out}$ with time delays because the controller stops at the time range.

![Figure 5: $T_{out}$ vs. $T_{room}$ by three controllers](image)

Temperature controlled by FIS and ANN show similar trajectories as compared to thermostat on/off controller. The FIS controller reduces overshoot which can be seen in thermostat on/off controls, but it is confirmed that the ANN controller reduces more than the level of FIS. Simultaneous control of mass and temperature by ANN shows the highest performance in terms of control accuracy for $T_{room}$.

Tables 4 and 5 show the results of Integral of Absolute Error (IAE: sum of absolute errors derived from the difference between $T_{set}$ and $T_{room}$) and energy consumption as Energy Use Intensity (EUI: kWh/m²-year) for heating air supply derived from the simulations of three design strategies. The ANN controller through the simultaneous control of mass and temperature shows higher control efficiency than other two controllers. This result can be derived from the effective reduction of overshoot at the time when the controllers turn on from 02:00 to 07:00 and from 14:00 to 19:00.
Table 4: Comparisons of IAE

<table>
<thead>
<tr>
<th>Controller</th>
<th>Cooling</th>
<th>Heating</th>
<th>Total</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermostat On/Off</td>
<td>81.45</td>
<td>62.55</td>
<td>144.00</td>
<td>-</td>
</tr>
<tr>
<td>FIS</td>
<td>80.02</td>
<td>61.50</td>
<td>141.52</td>
<td>-1.72%</td>
</tr>
<tr>
<td>ANN</td>
<td>77.96</td>
<td>57.99</td>
<td>135.95</td>
<td>-5.59%</td>
</tr>
</tbody>
</table>

In the U.S. market, typical thermostat controllers are operated in the deadband set up of ±2ºF (about 1.1ºC). The result describes the fact that most FIS and ANN models can improve control efficiency as compared to typical thermostat on/off controller equipped in U.S. buildings. However, as indicated in Figure 5, the ANN controller supplies unnecessary heating energy from 09:00 to 10:30, and cooling energy from 19:00 to 20:00 to maintain $T_{room}$ inside $T_{set}$. This can be one of the reasons why energy consumption is increasing. Table 5 summarizes the energy consumption level as EUI for three different controllers.

As indicated in Table 5, thermostat on/off controller shows higher efficiency in energy consumption as compared to the FIS and ANN controllers. This is directly related to the control sensitivity to maintain a desired $T_{room}$ which may increase energy consumption during heater and cooler turned on. In spite of the probable deficiencies, the ANN model shows higher efficiency rather than the FIS controller by about 60%, and also, it effectively mitigates energy consumption increase by 3.95% as compared to thermostat on/off controller. If the algorithm in the ANN is improved to rectify unnecessary signals from 02:00 to 07:00 and from 14:00 to 19:00, the energy efficiency can be improved rather than the result. This can be considered as one of follow-up studies. As indicated in Tables 4 and 5, the FIS model shows a much larger increase in energy consumption in comparison with the improvement of control efficiency. This implies a fact that the algorithm of the fuzzy membership function uses unnecessary energy to sensitively maintain $T_{room}$, and more precise configuration for membership function is required.

Table 5: Comparisons of energy consumption

<table>
<thead>
<tr>
<th>Controller</th>
<th>Energy Use Intensity (kWh/m²-year)</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling</td>
<td>Heating</td>
</tr>
<tr>
<td>Thermostat On/Off</td>
<td>29.04</td>
<td>22.85</td>
</tr>
<tr>
<td>FIS</td>
<td>39.69</td>
<td>43.62</td>
</tr>
<tr>
<td>ANN</td>
<td>28.79</td>
<td>25.14</td>
</tr>
</tbody>
</table>

In brief, thermostat on/off controller is still effective in terms of energy consumption only. However, it makes inconsistent $T_{room}$ which directly related to thermal dissatisfaction for occupants. The ANN simultaneous mass and temperature controller can effectively maintain desired $T_{room}$ by minimizing control errors, and also, it just consumes energy 3.95% more than thermostat on/off controller. Regarding the result, the ANN simultaneous controller can be used for some rooms or buildings with specific use such as hospitals and laboratories requiring huge energy and sensitive $T_{room}$ control.

In order to implement this ANN model to actual buildings, it needs to be considered that each control signal is converted into physical signals. The mass signals from the ANN are used to adjust fan motor speed in a heater and an air conditioner, or to change damper angle in ducts or diffusers. The temperature signals from the ANN are used to control temperature controllers of a heater and an air conditioner, or to operate resistance coils in ducts or diffusers. Therefore, a comprehensive simulation or experimental analysis for total energy costs including electricity used to drive the devices will be performed as a follow-up study.

CONCLUSION

In this research, neural network controller for heating and cooling supply air was introduced with simultaneous control of the amount of supply air and its temperature in-between season. In order to verify the effectiveness of the advanced controller, thermostat on/off and FIS controllers are tested, and the measures of IAE and heat and cooling gains a day were used.

The result concludes advantages of the ANN controller which effectively optimizes the supply air conditions to reduce
control errors by 5.59% and mitigate energy consumption increase by 3.95%, respectively. Under conditions requiring more sensitive control and consuming large amount of energy such as hospitals and laboratories, the ANN controller can be used to effectively optimize the supply air condition as it relates to workability and productivity. Despite its sensitive and accurate control, the ANN controller maintains an energy consumption level as low as a conventional thermostat on/off controller. Another advantage is that the model can also be used for other colder or hotter areas without any major changes or modifications because working properly at low temperature below $T_{\text{set}}$ and higher temperature above $T_{\text{set}}$ was confirmed.

REFERENCES


ABSTRACT: This paper explores an integrated approach to daylighting design in the Reid Building at the Glasgow School of Art (GSA) by Steven Holl Architect (SHA). It considers how SHA has skillfully and creatively bridged the poetic and practical potentials and complexity of daylighting to artfully reconcile the physical and measurable attributes of site, climate, program, and ecological performance with the intangible qualities of atmosphere, aesthetics, and human experience. Daylight studies using Velux Daylight Visualizer explored how the daylight supports design intentions, program, and performance. SHA’s Reid Building provides insight into an integrated approach to daylighting design strategies and methods to inform contemporary architectural practice and design education.

KEYWORDS: Daylighting Design, Glasgow School of Art, Steven Holl Architects

INTRODUCTION
To choreograph light is to create intentional relationships between the desired luminous qualities and other architectural design variables such as spatial sequence, activities, materials, structure, and performance. The dimension of time, while predictable in the apparent movement of the sun during the course of the day and the year, introduces an oftentimes unpredictable and transient beauty embodied in dynamic, fleeting, and momentary luminous phenomena. How does the choreography of daylight support the broader vision of a project, a program, and the desired qualities and performance criteria of light? How is time architectural and how might daylight be used to celebrate and respond to the changing diurnal and seasonal cycles? How do the movements of the body and the movements of time and light correspond? As with dance, music, or cinema, architecture can be orchestrated as a sequence of spatial, luminous, and experiential progressions to create desired atmospheric qualities while satisfying practical goals.

In the Reid Building at the Glasgow School of Art (GSA), in Scotland, by Steven Holl Architects (SHA), daylight is choreographed to support design intentions, program, and performance while celebrating the unique phenomena of light in place. Natural light and the movement of the human body is at the center of the architectural and spatial choreography. Movement along circulation pathways provides varied qualities of space, light, and view to foster interactions between students and faculty from diverse design disciplines. The building envelope, light shafts, circulation paths, spatial volumes, and structure encourage informal connections, afford rich interior and exterior views, create distinct atmospheric qualities, and define a “new language of light” in relation to Charles Rennie Mackintosh’s historic 1909 Mackintosh Building. The building form was studied and sculpted to reveal how space can be shaped by light and how light can be shaped by space to integrate experiential, lighting, and energy goals.
1.0 LIGHT AND PLACE
1.1. Glasgow School of Art
Located in the downtown core of Glasgow, the GSA is a center of creative activity within an international arts community. SHA, in collaboration with JM Architects and Arup, were responsible for developing GSA’s new Garnethill Campus masterplan and the phase one design and construction of the Reid Building. Internationally renowned as a preeminent school for the study of fine arts, architecture, and design, the GSA’s recent expansion reinvigorates the historic urban campus and fosters an animated conversation between Charles Rennie Mackintosh’s 1909 architectural masterpiece, the Mackintosh Building, and Steven Holl’s contemporary Reid Building.

As a precursor to the modern movement, Mackintosh’s innovative use of natural light, simplicity of form, design restraint, and honest expression of materials were considered unprecedented for its time. SHA approached the Reid Building with the same spirit of innovation and a desire to define a “new language of light,” which expresses the material and construction technologies of the day while remaining mindful of Mackintosh’s historic legacy.

Chris McVoy, design architect at SHA, explains: “We began with studying the Mackintosh Building, in particular, the quality of light. There are twenty-five ways light comes into the spaces. . . . Mackintosh elaborated on the basic typologies of light: skylights, clerestories, figural diffuse light, side lighting, direct lighting. We studied daylight deeply (McVoy, 2015).” There are five organizing ideas for the new school of art: 1) create well-proportioned and flexible studios; 2) define a new “language of light” in relation to Mackintosh; 3) use materiality as a “complementary contrast” between the Mackintosh and Reid Buildings; 4) use circulation as a “circuit of creative abrasion” to encourage interaction and 5) foster ecological innovation (McVoy, 2015).

Figure 2: Sections looking west: Charles Rennie Mackintosh (left) and Steven Holl Architects (right). Source: (SHA, 2016)
1.2 Light and Climate
The Reid Building, sited across the street and north of the historic Mackintosh Building, is oriented on an east-west axis, affording optimal solar access on a seasonal basis. The height and form of the Reid building responds to the particular climate and solar conditions of the geographic location. Glasgow is located at 55.9° north latitude with seasonal extremes of light and darkness, relatively low sun angles, and short winter days that contrast persistent summer daylight. All of these factors shape Glasgow’s unique qualities of light and related architectural opportunities. During the winter solstice, there are just seven hours of daylight and the noon sun altitude is only 10.6° above the horizon. During the summer solstice, the sun rises to a noon altitude of 57.6°, daylight lasts for 17 hours, and twilight persists throughout the night.

While located at a fairly high latitude, Glasgow has a maritime temperate climate of cool winters and mild summers, with an average low of 0.5°C (33° F) in December and an average high of 19.4° C (67° F) in August (Weatherspark, 2016). High humidity and frequent precipitation are experienced throughout the year, resulting in a soft and misty quality of light as it is refracted and scattered by moisture in the air. The cloudiest month is typically January, while the sunniest months are May through July. Grey skies and overcast conditions dominate in the winter, yet clear and partly overcast skies can result in dramatic lighting qualities and cloudscapes throughout the year. Occasional snow occurs from January to April and prevailing winds are from the southwest and west. Despite the overcast climate, daylight and natural ventilation are effectively coupled with high performance construction to optimize energy performance and comfort throughout the year.

2.0 LUMINOUS INTENTIONS
2.1 Light and Program
The GSA challenged the architects to reconsider the nature of design schools in the 21st century and to explore how the architecture could foster collaborations between the disciplines, as former GSA Director Seona Reid explains: “The
chance meetings, the chance conversations, the chance opportunities to see somebody else's work doesn't happen as much as it should. These opportunistic meetings are often the spark of ideas of working relationships and partnerships (Future of GSA, 2016). While the design studios are the heart of the GSA, virtually all spaces, including common spaces such as the entry, exhibition room, café and refectory, workshops, seminar rooms, and lecture hall, were designed to foster collaboration and support the creative process. The architects used “circuits of connection” (circulation ramps and stairs), “eddies of interaction” (niches and subspaces), “driven voids of light” (light shafts with openings), and interior views to encourage such informal exchanges and collaborations, while simultaneously increasing energy and lighting performance.

2.2 Choreographed Light
Daylight shapes the Reid Building from both the inside and the outside, with the movements of occupants and daylight carefully choreographed in space and time. While straightforward in organization, the building section, spatial variety, and atmospheric qualities of light are complex, as Holl explains: “If you look at our buildings in plan it looks very simple. A rectangle and three circles in a square. You can’t get anything out of the plan, which I really like. Because I think that’s the essence of architecture. It’s spatial – it’s three-dimensional (Spirit of Space, 2014).”

Three “voids,” inserted into the rectilinear plan, are created by concrete cylinders tilted 12 degrees to the south to capture the low sun angles and often grey “Glaswegian” light. McVoy explains that the interior openings, which were subtracted from the surface of the Euclidean cylinders, created “incredible curves and shapes” with unexpectedly complex forms and patterns of light as daylight enters the volumes and is borrowed to adjacent spaces (McVoy, 2015). The circulation paths, ramps, and stairs move through and around the voids to create rich spatial qualities, changing views, dynamic lighting qualities, and varied gathering opportunities.

Holl explains how the historic masterpiece by Mackintosh inspired his approach to the Reid Building: “I studied all the ways that light comes in the Mackintosh building and discovered many different interesting things and one in particular is in the library where [there are] three story elements in glass – we call them ‘driven voids of light’ - and we transferred that into this idea of concrete ‘driven voids’ (Spirit of Space, 2014)” The Reid Building is organized by “circuits of connection” (circulation paths) that intersect three “driven voids” (light shafts) to create south and north zones with distinct daylight qualities and program activities. As Craig Tait, project architect with JM Architects, explains: “There are rich and varied spaces with niches within. People occupy the spaces in many ways, the building makes people gather in different ways. It’s a joy to see how people react to space. The ‘circuit’ [circulation] doesn’t have a prescribed function, people are influenced by the space (Craig Tait, 2016).”

Figure 4: Driven voids of light and circulation. Source: (SHA, 2016)
Glimpses through openings in the “voids” and movement along the “circulation circuits” provide changing perspectives on the studios and shared spaces. Exterior views are provided on all levels, with the third-floor terrace and refractory framing a new perspective on the Mackintosh Building, the city, and surrounding hills. The roof, a fifth façade, includes skylights to admit diffuse north daylight to the upper-level south studio and clear skylights at the top of the “driven voids,” which open to the south and zenith. The studio spaces also express a fresh interpretation of daylighting, as Henry McKeown, design director with JM Architects, explains: “It’s not just the traditional north light of an art school. It’s an idea of different kinds of light blending and working with each other to create all sorts of atmospheres and ambiences within the space itself (McKeown, 2014).” Direct sunlight is admitted to the south zone of the building, while the diffuse northern light in the design studios is complemented by borrowed light from the voids and circulation paths. This dynamic meeting of warm south light and cool north light creates varied daylight patterns and atmospheric qualities that change with the time and seasons.

Figure 5: Fourth Floor: South studio looking west (left) and north studio looking west (right). Source: (SHA, 2016)

3.0 LUMINOUS STRATEGIES

3.1 A New Language of Light

Holl’s “new language of light” is revealed in his concept for the envelope and structure, which he characterized as “complementary contrast.” He describes the heavy stone cladding and steel frame of the Mackintosh Building as “thick skin and thin bones,” while the Reid Building’s delicate glass envelope and concrete structure are expressed as “thin skin and thick bones.” The “new language” emerges from the luminous effects of the translucent glass rainscreen and custom “ghost fittings” (which are subtly visible through the glass); a palette of transparent, translucent, and opaque materials; and aesthetically minimal details for windows, skylights, glass railings, and doors. In contrast to the underlying grid and uniform industrial windows of the Mackintosh Building, the seemingly idiosyncratic facades of the Reid Building are animated by windows of varied sizes, two and three-dimensional forms, and differing degrees of translucency and transparency.

On the interior, the Reid Building’s three “driven voids” define a new precedent for interior light shafts by skillfully combining functions for illumination, ventilation, circulation, views, and structure. The robust sculptural geometry of the voids and the openings, with windows of varying size, proportion, and shape affords differing views through the building of ever changing patterns and qualities of light. At the lowest levels, the metal workshop takes advantage of indirect light from the “void” and north toplighting, while the basement woodshop on the south borrows light and a connection to the street above from glazed pavers in the ceiling. The studio sections are designed to combine borrowed light from the toplit voids with side lighting from north clerestory windows. Lower level studios and seminar rooms are illuminated either with side lighting from the north or bilaterally with a combination of light from east or west. The upper-floor studio windows tilt upward to increase the view of the sky to the north and optimize indirect daylight, while the fourth floor studio employs a three-dimensional north window with a glass sill to admit borrowed light to the third-floor studio window below.

3.2 Luminous Atmosphere

The Reid Building’s ephemeral translucent rainscreen captures the varied moods and colors of the sky and seasons. During an overcast day, the glass has a soft and misty quality, while the surfaces are animated on a sunny day with light, shadow, and subtle color variations as the sun is reflected from translucent and clear surfaces. The character of the envelope transforms at night to reveal a translucent enclosure surrounding opaque walls with windows of different
size and form that open to activities within. Direct daylight is admitted through clear glass windows while three types of glass create diffuse conditions, including clear glass behind the translucent rainscreen, translucent glass behind the rainscreen, and a glass cavity with an inner layer of translucent paint flush with the rainscreen (McVoy, 2015).
3.3 Luminous Assessment

Daylight analyses under clear and overcast skies were conducted for “average conditions” in March and September at noon to assess light levels (illuminance studies in lux) and contrast ratios (luminance in candela/square meter) using Velux Daylight Visualizer. The studies explored how daylight is choreographed to support design intentions, program, and performance while celebrating the unique phenomena of light in place.

The illuminance studies illustrate a journey from lower daylight levels at the ground floor to increasing illumination in the upper level studios (Figure 6). As expected, daylight decreases quickly from the window wall in the sidelit spaces on the ground level and first floor, while the combined side lighting and toplighting on the upper levels provide an even distribution of daylight throughout the spaces under both sunny and overcast conditions. Although light decreases with distance from the skylights at the top of the “driven voids,” daylight is effectively gathered and redistributed through the lightwells to the ground level. Daylight meets ambient lighting needs on the upper floors while supplemental electric lighting is needed on the lower levels.

Luminance studies under clear and overcast skies in March/September at noon reveal minimal contrast ratios on the lower floors with the maximum ratio of 1:4 at the window wall (Figure 7). Luminance studies of the upper level north studio reveals a maximum contrast ratio of 1:8 along the south clerestory windows. This ratio falls within an acceptable range for visual comfort, with recommendations at a maximum of 1:10 ratio from task to the brighter distant background (IES, 2011, 12.20, Table 12.5). Given the high levels of daylight, operable interior shading in the studios would provide occupants a greater level of luminous control and visual comfort. Daylight is captured through the facades and within the “driven voids” to effectively receive and redistribute light throughout the building section.

Regarding the choreography and poetics of light, the studies reveal a vertical progression of daylight levels and an increased play of light and shadow. Given the predominantly overcast skies and urban context, the Reid Building’s white walls, concrete floors, and interior detailing of wood, steel, and glass create visually quiet environments that act as neutral canvases for the ever-changing atmospheric qualities.
Figure 7: Luminance studies in perspective; March/September 21 at noon, clear and overcast skies (candela/m²). Source: (Author, 2016)
LIGHT CONSTRUCTION

4.1 Light and Integrated Design

Key to the integration of aesthetic and practical design concerns throughout the building interior and exterior are the “driven voids,” which Holl states “were designed to do everything” by providing structural support, daylight, and ventilation while creating rich spatial and atmospheric experiences (Spirit of Space, 2014). Passive strategies for light and air are integrated into the voids, as McVoy explains: “[The Void] acts as a natural solar stack, with hot air rising and driving air up through it to draw air through studio windows. The building is completely naturally ventilated, there is no air-conditioning. When interior sensors get too warm they open up windows at the top of the voids (McVoy, 2015).”

The building envelope applies other innovative construction details. The rainscreen is a “thin shroud” of acid-etched laminated glass with translucent interlayers that are held 300 millimeters (11.8 inches) from the structural wall. To create a shroud effect, in which the brackets were not visible, SHA and JM Architects worked with Arup to design and test “ghost brackets,” custom glass fittings that enabled the team to create a subtle luminous and homogeneous envelope and to balance aesthetic and practical considerations.

The collaboration with Arup also included design and analysis of the energy and sustainability features. A radiant heating system is integrated into the concrete floor topping while the additional mass mediates thermal comfort on a seasonal basis. Passive strategies for daylight, natural ventilation, and cooling are coordinated with active mechanical, lighting, and ventilation controls. Ecological site strategies include a second-floor terrace and green roof with native landscaping and water feature, while a stormwater system on the north roof harvests rainwater for the sinks and lavatories. A shared biomass plant heats the Mackintosh, Reid, and nearby Bourdon Buildings. The integrated design strategies allow the building to meet the BREEAM Excellent standard and provide a reduction in energy consumption of 30 percent over current regulations – with an estimated annual energy consumption at 100 kWh/sq.m (31.7 kbtu sq ft.) and carbon emissions at 40 Kg CO2/sq.m (430 Kg CO2/sq ft.) (Steven Holl Architects, 2016).

Figure 8: Sustainable design section looking west. Source: (SHA, 2016)
CONCLUSIONS
Architecture is a three-dimensional experience of the body in space, brought to life by the fourth dimension of time through the changing rhythms of day and night and the cycles of the seasons. Steven Holl Architects reveal that luminous experiences can be choreographed as an architectural journey that engage the body, awaken the senses, and foster relationships between people and the built and natural environments. The Reid Building skillfully relates to the scale, proportions, and sectional qualities of the Mackintosh Building while introducing a new language of light, materials, structure, and performance criteria. Atmospheric qualities of light are choreographed with practical and pragmatic considerations such as energy, solar control, visual comfort, and light distribution to ensure effective luminous experiences that support the program and aesthetic vision. The variety of spatial and atmospheric qualities successfully fosters the desired interactions and creative collaborations across the disciplines and with the broader art community of Glasgow. Respectful of the legacy of Mackintosh, the Reid Building confidently embodies a fresh architectural language with a new and ecologically creative vision for the GSA. As the GSA requested, the Reid Building acts as a source of inspiration and as a three-dimensional canvas for the design and exhibition of creative work.

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REFERENCES


ABSTRACT: Current paradigms of sustainability move the design and construction industry to pursue a comforting “independence” in function; the pursuit of net zero goals. If an “interconnected” paradigm of ecological design supersedes the “independence” paradigm of sustainable design, alternative measures could look to define what particular performance niche a building must occupy or construct in an ecosystem. In evolutionary ecology, early definitions of niche refer to a location, independent of the organism occupying it, while more functional definitions refer to the role an organism assumes in sustaining ecosystem functions or constructing an environment. In architecture this may translate to site and performance, respectively. Recent translations in the architecture discourse explored principles of evolutionary ecology, including the notion of niche as site. This paper explores the notion of niche as ecological function, a view of performance with the potential to push design considerations beyond the system boundary of a site, and to understand how to best leverage technology and site construction, beyond site response, to perform in a larger ecosystem boundary. Thinking of buildings not only as consumers but also providers of ecological services, involves defining a niche, understood as the performance void or “recess” in a specific ecosystem to be occupied or replaced by the introduction of a building into an environment. The use of ecology as a metaphor in the design disciplines may be a productive catalyst for new collaborative ways of conceptualizing the relationship of architecture to the environment. However, the meaning of ecological has been stretched into countless definitions, modifiers and applications. This paper returns to the original science of ecology to examine how the concept of niche can trigger renewed thinking about the ecological performance of buildings. Real and speculative examples from practice and academia are presented to illustrate the concept.

KEYWORDS: Niche, Performance, Interconnected, Independence, Ecological

INTRODUCTION
Recently, scientists declared the dawn of the Anthropocene, a new human-influenced geologic epoch, marked by global signals of the spread of radioactive elements, unburned carbon spheres, plastic pollution, aluminum and concrete particles, high levels of nitrogen and phosphate in soils; and even the abundance of fossils of domestic chicken (Carrington 2016). The continued use of fossil fuels and increased carbon emissions are changing the climate at a faster pace than predicted, despite decades of mitigation efforts. Buildings still consume almost 40% of the primary energy and approximately 70% of the electricity in the United States, which continues to increase at a fast pace (Crawley 2009). Water withdrawals for thermo-electric power generation and irrigation have been reduced, but continue to be the largest uses of water (Kenny et al. 2009). In addition to sea level rise, climate change is expected to dramatically shift global groundwater patterns; reducing surface water flows while increasing use and depletion of groundwater in areas prone to drought; increasing heavy rainfall and flooding in regions of moisture convergence; decreasing groundwater levels in heavily urbanized areas due to low recharge, affecting surface and groundwater quality, and causing seawater intrusion in coastal areas (Richard G. Taylor et al. 2012). The urgency to design more sustainable and resilient buildings, cities, and landscapes, is very real, but generalized approaches can result in unnecessary redundancy and complicatedness, encouraging the implementation of highly technological solutions to loosely defined problems, increasing managerial requirements and the potential for accelerated obsolescence. A better understanding of the ecological impact of human–induced changes to the biosphere necessitates a dramatic transformation of ecological design thinking. In this new age, we must critically examine any existing paradigms of sustainability that yield universal solutions, while more intentionally defining the active ecological role of buildings—their performance niche—in multiple scales of specific ecosystems.

1.0. THE NET ZERO OR “INDEPENDENCE” PARADIGM
The current paradigm of sustainable architecture, embodied in the Bullitt Center in Seattle, pursues the idea of a self-sufficient building (Nelson 2011). While a powerful example of a building that performs like a complete and self-sustaining ecosystem; this approach is not feasible in all sites, and it is nearly impossible in many existing urban buildings. Net Zero Energy, Water, and Carbon, quantified as the net of inputs and outputs within a limited system boundary over a period of time (e.g. annually), pursues a comforting “independence” in function, but implies that each project must maximize the implementation of technology in each individual site without considering the optimal scale
of performance for each system. The most ambitious sustainability rating systems (e.g. Living Building Challenge) measure building performance against the highest goal of Net Zero, i.e. buildings that harvest, produce or reuse as many resources as they consume within a site; potentially having the unintended consequences of making the highest level of sustainability an isolated rarity, providing an alibi for limited agency, and limiting the ability to conceptualize alternative potentials for ecological performance.

Making the energy goal confusing and inconsistent, various modifiers emerged to differentiate baselines and units of reference for the Net Zero goal, including Site Energy, Source Energy, Energy Costs and Emissions; and various designations based on the type of on-site or off-site sources of renewables (Crawley 2009). Net Zero Energy promotes reductions in energy demand first, which is a good goal for all buildings. It requires on-site production as the second step. However, on-site production is not always feasible, the most cost effective or at the optimal scale (Marszal et al. 2012). Often Net Zero Energy means displacing other important capacities inherent in the surface of a building: roof-mounted solar energy production may not co-exist with a green roof that provides habitat, microclimate modifications through shade and evapotranspiration, stormwater management, and open space for recreation. While “independence” is the apparent goal, the connections a Net Zero building is dependent on are worthy of critical examination. Net Zero Energy buildings can be grid-connected, but this approach can be criticized if it is depending on an electrical grid that still relies on fossil fuels. Net Zero Carbon is criticized on the basis that the “net” approach still allows emissions through distant offsets, and may promote land-grabbing for afforestation that threatens equity in poor areas of the world (actionaid 2015). For Net Zero Water, the challenges of “independence” are not any less significant. The import of nitrates from rural to urban areas, and the scale of urbanization means that urban sites often do not have the capacity to treat high nitrate concentrations in storm or wastewater (Englehardt, Wu, and Tchobanoglous 2013). Clearly, the independence paradigm has real contradictions and limits.

1.1. An alternative ecological paradigm: interconnected systems

The definition of a system boundary is a critical aspect of ecological systems thinking (Kay 2008). It is imperative to redefine the appropriate scale of agency for every building site and for every resource. Unlike what LEED calls regional priorities, which apply equally to any project in any site within an entire region, this proposed alternative requires a campus or district–scale boundary, and a form of ecological cooperation for landscape–scale planning. The “interconnected” paradigm sees potential in buildings that, rather than isolated “self-sufficient” entities, are part of interconnected systems in which each organism, species, actor or component, has a unique space and role to play in the construction and destruction of ecosystems. For example, an emerging alternative to Net Zero, the Net Positive building, could conceivably provide energy for nearby buildings that cannot produce enough energy locally, are too shaded, or have limited area for renewables. Landscape–based water treatment systems require large open areas, which may be better managed at an intermediate scale—for example, within shared open space or ecological corridors. Strategies for stormwater recharge and mitigation of heat–island effect require a decentralized and networked approach, implemented as close as possible to the boundary of each site, to be most effective.

These scale shifts could suggest that some buildings may assume different or specialized roles at an appropriately larger boundary of investigation, based on their unique potential or place in the ecosystem. In that case building typologies could be categorized, similar to living species, based on their role and interactions in an ecosystem. Redefining the boundary of investigation requires a managerial understanding of how landscape or regional ecologies overlaps human ecologies. Some examples may include coupling programmatic requirements for open space in schools with landscape-based water treatment infrastructure that can support a neighborhood; identifying the waste from a high-intensity process or building program as potential input for another; and leveraging high potential sites through zoning based on ecological planning, where certain institutions or building types can adopt an infrastructural or ecological agency for the benefit of multiple buildings or the larger landscape.

If an “interconnected” paradigm of ecological design superseded the “independence” paradigm of sustainable design, an ecological design approach could help define what particular niche a building must occupy, construct or assume in an ecosystem. Examining the ecological concept of niche as a metaphor for design can enable rethinking the appropriate application of technology in each architectural project, requiring collaboration with and knowledge of landscape and urban ecologies.

2.0. THE ECOLOGICAL NICHE: CRITICAL DEFINITIONS

The word niche comes from the Latin word nidius for “nest,” and the French adaptation nichier for “making a nest,” also meaning “recess” (“Niche” 2017). The concept of nest, or recess, suggests a place to be occupied; thus the appropriation of the term by zoologist Joseph Grinnell to describe the relationship of an organism with its habitat, characterized by a set of environmental conditions including spatial and dietary dimensions, that influence behavioral, morphological and physiological adaptations (Odling-Smee 2003; Schoener 2009). Niche is a central concept of ecology, especially in autoecology, which studies the interactions of a single species with its environment; its counterpart being synecology which studies how multiple species interact with one another (Losos 2009). As a result of an expanding definition of the
niches concept to include functional aspects and multi-species interactions, the term was used in community ecology to combine insights at the individual, population and community levels (Leibold 1995).

Numerous definitions for the concept of niche have emerged in the field of ecology since the 1920s, some more theoretical than empirical. Differences emerge in ways in which each definition models, measures, validates or characterizes interactions with the environment; and recent reviews of the literature suggest categories to organize them. One makes the distinction between two primary categories: those that define the niche as characteristics of the environment, and those that define it based on the characteristics of the species occupying it; while a third category (from population ecology) considers not only the interaction of a species with the environment but also the effects of competition with other species that share or occupy the same niche (Schoener 2009). Grinnell's original definition of a niche is that which can be empty, considers the niche independent of the species occupying it. On the other hand, the zoologist Hutchinson's definition of niche focuses on the features of the species independent of a location; a conceptual n-dimensional hyper-volume defined by multiple axes for each essential environmental factor, such as required resources or tolerance range for a species to persist.

Both Grinnell's and Hutchinson's definitions have in common a focus on what the environment affords a species. In contrast, functional definitions emerged with Elton's trophic studies on what he called the species "roles," representing a fundamental shift from the evolutionary view: moving from how the environment influences the adaptation and evolution of the species, towards how a species affects the environment or "what is doing" to its community (Leibold 1995; Odling-Smee 2003). Two other types of ecological niche make this distinction: the "requirement niche," concerning the environmental requirements of species, and the "impact niche," concerning the short-term impacts of species on resource use (Leibold 1995). This distinction is, according to Leibold, different from discussions by others (Schoener 1989; Colwell 1992; Griesemer 1992), which distinguish the "habitat" and "functional" aspects of the niche.

There is one other category within niche theory that is of interest to the topic of this article. The notion of a species engaged in niche construction suggests that the niche is neither an independently formed place (or recess) in the environment waiting to be filled, nor is it only a result of the unique evolutionary adaptation of a species to external factors that allows it to persist in a particular place. "Niche construction occurs when an organism modifies the feature-factor relationship between itself and its environment by actively changing one or more of the factors in its environment, either by physically perturbing factors at its current location in space and time, or by relocating to a different space-time address, thereby exposing itself to different factors" (Odling-Smee 2003, 42). Odling and Smee's concept also applies to population and community dynamics, defines as the ecological inheritance left for other organisms, ecosystem engineering, when one population changes the relativistic niche of a second population, and ecosystem service, when a species replaces or compensates for the service provided by another outcompeted species or transformed ecosystem. The notion of niche as constructed provides an appropriate point of departure to apply the concept of niche to human-designed environments, and a metaphor for architecture as a species that is occupying, modifying, adapting to, and servicing its environment.

2.1 Parallels in architecture discourse

Two broad categories of ecological niche have parallels in architecture: one defines the location in the environment independent of the organism occupying it but affording its existence (geography, topography, climatic conditions, resource availability); the other defines the role that an organism assumes in a particular place it helps construct (ecological function, ecosystem service, ecosystem engineering, ecosystem construction).

In architecture discourse, the first category can clearly translate to site, a place architecture occupies, and the environmental condition to which architectural form can respond and adapt to. Recently, Caroline O'Donnell proposed the notion of niche tactics or niche thinking in architecture, "a scenario in which the architectural organism is considered as part of a complex and idiosyncratic network" (O'Donnell 2015, 6–7). This theory focuses on a design process that is analogous to an evolutionary process, emphasizing the importance of tactical design practices. Comparing Michel de Certeau's definition of tactical, which operates in isolated actions as opposed to plans, to Darwin's continuous scrutinizing of slightest variations in evolution, O'Donnell proposes a more nuanced response to site, "not only to the visible, the whole, and the objective, but also to the hidden, the systematic, and the idiosyncratic"(O'Donnell 2015, 24). This response rejects typologies, images or symbolism, and contextualism; instead making the site legible through form.

Other architects drew from niche theory, specifically Hutchinson's n-dimensional hyper volume, to propose a “process of designing with evolutionary algorithms” that could account for multiple axes, including the typical environmental concerns or climatic factors of sustainable design, and “a whole slew of additional niche axes” to be defined by architects, that would allow formal responses to all sorts of complex environmental forces acting on the architectural object (Koltick and Lutz 2013, 254). Their focus on a parametric process of form-finding resonates with O'Donnell, who references Greg Lynn, as "one of the original proponents of evolutionary thinking in contemporary architecture." The
The formal approach to evolutionary thinking, whether through algorithms of parametric design, bio-mimicry, animalism, or other forms of organicism, have plenty of proponents and critics in the discourse; and is not the main focus of this article. However, a critical distinction must me made; these formal translations are often confined to operations in the design process and internal to the discipline, culminating with the construction of architecture as a static form. An alternative translation of ecological niche concepts focuses on the performance of the architectural object that starts during and after its construction; thus the metaphor need only engage the design process of form-finding, insofar as it later affects ecological performance, which include human ecology factors.

While O'Donnell drew from views of perceptual psychologist J.J. Gibson, using the term affordance to distinguish between habitat (where it exists) and niche (how it exists) (O'Donnell 2015)—function was still a question of what the environment affords architecture, and how architecture formally responds to it. On the other hand, niche differentiation, according to landscape architects Sven Stremke and Jusuck Koh, sees individual sites, including buildings, as agents of sustainable energy landscapes through vertical stratification, horizontal and temporal zonation, increasing diversity of function, improving energy utilization and reducing resource competition (2011). The notion of performance niche, in its inherent need to push design considerations beyond the system boundary of a site towards scales of landscape and urban ecology, expands the scale and application of this translation. This is analogous to how functional definitions of niche enabled a shift from autecology to community ecology. Its potential is to elucidate how to best leverage technology and site construction into instruments of productivity in a larger ecosystem boundry.

3.0. PERFORMANCE NICHES: A DIFFERENT FUNCTIONALISM

Realizing a performance-based concept of niche means a new form of design thinking that not only acknowledges that buildings, rather than independent entities, are networked with other external systems to receive some ecological services, but that can conversely be leveraged to perform some specific ecological service for other buildings, for a local ecosystem or a larger landscape. Thinking of buildings not only as consumers but also as providers of ecosystem services, as agents of ecosystem engineering, or builders of ecological inheritance, means understanding their potential interactions with an entire ecosystem; defining the performance void or “recess” to be constructed, occupied or replaced by the introduction of a building into an environment. This ecological metaphor can be a productive catalyst for new collaborations between architecture and landscape planning, towards conceptualizing the productive relationship of buildings and the environment, through renewed thinking about their ecological performance beyond current paradigms of sustainability.

The following case studies, viewed through the lens of performance-niche, illuminate the potential applications of this principle to three primary forms of architecture performance: energy, water and carbon. These examples operate at the scale of a community, district or campus—one that is larger than the building’s immediate site but smaller than an entire region; to exchange resources, ecosystem services or building some capacity for the ecosystem in which they exist or will help construct

3.1. The energy niche: buildings that consume waste

District power and heat co-generation (co-gen) is an old and well-known example of a collaborative approach to building energy, commonly used on institutional campus settings, to locally recover excess heat from a power generation process, reduce energy losses from distribution, increase fuel flexibility, and reduce emissions. It is notable that district heating alone does not always result in reduced total energy when analyzed through Life Cycle Assessment or Emergy Analysis, because the savings are primarily dependent on fuel source and network size, with studies suggesting small to mid-size networks of renewables perform best (Andrić et al. 2017). Furthermore, while institutional co-gen plants find additional synergy between processes, these facilities are often single-use buildings, exclusively dedicated to primarily fossil-fuel energy infrastructure. The College of Environmental Science & Forestry at the State University of New York, in Syracuse, changes this typology by combining office, academic and research uses with a heat-and-power cogeneration plant that is interconnected with four adjacent campus buildings, providing 60% of the campus heating needs and 20% of its electrical peak demand (The American Institute of Architects 2014). This project provides an ecosystem service by metabolizing the by-product of a regional forestry management program into biomass for heat and energy that supplies not only its own site, but also sharing the surplus with campus buildings that cannot produce energy on their own, while connecting human capital in programs of research and education. Co-generation with biomass can have a Total Energy Cost 6.0 to 10.7 times lower than non-renewable fuels (Stanek, Czarnowska, and Kalina 2014), and when using waste wood, it can reduce the one-way flow of fossil fuel carbon emissions without significant impact to land use (Lippke et al. 2012). Finding waste from renewable sources, such as sustainable forest management, is most ecologically sound as a specific local or regional approach to cogeneration. The potential for district power and heating can be designed according to the fuel type available, optimal network size, growth conditions
Sources of residual heat or fuel resulting from the waste of an urban process or operation, such as landfills, abandoned mines, and contained deposit facilities, may not constitute a renewable source; but can last for decades or even centuries. For example, bacterial decomposition in landfills can produce methane for more than 50 years after a material is first deposited (Mann & ATSDR, 2001). Similarly, abandoned mines have great potential as energy storage. Mine water management keeps mines dry during operations, but shaft refilling continues to be necessary in order to seal off old mine shafts; an operation that can go on for several hundred years, and requires the discharge of water at relatively high temperatures to rivers (Thien 2015). Active mine operations are high consumers of energy and water, sometimes depleting aquifers and lowering groundwater levels; thus synergies and trade offs between lowering water use and increasing energy efficiency are being sought in many regions (Nguyen et al. 2014). Building energy use can become part of a regional approach to water and energy management in mining regions. Mapping those types of sources can identify sites to locate sinks of energy (Stremke and Koh 2011) Buildings in these sites can fill a resource-intensive performance niche. The Zollverein School of Management in Essen, Germany by SANAA and Transsolar (2007), built on the campus of a former mine, consumes the wasted heat of a local mine that would otherwise end up in the river, providing an ecosystem service to the riverine landscape. Energy is extracted from the high mineral mine water, through a heat exchanger and pumps, and cycles through tubing embedded in the walls and ceiling as a form of active thermal insulation, which loses close to 80% of the heat to the outside air (Moe 2010, 148), (Figure 1). This approach would not be sustainable in another place where energy was not being wasted anyway, and it may be improved on if it provided district heat. Yet in this case, the heat loss through the envelope has a trade-off in reducing resource use and embodied energy by eliminating the insulation and cladding layer, minimizing wall thickness to the minimum structural requirements, making the architectural expression possible, and improving access to daylight (Moe 2010).

3.2. The water niche: buildings that create ecological flow
Most buildings reduce the ability of a landscape to recharge ecological groundwater flow. While underground, engineered recharge strategies and green roofs can replace some of those functions locally, some buildings can engage in niche construction by becoming instruments for a more ambitious ecological restoration project. Often, large landscape planning for decentralized groundwater recharge in urban sites is hard to implement due to the discontinuity
and fragmentation of land uses. A form of landscape ecology planning can leverage critical sites for architecture projects as agents of niche construction.

Princeton University has proposed ambitious goals of integrated landscape and stormwater management towards ecological restoration of its campus natural systems. Working on an existing and dense campus means that the implementation must leverage strategic building sites that can serve the more ambitious and sensitive areas of the ecological restoration project. A campus master plan, for which landscape architect Michael Van Valkenburgh (MVVA) and Nitsch Engineering consulted (2005-2008), proposed strategies to restore a series of ecological streams and woodland buffer corridors that used to bring water from the campus on the north to Lake Carnegie on the south, using primarily landscape based strategies to reduce runoff, improve stormwater quality and increase groundwater recharge (Figure 2). MVVA initiated the implementation of the most significant stream restoration project on a site where new architecture was to be built adjacent to one of these corridors (MVVA 2017). The new Frick Chemistry building, completed in 2011, is located next to the Washington Road stream, which is slated for restoration. This building not only implements water use reduction strategies, including greywater recycling and rainwater collection (ARUP 2017) but most importantly, enabled ecological restoration through siting and landscape strategies.

While small on-site strategies for stormwater management, including green roofs in existing or new infill buildings across campus, are being considered to increase the capacity of the campus to retain stormwater, projects like the Frick Chemistry building filled a unique performative niche in the campus. The siting strategy prioritized the construction of an important ecological inheritance for the campus, building parallel to the stream to enable expansion and continuity of the woodland restoration project. Therefore the North–South orientation for the building favors water systems, rather than the energy-driven East–West orientation that governs most projects deemed sustainable. The extensive site work required for the construction of the building enabled the intensive landscape strategies, eliminating a 124-space parking lot that was a source of pollution adjacent to the stream, making space for three bioretention rain gardens that treat close to half of the stormwater from the roof, a 12,000 gallon cistern for the remaining rooftop runoff collection that is used for toilet flushing, and allowing the campus nature walks to extend through these formerly paved areas. That represents over 1.1 million gallons of stormwater that is retained on site (Princeton University 2011). The work to restore the Washington Road stream adjacent to the building was initiated with this project, which sponsored the extension and re-establishment of woodlands that once filled the stream valley and engineering rain gardens that provide biofiltration of campus stormwater (Stevens 2010). Through coordination of siting and construction strategies, the architecture engaged in a process of niche construction, building woodland buffers and rain gardens to reestablish ecological flows adjacent to the site. Other strategic architectural projects will be leveraged to expand the woodland corridors further into campus at each of the four corridors shown in Figure 2. This project demonstrates that by coordinating the design of major architecture with landscape planning efforts, the construction of buildings may have significant agency in implementing broader landscape ecological goals.

3.3. The carbon niche: buildings that capture emissions

Forests capture carbon from the atmosphere and store it in the tree wood material. Using wood for building products is more effective at carbon mitigation than using wood for fuels; especially if wood is substituting other products such as steel joists, the ratio of fossil carbon reduction per unit of carbon in the wood is 4.8 for building products versus 0.40 for gasoline (Lippke et al. 2012). Clearly, buildings as an aggregate can have significant impacts in the global climate mitigation efforts, and become agents of carbon sequestration, especially if coupled with sustainable foresting practices. The source of wood creates many challenges and opportunities: from raising issues of equity and social justice to enabling phytoremediation and recreational value, which can have broader impacts in landscape and ecological planning. For example, efforts to reduce emissions by developed countries by controlling deforestation and reducing forest degradation in developing countries, such as REDD+, has been criticized for promoting commercialization of forests based purely on carbon value, and touted as a new form of colonialism or land grabbing (Gotangco Castillo, Raymond, and Gurney 2012). Land-grabbing is defined as large-scale transactions by sovereign funds from resource-constrained nations to purchase large tracts of well-endowed land in poor rural areas of other countries to supplement, replace or offset their citizens’ consumption (Rudel and Meyfroidt 2014). Beyond increased attention in utilizing wood products in the building industry to help carbon mitigation, there are no specific real examples of buildings that engage in constructing a specific niche for forest management in local ecosystems, towards sustainable landscape planning. A collaborative design studio at Northeastern University gave students the opportunity to engage with this question in a speculative project.
This interdisciplinary studio project between architecture and landscape architecture students explored the construction of a hyper-productive landscape by proposing a vast program of forestation in brownfields, planting fields of a very fast-growing hybrid species of poplar, a workhorse for phytoremediation, in the industrial center of Boston. A proposal included the design of industrial buildings for processing and manufacturing timber building products; and suggested a policy allowing new development in this previously unbuildable district if it utilized the rapidly developing timber product in its construction as part of the program of carbon and contaminant capture. The buildings would also use the compost of the urban forest for heating. The design mapped the flow of planting, phytoremediation, harvesting, material processing and building construction in this district, through the full life cycle of components (Figure 3). The potential of this project is integrating reforestation, phytoremediation and carbon capture locally, especially when considering that developed countries seek land in rural areas, sometimes in developing countries, to offset carbon emissions, while acres of urban brownfields sit empty with potential. These sites are often located in already dense areas, near existing infrastructure, but remain unbuildable due to high levels of contamination. A method of niche construction can leverage available land that cannot be built on using conventional approaches, by engineering new hyper-productive ecosystems that can provide soil cleaning, carbon capture and building materials. Another studio proposal calculated that if all Massachusetts brownfield sites were planted with poplar and harvested, enough power could be generated to nearly replace the local natural gas power plant in Boston. The design of the power plant became an architecture project that would occupy a unique niche: to enable the financing of the phytoremediation project, service an entire district with power and heat, and provide industrial development and recreational opportunities. These hybrid architecture and landscape models engage in a more equitable form of land-grabbing, or niche construction, enabling the construction of urban architecture with timber sourced locally, building a productive urban forestry program for energy and recreational open space, and unleashing a new urban industrial economy.

CONCLUSION

The metaphor of performance niche acknowledges that buildings already act upon ecosystems, and can be agents of ecological productivity; rejecting a dichotomy between being fully independent or ecologically destructive. The performance niche defines ecological roles or functions for buildings, whether as providers of ecosystem services (metabolizing waste), producers of ecological inheritance (building ecosystem capacity), or engineers of ecosystems (niche construction). The paradigm of interconnectedness rejects the assumption that every building must be a closed system containing everything necessary to sustain life within—but finds efficiencies in the things that buildings can do in groups, or as part of ecological communities; creates symbiotic relationships between buildings and other urban processes’ by consuming many forms of excess or waste; leverages the energy of a destructive process (site excavation and construction) into an ambitious process of ecosystem construction; and creates keystone building species that are essential for ecosystem functions that allow other building species to co-exist. An interconnected paradigm replaces conventional sustainable design approaches with ecological design thinking, jumping scales from the architectural site to ecosystems.

ACKNOWLEDGEMENTS

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studio that stimulated additional thinking in this topic.

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Performance Niche: An Ecological Systems Framework for Technology and Design: Laboy


ABSTRACT: This paper assesses the climatic feasibility of water self-sufficiency of buildings that employ rainwater harvesting. The feasibilities of standard single-family residential buildings that employ rainwater harvesting in thirteen cities that represent a range of climatic regions across the continental U.S. were assessed. Using the water consumption data published by the United States Geological Survey (USGS) and the American Water Works Association (AWWA), the quantities of current water consumption in typical American households with the average population of 2.58 residents were analyzed. Using the NOAA 30-year average precipitation data, the volumes of rainwater that can be harvested from the rooftop catchment areas of standard two-story single-family homes in the test-bed cities were estimated. Comparing the volumes of water consumption and harvested rainwater, the water self-sufficiencies of the test homes were analyzed. Our analyses revealed that, with the current level of water consumption, rainwater harvesting can supply up to 33% of the total water demand and of typical homes in the Southeast subtropical region. In the arid Southwest, rainwater harvesting can meet less than 5% of the domestic water demand even in rainy months. However, when rainwater is used for indoor uses only, rainwater harvesting can supply a higher fraction of residential water demands. Supplemented by rainwater harvesting, conservation through the incorporation of water efficient technology and change in resident behaviors is instrumental for enhancing buildings' water self-sufficiency.

KEYWORDS: Rainwater Collection, Water Self-Sufficiency, Water Conservation

INTRODUCTION
Rainwater collection provides multiple benefits: an alternative method to increase a building's water self-sufficiency, to reduce reliance on municipal treatment plants, and to reduce stormwater runoff. In recent years, rainwater harvesting has reemerged as an alternative onsite water procurement method. Many large commercial buildings are equipped with rainwater harvesting systems not only to lessen the reliance on municipal water but also to mitigate detrimental environmental harms associated storm-water runoffs. However, it is uncertain how significant a role rainwater harvesting can play in attaining a building's water self-sufficiency. What fraction of domestic water demands can be met by rainwater harvesting? How much the climates affect rainwater harvesting in various US regions? What are architectural strategies for achieving zero or near-zero external water buildings? This paper examines these questions pertaining to rainwater harvesting and strategies for water self-sufficient buildings.

1.0 RESEARCH OBJECTIVES
This study assesses the water-self-sufficiency of residential buildings that utilize rainwater harvesting in the US. One of the key research questions is how a region's climate affects its rainwater harvesting prospect. Specifically, how much rainwater harvesting can contribute to the water self-sufficiency of single-family homes across the United States.

1.1 Test Building and Climatic Regions
A typical American single-family residence is a two-story home with a total floor area of 2,000 ft² (American Housing Survey, 2005). This study used a standard two-story residential building with 1,000 ft² for each story. The home was assumed to be occupied by a population of 2.58 residents, which was the average population of American households (US Census Brief, 2010). The test building has a flat roof with no eaves or overhangs. The rainwater catchment area is 1,000 ft². The collection efficiency of rainwater harvesting was assumed to be 30% that takes into account the various water losses in the process of harvesting. It was also assumed that the test homes were equipped with cisterns. All rainwater collected in rainy periods was assumed to be stored for consumption in dry periods. In order to evaluate the impact of the climatic variation on rainwater harvesting in the thirteen cities, each of them representing diverse climates of the continental U.S. including humid, dry, hot, cold, and various combinations, were selected.

2.0 RESEARCH METHOD
This paper defines water self-sufficiency of a building as the ratio of the volume of water collected on site to the volume of water consumption by its residents. The roof was assumed to be the sole catchment area of the building. The volume of rainwater harvested from a catchment area is a linear function of three factors: precipitation, horizontal footprint of catchment area, and the collection efficiency of rainwater harvesting systems. Harvested rainwater volume, thus can be...
2.1 Precipitation data
The volume of rainwater harvested was estimated based on the 30-year average annual and monthly precipitation data published by National Oceanic and Atmospheric Administration (NOAA, 2016). Among the thirteen test locations, Miami shows the highest precipitation of 160 cm per year, while Las Vegas was the lowest with a 10 cm of rain annually. Houston, New York, Chicago and Seattle are relatively wet cities, while Phoenix, Boise, Los Angeles and Denver are dry cities (See Figure 1).

2.2 Household water consumption
The per capita domestic water consumptions in the 13 regions of the U.S. were calculated using two sets of county-by-county data: 1) domestic water consumption and 2) population data published by the United States Geological Survey (USGS, 2016). The annual county-by-county domestic water consumption data were divided by the corresponding population to obtain the annual per capita residential water consumption. The household water consumption was then calculated by using the per capita water consumption by the number of residents per household. The domestic water consumptions of most cities analyzed in this study range from 200 liters (52.6 gal) per capita per day to 350 liters (92.1 gal), the average being approximately 300 liters (approximately 80 gallons), which is in conformity of data published US government agencies (USGS, 2010). Two distinct anomalies are Phoenix and Las Vegas, cities in the Southwest Desert, whose water consumptions are approximately 600 and 900 liters (158 and 237 gal)/persons/day respectively (See Figure 1). The water consumption in these desert cities are about two to three times of other cities. One might presume that residents in dry climates would spend water more parsimoniously, while those in wet regions would consume water more thriftlessly. However, the water consumption data shows that this is not the case. According to the residential water end use survey conducted by the American Water Works Association (Mayer, 1999), indoor water consumption is generally uniform regardless of climate. However, outdoor water use is highly variable with climate and the lifestyle of residents. This is due to residents in dry climatic regions using more water in landscape irrigation, swimming pools and decorative purposes (Inskeep 2014).

3.0 ANNUAL WATER SELF-SUFFICIENCY
On an annual basis, rainwater harvested from the rooftops can meet only varying fractions of the total household water consumption (See Figure 2). In the rainiest region of Miami, rainwater harvesting provides 34% of annual household water consumption, followed by Houston with 27% and New York with 26%. In arid cities, rainwater harvesting supplies can meet a small fraction of household water demands: 5% in Los Angeles, 2% in Phoenix and 1% in Las Vegas. Note that the test-bed buildings in this analysis do not have any eaves or shading devices that are typically present in single-family homes. When the roof catchment area is enlarged by extending eaves, water self-sufficiencies of homes will certainly be higher.
Figure 2: Annual water self-sufficiency of single-family homes in 13 US cities

4.0 MONTHLY WATER SELF-SUFFICIENCY
In most regions of the world, precipitation fluctuates during the course of a year. Some regions have rainy months in summer, while others experience more precipitation in winter. Thus, the seasonal water self-sufficiency of homes that utilize rainwater harvesting varies during the course of a year, and depends largely on the particular climatic patterns.

4.1 Southeast and South Central Regions
The Southeast and South Central regions from Houston to Miami are the most rainy regions in the US, and rainwater harvesting is most feasible in this region. In Miami, a distinctive seasonal disparity of water self-sufficiency exists. During the summer from May through October, the water self-sufficiency ranges from 35% to 65%, while in wintery months, November to April, the water self-sufficiency varies from 10% to 20%. In Houston, with the exception of June and October, the monthly water self-sufficiency is relatively monotonous in the range of 20% to 30%. This uniformity is advantageous in cistern sizing, i.e., a smaller cistern can be utilized throughout the year. While in Miami, a large cistern that is required to harvest high volume of rainwater in summer that is underutilized in winter (See Figure 3).

4.2 Pacific Northwest and Northern California Regions
In the Pacific Northwest and Northern California regions, rainwater harvesting is highly variable with season (See Figure 4). Precipitations are high in winter months from November to March, with little or no precipitation in the summer months. In San Francisco, rainwater harvesting provides over 40% of the total water demand in December through February, while in May through September the water self-sufficiency is less than 10%. In particular, during June through September, rainwater harvesting can meet the total water demands of homes in San Francisco less than 5%. Seattle shows a similar pattern of seasonal disparity in water self-sufficiency, but in a lesser degree. From October through March, water self-sufficiency of homes in Seattle’s is over 20%, while in May through September, it is less than 10%. In order to mitigate rainwater shortage in summer, maximum amount of rainwater should be harvested and stored in winter. And water conservation strategies to reduce water demands in summer must be developed.

4.3 Mountain regions
In the Mountain regions as representative in Denver and Boise, water self-sufficiencies of the test homes are less than 15% throughout the year. In Boise, Similar to Seattle, precipitation is high in wintery months and low in summer. On the other hand, in Denver water self-sufficiency is high in summer and low in winter. In Boise, during November through May, water self-sufficiency is approximately 15%, while in June through September it ranges from 2% to 8% (See Figure 5).
4.4. Northeast and Mid-Western regions
The pattern of seasonal water self-sufficiencies in Northeast and Midwestern cities is similar, higher in summer and lower in winter (See Figure 6). However due to its proximity to the Atlantic Ocean, in the Northeastern region, higher precipitation is available nearly throughout the year. The water self-sufficiency in New York is the lowest in February at 20% and highest in July at 30%. This uniformity of seasonal water self-sufficiency has an advantage of rainwater cisterns being utilized near full capacity throughout the year. In the Midwestern region such as Chicago, Detroit and Minneapolis, water self-sufficiencies are high in summer and low in winter. This seasonal disparity is more pronounced in inner continental cites such as Minneapolis than Detroit. In Minneapolis, the water self-sufficiencies are 7% to 10% from December through February, but are higher than 25% in May through September.
4.5. Southwest Desert Regions

As expected for desert climates, water self-sufficiencies of the Southwest regions are the lowest in the US (See Figure 7). Due to the proximity to the Pacific Ocean, the water self-sufficiencies of Los Angeles are higher than two other test cities: Phoenix and Las Vegas. In Los Angeles, the water self-sufficiencies during December to March are relatively higher than other months, ranging from 10% to 20%. Because water is more precious in arid regions, rainwater during the wet season in the city should be regarded as valuable natural resources to be harvested. In Phoenix and Las Vegas, the water self-sufficiency was less than 5% throughout the year. Here it should be noted that the low water self-sustainability in these two cities is due to not only low precipitation but also high water consumption. The per capita residential water consumption in Las Vegas is about three times higher than that of average American cities and Phoenix two times. The high water consumption in these desert cities is ascribed primarily to outdoor uses such as landscape irrigation and swimming pools. Accordingly, in arid regions, water conservation must be a higher priority strategy for enhancing the water self-sufficiency of residential buildings.

5.0 INDOOR WATER SELF-SUFFICIENCY

Water uses in single-family homes can be categorized in two types: indoor and outdoor uses. Outdoor water uses in American homes include primarily irrigation for gardens and lawns and swimming pools. According to a study conducted by the AWWA Research Foundation, the volume of indoor water uses per capita in America is, by and large, very uniform regardless of climatic regions. However, outdoor water uses vary significantly depending on the climatic conditions.
regions. The high domestic water consumption in the cities in the American Southwest, Las Vegas, Phoenix and Los Angeles, are due primarily to outdoor uses. Garden and lawn water uses can be reduced or avoided by incorporating water conserving landscaping methods such as indigenous landscaping, xeriscaping, or drip irrigation.

Outdoor water use can be characterized as non-essential, while indoor water uses are essential. In order to assess how much rainwater harvesting can meet essential indoor water demands of residential buildings, water self-sufficiency of single-family homes that excludes outdoor water uses was conducted. Figure 8 shows the fraction of “indoor” water uses that can be met by rainwater harvested on a yearly basis. In humid regions, a significant fraction (40% in Houston and 50% in Miami) of indoor water consumption can be met by rainwater harvested. In arid regions, indoor water self-sufficiency increased to a 10.6% in Los Angeles, 6.6% in Phoenix and 3.5% in Las Vegas. The indoor water self-sufficiencies of the test cities across the country are significantly, 40 to 90%, higher than the total (indoor and outdoor combined) water self-sufficiencies.

Figure 7: Water self-sufficiency of test single-family homes in Southwest desert cities.

Figure 8: Annual indoor water self-sufficiency of single-family homes in 13 US cities

6.0 SUSTAINABILITY OF RAINWATER HARVESTING
A building is an ecological system, in which water is an essential element for the life of people and other living organisms. In order to sustain human biological, hygienic and cultural activities, buildings require year-round reliable supply of water. The most common water supply method in the industrialized counties is distributing public water that was drawn from water-sources. When water that is drawn from water sources is greater than what is being
replenished by either precipitations or surface water flow, the balance of water is tipped. The water resources in the
local hydrosphere become unsustainable. The drying up of the Colorado River at the Gulf of Mexico is one of the most
drastic water resource depletions caused by unsustainable water withdrawal. Efficient use of water and onsite rainwater
harvesting reduce the draw, and help sustain the integrity of the local and regional natural water sources, surface waters
and aquifers.

Groundwater withdrawal has long been practiced as an alternative source of water procurement around the world. To
date, many single-family homes in American suburbia procure water by pumping groundwater from the subterranean
aquifer. The long-term sustainability of groundwater withdrawal depends the balance between drawing water from the
aquifer and recharging groundwater. Allowing stormwater to infiltrate into the ground is essential for recharging the
aquifer. Hard-finished surfaces (roads, parking lots, rooftops, paved yards) hinder the permeation of stormwater. Soft-
scaping and permeable paving help recharge groundwater and sustain the water table.

By holding stormwater runoffs, rainwater harvesting helps recharging groundwater. Rainwater collected during rain
and using it later for irrigating plants will hydrate soils and recharge groundwater. In addition, rainwater harvesting
contributes to the quality of water streams. Stormwater contains high levels of pollutants, fertilizers and herbicides
from lawns and other particulate matters. Harvesting rainwater and reducing storm water runoffs prevent pollutants
entering water streams and help sustain their water quality.

CONCLUSIONS
As found in water self-sufficiency analysis, it is infeasible to attain a total water self-sufficiency of single-family homes
by rainwater harvesting alone, even in most rainy regions in the continental US. However, being unable to attain
the total self-sufficiency does not make rainwater harvesting unworthy. A sizable portion of single-family homes’
water demands can be met by onsite water harvesting. With an exception of the Southwest desert regions, rainwater
harvesting can generally meet 20% to 30% of U.S. domestic water demands. Thus, municipal water supply will continue
to be the principal source of water to buildings and cities. Yet a combination of water conservation and onsite water
procurement will alleviate the reliance on the public water supply systems.

The first and foremost strategy for sustainable water supply must be geared to increasing the efficiency of water uses.
Incorporating design methods and technologies for promoting water efficiency in buildings and site planning is an
essential requirement for sustainable architecture. This is particularly the case in arid regions. Water efficient plumbing
fixtures such as small size toilets and low-speed showerheads are already widely being used in recent buildings. Because
a substantial fraction of residential water consumption in American households is ascribed to outdoor uses, xeriscaping
with indigenous plants, limiting size of lawns, or drip irrigation should be applied to landscaping.

Architecture is confronting with another facet of complexity: water as a critical factor for building and site designs.
A building needs to be designed as a rainwater collector in terms of formal design and system integration. The roofs
should be designed as not only catchment surfaces but also visual elements that expresses flow of water. How to
integrating rainwater channeling and storing systems such as gutters, downspouts, rain-chains, scupper, splash basins,
and even cisterns as expressive formal elements will be a question to be addressed in process of building design. Further
complexity is in site design that must be designed in consideration of sustaining the integrity of the local hydrosphere.
Retention ponds to collect and hold stormwater, bioswales that channels storm-water to local water streams, and
permeable soft-scaping that allow rainwater to recharge groundwater should be key elements of water conscious site
planning. How to make rainwater harvesting as a form-giver in building and site design will be one of key questions in
sustainable architecture of tomorrow.

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VISUAL QUALITIES AND PERCEIVED THERMAL COMFORT-
RESULTS OF SURVEY STUDIES IN A LEED PLATINUM OFFICE BUILDING

Amir H. Zarrabi1, Mona Azarbayjani1, Julia Day1,
Elizabeth Thariyan1, Elizabeth Stearns1, Brentrup Dale1

1University of North Carolina, Chapel Hill, North Carolina
2Kansas State University, Manhattan, Kansas
*This contribution was solely written by students and/or doctoral candidates.

ABSTRACT: Occupants are exposed to various interlinked environmental factors in office spaces. Office spaces have visual qualities, spatial characteristics, and building features that can have a significant impact on their overall perceived comfort and perceived thermal comfort. The analysis used subjective responses from 500 occupants collected from an energy efficient LEED platinum building in Charlotte, North Carolina. The survey addressed visual qualities of IEQ factors (View satisfaction, Natural daylighting, Quality of lighting, and. Based on the occupant survey, empirical analyses have examined the effects and interactions of Indoor Environmental factors (such as thermal, visual and the ability of control) on occupant perceptions. This evaluation was executed in different personal attributions, spatial locations, and configurations (classified by different floors, office layouts, distance to windows and cardinal directions) of their workspace. The results indicated that the pleasant visual qualities could positively impact the perception of thermal comfort, even when other measured visual or thermal comfort problems existed. Enhancing visual comfort (lighting and view) can improve occupants’ perception of thermal satisfaction indirectly and may provide better indoor conditions in office buildings. The study implies that occupant surveys can offer a systematic measure for evaluating office spaces to enhance the perceived comfort.

KEYWORDS: Thermal comfort, Thermal perception, Visual qualities, View, Quality of lighting

INTRODUCTION
Office employees spend a considerable amount of time in their workplace. Not only they are influenced by the thermal qualities of their environment, but also their perception of comfort over time (Schweizer et al., 2006). Thermal comfort is derived from a complex interaction between the occupant and their environment. The American society of heating, refrigerating and air conditioning engineers (ASHRAE) defined it as “the condition of the mind in which satisfaction is expressed with the thermal environment”. In accordance with this definition, thermal comfort is a state of mind rather than a state condition that can be influenced by personal differences and the individual perception of other environmental factors (Lin & Deng, 2008). The physical parameters play significant role in thermal perception and parameters such as visual comfort, activities, clothing, and psychological factors (Nikolopoulou & Steemers, 2003). Recently, the experiment of virtual reality has been employed as a tool to measure and assess the qualitative and quantitative aspect of human perceptions and their interactions. As the study shows, the lab experiment regarding the ten variations of the climatic context in urban spaces shows that the thermal perceptions of humans can be altered by visual qualities. For example, processing only sky, shadow and lighting effects (Vigier, Moreau, & Siret, 2015). Previous studies addressed the comfort factors that focused on the effects of a single human satisfaction. Their influences on occupant comfort remain the primary measure for predicting productivity and satisfaction within the workplace. The goal of this paper is to investigate if enhancing visual comfort (lighting and view) can improve occupants’ perception of thermal satisfaction indirectly to provide better indoor office building conditions.

This paper chose a LEED platinum office building to evaluate the statistical correspondence of visual and thermal perception of people through a survey to address the following questions:

(1) Does occupant satisfaction with thermal and visual qualities change depending on different occupant locations in the building (floor, cardinal direction, distance to window, and office layout)?
(2) Does the priority of visual and thermal quality change among different groups of occupants (groups in terms of gender, age, and work duration)?

2.0 METHOD
2.1 Research design
This study is based on a survey of occupants in an office building in Charlotte, North Carolina. The inhabitants were asked by email to complete a questionnaire concerning their experience in the office with a focus on indoor environment conditions. The survey was done in August, 2016. During the study, the building’s performance was
undergoing measurements and verification studies.

2.2 Site
The office building is 51 stories high on a one-million-square-foot city block in Charlotte, North Carolina. The building contains private, semi-private, and open-plan office spaces. The building was awarded an ENERGY STAR certification by the Environmental Protection Agency for its overall energy efficiency.

2.3 Survey participants
Random Occupants of the sample floors were selected and invited to complete a questionnaire on paper. Approximately 21% of people who received the email agreed to participate. The participants were equally distributed over the office building.

Table 1: List of personal attribution:

<table>
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<th>Personal characteristics</th>
<th>Description</th>
<th>Sample size (n)</th>
<th>Percentage (%)</th>
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<td>17.3</td>
</tr>
<tr>
<td></td>
<td>31-40</td>
<td>168</td>
<td>33.9</td>
</tr>
<tr>
<td></td>
<td>41-50</td>
<td>136</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>51 or above</td>
<td>93</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>I prefer not to answer</td>
<td>9</td>
<td>1.8</td>
</tr>
<tr>
<td>Time of working in the building where you currently work</td>
<td>Less than 1 year</td>
<td>176</td>
<td>35.5</td>
</tr>
<tr>
<td></td>
<td>1-5 years</td>
<td>306</td>
<td>61.7</td>
</tr>
<tr>
<td></td>
<td>5+ years</td>
<td>14</td>
<td>2.8</td>
</tr>
</tbody>
</table>

2.4 Measures
2.4.1. Questionnaire
Participants received a 25-item questionnaire. As the employees were informed, the intention of the questionnaire was to understand how office users perceive the office environments and how they rank the important factors. The table 1 indicates the personal attributions of occupant that include age, gender, and duration of time of working in the workspace. In addition to the demographic questions, the questions concerned perception of the office environment and overall occupant satisfaction into three main categories: Thermal, Visual qualities and General qualities that indirectly affect the other two major categories. These groups of items represent the satisfaction level of respondents with each questionnaire item on the seven-point scale ranging from ‘very dissatisfied’ (coded as 1) to ‘very satisfied’ (coded as 7). Table1 summarizes the questionnaire items used in the analysis for this study.
Since this study focuses on the influence of visual qualities on occupant thermal perception, the analysis is based on the workspace attributions such as cardinal direction, floor (as external factors), different office layouts, and distance to windows (as internal factors) that are described in table 2. Basically, work space attributions consider the occupant’s position in the horizontal and vertical axis as average quantities to assess the qualitative perceptions of human.
### Table 2: List of questionnaire items

<table>
<thead>
<tr>
<th>Category</th>
<th>Items</th>
<th>Survey questions</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal comfort</td>
<td>Thermal condition</td>
<td>I am satisfied with the thermal conditions in my office workspace.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>In general, how satisfied are you with the temperature in the workspace where you spend the most time?</td>
<td>1=Very Dissatisfied</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Very Satisfied</td>
</tr>
<tr>
<td>Visual qualities</td>
<td>Quality of light</td>
<td>I am satisfied with the QUALITY of light in my office workspace.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td></td>
<td>Access to daylight</td>
<td>I am satisfied with ACCESS to natural daylight in my office workspace.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td></td>
<td>View</td>
<td>I am satisfied with the VIEW from my office.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td>Control</td>
<td>ABILITY to alter the temperature</td>
<td>I am satisfied with the ABILITY to alter the temperature in my office workspace.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td></td>
<td>ABILITY to alter the electric lighting</td>
<td>I am satisfied with the ABILITY to alter the electric lighting to meet my needs.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
<tr>
<td></td>
<td>ABILITY to alter the blinds</td>
<td>I am satisfied with the ABILITY to alter the blinds and daylight source to meet my needs.</td>
<td>1=Strongly disagree</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7=Strongly agree</td>
</tr>
</tbody>
</table>

### Table 3: List of Work space attributions

<table>
<thead>
<tr>
<th>Work space attributions</th>
<th>Description</th>
<th>N</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Office Layout</td>
<td>Enclosed private</td>
<td>76</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>Enclosed shared</td>
<td>82</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Open-plan</td>
<td>169</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td>Open Office: cubicles with high partitions</td>
<td>160</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td>Open Office: cubicles with low partitions (lower than 5 feet)</td>
<td>9</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Open Office: workspace in open office with no partitions</td>
<td>76</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>128</td>
<td>25.8</td>
</tr>
<tr>
<td>Distance to Window</td>
<td>0-5 feet</td>
<td>62</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>6-10 feet</td>
<td>75</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>11-15 feet</td>
<td>231</td>
<td>46.6</td>
</tr>
<tr>
<td></td>
<td>16 feet or more</td>
<td>128</td>
<td>25.8</td>
</tr>
</tbody>
</table>
The internal work space attribution classifies the office layouts into five categories, depending on the level of personal enclosure: (1) Enclosed private office, (2) Enclosed shared office, (3) Cubicles with high partitions (about five or more feet high), (4) Cubicles with low partitions (lower than five feet high), and (5) Open office with no partitions or limited partitions. Another internal variable is the distance to the window that considers how close the primary workspace is to the nearest exterior window. In this internal category, the distance of work space to windows is divided to three types: 0–5 feet, 6–10 feet, 11–15 feet, and 16 feet or more. Cardinal direction related to external work space attributions is defined by the closest cardinal direction of the nearest exterior window. The four major orientations are used along with (North, South, West and East) the uncertain response (I don't know). The Floor is the other external work space attribution that influences the occupant’s overall satisfaction. The floor is grouped in three main groups: 1 to 4, 5 to 9 and 10 or above.

3.0 RESULTS

The radar charts are derived from regression coefficients to study the correlation of the visual, thermal and controls factors regarding the overall satisfaction of the occupant. In order to estimate impacts of different factors (visual, thermal and control) on occupant overall satisfaction, multiple regression analysis is concluded in the survey responses into two sub-groups (personal and work space attributions) for two major purposes. First specify the relation of different factors (visual, thermal and control) to each other. Second, the evaluate the impact of each factor to overall occupant satisfaction. Hence the increase or decrease in overall satisfaction, depending on whether an occupant is satisfied or dissatisfied with particular factors. The multiple regression analysis produces the coefficients for the significant factors of variables. (Kim & de Dear, 2013).

3.1 Personal characteristics and attributions

Based on the regression coefficients displayed in figure 1.a, the satisfaction of quality of light declines as the duration of working increases from ‘less than 1 year’ (0.25) to ‘1 to 5 years’ (0.16). However, the satisfaction of natural light increases respectively as the working duration of occupants ‘1–5 years’ (0.13) to ‘5+ years’ (0.23) increases. The ‘view satisfaction’ item follows this pattern as well meaning that occupants with less than 1 year of living in the building are less satisfied (0.16) in comparison to ‘1–5 years’ (0.17). The ‘thermal satisfaction’ is increased from ‘less than 1 year’ to ‘1-5 years’ or 0.18 to 0.21 correspondingly. Control items follow the same pattern This means that as the working duration in the building increases, the satisfaction of control items would also increase too, i.e. ‘Less than 1 year’ (0.02) to 5+ years (-0.16).

As Figure 1.b shows, there are two variables of visual factors for male and female that impact on occupant satisfaction. On the contrary of males, females are more satisfied with ‘quality of light’ (0.25) rather than ‘View’ (0.11). Males are more satisfied with ‘view satisfaction’ (0.22) and are less satisfied with ‘quality of light.’ The thermal satisfaction is more pleasant for males (0.22) than females (0.20). The control items are not significant for both groups except the ‘ability to alter the blind’ for males is 0.1. As the graph shows, the View satisfaction for man and quality of light for female are the visual factors that have the directional relationship with thermal satisfaction.

According to figure 1.c The higher age of occupant causes their satisfaction are more depend on the quality of light. The age groups: 21 to 30, 31 to 40 and 51 or above correspond to 0.13, 0.16, and 0.20 respectively. The view satisfaction is quite similar between ages ‘21 to 30’ (0.20) and ‘51 or above’ (0.21). The group age of ‘31–40’ (0.13) ranked second in all of the satisfaction factors. However, thermal comfort among the age groups does not follow the same pattern. The thermal satisfactions of the age groups are almost the same (0.20, 0.19, and 0.20) except for ‘20 or below’ because it is higher than the others (0.25). The ‘ability to Control’ ranked the third factor that influences overall satisfaction. Only the occupants who are in the ‘21 – 30’ group are the most satisfied with the ability to alter the temperature and blinds (0.11), but they are less satisfied with the ‘control’ factor in comparison to others. In summary, the people in the age range of “21 – 30” are the most satisfied (0.1).
3.2. Cardinal directions
As figure 2.a indicates, all occupants from different orientations of the building have a significant ‘view’ satisfaction except the East orientation. From the East to West side, satisfaction with the quality of light and natural daylighting declines but ‘view satisfaction’ does not show any correspondence with them. Apart from the East side, all of the other sides were significant in ‘view satisfaction,’ and the West was the highest ranked among other sides (0.283). Satisfaction with ‘thermal conditions’ that were facing the South significantly outscored the other cardinal directions (0.307). The rank of the West was as significant of a number for the North (0.192, 0.212). Thermal satisfaction for the East side was the second most influenced factor in overall satisfaction. Nevertheless, thermal satisfaction was the lowest among other cardinal directions. None of the control factors had significant numbers in all cardinal directions.

3.3. Floor groups:
As figure 2.b indicates, all occupants from floor groups had a similar overall satisfaction rate but with different factors that played different roles in their perception. Although the ‘quality of light’ and ‘view satisfaction’ in ‘10 floor or above’ have a higher rank (0.25, 0.247), the pattern is not followed when it compares to the floor group of ‘5–9’ since it has the lowest rank (0.12). The ‘natural daylighting’ satisfaction (0.124) plays a notable role in the visual perception of people which resulted because of the pattern change. In floors 1 to 4, the ‘view satisfaction’ (0.20) and ‘quality of light’ (0.16) are in second place among other floor groups. Thermal satisfaction is the first item that influences overall satisfaction of ‘5 to 9’ floors (0.24) while the visual factor ranked as second in compare to other floors and the ‘ability to alter the temperature’ on the same floor is notably high (0.24).

3.4. Office layouts
Regardless of office layouts, the ‘view’ satisfaction was identified as the most significant quality determinant of occupant workspace satisfaction. On the other hand, the relative importance of factors is varied between different office layouts. The ‘quality of light’ satisfaction is the main factor that most clearly differentiates them. The quality of light (0.31) is significantly different in enclosed offices (public and private) because the quality of light was one of the least important factors for those in open offices.
In open offices, its comparative importance to ‘view satisfaction’ (0.29) increased as the degree of the enclosure (partition) decreased among open offices. As a result, it ranked as the second most important factor for enclosed offices (0.248), low partitioned offices (0.162) and no limited partitioned offices (b 0.29). It was the most important factor for high partitioned offices (0.11). However, thermal satisfaction does not follow the same pattern; it becomes the third most important factor in enclosed offices since it is, relatively higher than other office layouts. Also, as the degree of enclosure was reduced, the thermal satisfaction decreased in open offices. (Figure 2.c)

### 3.5. Distance to the window.

Visual factors of the ‘distance to window’ are varied. The highest rank in quality of light belongs to occupants who work in ‘1–6 feet’ of a window (0.38), and the lowest belongs to those who work in ‘16 feet or above’. The highest number in satisfaction of ‘natural daylight is lower (0.202). This shows that the trend decreased as the distance of the occupants to a window increased. The thermal satisfaction has a directional relation with distance. In other words, as the distance to window increases, the occupant is more satisfied except for those who are in ‘16 feet or above’ (0.276) This is slightly less than 11–15 feet (0.283). All satisfaction with visual control abilities increases as the distance of the occupant to the windows declines. As the graph indicates, the occupants are more satisfied with ‘ability to alter blinds’ (0.20) in ‘0–5 feet’ and the ‘ability to alter the lighting’ (0.14) in ‘6–10 feet’ of distance. This has the highest rank among other distance groups.

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![Figure 2: The impact of visual, thermal, control factors in overall satisfaction estimated by regression coefficients for a) Cardinal direction, b) Floor, c) Office layout, d) Distance to window](image)

### 4.0 DISCUSSION AND CONCLUSION

According to regression coefficients of personal characteristics, (Fig. 1) individual attributions play a significant role in human perceptions. According to our hypothesis, the pleasant view and quality of lighting have a larger effect on overall satisfaction and can reduce the perception of dissatisfaction in thermal factors. Because of the adaptation process between occupant and environment, the work duration increases the satisfaction between visual qualities and thermal
comfort can potentially influence each other and alter the perception regarding cooler or warmer indoor environments. The assessment of age groups shows that the higher the age group is, the more satisfied they are with visual and thermal comfort even though they are more likely spend more time in the building. All of these individual factors imply how thermal and visual qualities are subjective and can be vary among other groups of people. It also emphasizes how flexible our perception of the environment is and that it can be easily altered by external factors such as the quality of lighting or view satisfaction.

Results show that the different workspace attributions can influence the occupant’s perception. However all of those influences are not direct, and because of the qualitative aspect of the data, concrete conclusions to of the hypothesis cannot be determined. The results do not explicitly show how much the thermal perceptions of an occupant are influenced by visual qualities. However, the assessment of cardinal directions shows how much the qualitative variables such as ‘view’ can strongly influence occupant perception. The West side can potentially be considered as an undesirable side of the building since it can be exposed to excessive amounts of light in the afternoon that cause glare while being deprived from natural daylighting. However, because of a pleasant view (as the occupant defined) it could influence the overall satisfaction. These findings highly support the qualitative results of virtual reality lab too, as their results shows, simple visual cues (sky, sun, shadows, light post–process effects) impact on thermal impressions during the virtual experience that can lead to change the person thermal comfort too(Kim & de Dear, 2013).

It is expected as the levels of the floors increase, the level of visual qualities increase as well. Although the ‘quality of light’ increases in accordance with expectation, the view in floor ‘1 to 4’ was perceived as more pleasant by the occupant of that floor. This reason might be derived from the connection of occupants and urban context. More importantly, the coefficient b of thermal satisfaction was higher in floors that emphasized the indirect relation of thermal satisfaction and view. As view satisfaction increases, thermal satisfaction can increase too(Vigier et al., 2015).

As the analysis and results of the office layout shows, increasing the visual qualities for both view and lighting can potentially increase thermal perception. Therefore, the open office layout with partitions had better performance and as the partitions became lower the satisfaction enhanced. In some cases, the high partition has a better view satisfaction in comparison to low office partition. These numbers are also influenced with by categories such as the distance from the windows. The distance to window shows that the closer occupants are to the window, the more the view and visual qualities increase. This In result, this could influence thermal perception and thermal satisfaction.

Because of the qualitative nature of data and analysis, the direct relation of visual qualities and thermal perception cannot be proved completely. However, the results from the virtual reality assessment can reinforce the hypothesis about the relation and domination of visual effect on thermal comfort.

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REFERENCES


ABSTRACT: Interaction between form and force defines the inseparable relationship between architecture and structural design. Many new architectural forms with complex curved geometries can be generated by active elastic bending and pre-stresses introduced by materials with large elasticity and inner stress state. In addition, these structural systems with reversible elastic deformations are shape adaptable. Three case studies were completed in this study, which include a static bending-active Textile Hybrid M1 at La Tour de l'Architecte designed by ICD/ITKE, a bending-activated tensegrity structure designed by Technische Universität München, and a bending active tensile membrane hybrid tower designed by CITA and KET. Based on the findings, principles for a new type of bending-active structure with biotensegrity logics are formulated through systems thinking to address its function, architectural form-finding, and structural stability. A pre-stressed and self-stabilized ecological “green” wall prototype was designed and built using elastically bent glass fiber reinforced plastic (GFRP) rods in combination with flexible and expandable connections. The new adaptive and dynamic structural form, coupling bending-active systems with biotensegrity logics, explores the opportunities of elasticity, resiliency, and strength within a self-supporting structure. This study presents the design, material selection and iterative form-finding of the wall prototype. The GFRP bending rods play an important role in the structural system, and need to be carefully arranged and connected to carry the loads transferred from the plants, and to enhance the rigidity and stability of the structure.

KEYWORDS: Form-finding; bending active; biotensegrity

INTRODUCTION
The inseparable relationship between architecture and structure is defined by the interaction between form and force. “Force follows form” is an essential precept for an efficient and sustainable structural design. Advanced technologies have enabled new types of structural thinking and making that support the testing of more complex and dynamic structural topologies including: shells/gridshells, lightweight membranes, tensegrity systems, and newly emerged bending-active assemblies.

The structural principles of 'tensegrity' have continued to advance research in disciplines from architecture to human anatomy. Since its formulation by Fuller, Snelson and Emmerich (Gómez-Jauregui, 2010), and subsequent adoption into the fields of biology and cellular mechanics by Steven Levin's and Donald Ingber's, 'tensegrity' logics have launched new paradigms of understanding in biomechanical movement and natural kinematic systems (Scarr, 2014). Arguably ‘biotensegrity’ has emerged as “one of the most significant developments in human anatomy” (Sharkey, 2015). More broadly, its principles introduce a relevant model for adaptive, ‘living’ structures characterized by networks of interconnected components and tendons with the capacity for “non-linear fluid movement” (Skarr, 2014). Lienhard et al (2013) first proposed the concept of “bending active”. Rather than a type of structural system, they contend bending-active structure is an approach to actively curve beams and surfaces based on the elastic deformation of their initial straight or flat geometries to form force equilibria (Lienhard and Knippers, 2015). Many new architectural forms e.g. bending-active textile hybrids, bending-active tensegrity, with complex curved geometries can be generated by active elastic bending and pre-stresses introduced by materials with large elasticity and inner stress state. In addition, these structural systems with reversible elastic deformations are shape adaptable.

Principles for a new type of bending-active structure with biotensegrity logics are formulated in this study through case studies on three bending-active architectural forms, and through systems thinking to address its function, architectural form-finding, and structural stability. The three innovative architectural forms studied include: (1) a static bending-active Textile Hybrid M1 at La Tour de l'Architecte designed by architects and engineers from the Institute for Computational Design (ICD), and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart; (2) a bending-activated tensegrity structure designed and built by designers from the Technische Universität München (TUM); and (3) a bending active tensile membrane hybrid tower designed by researchers from Centre for Information Technology and Architecture (CITA) at Royal Danish Academy of Fine Arts, and Department for Structural Design and Technology (KET) at University of Arts Berlin. This paper analyzes these case studies and discusses the design for a pre-stressed and self-stabilized ecological “green” wall developed and prototyped using elastically bent
glass fiber reinforced plastic (GFRP) rods in combination with flexible and expandable connections.

1.0 BENDING ACTIVE STRUCTURES
1.1. ICD/ITKE Textile Hybrid M1

Defined by Lienhard and Knipers (2015), Textile Hybrid integrates bending-active rods with form-active membranes, taking advantages of their flexibility, lightness, and adaptability to applied loads. The forms of Textile Hybrid structures depend on the mechanical behaviors of materials and pre-stresses applied to the structures. The Textile Hybrid M1 (Figure 1) was built to exhibit a historical and structurally sensitive tower originally designed by Leonardo Da Vinci from the 16th century in Monthoiron, France, which required minimum loading and least intrusion to the tower. 110 meters (361 feet) of glass fiber reinforced polymer (GFRP) rods and 45 m² (484 ft²) membrane created an overlapping grid-shell, arching with 6 to 8 meters (20 to 26 feet) span, covering an approximately 20 m² (215 ft²) area with doubly-curved tensile surfaces. The structure was anchored to existing masonry structure neighboring the tower with three supports, weighing only approximate 60 kilograms (132 pounds) (Lienhard et al, 2013; Ahlquist and Menges, 2013; Lienhard, 2014; Lienhard and Kniper, 2015).

Physical, computational, and finite element modelling (FEM) were employed to find the form of Textile Hybrid M1 (Figure 2). Exhaustive physical form-finding experiments were carried out at various scales informed by intuitions to initially define configurations of bending-active rods and geometries for the interaction of pre-stressed membranes. “The complexity of the form-active textile hybrid belies intuition, iterative feedback through the computational environment elicits knowledge in particular topological and behavioral manipulations” (Ahlquist and Menges, 2013). The complex topologies of the Textile Hybrid were then explored using spring based computational modelling with established numerical methods including cross-over, vertex position and vertex normal (Volino and Magnenat-thalmann, 2006). The computational modelling allowed quick feedback from the prototypical physical modelling, and explored relationships between complex topologies of the structure and physical behaviors of the materials. The overall geometry of the structure and configurations of the rods, which were defined in physical and computational modelling, informed the finite element analysis using Sofistik® to evaluate its structural stability and specify materials for construction. Elastic cable approach was adopted in the Sofistik® to pull an initial planar system of the rods into a bending-active configuration. Then the membrane was attached to the beams and applied with pre-stress. The pre-stress in the membrane was iterated and the structure was reshaped until the permissible stresses occurred in the bending-active rods. The finite element modelling verified the geometrical shape of the structure, evaluated its residual stresses in the rods, and analyzed the deformations as well as stress levels under external loads.

Figure 1: Textile Hybrid M1, (Lienhard and Knipers, 2015; reprint with permission)
1.2. Bending-activated tensegrity structure designed by TUM
Schling et al (2015) presented a full scale bending-activated tensegrity structure in the symposium of the International Association for Shell and Spatial Structures (Figure 3), which integrates “principles of active bending, tensegrity, and structural membrane”. The 6m X 6m (19.7 ft X 19.7 ft) structure was constructed using four 10m (32.8 ft) long elastic GFRP bundles each consisting of three GFRP rods, four polyvinyl chloride membranes and eighteen polyester belts. The minimum radius of curvature designed for the GFRP bundles was 1400 mm (55 in.), which is larger than the theoretical minimum radius of curvature of 1,250 mm (49 in.).

The structural prototype was originally proposed in a design studio at TUM. The prototype was scaled up approximately tenfold, which required studying the impact of self-weight and physical properties of materials. Bending tests were performed to verify the flexural strength and modulus of elasticity of the GFPR rods. A FEM software Strand7® was used by the researchers to simulate the form-finding and perform the structural analysis. In the simulation, the GFRP bundles were bent by induced displacement of supports. Tension elements e.g. cable nets and membranes were incorporated into the model to define the configuration of the structure by adjusting pretensions in these elements. Modal analysis was completed to detect the most flexible locations in the structure. Additional tension elements were used to connect the bundles at the middle points to increase its stiffness.

1.3. CITA/KET tower
A bending-active tensile membrane hybrid tower was designed and constructed using GFRP rods and membranes, by researchers from CITA and KET (Holden Deleuran et al, 2015). The tower was exhibited in the Courtyard of the Danish Design Museum (Figure 4). Computational modelling was employed to find its form and FEM was used to evaluate its structural performance. A newer version of the tower was built by the research team in 2016 with “convergence of the simulated and real behaviour of the structure” (Tamke et al, 2016).
Due to its complex bending-active system, the elastic cable approach proposed by Lienhard (2014) using FEM hit its limits and did not work for this project. The researchers proposed a two-stage strategy to find the form of the tower using Kangaroo 2, a plug-in in Grasshopper/Rhino environment first, and then to evaluate its structural performances using Sofistik®, a FEM software. The form-finding process is illustrated in Figure 5.

Equilateral polylines input in the computational model were further processed to generate the tower typology with “overlapping bending members around a central vertical axis”. A mass spring system in the Kangaroo 2 was used to perform the form-finding and dimension the structural members with three stages, e.g. “generating, exercising, and refining constraints”. Real-time feedback was provided to evaluate if the form-finding was acceptable. The residual stresses in the bending active GFRP rods can be determined theoretically according to the form found geometry. However, axial and bending stiffness of structural members in Kangaroo are based on mathematical approximations. Its precision needs to be validated by the FEM. After the form-finding, the geometry of the tower was baked and exported to Sofistik® to evaluate its structural integrity and stability under the dead load and external wind forces by superimposing residual stresses generated from the form-finding.
2.0 ECOLOGICAL “GREEN” WALL USING BENDING ACTIVE BIOTENSEGRITY STRUCTURE

2.1. Design steps and processes
Biotensegrity precepts were instrumental in developing new concepts for an adaptive, structural indoor farming system. The proposed ecological “green” wall (Figure 6) incorporates aeroponic (soilless) gardening system within a modular bending active structure. The biotensegrity typology was selected for its ability to test techniques of structural efficiency in combination with flexural dynamics of wall geometries. Inspired by the biomechanical organizational principles of the spinal column (Figure 7), the project builds from a single regular tetrahedron module approximately 91cm x 91cm x 30cm (3ft x 3ft x 1ft) in dimension. The tetrahedron was selected for its structural, geometric efficiency and aggregation patterning.

![Conceptual Rendering](image1) ![Diagram (Exploded and Top View)](image2)

**Figure 6:** Bending-active biotensegrity “green” wall

![Tetrahedral vertebral masts model](image3)

**Figure 7:** Tetrahedral vertebral masts model (@copyright Flemons 2006, reprint with permission)

Individual tetrahedral modules were constructed of 3.175 mm (1/8 in.) solid GFRP rods that were tensioned with a layered waterproof, knit membrane enclosure that retains internal moisture for plant germination and growth. Each tetrahedron shell houses one custom-growing tray within its cavity. Trays are composed of a waffle weave set with integration irrigation channels that supports plant growth. Researchers at the Kent State University tested two custom woven growing tray patterns for crop development. Each test found germination of culinary vegetation from seed through agricultural harvest. The crafting of textile trays included the development of a three-dimensional weaving pattern with integrated irrigation channels to support a low-pressure aeroponic system. Two fiber combinations were also tested including: 1) all monofilament, and 2) monofilament and nylon thread. Curly Cress and Alfalfa microgreen crops were tested on each tray; both with and without growing media. A total of four experiments were completed, and analyzed against a commercial aeroponic system that served as a control.

Outcomes for plant development and growth were promising within our sample set, particularly within the two main performance categories analyzed (germination rate and root length) (Figure 8). Germination for all experiments ranged between 50% and 84%, a statistic competitive with, if not well above, the rates for the aeroponic control. Equally encouraging were the sampling of root lengths for the Alfalfa, which grew longer than the control among all trays.
tested. Root lengths for the Curly Cress were generally near or matching the lengths of those in the control. Stem length data was also competitive with the overall growth of the control for each sample set tested. Fresh weight, stem, and root length data collected from these studies drove the size and scaling of tetrahedral geometries, edge lengths and aggregation patterns. A maximum 22 cm (8.66 in.) root length identified in initial growing tray tests served as the minimum benchmark for the lowest tetrahedron cavity interior depth. The growing wall benefits include: 1) materially efficient construction, 2) low-consumption irrigation, 3) a year-round, pesticide free, growing environment, and 4) locally sourced access to sustainable fresh produce.

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*Trays            *Roots          (c) Measurement              (d) Germination Rate*

Note: * 1 Control; 2 Nylon+ Monofilament with Media; 3 Nylon + Monofilament without Media; 4 Monofilament with Media; 5 Monofilament without Media

**Figure 8:** Plants harvest and data collection

The growing wall is composed of a linear array of self-stabilized, regular tetrahedron modules, individually balanced on two vertices. Each tetrahedral structure is pre-stressed with a network of 1.588 mm (1/16 in.) GFRP rods. These rods provide additional structural support though elastic bending, as well as outline the geometry of each tetrahedron's fabric enclosure. Top and bottom vertices of each tetrahedron module are networked within this ‘tendon’ system. Final textile design will be outfitted with a flexible, sewn in LED grow lighting systems within each tetrahedral canopy surface.

2.2. Form-finding method

Based on the three case studies, physical modeling, computational modeling, and FEM inform each other to address the function, architectural form–finding, and structural stability of the design. Extensive physical modeling was adopted in this project to define the form of individual tetrahedral module. Testing indicates these models are self-supported and stable. Pre-stress applied by the knit membrane could further increase the global structural stability of the bending-active biotensegrity structure. A full-scale physical bending-active tetrahedral module was designed and built. The final typology was then modeled in the computer to confirm the selection of construction material, and determine its ultimate loading capacity by employing FEM.

The design process was initiated with a set of full-scale physical experiments that tested material elasticity associated with a variety of GFRP rod cross-sections. Preliminary studies included tetrahedron and closed ring geometry investigations (Figure 9). Computational simulations in Kangaroo 2 (plug-in for Rhinoceros® and Grasshopper®) were used in tandem with full-scale prototyping, to compare active bending behaviors with physical models. Formal qualities of bending experiments and tessellation patterns were also explored during this phase. Similar to the form-finding process of CITA/KET Tower, polylines were input in Kangaroo 2 using mass spring system, combining dynamic mesh relaxation and active bending protocols.


2.3. Materialization and structural performances
Physical modeling used solid fiberglass rods with plastic connectors. The engineering properties for the fiberglass rods are listed in Table 1.

Table 1: Engineering Properties of Fiberglass Rods

<table>
<thead>
<tr>
<th>Flexural Strength</th>
<th>Flexural Modulus</th>
<th>Compressive Strength</th>
<th>Density</th>
<th>Coefficient of Thermal Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>ksi</td>
<td>MPa</td>
<td>ksi</td>
<td>kg/m³</td>
</tr>
<tr>
<td>827</td>
<td>120</td>
<td>41,368</td>
<td>6,000</td>
<td>2,021</td>
</tr>
</tbody>
</table>

The relationship between the flexural strength and minimum radius of curvature of the GFPR rod characterizes the bending active nature of various rod types, which can be derived from classical mechanics of materials for beams (Eq. 1-2).

\[
\sigma = \frac{M}{I} \quad \text{Eq. (1)}
\]

\[
\frac{1}{r} = \frac{M}{EI} \quad \text{Eq. (2)}
\]

Where
- \( \sigma \) = flexural strength
- \( M \) = bending moment applied to the rod
- \( t \) = radius of the rod
- \( I \) = moment of inertia of the rod
- \( r \) = radius of curvature due to the applied bending moment

Solving for \( \frac{M}{I} \) from Eq. (1) and substituting derived \( \frac{M}{I} \) into Eq. (2),

\[
r = \frac{\sigma}{\sigma} \quad \text{Eq. (3)}
\]

Based on the Eq. (3), the minimum radii of curvature are determined to be 7.9 cm (3.125 in) for rods with a diameter of 3.175 mm (1/8 in.) and 3.9 cm (1.55 in.) for rods with a diameter of 1.588 mm (1/16 in) respectively. The minimum radius of curvature of the bent rod in the physical prototype is 19.41 cm (7.64 in.), which is 2.45 times larger than the minimum
value determined by its flexural strength. The early prototype of the bending active, tetrahedral growing wall module is shown in Figure 10 (a).

Regions between modules are designed as flexible, form active connections that offer restricted yet effectual patterns of expansion, contraction and omni-directional movement. The prototyping and testing of the networked tetrahedron modules confirmed high degrees of spatial adaptability and flexure with sustained structural integrity. Studies revealed continued loading-bearing capacities and limited geometric deformation to be well within the system’s elastic range. Final prototypes employed a hybridized biotensegrity and bending active system in which legs of one tetrahedron module are interwoven with the adjacent leg of the neighboring tetrahedron module (Figure 10b). Preliminary prototyping and testing of this technique has revealed a more robust structural assembly system based upon preferred module size and levels of flexural control needed for the growing wall system. The authors will “bake” and export the computational model from Rhino to ANSYS, a finite element analysis software, to determine the ultimate loading capacity of the designed prototype by including the residual stress in the bending-active rods.

2.4. Context of Application
The proposed growing wall system is designed as an urban repurposing strategy that transforms vacant, large-volume structures into indoor farming environments. It asks if it is possible to rebuild social capital at the community and neighborhood level through temporary agricultural programming. Urban vacancy has for decades challenged the economic development of post-industrial cities. Strategic demolition has successfully reduced foreclosures in targeted legacy cities; though recent discussions question if demolition alone can resolve a building surplus rooted in low demand (Warminski, 2014). This project therefore proposes an interim solution for these large properties that supports healthier urban living that is local, deployable, and community-based.

CONCLUSION
FEM and physical and computational modeling, are important techniques for architects and structural engineers to explore the interaction between stress and form in the design of innovative structural systems. Iterative design processes have been adopted by the three bending active hybrids studied in this paper. A pre-stressed and self-stabilized ecological “green” wall was designed and prototyped using elastically bent GFRP rods in combination with flexible and expandable connections, which were then wrapped by the knit membrane to generate the form. The GFRP bending rods play an important role in the structural system. They are strategically arranged and connected, to carry the loads transferred from the plants and to enhance the rigidity and stability of the structure. The new adaptive and dynamic structural assembly couples bending-active systems with biotensegrity logics. It explores the opportunities of elasticity, resiliency, and strength within a self-supporting structure. The project also presents an opportunity to address the challenge of food equity and social resilience in legacy urban communities.

ACKNOWLEDGEMENTS
The authors would like to acknowledge the following individuals from Novel Ecology Design laboratory (https://www.kent.edu/caed/nedlab) at College of Architecture and Environmental Design, Kent State University for their assistances in testing the germination of culinary vegetation: Dr. Reid Coffman, Catalina Estrada, Megan Haftl, and J. Max Wagner. In addition, special thanks go to Professor Janic Lessman-Moss and textile artist Trey D. Gehring for their contributions to the designs of growing trays in the proposed green walls.
REFERENCES


ABSTRACT: Water serves as a medium through which to explore architectures of complexity and ecological responsiveness. I offer an encapsulation of the multiple water crises facing cities in the American West, in part a function of the reality that we dwell in what environmental historian Donald Worster, borrowing from Karl Wittfogel, labels a hydraulic society. Acknowledging the health, environmental and economic consequences of the ways we currently appropriate water resources, I advocate for the value of decentralized, site scale water systems in urban environments that integrate harvesting, storage, treatment, recycling and ecosystem recharge. In a time of the population growth and climate change, the ‘big move’ in a next generation of thinking about water and the built environment is counter-intuitively a focus on the urban site, the very location to put into meaningful relation pressing matters of supply with those of downstream effects.

Building from this larger contextual understanding, this paper offers the beginnings of a hydro-logical design approach, that is to say, a systems-oriented, water centric manner of conceptualizing and making architecture, one that involves:

1. Tracing the journey of water through a site as a way to begin to internalize impacts that have historically been external to architectural design
2. Identifying synergies amongst water system elements
3. (Re)Defining the system as a coupling of architecture and environment
4. Narrating the steps in the architecture-environment system

Two interrelated motivations guide this undertaking: (1) a growing realization of the exciting and important design implications that follow from foregrounding water concerns in architecture, and (2) an interest in the ways such a focus allows for the identification of important and often neglected systems interconnections, not the least of which are the many functional synergies to be derived between sustainable architectures and ecologically functional urban landscapes.

KEYWORDS: Water, architecture, hydro-logical, decentralized, passive

1.0 HYDRAULIC OR HYDRO-LOGIC

A growing population, expanding cities, and climate change exacerbate longstanding water supply problems in the American West. Overall, and typically relying on relatively moist climate spells as a baseline for apportioning water, we have over-allocated our sources, the Colorado River being the most celebrated example. In addition, aging water supply infrastructures are out of sync with changing hydrological regimes. Snowpack in the mountains, a critically important natural storage reservoir, is now much reduced and causing summer shortages (simply filling up dams with the rains of winter and spring to meet summer demand would lead to reduced flood storage capacity; water managers must proceed cautiously).

Borrowing from and recasting Karl Wittfogel’s controversially framed argument, environmental historian Donald Worster describes the American West as a hydraulic society. Like others in arid environments throughout history, it is one in which impoundment, irrigation and related water infrastructures have allowed for both spectacular economic growth and a decidedly technocratic management structure necessary to the system’s construction and maintenance. According to Worster hydraulic society “is a techno-economic order devised for the purpose of mastering a difficult environment” (Worster 1985, 6). That centralized water systems are conjoined with centralized energy infrastructures (“the water–energy nexus”) compounds vulnerabilities and resource inefficiencies. We need only look to the now famous California Energy Commission finding of 2005 that water related energy uses account for 19% of all electrical and 30% of non-power plant natural gas consumption in the State. Or the fact that “in 2000 generation of electricity ranked first in total water withdrawals in the United States (fresh plus saline),” as incredibly large volumes are needed to provide cooling to dissipate rejected heat (Viessman et al. 2005, 85).

Worster is persuasive in articulating relationships between the manner of appropriation of natural resources and the
prevailing characteristics of a culture. For Ingram and Malamud-Roam as with many other contemporary theorists, a defining trait of our hydraulic society is that of estrangement:

Water is uniquely vulnerable to overuse. It falls freely from the sky, giving a false sense of abundance. Water policy in the West has made it a resource that is easy to seize and exploit by those with the power and will to do so. As yet there is little incentive to conserve water for the common good, despite scores of ingenious water conservation proposals. Society in the West lacks any sense of urgency concerning the growing scarcity of this life-sustaining resource. People in the region are oddly estranged from their natural relationship – living in human-created oases of concrete, manicured lawns, and air-conditioned homes. Few are aware of the origins of the water flowing out of their taps, which is probably due, in part, to the complexity of the region's modern, highly engineered hydrology (Ingraham and Malamud-Roam, 2013, 212).

The estrangement with respect to the origins of our waters has as its corollary insufficient awareness of downstream impacts. Few appreciate the severity of the health threats for those millions who live in cities in the US where a significant portion of drinking water comes from treated effluent of those living in communities upstream. We also witness increasingly detrimental ecological consequences when “ultra urban pollutants” of non-point load sources combine with urban waters during increasingly severe storm events that punctuate prolonged periods of drought (see Salmon Safe, 2016). Motor oils, heavy metals and a suite of other toxics that collect on roadways and other urban surfaces during the dry summer months are conveyed in minutes to water bodies during the first fall rains with devastating impacts on salmonids and other forms of aquatic life.

These compounded impacts speak to the value of engaging in initiatives that explore different manners of dwelling in the (urban) watershed, of conceiving design as a means to overcome estrangement, of expanding the scope of concern while attending more carefully to the details of the systems we design, and of making buildings and neighborhoods better functioning elements of hydrological cycles. In the search for an environmentally responsive, hydro-logical antidote to the massive problems associated with hydraulic society, we need to embark on the kind of “intermediary projects” called for by philosopher Paul Ricoeur:

Our expectations must be determined, hence finite and relatively modest, if they are able to give rise to responsible commitments. We have to keep our horizon of expectation from running away from us. We have to connect it to the present by a series of intermediary projects that we may act upon (Ricoeur 1988, 215)

Landscape architect Carl Steinetz contends that if we do not make sound decisions about land use and urban growth at the region scale, it matters little what an architect proposes for a site. Perhaps in this regard and with “responsible commitments” to our waters in mind, the appropriate metropolitan scale strategy would be to seek a greater diversity of assets, what water managers call a portfolio approach. San Francisco Public Utilities Commission for example, recognizing the vulnerability of relying on 85% of its supply from the Hetch-Hetchy Reservoir (with the increasingly dependable snowpack in the Sierras as its source), is searching for alternatives, encouraging use of potable water only where needed, and promoting strategies for conservation and greywater recycling. This is becoming the standard for urban areas in this and nearby regions and will continue to gain in emphasis as necessity dictates; as the authors of Climate Change in the Pacific Northwest contend: “With lower summer flows, it is projected that diversification and development of water supplies…and increasing drought preparedness would be required” (Dalton, Mote and Snover 2013, 49).

As a central component of a portfolio approach and as a corollary to hydraulic society, a hydro-logical commitment is predicated upon the conviction that as we modernize our water infrastructures, the soundest large scale investment – Steinetz’ big move – is counter-intuitively a focus on the site and urban district. As engineer and author David Sedlak encourages, “to wean cities from centralized systems and all their associated problems, we might simply have to find a way to make decentralized water supply and treatment practical at higher population densities’ (Sedlak 2014, 244). As he makes clear, this is not abandonment of existing infrastructures but a process of weaning or a transitioning to a localized and ecologically responsive set of approaches.

The site becomes the very locus for thinking holistically and for putting into meaningful relation pressing issues of supply and those of downstream effects, for engaging in micro-hydrological loops and nutrient flows that are responsive to those of larger magnitude. In essence we graft the two water ‘petals’ put forth in the Living Building Challenge:

One hundred percent of occupants’ water use must come from captured precipitation or closed-loop water systems that account for downstream ecosystem impacts and that are appropriately purified without the use of chemicals.

One hundred percent of storm water and building water discharge must be managed on-site to feed the
To examine this grafting in greater detail is to explore a series of design operations that both frame and follow from a water centric orientation. At a macro-level, this approach exemplifies a systems orientation: while it is critical to attend to sub-functions (collection, storage, filtration, recycling, wastewater treatment, other), what is most essential to operational effectiveness is the deriving of synergies amongst elements, honoring the capacity and creating the conditions for water to perform beneficial work in multiple ways, and being vigilant about water quality and its resourceful use throughout its journey.

2.0. GROUNDWORK FOR A HYDRO-LOGICAL APPROACH TO ARCHITECTURAL DESIGN
The following design strategies are intended to help shape a water-centric approach to urban architecture. This represents but one way of sequencing a hydro-logical design cycle, a narrative more suggestive than comprehensive as far as what design opportunities present themselves when we attend more carefully to our urban waters. In truth one can enter the process at any point, as one can productively float multiple options for sub-elements simultaneously, continuously moving up and down the system in its entirety in the search for positive feedbacks.

2.1 Tracing the journey of water through a site as a way to begin to internalize impacts that have historically been external to architectural design
To consider the journey of a droplet of water entering, moving through and off the landscape prior to urbanization is to tell a larger story of historic (baseline) ecological and hydrological conditions. In all likelihood, given the presence of vegetation and quite possibly more variegated terrain, the pre-urban 'coefficient of friction' of the landscape would have been significantly greater than today, with the water moving more slowly and becoming cooler and more oxygen rich along the way. These system attributes provide a basis for reworking the journey as a consequence of project development so as to recover functionality and achieve positive downstream effects.

While the hard surfaces of the city have proven most effective at channeling water and pollutants rapidly to urban water bodies, they also provide shade (and therefore can reduce losses due to evaporation) and can be configured to decelerate flows for the purposes of floodplain storage and numerous other uses. In other words, the morphological characteristics of the urban environment, what landscape architect and theorist Bart Johnson succinctly describes as in effect geological formations of rock outcrops, can be enlisted to perform ecologically beneficial work. In most instances this will mean manipulating building form in synchronization with the landscape so as to optimize the harvesting, use, recycling and treatment of water, in other words to instantiate micro-hydro loops that ultimately benefit the parent system in which a project is situated. The challenge and opportunity is to achieve this functionality in tight urban quarters and given competing demands for use of space. In this sense and in a most basic way, the design challenge becomes that of increasing surface area.

Figure 1: Manipulating the hard surfaces of the city to decelerate flows, put water to work, and cleanse it

2.2 Identifying synergies amongst water system elements
To rise to the Living Building Challenge is to commit to harvesting as much rainwater on site as possible to meet building occupant needs. Given that in much of the American West the majority of precipitation arrives in summer,
and anticipating more prolonged drought events in an era of climate change, to follow through on this commitment in
the design of any multi-level urban building is to incorporate significant capacity for storage. And as Brent Bucknum of
the Oakland-based ecological infrastructure firm Hyphae Design Laboratory exclaims, “above 100,000 gallons, it gets
expensive” (Personal correspondence, July 18, 2016). Justifying these costs requires identifying other potential uses for
stored water; for example integration of preliminary filtration in a matrix of storage, or use of stored water as a fire
suppression reserve or for the purposes of seismic dampening. Perhaps most promising for certain building types would
be to utilize this water as thermal mass to reduce cooling loads.

Instead of the customary approach of delivering harvested water to underground cisterns and then pumping it
to where it is needed, Cook and Fox architects, in their One Bryant park skyscraper project in New York, organize
storage elements on different levels throughout the building. This localized and largely passive method of storage and
distribution leads in essence to the formation of vertically deployed water ‘precincts.’ And yet instead of burying these
storage elements in the building's interior, as is the case with One Bryant Park, they could be configured in more overt
ways to shape space and to help establish architectural identity. For example, tanks in an atrium space could be clad
with light reflective materials to help distribute daylight admitted through skylights to darker, recessed spaces below.
And perhaps the building's hydro-logic can positively inform a building's social logic: water precincts gather neighbors
inhabiting a suite of dwelling units around a common and precious resource. Where water collects, people collect.

Figure 2: Storage elements and other water system elements shape space and impact architectural identity

Pushing out to a project’s perimeter, it warrants considering synergies derived through the introduction of ecological
envelopes, matrices of vegetation and water features operating in tandem with facades, roofs and other building
elements and systems to deliver myriad benefits. Mecanoo Architects’ competition entry for the Kaohsuing Public
Library in Taiwan, for example, a cube-like building in a subtropical garden landscape, uses planters and vegetative
screens on each level along the building's perimeter in association with chilled beams and other elements in the
building's interior to create a range of comfort-providing microclimatic gradients and to offer visual delight while
reducing energy loads. For Hyphae Design Laboratory, a common strategy is to utilize recycled water to irrigate living
roofs that provide habitat and visual amenity while reducing cooling loads and decelerating stormwater flows. With
Mick Pearce's Council House 2 project in Melbourne of 2004-2006, water is drawn to the tops of 'shower towers' on the
building's south façade. This water then falls and cools by evaporation; it is then used to pre-cool water from chilled
ceiling panels, resulting in a significant reduction in overall energy consumption.

Given the water and energy inputs and maintenance regimes required to keep them alive and healthy, Brent Bucknum
of Hyphae describes living walls, modish as they are, as “ICUs” (intensive care units). Hyphae focuses on an alternative
ecological envelope strategy that utilizes extensive trellises to support vegetation that is watered at grade and that
assists with cooling, pretreating air and serving in other capacities (Personal correspondence, July 18, 2016). And yet
perhaps living walls are warranted if enlisted in a synergistic manner, whether as part of a greywater filtration and
recycling system as is the case with Bertschi Living Science Wing in Seattle (the greywater is also used by the plants),
or in lieu of cooling towers, a strategy now being investigated by Alexander Felson of the Urban Ecology and Design
Laboratory at Yale University.

Hydro-Logical Architecture: Muller
This handful of examples begin to suggest how an emphasis on resourceful and passive use of water has ripple effects that touch other aspects of buildings, both along its surfaces and in the depths. And this syncretic design force continues outward, shaping the landscape along its course and intensifying relationships between buildings and the sites in which they are located.

2.3 (Re)Defining the system as a coupling of architecture and environment

While there are numerous aspects of this coupling, the aforementioned ecological envelopes offering one example, recent incorporations of environmentally responsive wastewater systems on urban sites are particularly significant for the architectural/landscape architectural impacts they bring about. While there are a range of options for on-site treatment, with choice of system dependent on building type, project scale and site conditions, Kieran Timberlake (architects) and Andropogon Associates (landscape architects) Sidwell Friends School in Washington, D.C offers and illustrative, integrated example. With Sidwell 100% of wastewater is treated “through a terraced, subsurface−flow constructed wetland designed into the site landscape” that students and faculty monitor (Cascadia Green Building Council 2011, 99). This becomes a didactic device and a central site feature that works in tandem with the channeling of harvested rainwater through wetlands, downfalls for aeration, and into a biology pond where it is infiltrated to recharge groundwater. Rainwater makes its way from building to landscape; some of this returns to the building for use in the wastewater system; the wastewater returns to the landscape in a co-dependent, multi−loop flow.

Another manner of coupling involves conceiving processes of building construction as processes of ecological regeneration. Portland−based urban ecologist Mark Wilson gives us some insight as to how we might align sought after ecological attributes with desired characteristics of a project from a human−centric perspective. Wilson visits building sites near riparian corridors where historic wetlands have been largely obliterated (and where the city has encouraged their reintroduction), observing locations of staging areas, patterns of movement of construction equipment, and the reshaping of terrain. He conducts percolation tests where soils have been compacted and identifies locations where proper subsurface conditions for constructed wetlands have been established.

Using this example of ‘accidental regeneration,’ what Wilson describes as “opportunistic ecologies,” we might proceed with a greater level of intentionality and identify ecological and hydrological goals as part of the problem definition statement itself, goals that will depend in great measure on where a particular project sits in the urban watershed. In the case of low lying development sites and goals of wetland complex restoration, a building could release recycled and treated water at critical times to ensure the hydroperiods (water levels) necessary for aquatic species to complete their life cycles. In an era of climate change, prolonged drought, and greater meteorological unpredictability, architectures become in effect ‘hydrological batteries’ that help enable the perpetuation of critical ecosystem services and biological processes.

Figure 3: A project acquires particularity by virtue of where it sits in the urban watershed

2.4 Narrating the steps in the architecture−environment system

What the above suggests is a different way of designing and thinking in systems than architects ordinarily pursue. Following a journey of water, viewing the built environment as conduit and decelerator, seeking synergies and couplings
also require the effective representation and narration of systems. An early step in the design process may be to build up a perspective from the sky looking obliquely down on the site in question and describing graphically and in proportion sources, flows and points of recharge, as for example Hyphae Design Laboratory’s “Sankey” operational depiction of inputs and outputs and relative volumes for the Waterman Gardens multi-family residential complex in San Bernardino, CA. Next and focusing in on the site, a water schematic in section or section perspective would depict the basics of systems elements and their interactions (see Figure 2). Coupled with this would be a bulleted sequence of steps in the hydrologic design cycle.

In the design of a parking garage adjacent to a constructed wetland as part of a university level design studio investigation, students Lore Burbano, Andrea Detweiler and Nicki Ghiseli devised a particularly novel sequence that contended aggressively with a highly problematic building type from the standpoint of environmental quality:

1. Owner drops off car
2. Car is given a shower (is washed)
3. Mechanical lift hoists car to parking space
4. Polluted water is directed to facade to grow algae
5. Algae cleans water
6. Excess water is sent to adjacent constructed wetlands
7. Algae is used to produce biofuels

![Figure 4: “A motorcycle is part of the hydrological cycle” parking garage design water system sequence by Lore Burbano, Andrea Detweiler and Nicki Ghiseli. The constructed wetlands are configured as part of the proposed project development (winter 2014)](image)

As this proposal demonstrates, the basics of project organization follow not only from manipulation of space but thoughtful devising of processes as they would play out over time. While beyond the ability to examine in detail in this essay, the water emphasis, building-environment coupling and attention to temporality that this project and the “opportunistic ecologies” approach represent also speak to the value of new and highly integrated interdisciplinary partnerships at the intersection of buildings, ecologies and economies.

**CONCLUSION: ANCHORING**

Detail anchors perception in a context of vastness (MacFarlane 2014, 212).

Herbert and Grau Ludwig Dreiseitl’s reflection that “we are constantly discovering that water is our best teacher” inspires the ruminations in this essay (Dreiseitl and Dreiseitl 2001, 42). To draw from our urban water in driving a design process is to seek syncretic relationships between ecologies, interiors and envelopes. In this way and much like low energy, passive approaches to heating, cooling, lighting and ventilating of buildings, a water-centric commitment offers a means of arriving at a place-based architecture: while any one project necessarily has multiple functions to perform, its hydro-logic adjusts in relation to its location within the urban watershed. Such built interventions in aggregate and in a time of reduced snowpack form surrogate mountain ranges that collect water during the rainy season and make it available throughout the year.
To draw on our urban waters is also to begin to overcome the estrangement touched on earlier. Rick Basatch says of the current water situation in the State of Oregon, “if a measure of caring is the degree to which society organizes its thinking and allocates resources to the future, then on this score there is no contest: in Oregon, roads trump water any day” (Bastasch 2006, 281). This degree of neglect and unpreparedness in light of climate change and population growth plays itself out in many states and municipalities in the American West. A culminating argument of this essay is that to concentrate on localized, site-based water systems is to heighten our concern over our common dwelling place and to galvanize attention to the larger water predicament contemporary society finds itself in. As Robert MacFarlane has said, “if we attend more closely to something then we are less likely to act selfishly toward it” (MacFarlane 2014, 211).

What is at stake is not only different manners of attending to and thinking in systems, but altogether different notions of temporality, progress and purposefulness than what obtains in hydraulic society. Paul Ricoeur encourages that “when confronted with the adage that the future is open and contingent in every respect but that the past is unequivocally closed and necessary, we have to make our expectations more determinate and our experience less so” (Ricoeur 1988, 216). More determinate expectations mean working toward a future in which the material, experienceable and environmentally responsive – vs. the buried, invisible and damaging – characterize our infrastructures and architectures. Less determinate experience means viewing the past as fluid, diverse and laden with constructive possibilities; while we face unprecedented urban challenges, simple and robust, pre-modern and passive approaches to water infrastructures are well worth revisiting as a means of addressing them.

An ecologically oriented emphasis on water in the built environment, what amounts to in effect a hybridization of water infrastructure and architecture, leads designers to circulate across scales, erode distinctions amongst systems, and dissolve boundaries between buildings and landscapes, ecologies and cites. Such sustained attention can bring about a sense of satisfaction and enchantment, “a pleasure at moving with the world and being swept along in its rhythms rather than sweeping it along with us” (MacFarlane 1985, 6 2014). Through this effort and at the same time we reconnect people in the present to the larger systems on which they depend, our successes become a legacy of care.

**Drawings by author**

**REFERENCES**


ENDNOTES

1 Water 4.0 is the title of David Sedlak’s book of 2014

2 Worster 1985 borrows this term from Wittfogel 1957. Wittfogel controversially suggested that oriental societies were hydraulic and as a consequence despotic; Worster argues persuasively that the American West is a hydraulic society par excellence

3 We might triangulate as many do and add food to the energy-water nexus

4 We also ought to attend to another dimension of this nexus: while hexavalent chromium, a chemical linked to cancer, is used in a number of industrial processes, the greatest source of contamination is the electric power industry

5 Of particular concern are those “contaminants of emerging concern,” pharmaceuticals and personal care products for example, that are not regulated through the National Pollution Discharge Elimination System, the regulatory structure set up with the passage of the Clean Water Act in 1972

6 That said, there are emerging systems involving ‘contained treatment’ and localized resource recovery that when commercialized will render the term wastewater meaningless, as water will no longer be the means of conveyance, and where human waste will be processed into a nutrient rich precipitate

7 This paragraph is based on personal correspondence
ABSTRACT: The goal of this paper is to investigate and determine the significant impact of building facade information (i.e., basic façade features), as well as climatic impact, on building energy performance. Compared with these easily accessible façade features, parameters including envelope thermal properties, internal systems, and operating schedules are regulated by building codes and regulations, based on different building functionalities. Such façade parameters are variables that have large potential for affecting building energy performance. These attributes were extracted to conduct a data mining process to establish a correlation between building energy consumption and relevant physics information. Stepwise regression, and artificial neural network (ANN) are techniques used in this research. A façade visual information-driven benchmark model was developed as a building energy use intensity estimation baseline. Considering its comprehensive interpretation of variable variance and better predictive ability, it was proved that it is capable and feasible to use the façade visual information as the building key performance indicator, for estimating the building energy use, which is a fast and straightforward way to predict the energy use at urban scale. Traditional energy predictions, as a very complicated and time-consuming process, require multiple details and information about a building when preparing for energy modeling. Incorporating a transformative building energy performance estimation approach may enable stakeholders to easily assess their existing building energy consumption as well as establish a viable integrated energy master plan.

KEYWORDS: Facade Features, Data-Driven Model, Benchmarking, EUI Estimation, Energy Performance

INTRODUCTION
As urban built environment is the largest contribution to world’s fossil fuel consumption and greenhouse gas emissions, it is imperative to transform the irreversible climate change problems into solutions through the built environment, in paving to a carbon neutral future. In California, with the aim of minimizing the fossil fuel energy consumption, California Public Utilities Commission (CPUC) established the tangible goals that all new residential construction in California shall be zero net energy (ZNE) by 2020, and all new commercial construction shall be ZNE by 2030. Per the ZNE Action Plan, K-12 schools and community colleges are prior than other types of building at this stage to implement the ZNE retrofit. To make this change possible, major efforts shall go beyond individual buildings to urban planning by modelling the campus energy performance as well as proposing the energy use metrics for energy goals. It is concerned with the measurement and benchmarking of the whole building energy consumption. However, due to the complexity of the energy consumption structure, it is quite difficult to estimate the energy consumption precisely. In spite of the prevalent use of advanced building simulation, it is not mature for urban scale energy analysis. The critical limitations of existing simulation tools are the excessive amounts of building information required and the time-consuming process. The lack of sufficient building information will significantly restrict the utilization of a computational performance diagnostic method, hinder the effective management of energy in old or existing facilities. Therefore, under this situation, there is a high potential in developing a fast and straightforward energy estimation approach, which facilitates the energy management at the urban scale.

Building energy consumption is influenced by multiple variables including building envelope information, local climate characteristics, building principal activities and internal energy systems. Among these influential variables, building envelope, as the elegant component that helps shape the architectural aesthetics of the building, is a crucial factor in determining the energy performance (McFarquhar, 2002). In addition, façade features are more easily obtained as opposed to obtaining the detailed building system information. The goal of this research is to provide stakeholders with a simplified but reliable energy benchmark model to assess their existing building performance while motivating the establishment of performance goals. To accomplish this goal, the façade visual information-driven benchmark performance model as a function of architectural physical frames, facades, and their dynamic climate conditions was developed to facilitate energy management of a whole building or urban scale to provide a scalable and extensible tool.

1.0 BACKGROUND AND CONTEXT
The AEC industry has stepped into the prime time, revolutionizing from traditional construction to sustainable designed with concerns for high-efficiency and high cost-effectiveness. In the long term, measuring the energy performance at a
community or city scale do contribute in achieving the urban sustainability targets.

1.1 Building energy use baseline and benchmarking
Creating the baseline for current energy consumption will assist both the stakeholders and the design team in evaluating the energy performance as well as understanding the energy expenditures associated with the building operation costs. It is the starting point for setting the energy efficiency improvement goals as well as providing a comparison point for assessing future efforts and trending overall performance. For instance, the 2030 Challenge established by Architecture 2030 uses the national average or median energy consumption of existing U.S. commercial buildings reported by the 2012 Commercial Building Energy Consumption Survey (CBECS) as its baseline for the target goals (Architecture 2030, 2015).

Building energy benchmarking is an approach to evaluate the building performance and establish the comprehensive energy reduction goal, which has already become a standard process across the nonresidential building markets. There are a wide variety of benchmarking tools for building energy performance. The Building Performance Database is the national largest dataset for users to perform the statistical comparison in both commercial and residential buildings across the national real estate sectors (U.S. Department of Energy, 2016). In addition, Energy Star Portfolio Manager is an interactive online energy management tool tracking energy consumption across the life cycle of the building. It is a well-established whole building benchmarking tool in the U.S (Borgstein & Lamberts, 2014). Energy use intensity (EUI) is the key metric used for energy consumption baseline. It is the building energy use as the function of the building size, normally square footage, with the unit in kWh/m²yr (kWh/sf.yr). Buildings with different internal principal activities may have different EUIs, for example, hospitals have relatively higher EUI since there are large amounts of testing and inspection instruments, which consume higher electricity loads. There are different ways to predict the building EUI with different levels of accuracy. Estimating and modeling the building EUI precisely, especially in the community or urban level, is an essential process for future energy benchmarking and urban energy infrastructure planning.

1.2 Building energy performance estimation approach
There are three mainstream approaches to estimate the building EUI: national benchmarking tool, energy modeling software, and energy bill based analysis. The national or local average or median energy consumption is one approach to estimate the building EUI. Commercial Buildings Energy Consumption Survey (CBECS) is a national sample survey compiled by the U.S. Department of Energy, which collects the information on the stock of U.S. commercial buildings (U.S. Energy Information Administration, 2016). It includes the basic energy-related building characteristics as well as the building energy consumption and expenditures. CBECS provides the average EUI for buildings in geographic regions based on climate zone, building size, floor space and building principal activity. The benchmarks were developed by multivariable regression to compare buildings of different typologies, based on various characteristics (U.S. Environmental Protection Agency, 2010). It is a simple normalization which is inexpensive and easy to implement, however, it only concerns with limited building factors, which cannot normalize for the thorough building physical characteristics which may affect the building energy consumption (Borgsteina & Lamberts, 2014).

Other ways include the computer-aid energy modeling software. There are various simulation programs in the industry that are well developed for modeling the building energy consumption, for example, EnergyPlus, DesignBuilder, IES-VE, eQuest, EnergyPro, etc. With inputs of detailed building information such as building envelope assemblies’ thermal properties and building systems’ efficiency, the energy program will calculate the energy usage and analyze the end-use consumption. It is powerful for designers to evaluate potential savings of different design schemes or sustainable strategies at the predesign stage. However, the accuracy of the energy modeling depends on how much specific information related to envelope thermal properties, internal system performance and operation schedule, can be input to the model, as well as the similarity between the real design and the 3D model built up inside the modeling module. It is almost impossible to obtain all the detailed and accurate building information, especially for those old buildings built decades before, since some parameters may be unavailable to many organizations, for example, the detailed information of internal individual rooms (Zhao & Magoulès, 2012). For the large urban scale energy analysis, it is extremely time-consuming and cost-ineffective to perform the energy simulation building by building. The expertise level of the building energy analyst may also affect the accuracy of the modeling results. Daly and colleagues clearly state that “building energy modeling typically relies on a range of simulation assumptions and default values for certain ‘hard-to-measure’ building and behavioral inputs to building performance simulations”. In addition, different simulation programs may result in different energy consumption, even with the same settings, since it varies with different algorithms in the modeling engine. Grawley, Hand and their research team (2008) conducted a comparison and contrast study on capabilities of different building energy performance simulation programs. Similarly, Sun (2015) conducted a result variation analysis of different simulation programs. In his research, 11 case buildings were selected to run the energy modeling by using several different prevalent software, see Figure 1. It is clearly that there are large discrepancies among different simulation program. The modeling capabilities and detail level vary with different software even if they share the same energy modeling algorithm. There is a need to further develop a simple, robust and validated model for energy prediction.
For energy prediction of existing facilities, the energy-bill based method is the most precise one as well as the most cost-effective. However, the monthly bills only provide the total energy usage of the whole building, thus it could not help with the multi-level assessment and diagnosis. In fact, at the urban level, it is sometimes not feasible to collect the 12-month of energy bills for all buildings. Compared with the energy bill, building sub-metering system is an approach to monitor the real-time energy consumption. However, it is not practically applied in the real industry due to the high initial investment (Piette et al, 2001). Therefore, under this situation, there is a high potential in developing a fast and accurate energy estimation approach, which facilitates the energy management at the urban scale.

1.3 Urban scale modeling approach

There are numerous researches on the urban energy models, focusing on data, algorithms, workflow and potential applications on city-wide energy supply/demand strategies, urban development planning, electrical grid stability and urban resilience (ASHRAE 2017 Winter Conference). There are several urban energy modeling tools that have been developed or at on-going research stage. Hong and his colleagues (2016) from Lawrence Berkeley National Laboratory proposed a web-based data and computing platform to facilitate the urban scale energy efficient planning. City Building Energy Saver (CityBES) is a web-based platform for urban scale energy performance modeling of a city's building stock. It employs EnergyPlus as the simulation engine for investigating the building energy use and potential savings under various energy efficient strategies. CityGML, as an XML-based open data model, was used to represent and exchange the 3D city models, and provide virtual 3D city models for advanced analysis and visualization. The MIT Sustainable Design Lab is currently developing a new generation of urban building energy models (UBEM), for estimating the citywide hourly energy demand loads down to the individual building level (MIT Sustainable Design Lab, 2017). Urban Modeling Interface (UMI) is a Rhinoceros 3D software-based tool for urban level modeling including the operational and embodied energy use, daylighting and walkability analysis (Reinhart et al., 2013). It used the EnergyPlus and Radiance as the simulation engine. It works as the plug-in for the commercial 3D computer graphics and CAD modeling software. CitySim is a new software developed by Robinson and his research team in 2009, providing the decision support for urban planner on energy and emission reduction. It was developed based on its own XML schema to represent the building information. And the developers plan to incorporate water, transportation, and urban climate modeling into CitySim in the future (Robinson et al., 2009). However, at this stage, this software is isolated for specific applications, since they are not using the open standards, such as CityGML (Hong et al., 2016).

2.0 METHODOLOGY

In this research, a data-driven performance benchmark model based on building visual façade information was proposed. It aims to provide a direct and real-time forecast of the existing building energy performance, especially for urban scale energy analysis and benchmarking, as well as to provide a fast and straightforward tool for evaluating the building envelope design decision at the project predesign and schematic design stage.

To accomplish this goal, a data-driven benchmark performance model as a function of facades, and dynamic climate conditions was developed upon the following research methodology diagram, see Figure 2. There are three main parts of methodology in this research: data collection, data mining and validation. Finally, the building performance benchmark model used to predict energy consumption were derived based on building visual façade information, basic climatic characteristics and building monthly energy consumption. The following sections gave an explicit methodology for this
research and documents the overall workflow.

![Methodology Workflow Diagram]

### 2.1 Data collection
Research dataset of 32 different buildings were collected from two California colleges in different climate zones. The dataset includes the real building energy consumption data, building façade features information, climate and weather data, and building vintage. The building energy consumption dataset were collected for each building including the yearly and monthly end use consumption in heating, cooling, fan/pump, lighting and miscellaneous plugins and the total building site EUI. Instead of using the detailed building information including construction assembly thermal properties, internal system performance, operation schedule, only accessible façade features such as height, floor area, WWR and basic climate characteristics were considered.

<table>
<thead>
<tr>
<th>No.</th>
<th>Façade &amp; Climate</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vintage</td>
<td>Year of construction complete</td>
</tr>
<tr>
<td>2</td>
<td>Height</td>
<td>From open air pedestrian entrance to highest occupied floor</td>
</tr>
<tr>
<td>3</td>
<td>Floorarea</td>
<td>Total floor area inside the building envelope</td>
</tr>
<tr>
<td>4</td>
<td>Orientation</td>
<td>Posting of a building with respect to the North</td>
</tr>
<tr>
<td>5</td>
<td>WWR</td>
<td>Window-to-wall ratio (total window area/total exterior wall area)</td>
</tr>
<tr>
<td>6</td>
<td>Volume</td>
<td>Inner space volume enclosed by external envelope</td>
</tr>
<tr>
<td>7</td>
<td>Window Area</td>
<td>Total glazing area</td>
</tr>
<tr>
<td>8</td>
<td>Façade Area</td>
<td>Total area of all parts of the structure’s façade</td>
</tr>
<tr>
<td>9</td>
<td>Aspect Ratio</td>
<td>Proportional relationship between the width and height</td>
</tr>
<tr>
<td>10</td>
<td>Shape Coefficient</td>
<td>Ratio of volume to façade area</td>
</tr>
<tr>
<td>11</td>
<td>Shading</td>
<td>Any external shading device</td>
</tr>
<tr>
<td>12</td>
<td>Number of Floors</td>
<td>Total occupied stories or levels</td>
</tr>
<tr>
<td>13</td>
<td>FAR</td>
<td>Floor to Area Ratio</td>
</tr>
<tr>
<td>14</td>
<td>Operable Window</td>
<td>Window could be open or close based ventilation need4</td>
</tr>
<tr>
<td>15</td>
<td>South WWR</td>
<td>Window-to-wall ratio of south facing façade</td>
</tr>
<tr>
<td>16</td>
<td>West WWR</td>
<td>Window-to-wall ratio of west facing façade</td>
</tr>
<tr>
<td>17</td>
<td>North WWR</td>
<td>Window-to-wall ratio of north facing façade</td>
</tr>
<tr>
<td>18</td>
<td>East WWR</td>
<td>Window-to-wall ratio of east facing façade</td>
</tr>
<tr>
<td>19</td>
<td>Monthly CDD</td>
<td>Cooling degree day (the demand for energy to cool a building)</td>
</tr>
<tr>
<td>20</td>
<td>Monthly HDD</td>
<td>Heating degree day (the demand for energy to heat a building)</td>
</tr>
<tr>
<td>21</td>
<td>Dry-Bul Temperature</td>
<td>Monthly average outdoor air temperature</td>
</tr>
<tr>
<td>22</td>
<td>Diurnal Temperature</td>
<td>Monthly average daily temperature swing range</td>
</tr>
<tr>
<td>23</td>
<td>Monthly Average RH</td>
<td>Average of relative humidity</td>
</tr>
</tbody>
</table>

Building vintage was used to indicate the minimum requirements on building envelope and internal systems. Climate feature is one of the most significant factors in influencing the building energy performance. HDD and CDD are commonly used in calculations relating to the energy consumption for heating and cooling the building. Other climate factors including dry-bulb temperature, diurnal temperature and relative humidity were taken into consideration since they are important factors for establishing the indoor thermal comfort. Annual and monthly heating degree day and cooling degree day were collected from Degree Days.net, which is an online open source for worldwide weather data. Other weather data shown in the table were collected from the nearest weather stations from the online open source Weatherbase.com. Table 2 shows a sample dataset demonstrating the data organization of building monthly EUI and different attributes associated with façade and climate factors. All 32 groups of buildings data were organized in this format for future data mining.
Table 2: Sample Data Organization

<table>
<thead>
<tr>
<th>Month</th>
<th>BLDG 1</th>
<th>BLDG 2</th>
<th>BLDG 3</th>
<th>BLDG 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>3.163</td>
<td>215</td>
<td>71</td>
<td>58.8</td>
</tr>
<tr>
<td>Feb</td>
<td>2.857</td>
<td>150</td>
<td>131</td>
<td>60.1</td>
</tr>
<tr>
<td>Mar</td>
<td>3.226</td>
<td>147</td>
<td>62</td>
<td>61.2</td>
</tr>
<tr>
<td>Apr</td>
<td>3.224</td>
<td>93</td>
<td>111</td>
<td>63.8</td>
</tr>
<tr>
<td>May</td>
<td>3.730</td>
<td>70</td>
<td>71</td>
<td>64.3</td>
</tr>
<tr>
<td>Jun</td>
<td>3.824</td>
<td>23</td>
<td>228</td>
<td>77.7</td>
</tr>
<tr>
<td>Jul</td>
<td>4.134</td>
<td>63</td>
<td>339</td>
<td>82.3</td>
</tr>
<tr>
<td>Aug</td>
<td>4.694</td>
<td>71</td>
<td>313</td>
<td>83.1</td>
</tr>
<tr>
<td>Sep</td>
<td>3.666</td>
<td>12</td>
<td>264</td>
<td>80</td>
</tr>
<tr>
<td>Oct</td>
<td>4.026</td>
<td>44</td>
<td>169</td>
<td>73</td>
</tr>
<tr>
<td>Nov</td>
<td>3.101</td>
<td>197</td>
<td>79</td>
<td>64.9</td>
</tr>
<tr>
<td>Dec</td>
<td>3.025</td>
<td>334</td>
<td>33</td>
<td>60.5</td>
</tr>
<tr>
<td>Total</td>
<td>42.165</td>
<td>1330</td>
<td>1818</td>
<td>65.1</td>
</tr>
</tbody>
</table>

*Building long axis along with North to South is marked as 1, NE-SW is 2, E-W is 3, SE-NW is 4

2.2 Data mining and validation

Until now, there are numerous researches on data-driven building energy prediction model. Possible techniques include principal component analysis, multivariable regression, decision tree and artificial neural network (ANN).

Ruch and colleagues (1993) developed a data-driven method for estimating the daily electricity consumption in a commercial building by utilizing the principal component analysis to minimize the collinearity of the performance parameters and hence derive a more stable regression equation. Kalogirou et al (1997) applied the back propagation neural networks for estimating the heating load of buildings. In 2000, they conducted a research on application of artificial neural network on energy consumption prediction for passive solar buildings without mechanical systems for heating or cooling. Later, Ma et al (2010) derived a monthly energy consumption prediction model for large scale public buildings by integrating multiple linear regression. Yu, Haghighat and their research colleagues (2016) proposed a decision tree method for building energy demand estimation, which is a flowchart-like tree structure segregating a set of data into various predefined classes.

Figure 3: Possible Data Mining Techniques

In this research, two main data mining techniques were used including multivariable regression and artificial neural network to compare the result and accuracy, see Figure 3. Minitab and WEKA are two data mining tools used for multivariable regression and ANN separately. Minitab is a statistics package developed by the Pennsylvania State University. It contains a complete set of statistical tools including descriptive statistics, hypothesis tests, confidence intervals and normality tests, and could help uncover the internal relationships between variables and identify the important factors affecting the quality of the products and services (Minitab, 2016). WEKA is a collection of machine learning algorithms for data mining tasks. It can either be applied directly to a dataset or called from user's own Java code. It is a workbench contains a collection of visualization tools and algorithms and graphical user interfaces for data pre-processing, classification, regression, clustering, association rules. (WEKA The University of Waikato, 2016).

As an extension of simple linear regression, multivariable regression is a technique that estimates the relationship between several independent or predictor variables and a dependent or criterion variable (StatSoft, 2016). It is used to predict the value of a variable based on the value of two or more other variables. Stepwise regression is a dimension reduction measure to screen out the best combination of the predictor variables (façade & climate attributes) for predicting the dependent variable (EUI). Minitab stepwise regression feature can automatically outputs the most significant attributes by adding the most significant variable or removing the least significant variable during each
regression steps (Minitab 17 Support, 2017). In machine learning and cognitive science, an artificial neural network (ANN) is a network inspired by biological neural networks which is the central nervous systems of animals, in particular, the brain. Artificial neural network is commonly used to estimate or approximate functions that can depend on a large number of inputs that are generally unknown.

3.0 RESULT AND DISCUSSION
The 32-building dataset with 23 façade and climate attributes were firstly analyzed in Minitab for stepwise regression. Table 3 and Table 4 summarize the result and corresponding regression coefficient of the stepwise regression. According to the Minitab stepwise regression, HDD, dry-bulb temperature, south WWR, RH and façade area are five significant independents selected for the regression model to predict the site building EUI.

Table 3: Minitab’s Stepwise Regression Output & Coefficient Summary

<table>
<thead>
<tr>
<th>Term</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coef</td>
<td>P</td>
<td>Coef</td>
<td>P</td>
<td>Coef</td>
<td>Coef</td>
</tr>
<tr>
<td>Constant</td>
<td>0.897</td>
<td>-26.21</td>
<td>-28.49</td>
<td>-39.51</td>
<td>-43.68</td>
</tr>
<tr>
<td>HDD</td>
<td>0.028429</td>
<td>0.000</td>
<td>0.027461</td>
<td>0.000</td>
<td>0.027622</td>
</tr>
<tr>
<td>Dry-Bulb Temperature</td>
<td>0.3673</td>
<td>0.000</td>
<td>0.3839</td>
<td>0.000</td>
<td>0.3537</td>
</tr>
<tr>
<td>South WWR</td>
<td>0.139</td>
<td>0.000</td>
<td>0.1009</td>
<td>0.000</td>
<td>0.0932</td>
</tr>
<tr>
<td>RH</td>
<td>0.2159</td>
<td>0.000</td>
<td>0.3124</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Façade Area</td>
<td></td>
<td>0.000039</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Minitab's Stepwise Regression Output & Coefficient Summary

Table 4: Minitab's Stepwise Regression Output & Coefficient Summary

Minitab's stepwise regression can automatically output the most significant models. A good prediction model should have a small S value, a high R2, adjusted R2 and predicted R2 as well as a relatively small Mallows' Cp close to the number of the predictors. As can be seen from Table 3, the HDD has the largest R2 of 68.27%, which means it is the most dominant attribute for predicting the building site EUI. The S value of 5.48 shows the average distance the observed value fall from the regression line. The final model was highlighted in red with the R2 of 79.49%, representing the overall accountability. The output shows HDD, Dry-Bulb Temperature, South WWR, RH and Façade Area are five key attributes predicting building EUI. Normally, the attribute with the accountability (R2) less than 1 can be neglected. The standard error coefficient (SE Coeff) of the RH is the lowest, which means the model is capable of predicting the coefficient for RH with greater precision. VIF refers to the variance inflation factor for describing the multicollinearity, the larger the multicollinearity, the higher variance of the regression coefficient. With the lower VIF, the less correlation between each predictor. The VIF shown in Table 4 is low as no more than 2, which means a relatively stable prediction model.

However, the stepwise regression performed in Minitab shows a basic linear correlation between the building site EUI and corresponding building facade visual information and climatic factors. Artificial neural network (ANN) was also used to conduct the data mining for the original dataset and compare with the Minitab regression result for accuracy.
The algorithm of the ANN used in WEKA is the multilayer perceptron, which uses the backpropagation for classification. The dataset was divided into a large portion of training dataset for creating ANN and the remaining small portion of testing dataset for validating the accuracy. Figure 5 shows the interface of artificial neural network processed in WEKA data mining software.

Table 4: WEKA’s ANN Output Summary

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.9939</td>
</tr>
<tr>
<td>Mean absolute error</td>
<td>0.7325</td>
</tr>
<tr>
<td>Root mean squared error</td>
<td>1.4335</td>
</tr>
<tr>
<td>Relative absolute error</td>
<td>12.1756%</td>
</tr>
<tr>
<td>Root relative squared error</td>
<td>11.9319%</td>
</tr>
<tr>
<td>Total Number of Instances</td>
<td>416</td>
</tr>
</tbody>
</table>

It can be seen that the correlation coefficient is 0.9939, which implies 99.39% of the attributes in the dataset have been explained by the model. It can be considered as a perfectly correlated set of predictions. The relative absolute error shows the accuracy of the predicted model, which is within the common acceptable accuracy of 70% in the data mining field (Manaf et al., 2011).

Due to the limitations of time and resource accessibility, several research limitations, that may cause inaccuracy or error in the outcome, were addressed in this section. Limitations were mainly countered with the data collection process including the insufficient research database and inaccurate data inputs. The research database includes 32 buildings' energy consumption data, which may not be enough to establish a robust data-driven energy prediction model. Besides, all the buildings are education facilities, thus the variety of the building type is very limited, while more than half are classrooms with similar geometry. In this case, the model might be limited to a specified group of buildings and may not be applicable to other building types. In addition to building EUIs, most facade features were collected from building 3D models and some of them may require manual reading and estimate due to information inaccessibility. It is sometimes not accurate due to the subjective and cognitive influence. Building monthly EUIs were obtained based on the energy modeling program, weather files (epw.) were imported for simulation. However, climate data considered in this research were collected from the online open source, they might be inconsistent with the weather input to the energy modeling program. This may also contribute to inaccuracy of the predicted model.

4.0 CONCLUSION AND RECOMMENDATION

With more and more attention on urban sustainability, the large-scale building energy master plan with the comprehensive energy reduction strategies are essential today in meeting the energy reduction goal. To facilitate the building energy performance estimation process at the urban level, the facade visual information-driven benchmark performance model was introduced as a transformative approach to estimate energy performance. It is a fast and more accurate way to predict the energy use intensity in the schematic design stage and it will facilitate the energy consumption analysis of multiple buildings in the urban scale to establish the comprehensive energy master plan as well as establishing the EUI metrics and helping propose the feasible energy management strategy plans. For this paper, due to the limited time and sources, 32 buildings were analyzed at this stage. The research will be continuing all along with more groups of buildings for the data mining to develop a more robust benchmark performance model.
ACKNOWLEDGEMENTS

This study was made possible by the encouragement and dedication of many people. First and foremost, I would like to express my sincere gratitude and respect to Prof Joon-Ho Choi, for his infinite patience and supervision throughout the whole research process. Secondly, I would like to thank to Prof Douglas Noble, Prof Marc Schiler with their suggestions come from their rich experience in this academic field. I would like to give special thanks to Mr. Bharat Patel, who has been an excellent guide and a great source of inspiration of my work. Last but not least, I would also like to extend my appreciation to those who could not be mentioned but here supported as my backbones.

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US Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS), www.eia.gov/consumption/commercial


ABSTRACT: Buildings are large consumers of energy worldwide, responsible for roughly 40% of the world’s primary energy consumption. This paper analyzes the thermal performance of two passive roof construction technologies as a means of improving the indoor thermal conditions under summer conditions. Three identical Test Cell Structures (TCS) were constructed in eastern Kansas. All the TCSs were calibrated and two types of roofing technologies, Radiant Barrier (RB) and Phase Change Material (PCM) were individually applied to a TCS and their performance in terms of indoor air temperature reduction was compared. A one-way analysis of variance (ANOVA) was calculated for the study. The experimental results show that the thermal performance of RB obtained the best thermal improvement. TCS equipped with RB registered indoor air temperature 1.6 °C (2.9 °F) lower than the control test structure.

KEYWORDS: Thermal performance; Passive roofs, Energy; Test cell structures

INTRODUCTION

The issue of energy consumption in various sectors of life, especially in buildings, has become a fundamental concern for all countries. Buildings in most countries are responsible for large amounts of energy consumption, for both space cooling and heating. Undeniably, space cooling loads due to solar gains represent about half of the global space cooling loads for residential and non-residential buildings (Datta, 2001). Residential energy consumption represents a substantial proportion of total global energy consumption. The percentage of residential houses using air conditioning has increased, reaching 80% in 2000 attributed to the continuous rise in urban population and air temperature year after year (Aixing, 2002). The use of mechanical and electrical systems in buildings is necessary to ensure a suitable internal environment for the occupants, especially in the hot summer. Use of these systems has led to an increase in the rate of energy consumption in buildings.

The roof represents the most important component of the building envelope. It is highly subjected to solar radiation and other environmental modifications, and hence it influences the thermal performance of the buildings. Larger amounts of heat gain and loss are attributed to roofs, principally in buildings with large roof areas (Sadineni, Madala, & Boehm, 2011). The energy efficiency of a building depends on the thermal envelope, specifically the thermal behavior of roofs (Silva, Gomes, & Silva, 2016). Even though the building enclosure components are in contact with the environmental conditions, the roof experiences the highest temperature swings (Haider Mohamed, Chang, & Alshayeb, 2015). Heat gain through the roof is a major part of the space cooling load for a single–story building during the cooling season (Hosseini & Akbari, 2015). A study shows that indoor temperatures inside buildings are above comfort levels during the summer period due to the fact that 50% of the heat loads in the buildings come from the roof (Nahar, Sharma, & Purohit, 1999). The way that solar radiation is affecting space cooling load in buildings could be impacted by the properties of external and internal roof technologies (Kokogiannakis, Tuohy, & Darkwa, 2012). Therefore, controlling temperature gains, as a passive strategy, are required in most of the cases.

Several experimental studies have been carried out using passive roof technologies (Haider Mohamed & Chang, 2016). All these aim to reduce and/or control thermal gain through direct radiation. Among them are Radiant Barrier (RB) and Phase Change Material (PCM). The performance of these passive roof technologies has been individually investigated. Review of literature didn’t find any previous studies that looked at the aforementioned technologies under the same settings and conditions. This study intends to determine the most effective technique that will reduce the heat transmission via roof system. Consequently, the goal of this research is to put forward passive solutions that can contribute to increasing the thermal performance by minimizing indoor air temperature and heat gain. These technologies have received considerable attention because of their potential to reduce radiant heat transfer across vented spaces between roofs and ceilings of buildings (Haider Mohamed, Lee, & Chang, 2016). RBs consist of a highly reflective material that reflects radiant heat rather than absorbing it. Most often, RBs are aluminium foil laminates or metalized synthetic films sheets. A study showed that radiant barriers contribute to a reduction of heat transfer rate in attics when compared to attics without radiant barriers. The percent of reduction varied from approximately 6–7.7% (Haider Mohamed et al., 2015). (Asadi & Hassan, 2014) showed that RBs could reduce energy loads from 8% to 25% depending on the climatic conditions. Michels conducted an experiment measuring different samples and the results.
showed that a 70% reduction in heat flux to the inside of the residence on the day of higher solar radiation can be obtained by using RBs (Michels, Lamberts, & Güths, 2008).

PCM is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. PCMs are used on building interiors to reduce the absorption of solar energy. Reduced solar energy absorption results in lower interior temperatures and consequently, less heat flow across the building envelope, and reduced mechanical requirements to maintain air-conditioned space. PCMs represent an innovative and relatively inexpensive technique to reduce building energy requirements for space cooling (Cabeza et al., 2007). reported that the PCM can reduce the peak temperatures up to 1°C (1.8°F) as well as the electrical energy consumption was reduced by as much as 15%. An experiment was performed with a PCM roof panel compared to a reference room without the PCM panel. The results showed that the PCM panel on the roof narrowed the indoor air temperature swings, and better suit for all seasons (Pasupathy & Velraj, 2008).

1.0 Methodology
1.1. Experimental setup
This experimental study seeks to evaluate the thermal performance of two passive roof construction technologies as a means of improving the indoor thermal conditions under summer conditions. The study site, which was located at the Center for Design Research in Lawrence, Kansas, was selected for its orientation and unobstructed solar access as shown in (Fig. 1).

Figure 1: The identical test cell structures on site

Each TCS was 1.14 m (3.74 ft) x 1.14m (3.74 ft) x 1.42 m (4.65 ft) and faced south. All the TCSs were tested simultaneously under the same orientation and weather conditions. All sides are made of one layer of ISO 95⁺ GL Woodfiber Composite 0.05m (2 in) thick and two layers of Oriented Strand Board (OSB) 0.01m (0.4 in) thick. The external layer of OSB was finished with white paint. The roof assemblies were built of 0.1 m (4 in) thick cast concrete over the test structures, 0.01m (0.4 in) bitumen, 0.06m (2.36 in) clean soil and 0.05m (1.96 in) thick concrete tiles. The plan of the TCS is shown in (Fig. 2). The roof was slightly sloped for drainage. The roof was the only envelope parameter that changed among the TCSs.

Figure 2: Test cell structure section
1.2. Monitoring system
A 15 channel HOBO U30 data logger equipped with thermocouples was used for data acquisition. The thermocouples were installed in multiple locations of each TCS to monitor temperature. Data were recorded every 5 minutes and averaged hourly, which minimized the effects caused by sudden changes in outdoor and/or indoor conditions such as wind speed and passing clouds. The meteorological parameters (solar radiation, air temperature and relative humidity) were obtained with a weather station positioned near the TCSs. The external parameter registered by the system was the surface temperature of roofs. The locations of the sensors are presented in (Fig. 3) and the specifications of the sensors are shown in (Table 1).

![Figure 3: Sensor placement](image)

**Table 1: Manufacturer specifications for the loggers and sensors**

<table>
<thead>
<tr>
<th>Data Logger</th>
<th>Operating Range</th>
<th>Sensor Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset HOBO U30</td>
<td>-40 to 60°C (-40 to 140°F)</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Operating Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset S-TMB-M0X</td>
<td>-40°C to 100°C (-40°F to 212°F)</td>
<td>±0.2°C (±0.36°F)</td>
</tr>
<tr>
<td>Onset RH Smart</td>
<td>0-100% RH</td>
<td>±2.5% to ±3.5%</td>
</tr>
<tr>
<td>Onset Solar Radiation</td>
<td>0 to 1280 W/m²</td>
<td>±10 W/m²</td>
</tr>
<tr>
<td>Onset Wind Speed</td>
<td>0 to 76 m/s (0 to 170 mph)</td>
<td>±1.1 m/s (2.4 mph)</td>
</tr>
</tbody>
</table>

1.3. Calibration phase
Calibration tests were performed to verify the thermal performance of the experimental bed before applying any treatment. The calibration was initiated on July 17, 2015 at 12:00 a.m. and ended on August 1, 2015 at 11:55 p.m. The maximum recorded value of solar radiation was 918 W/m² (291 Btu/hr.ft²) and the maximum air temperature was 37.4°C (99.3°F). July 24, 2015 was selected as it had the highest maximum of ambient temperatures throughout the day, which represents the warmest day during this phase of the study, as shown in (Table 2).

**Table 2: Weather conditions for July 24, 2015**

<table>
<thead>
<tr>
<th>Solar Radiation W/m² (Btu/hr.ft²)</th>
<th>Ambient Temp. °C (°F)</th>
<th>Max °C (°F)</th>
<th>Min °C (°F)</th>
<th>ΔT °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>918 (291)</td>
<td>30.2 (86.4)</td>
<td>37.4 (99.3)</td>
<td>23.8 (74.8)</td>
<td>13.6 (24.5)</td>
</tr>
</tbody>
</table>

1.4. Retrofit phase
The local climate of the experimental site is generally hot and humid. Measurements were taken between August 6, 2015 at 12:00 am, and August 18, 2015 at 11:55 p.m. The preliminary results, under such conditions, indicated that the average temperature inside the STCs exceeds 25 °C (77 °F). The materials examined during this stage were applied only to the roofs, since the focus of this work was roofs. One TCS was kept as a Basecase (BC), control unit without any treatment,
and the proposed modifications were applied to the other TCSs. The passive modifications were introduced to the roof of the modified TCSs as follows:

- **Radiant Barrier (RB) underside the roof:**
  By placing a radiant barrier on the underside of the roof, thermal heat that conducts through the roofing material is reduced, hence, lowering the indoor temperature. Radiant Shield having thermal emittance of 0.03, which consists of two layers of aluminum foil laminated to a layer of woven polyethylene, was installed between the underside of the roof and above the roof ceiling, see (Fig. 4).

![Figure 4: Installation of radiant barrier (RB)](image)

- **Phase Change Material (PCM) over the ceiling**
  PCM works by increasing the thermal mass of a building, increasing the time it takes for the structure of a building to warm up or cool down. The melting temperatures of PCMs employed in building heat storage systems for passive heating and cooling vary starting from 17 °C (62.6 °F). This study used PCM with a melting temperature of 27 °C (80.6 °F) over the ceiling of the model under consideration based on the PCM manufacturer’s recommendation, see (Fig. 5).

![Figure 5: Installation of PCM](image)

The weather data showed the average ambient temperatures varying between 16.61 °C (61.89 °F) during the night and 34.36 °C (93.85 °F) during the day with an average of 25.67 °C (78.20 °F). That is, an average temperature difference of 17.76 °C (31.96 °F) between day and night was recorded. The maximum recorded value of solar radiation was 891.6 W/m² (282.6 Btu/hr.ft²). August 7th was one of the hottest days in the data collection period and was selected to evaluate peak influences of materials under investigation on indoor air temperature for all TCSs. More details for the weather condition are presented in Table 3.

<table>
<thead>
<tr>
<th>Solar Radiation (W/m² (Btu/hr.ft²))</th>
<th>Ambient Temp. °C (°F)</th>
<th>Max °C (°F)</th>
<th>Min °C (°F)</th>
<th>ΔT °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>875.6 (277.6)</td>
<td>27.7 (81.8)</td>
<td>34.4 (94)</td>
<td>21.8 (71.2)</td>
<td>12.6 (22.6)</td>
</tr>
</tbody>
</table>

### 2. Results and discussion

#### 2.1. Calibration phase

The thermal performance of the TCSs was compared and recorded as reference. The temperature inside all TCSs was continuously measured at the center of each TCS. The average value of all measurements was plotted against the time of day to show the nature of air temperature variation inside the TCSs. The indoor air temperatures were recorded as
shown in (Fig. 6). The recorded data showed that the indoor air temperature for all TCSs varying between 35.2 °C (95.3 °F) during the day and 22.7 °C (72.8 °F) during the night. That is, an average temperature difference of 12.5 °C (22.5 °F) between day and night was recorded.

**Figure 6:** Variations in the ambient temperatures inside TCSs

The pattern shows a constant difference in temperature for all the TCS. That means the average indoor air temperatures are close to each other. The comparison explains that indoor air temperature was considered identical and acceptable for all the TCSs since the maximum difference of 0.5 °C (0.9 °F) was recorded.

**Figure 7:** Average hourly indoor air temperatures recorded during July 25 measure period

The indoor air temperature for all TCSs plotted against ambient temperature are reported in (Fig. 7). The average indoor air temperatures were between 31.1°C (87.9°F) and 30.8°C (87.4°F). An average temperature difference of 0.3 °C (0.5 °F) between all indoor air temperatures for all TCSs was registered. A one-way analysis of variance (ANOVA) was conducted as a powerful statistical method using SPSS to evaluate and compare the relationship between the indoor air temperatures for all TCSs. The indoor air temperature was used as a dependent variable to evaluate the performance of each TCS and also to investigate whether there is a statistically significant difference between them. The omnibus hypothesis for our data of interest assume that there is no significant difference between the indoor air temperature means for the TCSs while the alternative assumes there is a significant difference. The ANOVA results showed that there is no statistically significant difference between indoor air temperature means for TCS1 (M= 31.1; SD= 2.5), TCS2 (M=30.9; SD= 2.4) and TCS3 (M= 30.8; SD= 2.4). The strength of the relationship, as assessed by $r^2$, was not strong, with the TCS factor accounting for 0.4% of the variance of the indoor air temperature.
2.2. Retrofit phase

2.2.1. Thermal performance of Radiant Barrier underside the roof (TCS2)

The variation of indoor air temperature inside the BC and indoor air temperature inside the TCS2 for August 7th are presented in (Fig. 8). The results indicate that application of a radiant barrier shield reduces radiant heat transfer across the space which it faces. The drop in the average air temperature inside the TCS2 as compared to the BC was 1°C (1.8°F). The maximum indoor air temperature of TCS2 was reduced by 1.6 °C (2.9 °F) as compared to the BC. The thermal performance of the TCS2 demonstrates that the average indoor air temperature is dependent on application of the Radiant Barrier Technology.

![Diurnal variations of indoor air temperature for BC and TCS2](image)

Figure 8: Average hourly indoor air temperatures recorded during August 7 measure period

The ANOVA outputs indicated a statistically insignificant difference between indoor air temperature means for BC (M=28.3; SD=2.3) and TCS2 (M=27.4; SD=1.9), F (1, 46) =2.4, p=0.1. The strength of the relationship, as assessed by n², was not strong, with the TSCs factor accounting for 5 % of the variance of the indoor air temperature.

2.2.2. Thermal performance of Phase Change Material over the ceiling (TCS3)

The variation of indoor air temperature inside the BC and indoor air temperature inside the TCS3 for August 7th are presented in Figure 9. As seen, the average indoor air temperature of TCS3 was reduced by only 0.9 °C (1.6 °F) compared to the BC. The maximum indoor air temperature of the TCS3 was 1.2 °C (2.2 °F) lower than that of the BC, while the minimum of the TCS3 was reduced by 0.5 (0.9). The ANOVA outputs reported that there is a statistically insignificant difference between indoor air temperature means for BC (M=28.4; SD=2.4) and TCS (M=27.5; SD=2.1), F (1, 46) =1.8, p=0.1. The strength of the relationship, as assessed by n², was not strong, with the TCSs factor accounting for 3.9% of the variance of the indoor air temperature.

![Diurnal variations of indoor air temperature for BC and TCS3](image)

Figure 9: Average hourly indoor air temperatures recorded during August 7 measure period
CONCLUSION
This paper analyzes the thermal performance of two passive roof construction technologies using three identical Test Cell Structures (TCSs) as a means of improving the indoor thermal conditions under summer conditions. All the TCSs were calibrated and two types of roofing technologies, Radiant Barrier (RB) and Phase Change Material (PCM) were individually applied to a TCS and their performance in terms of indoor air temperature reduction were compared. The thermal performance of the radiant barrier was 1°C (1.8°F) lower than the indoor air temperature for the BC. The phase change material showed only 0.9 °C (1.6 °F) reduction in indoor air temperature. A general conclusion is that the investigated technologies can be arranged in descending order according to their performance as radiant barrier and then phase change material. This study arises from the need to put forward passive solutions that can contribute to reducing energy use and improving building thermal performance by minimizing indoor air temperature and heat gain.

REFERENCES


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DEVELOPMENT OF STUDENT SATISFACTION SURVEY TOOL TO EVALUATE LIVING-LEARNING RESIDENCE HALL

Sharmin Kader
TreanorHL, Lawrence, Kansas

ABSTRACT: Post-occupancy evaluation (POE) is becoming increasingly significant for continuous improvement in designing and operating any building facilities. As user’s satisfaction is a significant indicator (Zimring, 1990), development of a valid and reliable data collection instrument is one of the important actions for a successful POE (Federal Facilities Council, 2001). Today’s trend of building residence hall incorporating living-learning programs is increasing to achieve better student success in social and academic life. These new concepts are resulting in the creation of innovative design ideas and new space requirements (e.g., maker’s space, innovation lab). To assess the residents’ satisfaction about their college housing environment, various authors had focused on various objectives and parameters (Davis & Roizen, 1970; Foubert et al., 1998; Kaya & Erkip, 2001; Amole, 2005; Hassanain, 2008; Amole, 2009; Dhalan et al., 2009; Khoeaizi et al., 2010; Najib et al., 2011; and the EBI survey tool). Among all, Najib et al. (2011) in Malaysia focused on physical and social variables combining some parameters mentioned by other authors, but the tool needs more modification to accommodate today’s living-learning residence hall design in the United States. The EBI tool mostly focuses on student affair program, not architectural design. The need to develop a new student survey tool is evident, considering the environmental dimensions and architectural determinants. This study followed several methods while developing this survey tool. First, analyzed previously developed tools and scales for student housing to obtain the initial pool of questionnaire items. Second, reviewing several newly constructed projects’ Program of Requirements to modify this list. Third, conducted a post-occupancy evaluation in a 648 beds living-learning center considering the initial questionnaire items. Fourth, the instrument was further modified (based on the feedback from the POE). This tool has developed for the undergraduate student residence hall and it carries a great significance to the architects and to the university housing professionals.

KEYWORDS: Post-Occupancy Evaluation, Residence Hall, Student Satisfaction, Survey, Living-Learning

INTRODUCTION

In 1965, Harold C. Riker, one of the pioneering residential educators, explicitly pointed out that residential life can be intentionally designed to enrich students’ academic learning and personal development. Since the 1970s, the housing professionals started to develop a more intentional approach to residential education, guided by principles of student intellectual, moral, and psycho-social development theories (e.g., Kohlberg, 1969; Perry, 1970). By the 1990s, the idea of transforming conventional residence halls into living-learning centers captured the interest of institutional leaders (Blimeking, 1993). New evidence generated by empirical research (Schroeder, Mable, & Associates, 1994; Terenzini & Pascarella, 1994) highlighted the need to design environments where students can integrate classroom-based and out-of-class learning and can meaningfully interact with peers and faculty. Today’s college students demand a different type of housing than has traditionally been offered on university campuses (Argon, 2003; and Blimeking, 1993). Many students today who have rarely shared a bedroom or even a bathroom with a family member, seek increased levels of privacy and more amenities than ever before in their residence halls (Kellogg, 2001). In a 1995 qualitative study of housing administrators, the issue of lack of privacy was the most consistent student concern noted by administrators (Banning, McGuire & Stegman, 1995). Considering these demands, in recent years, the living-learning center design has produced a variety of trends; such as, a shift from corridor-style to suite-style housing (Agron, 2003), the building of luxurious residence halls (Macintyre, 2003, p. 110). Overall, student housing has shown itself to be a lucrative and growing business for universities. The exponential growth in the postsecondary population suggests that the need for student housing is likely to increase in coming years.

Post-occupancy evaluation (POE) is becoming increasingly significant for continuous improvement in designing and operating any building facilities. Although POE has not been in the forefront for several decades, in recent years, the interest is reviving and demanding further research endeavors to enhance POE methods. User satisfaction is a significant indicator, which is explained in Zimring’s (1990) definition of POE, “the examination of the effectiveness of designed environments for human users.” Developing a valid and reliable data collection instrument is one of the important actions for a successful POE (Federal Facilities Council, 2001). There are few student satisfaction survey tools have been developed by many researcher since the 1970s, but those tools are suitable to assess the traditional style residence hall. These tools need further modification to accommodate today’s living-learning residence hall designs.
in the United States, which incorporates the living-learning programs to achieve student involvement and success in academic and social life. New space requirements and innovative design ideas are evolving to accommodate this living-learning program in the residence halls, such as innovation lab, media room, music practice rooms, classrooms, etc. The need to develop a new student survey tool is evident, considering the environmental dimensions and architectural determinants mentioned above (e.g., social interaction, community involvement, academic success, common spaces utilization rates). This study has focused on developing a tool to survey user's satisfaction for the undergraduate student residence halls.

RESEARCH METHODS
To develop a survey tool, this study has considered several methods. First, it considered a literature search in multiple databases to identify and analyze of previously developed tools and assessment-scales to obtain the initial pool of questionnaire items (those literatures are discussed in the next section). Second, reviewing several newly constructed projects' Program of Requirements to modify this list. Third, a post-occupancy evaluation had conducted in a 648 beds living-learning center considering the initial questionnaire items. The instrument was further modified based on the feedbacks from the POE. The POE has considered a mixed method (quantitative and qualitative research) of data collection. This POE study is Institutional Review Board (IRB) approved. Data had collected using four methods.

1. **Student Satisfaction Survey**: An online survey was conducted using the initial pool of questionnaire inviting all the residents. The response rate was 32%. The survey started on April 26, 2016 and continued till May 31, 2016. The questionnaire was designed with 70 questions, and it took average 9 minutes to answer the questions.

2. **Observation by the Researcher**: Walk-through observation of the facility by the research for 5 times a day for 7 days during spring semester of 2016.

3. **Focus-group Interviews with Stakeholders**: Focus-group interviews with eleven stakeholders group was conducted: Custodial/Facilities Services; Transportation Services; UPD/Security/EHS; Housing Assignments, Conferences, Tours; ResLife CAO; University Energy Service; Res Ed-Hullabaloo Staff; Academic Partners/ASI Staff DRL; Telecom & Computing Info; Dining service; and student leaders of the campus. These stakeholders were involved to develop this project's goal and programming. They were asked mostly three questions: How successful is the project to fulfill the mission statement and goals? What are the positive feedback? What are the areas of improvement? Some meeting was twenty minutes long, and some lasted for more than one hour.

4. **Individual Interviews**: The research interviewed the students and resident assistants (RAs). Face-to-face interviews was conducted with students of each type of room layout (four different types of rooms) and eight RAs out of total sixteen. All the interviews were conducted face-to-face and were audio recorded.

LITERATURE REVIEW
To assess the residence satisfaction about their housing environment, various authors had focused on various objectives and parameters. In 1970, Davis & Roizen suggested 25 items as the architectural determinants of student satisfaction (hominess, privacy, storage space, size, quietness, etc.). In 1998, Fouhert et al. suggested: high-quality facilities, positive roommates’ relationship, strong floor, community and quiet study environment; in 2001, Kaya & Erkip propose: room size and crowding; in 2003, Amole Nigeria) considered: level of crowding and privacy; in 2008, Hassanain (Saudi Arabia) focused: thermal comfort, room layout and furniture; in 2009, Amole again proposed: characteristics of residence halls, rules, fees and attitude of hostels’ employee; in the same year, Dhalan et al. recommended: thermal comfort in non-air-conditioned rooms; and in 2010, Khoozai et al. (Malaysia) suggested: students’ attachment to housing. The Association of College Unions International (ACUI) has developed a student assessment tool focusing on student affairs program, the Educational Benchmarking Inc. (EBI) survey tool. This tool is utilizing to assess students’ satisfaction, but a very little part of this tool considered architectural design. In 2011, Najib et al. (Malaysia) developed a survey instrument focusing on physical and social variables combining some above-mentioned parameters. Though Najib and his colleague's approach were more comprehensive, but this tool needs more modification to accommodate today's living-learning residence hall design in the United States. Today's trend of building residence hall incorporating living-learning programs is increasing significantly to achieve better success in students' social and academic life. These new concepts are resulting in the creation of innovative design ideas and new space requirements such as maker's space, community learning center, computer lab, music practice room, lecture halls, classrooms, tutoring spaces, etc.

LIVING-LEARNING CENTER DESIGN
As discussed earlier, Universities are designing residence halls with mainly two objectives: to blend academics with living spaces and to foster a sense of community on campus. To compete for students with off-campus housing, today's residence halls are designed with more privacy in accommodation and more vibrant common areas that support academic and social life. According to David J Neuman (2013), student housing needs to provide choices of community on a sliding scale to respond student social needs during undergraduate years. "A worthy rule might be that the better the housing as a place, the more scales and kinds of community it can sustain" (Newman, 2013, p.222). The residence halls are most commonly organized as a “social plaid” of hierarchical groupings: sharing room by two students, sharing a floor or wing up to thirty students, and 100 students per ground floor lounge.
Student bed-room is the basic component for living in a residence hall. It is the basic unit planning is the single or double occupancy room. Some authors call it "study-bedroom" because of its multi-purpose use for study, living, and sleeping (Amole, 2005; Hassanain, 2008; Oladiran, 2013). Today, a residence hall design considers several other new emerging factors such as sustainability. Today's buildings are designing with energy efficient considerations and it also provide education and encouragement to students for adopting sustainable living. Each residence hall project designs with some significant common goals: to support student academic success, to create a sense of community, to improve student social interaction and campus involvement, increase utilization rate, to increase student retention. Therefore, the student satisfaction survey tool needs to address the questions to measure the overall outcome of a residence hall regarding these objectives.

**EVALUATION TOOL**

As discussed earlier, a student satisfaction survey tool was developed through a research process. This tool has discussed very briefly in the following sections. Each section will briefly introduce the design criteria and evaluation criteria about each area such as bathroom.

**Room or Suite:** Most study-bedrooms are designed to accommodate two people in a single room, or two to four students in a suite. The standard room size for residence halls is approximately 100 sq ft per bed (Newman, 2013). From the POE, it found that Room ceiling height plays a significant role to overcome the claustrophobia that might come with eight-or-nine foot ceilings, also it allows the beds to be elevated to create enough room for storage below the beds, or overhead storage area. The minimum furnishings for each student are a single bed, a small desk and chair, and a closet or wardrobes to built-in closets. The students want to have enough room to move furnishings around from time to time. To allow that flexibility, sometimes rooms are designed in combination with bunk beds or a system that allows a bed to be stacked over desk. The residence hall personalization programs which allow students to paint and decorate their rooms are significant to achieve student territorial behavior and other positive behaviors (e.g., increase retention rate, lessen damage to public areas, increase cohesiveness among students). In the POE, student mentioned about the significance of having a nice view, enough storage space, furniture quality, and privacy. There are several types of arrangements. According to Neuman (2015), the most common types are:

"Rooms on a path": Rooms are arranged along a double-loaded corridor with up to 20-24 beds per length of hallway, typically for first and second year students. These group of rooms typically shared a central bathroom and a common lounge. Bathrooms may also be distributed separately as a series of single-fixture rooms shared by the hall.

**Two-rooms suites:** Two single-occupancy rooms may be adjoined and share a bathroom. The adjoining rooms allow students the opinion of using one room for sleeping and other as a study or lounge, or use each as a single-occupancy, usually call semi-private suite.

**Larger suites:** For upper-class, two to four room suites address their desire for greater privacy and choice of roommates. Each suite may have a small living area, a single bathroom, and two double-occupancy rooms or up to four single-occupancy rooms and two bathrooms. Larger combinations may be created by adjoining the living areas of two suites to form a “house,” possibly with a shared kitchen.

**Mix Room Styles:** The new design trend encourages to mix in suite-style housing with more traditional single and double rooms in each residential college.

<table>
<thead>
<tr>
<th>Evaluation Criteria of Room/suite</th>
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<tr>
<td><strong>Size</strong></td>
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<tr>
<td>Interior design (color, finishes, fixtures)</td>
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<tr>
<td><strong>Layout – arrangement of foyer, bath and room(s)</strong></td>
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<tr>
<td>Privacy</td>
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<tr>
<td><strong>Provided amenities</strong></td>
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<tr>
<td>Noise control</td>
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<tr>
<td><strong>Window – size, location, and outside view</strong></td>
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<tr>
<td>Room temperature/thermal comfort</td>
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<tr>
<td><strong>Amount of daylight</strong></td>
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<tr>
<td>Security of property</td>
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<tr>
<td><strong>Quality of artificial lightings</strong></td>
</tr>
<tr>
<td>Scope for personalization</td>
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<tr>
<td><strong>Wi-Fi and phone connection</strong></td>
</tr>
<tr>
<td>Comfort in sleeping and resting</td>
</tr>
<tr>
<td><strong>Furniture quality (aesthetics, durability, comfort, etc.)</strong></td>
</tr>
<tr>
<td>Comfort in studying</td>
</tr>
<tr>
<td><strong>Number of furniture</strong></td>
</tr>
<tr>
<td>Comfort in entertaining friends</td>
</tr>
<tr>
<td><strong>Flexibility in arranging furniture</strong></td>
</tr>
<tr>
<td>Helps create positive roommate relationship</td>
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</tbody>
</table>
Bathroom: The bathroom must be provided in student housing so that it can serve two adjacent double bedrooms or a common bathroom can serve a set of four or five bedrooms. The changing dynamics of the residence hall bathroom is to provide safe and equitable facilities for transgender and nongender-identified students which reflect institutional values of inclusion and community. More than 200 U.S. colleges and universities now offer some form of gender-neutral, or all-gender, bathrooms and/or housing on campus. From the POE, there are several criteria have evolved:

<table>
<thead>
<tr>
<th>Evaluation Criteria of Bathroom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of bathroom</td>
</tr>
<tr>
<td>Number of people sharing the bathroom</td>
</tr>
<tr>
<td>Layout (arrangement of sink, shower &amp; toilet)</td>
</tr>
<tr>
<td>Shelves for toiletries</td>
</tr>
<tr>
<td>Fixtures and finishes</td>
</tr>
<tr>
<td>Heat lamps</td>
</tr>
<tr>
<td>Ventilation</td>
</tr>
<tr>
<td>Privacy</td>
</tr>
<tr>
<td>Lighting</td>
</tr>
<tr>
<td>Door signage system helps to understand occupancy</td>
</tr>
<tr>
<td>Temperature/thermal comfort</td>
</tr>
<tr>
<td>Positive communication with your floor mates in the bathroom [if common bathroom]</td>
</tr>
</tbody>
</table>

Common Areas: Common areas in residential hall plays a vital role in creating a better community and becoming a place for students to release their stress with peers. Today, residential housing projects are offering a variety of common areas: lounges, seminar rooms, game rooms, and other socially oriented amenities, such as nooks with seating arrangements. Advances in technology are energizing the design of common areas in residence halls. Mobile computing and Wi-Fi connectivity make every space a potential study nook therefore the study areas no longer require lots of desks or tables, comfortable sofas and chairs are taking place. Some provides innovative common areas to enrich learning experiences. Classrooms and multipurpose rooms with movable furniture and partitions are desirable features in some residence halls for academic support. According to Neuman (2013), the essential planning principal for shared spaces (facilities) is hierarchy: “that is, spaces for special activities are located according to their function along the path from the building entry to the individual rooms or suites. The most unique facilities are placed at or near the entry to the building or at the center of the complex. The more repeated facilities are closer to the rooms” (p.226).

Floor Common Area: As Najib and his colleagues (2011) mentioned, after room and bathroom, the floor common areas are important. The basic kit of the residence hall includes multi-use lounges for study and social contact. Each cluster of bed-rooms will benefit from at least 10-15 sq ft of lounge area per bed – particularly where rooms are mainly double occupancy. Larger lounges provide more active space; smaller ones offer quite retreats for late–night work. Such spaces can also function as the hinge between floors or corridor suites. Smaller workrooms can be distributed as hideaways or clustered to bring together. Laundry and kitchen facilities also promote community, linking separate suites and groups by bringing students upstairs or down and inviting interaction. As with other factors, entering freshman may benefit from larger facilities shared by more neighbors, and returning undergraduates may prefer the greater privacy and convenience of smaller, more distributed facilities. Shared kitchen is typically equipped like residential kitchens, with additional care for durable finishes. Launderies serving larger numbers of students are treated and equipped like commercial laundromats (and may be operated by commercial firms), but benefit from additional space for seating, television viewing, and conversation (Neuman, 2013). Laundry rooms have become a popular requirement in student housing and should be large enough to accommodate enough washer and dryer, and also recreational facilities for students (Najib et al., 2011). Hallways are possibly the most social spaces in any residence scheme and should be laid out with some variation in width to allow places for spontaneous conversation. At intervals, or at the ends, natural light is extremely valuable, even as borrowed light from lounge/study rooms and stairways. Some articulation at entries to bathrooms and even student rooms allows for an important sense of threshold (Neuman, 2013). From the POE, there are several factors revealed, such as location of Resident Assistant (RA) room, trash room, distance from room to circulation.
<table>
<thead>
<tr>
<th>Provided amenities</th>
<th>Room temperature/thermal comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window view</td>
<td>Wi-Fi and cell phone connection</td>
</tr>
<tr>
<td>Amount of daylight</td>
<td>Comfort in Group Study</td>
</tr>
<tr>
<td>Quality of artificial lightings</td>
<td>Comfort in Individual Study</td>
</tr>
<tr>
<td>Furniture quality (aesthetics, durability, comfort, etc.)</td>
<td>Comfort in socializing/gathering</td>
</tr>
<tr>
<td>Number of furniture</td>
<td>Comfort in relaxing</td>
</tr>
<tr>
<td>Flexibility in arranging furniture</td>
<td>Helps to organize social event</td>
</tr>
<tr>
<td>Comfort in cooking at the kitchenette</td>
<td>Helps create floor community among students</td>
</tr>
<tr>
<td>Ventilation in kitchen</td>
<td></td>
</tr>
</tbody>
</table>

**Evaluation Criteria of Wing Study Area**

<table>
<thead>
<tr>
<th>Location</th>
<th>Interior design (color, finishes, fixtures)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Privacy</td>
</tr>
<tr>
<td>Layout and furniture arrangement</td>
<td>Noise control</td>
</tr>
<tr>
<td>Provided amenities</td>
<td>Room temperature/thermal comfort</td>
</tr>
<tr>
<td>Amount of daylight</td>
<td>Wi-Fi and cell phone connection</td>
</tr>
<tr>
<td>Quality of artificial lightings</td>
<td>Interior design (furniture, color, finishes, fixtures)</td>
</tr>
<tr>
<td>Number of furniture</td>
<td>Comfort in Group Study</td>
</tr>
<tr>
<td>Furniture quality -flexibility in arranging furniture</td>
<td>Comfort in individual study</td>
</tr>
</tbody>
</table>

**Ground Floor Common Areas**: As mentioned by Neuman (2013), the most unique facilities are placed at or near the entry to the building or at the center of the complex. In today's living learning residence hall, the ground floor work as a community village which accommodates all the unique social and academic areas, such as game room, multi-purpose classroom. Some residence halls are incorporating some retail stores and restaurants. The case-study hall of this study has created the ground with various social and academic amenities and provided access to other students along with the residents. The unique areas are: a Starbucks coffee shop, a convenience store, a music practice room, a media room, a multi-purpose recreational room or game room, a multipurpose academic room, called Community Learning Center (CLC), which employs an open office design concept. The space has individual and group study areas and is equipped with high-end computers with access to special engineering programs and other expensive software that most students can't afford. Lobby area should have an informal and intimate atmosphere so that students feel comfortable entertaining parents or guests (Najib et al., 2011; Bland and Schoenauer, 1966; Ibrahim et al., 2010). The lobby may also be used as a reading area and social activities. In addition to exit stairs, open stairs linking lounges can enhance social life. At least one stair and/or elevator should provide additional width for moving furniture and for emergency/disabled access (Neuman, 2013).

**Front Lobby**

<table>
<thead>
<tr>
<th>Easily accessible and welcoming entrance</th>
<th>Community art to represent college identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Branding</td>
</tr>
<tr>
<td>Size and number of seating arrangements</td>
<td>Provided amenities</td>
</tr>
<tr>
<td>Layout, arrangement, Openness</td>
<td>Arrangement</td>
</tr>
<tr>
<td>Interior Design (attractive appearance and</td>
<td>Meeting and entertaining guests</td>
</tr>
<tr>
<td>Ensure security or filtering others</td>
<td>Aesthetic/ appearance</td>
</tr>
<tr>
<td>Convenient location of the front desk</td>
<td>Public accessible restroom</td>
</tr>
<tr>
<td>Scope for entertainment (vending machine or access to retails or TV-lounge, etc.)</td>
<td></td>
</tr>
</tbody>
</table>
**Evaluation Criteria of Ground floor community areas**

| Main lobby and reception area | Game room |
| Media room | Mail boxes and parcel area |
| Multipurpose room | Outdoor gathering spaces |
| Specialty rooms | |

* Each space or area has its unique requirement for evaluation. But there are some common criteria for each space. Due to space limitations, only the following three have presented.

### Innovation Centre / Makers Space

| Size | Access to daylight and views |
| Provided amenities | Number of maker board, roller shades, |
| Number of furniture and equipment | Media centre/modelling/Fabrication |
| Interior design (color, finishes, etc.) | Number of working desk |
| Acoustic design (noise control in both ways) | Visual connection with other spaces |
| Technology | Fabrication space |
| Lighting | Card access doors |

### Retail centre (Convenience store/ Coffee shop)

| Location and access | Size |
| Acoustic/ Sound attenuation | Number of equipment and technology |
| Arrangement | Visual connection |
| Provided amenities | Comfort in practice |
| Easy accessibility | Comfort in group practice |
| Price of the food/item | Acoustic/ Sound attenuation |
| List of available Items | Provided amenities |

### Music room

### Site planning and building Entrance:

Site planning and building accessibility is a significant one. From the literature review, stakeholders meeting and students feedback, there are some points found significant: pedestrian, bicycle, and vehicular access, “moving day” access with temporary vehicular use of main pedestrian paths; bicycle parking on most campuses is a great challenge, accommodating large numbers of bikes as close as possible to building entrances; security establishes clear visibility along paths into and out of the buildings and site; organizes residents’ windows to overlook public areas; activities ground-floor building edges with views into and out of public rooms; placement of dining and other shared social activities to “capture the energy” campus or to energize the center of a large complex.

### Accessibility and parking

| Number of parking | Easily accessible entrance |
| Bicycle parking area (number and location) | Convenience to move-in and move-out |
| Auto Parking area | Safety and security |
| Site and Context | Exterior appearance and aesthetics |

### Outcome Measures:

It is significant to measure the student self-reported evaluation about their academic success, social involvement, space utilization, sense of community, and retention. Questions related to measure these outcomes are as follows:
Academic Success

This hall provides environment and opportunity to feel like home.

This hall provides enough facilities & amenities to create a living-learning community.

How satisfied are you with your GPA? □ Doesn't meet expectation □ meets expectations □ exceeds expectations

How important is it to you to feel supported academically by Residence Life? Please rate below.

<table>
<thead>
<tr>
<th>Less</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Very</th>
</tr>
</thead>
</table>

Social Success

Students of this hall have a sense of community.

Students of this hall socially interact with each other.

Students are frequently participating in the social activities (play game, watch TV, etc.).

How much do you socially interact with other students from the same wing? (write number)

□ You know name & talked once with ______ person □ You say “Hi” frequently of ________ person
□ You hangout frequently with ________ person □ You study together with ________ person

Utilization Rate

Please answer the following questions based on your activity:

<table>
<thead>
<tr>
<th>Never</th>
<th>Once a month</th>
<th>Once a week</th>
<th>2 - 4 times a week</th>
<th>Almost daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

How often do you use the community lounge in your floor?

How often do you use the study room in your floor?

How often do you use the main floor community Amenities?

How frequent do you spend time with other students from this hall?

How frequent do you group study with other students in this hall?

How often do you invite other students for study or socialization?

How often do you group-study in the lounge/study room?

Overall Success (How satisfy with the following statement)

Overall functions and amenities of this hall supports students' personal, social & academic success.

Please Provide your comments:

Why did you choose this Hall when applying for on-campus housing? [Question about retention]

Are you considering living in this residence hall next year? Why or why not? [Question about retention]

Please provide any other opinion or suggestions.

EXPECTED OUTCOMES

The study has developed a satisfaction survey tool for student housing. It provides a standardized tool for the user's evaluation about the physical environment, functional or social environment, and utilization rate. This tool articulate student opinions about their physical setting in three levels. Fixed or structural features include those which are permanent architectural elements, such as building layout or location of window. Semi-fixed features include less
permanent architectural elements (presence or absence of handrails, or finish materials). Non-fixed features include the presence of wall hangings, activity supplies, and others. The anticipated outcomes of this tool are:

- The users’ satisfaction rate of this newly designed residence hall will provide information to develop a design guideline for architects and interior designer for applying design skills more effectively.
- The findings will improve commissioning process by defining students’ requirements about their living learning environments.
- It will improve the management procedures by providing knowledge about operation and refurbishment.
- It also carries values in future research on students housing environments.

**SIGNIFICANCE**
This research was evaluating a student housing design to develop better guidelines for architects and to provide feedback about the existing condition of the housing to the administrator for further improvement. These will benefit the greater audience: students, professional architect, and residence hall administrator. It also carries significance for future research for these disciplines. So, as a member of broad society the students will be benefited.

**Architectural Practice.** This tool carries the same significance as any post occupancy evaluation tool does in architectural practice; which is defined by the Royal Institute of British Architects Research Steering Group as “a systematic study of buildings in use to provide architects with information about the performance of their designs and building owners and users with guidelines to achieve the best out of what they already have” (RIBA, 1991). More anthropologically it was defined by Friedmann (1978) as “an appraisal of the degree to which a designed setting satisfies and supports explicit and implicitly human needs and values of those for whom a building is designed”. This tool can be used as evidence of the effectiveness or the weakness of design decisions in relation to student with their living-learning environments. So, the plausible benefits of this tool also include: applying design skills more effectively; improving the building commissioning process; improving user requirements; providing knowledge for design guides; and targeting of refurbishment (Whyte & Gann, 2001). The study findings contribute to evidence-based design (EBD) research and practice (Diaz Moore & Geboy, 2010). The evaluation criteria can be used to determine project goals and the tool can be used to measure the baseline performance and the post occupancy performance results.

**Residence-life profession.** As mentioned earlier, this tool assesses the living-learning environment in global context: physical setting, social environment, utilization rate, self-reported outcome such as GPA, or academic success. This tool will provide valuable information to support the goal of continuous improvement of any student housing facility (Zimmerman & Martin, 2001) and also be utilized for improving organizational policy and facility management (Green and Moss, 1998; and Whyte & Gann, 2001).

**CONCLUSION**
This tool has developed as an initial effort. The study has limitations which need further research. This study needs to consider experts’ opinion (architects and housing professionals) and further field testing to validate and modify these list of evaluation criteria. Also, it needs further quantification of each criteria to support these findings and to determine the weightage of each criteria. Although, this tool has developed to use in undergraduate student housing so it is not generalizable for other types of student housing, it can be work as opening template to develop others.

**REFERENCES**


Rutledge, K. (2012). The influence of residence hall design on college students' grade point averages, on-campus involvement, and sense of community.


ABSTRACT: Often for historic buildings air infiltration and thermal resistance values for the envelope are not well known and can significantly influence accuracy of building energy simulations as well as the actual energy performance of a building. This paper will detail some of the methods used in a funded research project to improve energy modeling for historic buildings using low cost preliminary verification methods. By using in-situ non-destructive testing methods to measure heat flux and surface temperatures more accurate thermal resistance values were determined for two buildings. By using door blower pressurization tests the air tightness of both buildings were measured allowing for a more accurate understanding of air infiltration rates. By using these field derived parameters building energy simulations with calibrated input parameters were created and compared with baselines (using standard assumptions for materials and air infiltration) to study the significance of preliminary verification methods on the predictive nature and accuracy of building energy simulations for historic buildings. Using this method of modeling coupled with field testing should improve confidence and accuracy in future building energy simulations for historic buildings and ultimately help provide more meaningful energy data in the decision-making process for owners and operators of historic buildings.

KEYWORDS: historic buildings, energy modeling, heat flux, in-situ testing, air tightness

1.0 INTRODUCTION
1.1 Modeling and Simulation
The nouns modeling and simulation are often used interchangeably in architectural discussions regarding the analysis of energy flows of buildings. In this paper, modeling activities and simulation processes will be divided into two separate categories related to energy analysis of buildings. Modeling will refer to the activity of gathering building characterization and other input parameters used in building energy analysis. Modeling often includes the definition of geometry, orientation, material properties and climate data. The term simulation will refer to the physics-based analysis of past or future energy flows for buildings. Energy simulation is usually governed by numerical techniques regarding mass and energy balances. Energy consumption in buildings is often dominated by energy used by mechanical systems to condition the interior space for thermal comfort. This research focused on improving understanding and accuracy of modeling parameters that impact energy consumption for heating, ventilation and air conditioning (HVAC) systems by improving characterization of the building envelope used in building energy simulations. While the research project involved the creation of detailed building energy simulations including internal gains, occupancy schedules, HVAC systems and local microclimate parameters, this paper focuses on the preliminary verification techniques used to improve input parameters for building energy simulations of historic buildings.

1.2 Unique Considerations for Historic Buildings
The analysis methods and building physics equations that are used in most building energy simulation software are generally based on one-dimensional heat transfer analysis (IESVE, eQuest and DOE 2.2 all are based on 1-D heat transfer) and the same analytical techniques are used in both existing and new construction. The simulation process however is heavily dependent on the modeling inputs. For historic buildings, a significant concern is collecting meaningfully accurate characterization data. Although characterization is an important issue for all building energy simulations, it often is more of an issue for historic buildings due to two issues. The first is that historic buildings that were built before modern insulation materials tend to have low thermal resistance values (such as R-values less than 5 h·ft²·°F/Btu) and consequently small absolute inaccuracies in characterization can have a large relative influence in simulated performance. For example, if a wall assembly has a relatively high resistance value of 20 h·ft²·°F/Btu and the amount of inaccuracy is ± 1 h·ft²·°F/Btu. This is within 5% and most likely will have only a small impact on the overall energy simulation results. For a wall assembly with a relatively low resistance value of 3 h·ft²·°F/Btu, an inaccuracy of ± 1 h·ft²·°F/Btu would be an inaccuracy of ± 33% and could have a large impact on the overall energy simulation results. The second issue is that many historic buildings utilize envelope material assemblies that are non-uniform or have been significantly altered over time. This is of concern because assembly and material uniformity are often assumed when performing building energy simulations.
2.0 Methodology

2.1 Equipment

This research was funded by a grant from the National Center for Preservation Technology and Training. The following equipment was purchased through these funds and used for collecting thermal data.

1. FLIR E6 thermal IR camera with 160x120 resolution, $1,262.00
2. Hukseflux HFP01-05 heat flux plate (used with the Omega datalogger), $640.00
3. (8) Standard k-type thermocouples (used with the Omega and Amprobe dataloggers)
4. Omega Engineering, OM-DAQLINK-TEMPRH hand held datalogger, $506.00
5. (2) Amprobe TMD-56 Multi-logger Thermometer, $109.84
6. REED Temperature & Humidity Datalogger model ST-171, $77.42
7. Extech RHT10 Humidity and Temperature Datalogger, $70.84
8. Davis Instruments 6250 Vantage Vue Wireless Station, $665

2.2 Energy Models

The equipment was used to perform in-situ non-destructive testing of building envelopes to measure thermal properties. The two buildings that were studied in this research project are Roxboro House on Philadelphia University’s campus and the RittenhouseTown Homestead in Fairmount Park (both in Philadelphia, PA). These two buildings were selected for the research since they are both historically registered buildings and either have their original envelope assemblies or have been reconstructed and restored to the original assemblies. Energy models were developed for Roxboro House and RittenhouseTown Homestead using IES Virtual Environment 2014. Baseline and in-situ energy models were created for each building. The baseline model is composed of building properties based on physical surveys and existing drawings. The in-situ model uses properties derived from in-situ testing.

![Virtual representation of Roxboro House in IESVE]

![Virtual representation of RittenhouseTown Homestead in IESVE]

2.3 Basic Parameters

In building energy simulation, the basic information to collect for input are (1) the material thermal properties (conductance and resistance) of the building envelope, (2) the air exchange rate, (3) the internal gains and (4) the climate conditions. Existing drawings, field surveys and readily available visual information of the two buildings were used to create baseline models. Baseline models were developed using local weather station inputs and standard materials assumptions using thermal properties published in existing literature and databases. This baseline model attempts to represent the typical professional practice that normally precludes in-situ building testing. The heat transfer coefficients used in the baseline model are listed in Tables 1 and 2. The outdoor climate is modeled by using a weather file that attempts to represent a typical meteorological year (TMY). The Northeast Philadelphia Airport weather station is the closest weather station to both sites and has TMY3 weather data available. The weather station is located at coordinates of 40.08°N, 75.02°W and is approximately 10 miles away from the two building sites.
Table 1: Overall heat transfer coefficients (Btu/h·ft²·°F) for Rittenhouse Town Homestead Envelope Assemblies

<table>
<thead>
<tr>
<th>U-value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9502</td>
<td>Single-glazed windows (frame occupies 33% of area)</td>
</tr>
<tr>
<td>0.3756</td>
<td>Stone masonry exterior walls 23 inches thick (sandstone)</td>
</tr>
<tr>
<td>0.4408</td>
<td>Stone masonry exterior walls 18 inches thick (sandstone)</td>
</tr>
<tr>
<td>0.2466</td>
<td>Wood floors over wood joist and plaster ceiling</td>
</tr>
<tr>
<td>0.0445</td>
<td>Sloping roof, wood shingle, exposed wood framing + glass fiber insulation</td>
</tr>
<tr>
<td>0.3658</td>
<td>Wood framed wall partition plaster both sides</td>
</tr>
<tr>
<td>0.3195</td>
<td>Stone masonry load bearing internal wall 18 inches thick with plaster both sides</td>
</tr>
<tr>
<td>0.4750</td>
<td>Solid hardwood door (oak)</td>
</tr>
</tbody>
</table>

Table 2: Overall heat transfer coefficients (Btu/h·ft²·°F) for Roxboro House Envelope Assemblies (historic portions only)

<table>
<thead>
<tr>
<th>U-value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7032</td>
<td>Large single-glazed windows (frame occupies 10% of area)</td>
</tr>
<tr>
<td>0.9502</td>
<td>Single-glazed windows (frame occupies 33% of area)</td>
</tr>
<tr>
<td>0.2779</td>
<td>Wood framed, plaster on wood lath, wood clapboard on plywood exterior walls</td>
</tr>
<tr>
<td>0.2466</td>
<td>Wood floors over wood joist and plaster ceiling</td>
</tr>
<tr>
<td>0.0445</td>
<td>Sloping roof, wood shingle, exposed wood framing + glass fiber insulation</td>
</tr>
<tr>
<td>0.3658</td>
<td>Wood framed wall partition plaster both sides</td>
</tr>
<tr>
<td>0.4750</td>
<td>Solid hardwood door (oak)</td>
</tr>
</tbody>
</table>

2.4 Air exchange rate

Air exchange rates used in building energy simulation typically represent the rate at which outdoor and indoor air are being exchanged within the volume of the building being studied. As air is a fluid with heat carrying capacity, the exchange of air between the inside and outside is a source of heat gain/loss for the building interior. In some cases the heat loss/gain from air infiltration can exceed the loss/gain related to conductance and radiation and thus is an important building energy simulation variable. The air exchange rate is typically expressed as Air Changes per Hour (ACH) which is the number of times that the total volume of air inside the building has been exchanged with the outside air. In developing energy models for modern buildings of similar scale to the two buildings in this project air exchange rates can range between 0.33 to 1.47 ACH depending on the outdoor temperature, wind speed and tightness of construction (Grondzik et al. 2011). 0.33 ACH represents a relatively well-sealed building while 1.47 ACH represents a building with relatively poor air-tightness. A building with medium air-tightness is expected to have a range of 0.46 ACH to 1.05 ACH depending on wind speed and outdoor temperature.

Using wind speed and seasonal design temperature values, the expected medium air-tightness values could be estimated to be 0.46 ACH in the summer and 0.85 ACH in the winter (Grondzik et al. 2011). Since building energy simulation software typically require the input parameter of a baseline ACH for the entire year this would be typically the average of the summer and winter ACH values. In the case of developing energy models in Philadelphia this leads to an expected average medium air-tight building with a value of 0.66 ACH. This is a reasonable air exchange rate value if one does not actually know the air-tightness condition of a building via testing. This is the rate that is used in the baseline models for this research project.

2.5 Verification & Testing

Air infiltration rates can be tested by using door blower tests and material uniformity can be studied via thermocouples, hygrometers, thermographic photography and heat flux sensors. This research utilized each of these relatively low cost techniques to enhance the building characterization process with the goal of increasing accuracy of the associated building energy simulations.

2.6 Testing Methodology for Thermal Resistance

To determine the in-situ thermal performance and resistance values of the wall assemblies a day long test was conducted at both sites. ASTM C1046-95 and C1155-95 both provide detailed methods for collecting in-situ data of building envelopes performance parameters and were used as starting points for the testing performed in this research project (ASTM 2013a, b). Using the equipment listed in section 2.1, thermocouples were placed on both inside and outside surfaces of an exterior wall. A heat flux plate was attached to the inside surface and temperature data loggers were also used for the room and outdoor air temperatures. The dataloggers recorded readings at 30 second intervals over a 23-hour or 24-hour period. Using these readings along with thermal images of the walls taken with the IR camera the thermal resistance of the wall and air films were calculated. This procedure is detailed in the article titled “Historic Building Facades: Simulation, Testing and Verification for Improved Energy Modeling” (Chung 2015). This article covers step-by-step calculations using a method derived from EN ISO 6946–2007 using the collected in-situ data to calculate thermal resistance and transmittance (ISO 2007). Heat transfer through the building envelope varies spatially and over time. Although the resistance value of the envelope can be measured over a short time interval at a single point, this
research collected data to determine the resistance value over a broad area of the envelope and over many hours. To use this data in the software simulations, the sum of the resistance values over time and area are divided by the area and time to determine a time and spatially average resistance value. This is denoted as “R_{env av tav}” in the results section. Additional information and requirements of this testing methodology are discussed in the article and are available online at: http://digital.journalofthenationalinstituteofbuildingsciences.com/nibs/february_2015?pg=17#pg17.

2.7 Testing Methodology for Air Infiltration
To test for the air exchange rate due to air infiltration for a building one can use a door blower test to determine the amount of air flow through the building envelope at a specific pressure. The standard for testing airtightness of buildings using a door blower sets the target pressure at 50 pascals (Standard 2011). By placing a fan within a sealed collar at an exterior doorway and using a pressure and flow gauge the flow rate of air in cubic feet per minute (CFM) can be determined at the target pressure. This is typically known as the CFM@50 Pa or CFM_{50}. If the building interior air volume (in cubic feet) is known then the air exchange rate can be calculated at the target pressure. This air exchange rate is known as ACH@50 Pa or ACH_{50} and is calculated as ACH_{50} = CFM_{50} / building volume. See ASTM Standard E1827-11 for more information on this testing method. Both RittenhouseTown Homestead and Roxboro House are buildings that are approximately 2-1/2 stories tall with a normal exposure to wind. Using ASHRAE Standard 136 for such buildings in Philadelphia provides an N-factor = 17.6 (Standard 1993). The conversion from ACH@50 Pa to an estimated naturally occurring ACH is calculated by: ACH_{natural} = ACH_{50}/N-factor. See figure 4 for images of the door blower test at RittenhouseTown Homestead.

3.0 Results and Discussion
3.1 In-Situ Thermal Resistance Rittenhouse Town Homestead
On December 26-27, 2014 RittenhouseTown Homestead had a measured thermal resistance time averaged value (over a 24 hour period) of 5.74 h·ft²·°F/ Btu at the location of the heat flux sensor. Using the thermal images and sensor readings taken at 5:59 AM at RittenhouseTown Homestead on December 27, 2014 the following resistance values were estimated:

1st Floor, 23 inch thick masonry stone wall:
- Resistance area averaged instant value, R_{env av inst} = 4.888 h·ft²·°F/ Btu
- Resistance 24 hour time average spot value, R_{env spot tave} = 5.74 h·ft²·°F/ Btu
- Resistance instant spot value, R_{env spot inst} = 4.636 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, R_{env av tav} = R_{env av inst} x R_{env spot tave} / R_{env spot inst} = 6.05 h·ft²·°F/ Btu

2nd Floor, 18 inch thick masonry stone wall:
- Resistance area averaged instant value, R_{env av inst} = 4.672 h·ft²·°F/ Btu
- Resistance 24 hour time average spot value, R_{env spot tave} = 5.74 h·ft²·°F/ Btu
- Resistance instant spot value, R_{env spot inst} = 4.636 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, R_{env av tav} = R_{env av inst} x R_{env spot tave} / R_{env spot inst} = 5.78 h·ft²·°F/ Btu

The in-situ determined thermal resistance of the 23 inch thick masonry wall of R_{env} = 6.05 h·ft²·°F/ Btu is approximately 204% the default value used in the baseline model of 2.96 h·ft²·°F/ Btu. The in-situ determined thermal resistance of the 18 inch thick masonry wall of R_{env} = 5.78 h·ft²·°F/ Btu is approximately 255% the default value used in the baseline model of 2.27 h·ft²·°F/ Btu. See figure 3 for a thermal image of RittenhouseTown Homestead. These in-situ values appear to reflect the uncertainty and range that exists in the assumed values for sandstone masonry walls. Since sandstone is a naturally formed sedimentary rock, variations in composition, density and homogeneity may exist that can lead to variations in thermal properties.

3.2 In-Situ Thermal Resistance Roxboro House
On February 12-13, 2015 Roxboro House had a measured thermal resistance time averaged value (over a 23 hour period) of 4.29 h·ft²·°F/ Btu (which corresponds to a U-value of 0.2331 Btu/h·ft²·°F) at the location of the heat flux sensor. Using the thermal images and sensor readings taken at 6:39 AM at Roxboro House on February 13, 2015 the following resistance values were estimated:

- Resistance area averaged instant value, R_{env av inst} = 4.322 h·ft²·°F/ Btu
- Resistance 23 hour time average spot value, R_{env spot tave} = 4.29 h·ft²·°F/ Btu
- Resistance instant spot value, R_{env spot inst} = 4.070 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, R_{env av tav} = R_{env av inst} x R_{env spot tave} / R_{env spot inst} = 4.56 h·ft²·°F/ Btu

The in-situ determined thermal resistance of the wood framed wall of R_{env} = 4.56 h·ft²·°F/ Btu is approximately 27% higher than the default value used in the baseline model of 3.60 h·ft²·°F/ Btu.
3.3 In-Situ Air Infiltration

A door blower test for RittenhouseTown Homestead was performed on May 14, 2014 (see figure 4). The test was performed by a Building Performance Institute (BPI) certified technician from the Energy Coordinating Agency (106 W Clearfield Street, Philadelphia, PA 19133). This service was provided at a cost of $125. The test measured 6002 CFM@50 Pa. With the building volume modeled at 12,270 cubic feet of interior volume this results in an air exchange rate of 29.35 ACH@50 Pa. This the door blower tests results can be used to estimate a natural air exchange rate of 1.67 ACH for RittenhouseTown Homestead.

A door blower test for Roxboro House was performed on August 14, 2014. The test was performed by a Building Performance Institute (BPI) certified technician from the Energy Coordinating Agency. This service was provided at a cost of $250. The test used two door blower fans and two pressure and flow gauges with a combined measurement of 9410 CFM@50 Pa. Two door blower fans were needed due to the larger volume of Roxboro House. With the building volume modeled at 38,570 cubic feet of interior volume this results in an air exchange rate of 14.63 ACH@50 Pa. Thus door blower tests results can be used to estimate a natural air exchange rate of 0.83 ACH for Roxboro House.

When comparing these air infiltration rates derived from the door blower tests to the baseline value of 0.66 ACH one can see that for both of these historic buildings air infiltration rates are higher than might be normally predicted without testing. For RittenhouseTown Homestead the air exchange rate determined from testing increased significantly by a factor of 2.55. For Roxboro House the air exchange rate determined from testing increased by a factor of 1.27.
3.4 Weather comparison
At the RittenhouseTown Homestead site a small lab grade weather station (Davis Instruments 6250 Vantage Vue Wireless Station) was installed to help monitor differences between local/regional climate (from local weather stations) and micro-climate at the target building site. Figure 5 shows a comparison of the monthly average weather data from June 2014 through March 2015 between the local airport weather station and the onsite weather station at RittenhouseTown Homestead. The Northeast Philadelphia Airport weather station data was downloaded from the National Oceanic and Atmospheric Administration website. The on-site weather station was located approximately 30 feet north of the building in a clearing on the building property. This allowed the on-site weather station to be out of any direct shadows cast by the building but still within the range of experiencing similar climate effects. The graph shows that the airport weather station is consistently higher in terms of both high and low temperatures throughout the year. The difference in rainfall appears to be minimal to non-existent. When comparing all the values during the 10 months the average air temperature daily high is 2.92°F greater and the average daily low is 2.94°F greater at the airport. This will have some impact on the building energy simulation accuracy since cooler months will require less air conditioning (thus less electricity) in the summer and greater heating (thus more natural gas) in the winter. One way to include this micro-climate information would be to edit the airport weather file to reduce the outdoor air temperature values to produce a customized weather input file for building energy simulation. An alternative to editing the weather file is to increase the indoor thermal set points by the average offset of 2.93°F. The second method is what was employed in this research and should provide some compensation for the difference in airport and site weather conditions.

Figure 5: Comparison of weather station data between the RittenhouseTown Homestead site and the NE Phila. Airport

3.5 Building Energy Simulation Results
The results of the building energy simulations for RittenhouseTown Homestead are shown in table 3. The results for Roxboro House are shown in table 4. These include simulations with the baseline models using typical assumptions and the in-situ models using thermal resistance and air infiltration test data. For each of the simulations the total energy due to lighting loads, heat gain from occupants and thermal conditioning were calculated. The total cost of annual energy was calculated by using 15.15 cents per kWh to represent the cost of the base rate plus transmission and delivery charges charged by PECO Energy Company, the local utility. The cost for natural gas used was 1.013 per CCF (100 cubic feet) with a heat value of 1040.5 Btu/CF. These values were listed for Pennsylvania on the Energy Information Agency’s website for commercial properties. The cost of natural gas was the average value for 2014 and the heat value used was the average value for the 6-year period from 2009-2014. Looking at the results one can see that in both buildings their simulations with baseline models predicted a higher amount of energy use when compared to the simulations with in-situ models. This was primarily due to the fact of having much lower thermal resistance values for the walls than what was measured in the field tests. The calculated total annual energy costs for RittenhouseTown Homestead in the simulation with the in-situ model is approximately 10% less than the simulation with the baseline model. The calculated total annual energy costs for Roxboro House the simulation with the in-situ model is approximately 14% less than the simulation with the baseline model. Historical energy consumption records for Roxboro House were not available.
Some recent energy use records for RittenhouseTown Homestead were available. Natural gas consumption in 2014 was 1344 CCF. Electricity consumption in 2012 was 4381 kWh. These historical data points suggest that the energy models may be overestimating the future energy use. This may be due to the difference between the simulated and actual indoor temperature set points and occupancy schedules.

### Table 3: RittenhouseTown Homestead Building Energy Simulation Annual Energy Consumption Results

<table>
<thead>
<tr>
<th></th>
<th>Baseline Existing</th>
<th>In-situ Model Existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>electricity (kWh)</td>
<td>9,025</td>
<td>6,030</td>
</tr>
<tr>
<td>natural gas (CCF)</td>
<td>1,876</td>
<td>1,988</td>
</tr>
<tr>
<td>electricity cost</td>
<td>$1,367.27</td>
<td>$913.53</td>
</tr>
<tr>
<td>natural gas cost</td>
<td>$1,899.89</td>
<td>$2,013.78</td>
</tr>
<tr>
<td>Total annual cost</td>
<td>$3,267.16</td>
<td>$2,927.31</td>
</tr>
</tbody>
</table>

### Table 4: Roxboro House Building Energy Simulation Annual Energy Consumption Results

<table>
<thead>
<tr>
<th></th>
<th>Baseline Existing</th>
<th>In-situ Model Existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>electricity (kWh)</td>
<td>66,491</td>
<td>57,397</td>
</tr>
<tr>
<td>electricity cost</td>
<td>$10,073.40</td>
<td>$8,695.63</td>
</tr>
</tbody>
</table>

**CONCLUSION**

By using in-situ non-destructive testing methods to measure heat flux and surface temperatures more accurate thermal resistance values were determined for both buildings. By using a simple door blower pressurization test the air tightness of both buildings were measured allowing for a more accurate understanding of air infiltration rates. By using these field derived parameters, the building energy simulations should provide a better approximation of future energy use when compared to simulations with baseline models. Using this method of energy modeling coupled with field testing should improve confidence and accuracy in input parameters used in building energy simulations for historic buildings and ultimately help provide more meaningful energy data in the decision-making process for owners and operators of historic buildings. It should be noted though that variations in occupancy schedules and building use can highly influence energy simulation outcomes. Also, building energy simulations for future use are predictions based on a multitude of assumptions and thus should not be interpreted as precise estimates but a quantitative method to help make more informed decisions.

**ACKNOWLEDGMENTS**

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**REFERENCES**


ABSTRACT: Due to the almost 40% share they have of all energy produced and 70% of all electricity produced and 38% share of all greenhouse gas emissions, the existing building stock needs immediate attention. Several studies identify the complexity and variability of conditions that cause the behavioral, financial and informational barriers preventing owners and occupants from adopting one-size-fits-all energy efficiency approaches despite the fact that these measures have cost-saving potential. Hirst and Brown coined the term “energy efficiency gap” and noted the failure of households, businesses, manufacturers and government agencies to take full advantage of cost-effective energy-conserving opportunities.

The Georgetown University Energy Prize (GUEP) was launched in 2014 and challenged cities and counties of populations ranging from 5,000 to 250,000 to reduce their energy use during a two-year competition period (2015-2016). The focus of the competition is on the reduction of municipal and residential building energy use by increasing energy efficiency. This makes it one of the largest national efforts to focus attention on closing the energy efficiency gap. The design strength of the competition is that it allows communities to create the approaches that best fit their needs in order to address one or more of these barriers.

This paper surveys public sources of information to identify the efforts that have been undertaken by the 50 semi-finalist cities. It further categorizes these efforts into three major typologies and several sub-typologies of energy-efficiency efforts. These typologies are sorted according to the hierarchy of rankings based on the GUEP dashboard providing a cluster visualization of impactful efforts.

The paper concludes with a discussion of typology combinations that appear to have the greatest utility in this preliminary study and outlines further research directions based on future data submitted by the actively participating cities.

KEYWORDS: Energy-efficiency, energy-efficiency gap, Energy Prize, GUEP

INTRODUCTION
As compared to other uses such as transportation and industrial sectors, residential and commercial buildings together add up to almost 40% of energy use (U. S. Energy Information Administration “Energy Consumption by Sector,” 2016). Over the lifetime of buildings 80–90% of this energy use is in operations (heating, cooling, lighting, devices) whereas only 10–20% is in embodied energy (manufacturing, demolition) (Ramesh et al 2010). As a result, investments in reduction of operational energy use of buildings or their energy efficiency can have a large impact on reducing building energy use. Per Raman (2009), 70% of the existing building stock will still be functional in 2050. Seto et al (2014) projected that urban areas are responsible for 67%–76% of global energy use and 75% of carbon emissions. Per Creutzig, Baiocchi, Bierkandt, Pichler, and Seto (2015), urban interventions have the potential to reduce global energy use by 26%. These conditions present an opportunity for impacting global energy use and carbon emissions by acting at the city scale on energy-efficiency.

Per Molina (2014), energy efficiency is the cheapest method to provide Americans with electricity. Though energy efficiency is a much-needed and necessary strategy to reduce energy use, the energy efficiency gap needs to be addressed. Despite the fact that energy-saving measures have cost-saving potential, several studies identify barriers preventing owners and occupants from pursuing them. Hirst and Brown (1990) coined the term “energy efficiency gap.” They identified behavioral barriers under the control of occupants, including attitudes towards energy efficiency, the perceived risk of energy-efficiency investments, and barriers that were not under the control of the occupants such as information gaps, and misplaced incentives.

Gillingham and Palmer (2013) outline and discuss three primary approaches to addressing energy efficiency: information
strategies, economic incentives, and energy efficiency standards. Information strategies include low- or no-cost energy audits for households; product labels such as Energy Guide or Energy Star certification for buildings and the Energy Star label for products; and public disclosure of buildings’ energy use. Abrahamse et al. (2005), Stern (1985), and Stern and Aronson (1984) have found that by themselves, information programs identifying energy saving investments and behavior changes have limited effects on energy consumption. Schultz, Khazian, and Zaleski (2008) have shown that combining energy-use reduction information combined with comparison information produces results. This social and informational comparison approach works on energy consumers (Ayres, Raseman, and Shih, 2013).

Financial incentives in the form of rebates, tax incentives, and low-cost loans are used to encourage energy-efficient purchase and use behavior. Documented concerns about the effectiveness of such approaches in reducing energy use include the requirements for funding sources; and a rebound effect which reduces energy savings (Joskow & Marron 1992). Studies report mixed cost-effectiveness of such programs (Arimura, Li, Newell, & Palmer, 2012; Auffhammer, Blumstein, & Fowlie 2008; Rivers & Jaccard 2011). In the United States, building energy codes and standards have been used to achieve energy efficiency. Studies cited by Gillingham & Palmer (2013) show that the effectiveness of building efficiency standards have shown mixed results. According to Gillingham & Palmer, Jaffe & Stavins (1995) conclude that “building codes have no significant effect on energy demand,” but Aroonruengsawat, Auffhammer, and Sanstad (2012) report that “building codes decreased per capita residential electricity consumption by 3 to 5 percent, and Jacobsen and Kotchen (2012) find electricity savings of about 4 percent.”

In summary, research shows that the causes of the energy efficiency gap are difficult to explain and pinpoint, and consistent results on energy-efficiency programs’ effectiveness are elusive. It is becoming increasingly clear that heterogeneity of needs and conditions of consumers might be the ultimate cause of difficulties in measuring and addressing the energy efficiency gap (Srivastava 2017). Different issues are relevant to different consumer groups making one-size-fits-all efforts effective only to a limited audience and less effective to other audiences. According to Gillingham and Palmer (2013), heterogeneity presents researchers with both an opportunity and a challenge.

1.0 GEORGETOWN UNIVERSITY ENERGY PRIZE

The Georgetown University Energy Prize (GUEP) conceived in 2012 by Francis Slakey, PhD, a physics professor at Georgetown University whose work in the area of energy policy indicated the tremendous potential for energy efficiency, but showed how underutilized efficiency strategies were among mid-sized American cities and counties. The team at Georgetown developed the GUEP to incentivize and inspire cities and counties across the U.S. to develop and begin implementing plans for innovative, replicable, scalable and continual reductions in the energy-per-residential-account consumed from local natural gas and electric utilities.

The GUEP was formally opened in April 2014 to any U.S. city or county with a population between 5,000 and 250,000. The competition garnered significant interest from communities throughout the country, and by December 2014, 50 communities had submitted comprehensive energy plans and had been selected to compete for the prize. These communities came from 26 states and included every geographic, demographic, and political region of the country.

The GUEP structure was based on historical incentive prizes that have spurred innovative solutions to problems for centuries, dating back as far as the Longitude Prize in 1714. Sobel 1995. In the modern era, incentive prizes have been deployed on a wide range of problems from computer algorithms to developing commercial spacecraft. A 2009 McKinsey & Company Report, “And the winner is...Capturing the Promise of Philanthropic Prizes,” described the ways in which prize competitions were being deployed and how public institutions could utilize this methodology to spur innovation. A 2014 report from Deloitte University Press, “The Craft of Incentive Prize Design,” showed the growth of prizes as an innovation tool, stating, that “In the last five years, incentive prizes have transformed from an exotic open innovation tool to a proven innovation strategy for the public, private, and philanthropic sectors.” Vine and Jones (2016) assessed the energy savings potential of energy efficiency competitions, studying twenty competitions in the United States from 2006 to present. Three of the competitions that they studied were national competitions: the Campus Conservation Nationals (limited to University campuses); OPower, a social media based competition; and EPA’s Energy Star Building Competition. They concluded that for competitions to be effective, there needs to be long-term and appropriate commitment of resources for design, implementation and rigorous evaluation from policy makers at the federal, regional, state and local levels.

The GUEP, currently in its first implementation, has been a key part of the growing landscape of incentive prizes, and is an example of what the McKinsey & Company report described as a “participation prize,” designed not only to identify end-solutions, but to create substantial benefits through increasing the engagement of the competitors in advancing a field. Prizes have a number of advantages over other innovation approaches, but one key advantage is that innovation prizes function by defining an ambitious goal without needing to predict which methodology will be most successful.

The GUEP established the core goal of reducing community-wide residential and municipal electricity and natural gas consumption, but left it up to each individual community how best to accomplish this goal. Moreover, the final...
2.0. PROCESS

2.1. Data collection and ranking methodology for GUEP

To participate in the GUEP, each community was required to submit letters of commitment from the following three entities: (1) the municipal government, (2) all of the electric and natural gas utilities that service the municipal and residential buildings within the geographic boundaries of the community, and (3) local non-profits or other community groups representing the residents of the community. The competition guidelines stipulated that any one of these entities may take the leadership role in managing the community’s participation in the GUEP, however, all three entities must be committed to participating and supplying data as requested by Georgetown University.

During the competition performance phase, from January 1, 2015 through December 31, 2016, each community submitted quarterly reports of their energy consumption to the GUEP administration team. These reports included monthly aggregate electric and natural gas energy consumption for the residential and municipal sectors, plus the total number of residential bills issued for electric and natural gas service. Communities also submitted baseline energy reports for 2013 and 2014, which were compared to the quarterly reports submitted throughout the competition period to assess overall savings. While communities were competing against their peers, their energy data was only compared to themselves and how much energy they saved in 2015 and 2016 over the baseline years. Performance in the competition, and the energy performance rankings are based on the 24-month average of the normalized energy performance per residential energy customer using the simple formula:

\[
\text{Overall Energy Score} = 100 \times (\text{Competition Average} - \text{Baseline Average}) / \text{Baseline Average}
\]

Competition data was normalized for weather, population, and to account for the “source energy” required in to produce the energy in the “full-fuel-cycle”. Weather normalization and source-energy conversion was handled by the U.S. Environmental Protection Agency’s Energy Star Portfolio Manager, a free and web application. To normalize each community for its relative size, GUEP divided the total normalized energy consumption by the number of residential bills issued each month. Residential energy bills were used as a standardized way of comparing energy use of two different sized communities by calculating the average energy consumption per residential customer. It is important to note that the final evaluation of the Prize will be based on the additional qualitative criteria described above, but the monthly performance ranking was based solely on performance.

2.2. Data collection and categorization

Since the final GUEP performance data will not be available till Fall 2017, extensive keyword searches of online public sources including published articles and community websites were the primary data source of this study. This was done in order to identify categories of major activities and efforts that the various cities were utilizing to reduce their energy use. The three common categories that emerged from this extensive search of online materials and subsequent categorization exercise were Engagement, Financial investments and Assessments.

2.2.1 Engagement:

E1 – Gaming & Competitions

Games are typically categorized as individual efforts at homes and businesses to make buildings more efficient. Competitions were dependent on team efforts or individual efforts that contributed to teams for homeowners and neighborhoods. Games and competitions were available to their communities most often in digital formats as web-interfaces or apps. Physical games like Energy Bingo or the Fargo K-12 Energy Challenge were implemented as well. For example, Walla Walla, Washington implemented Walla Walla Power Play, where residents track energy-saving actions on a bingo card. Fremont, California had the Green Challenge awards points which ranks participants for energy-efficient actions. Fargo, North Dakota designed, coded and implemented two games, a web-based digital platform for community members to reduce energy in homes, and the K-12 Energy Challenge for teachers, students and administrators to reduce energy in their schools.

E2 – Community Education, Engagement

This category includes sustainability workshops, community education and outreach and all such approaches to raising community awareness about sustainability. For example, Sunnyvale, California had monthly Compost Workshops teach residents how to reduce food waste and create their own fertilizer free of charge.

E3 – Messaging / Branding

Cities invested in creating awareness and energy messaging around branding efforts for businesses and homes. These were typically acknowledgements of efforts and results that people or organizations made in order to become more energy efficient. For example, Bend, Oregon had the Do Just One Thing campaign aims
to highlight how small actions can have a large impact over time; the Bend Energy Challenge also refers to all participants as “Energy Heroes.”

E4 - Prizes
Prizes, in-kind or financial prizes were often used as rewards for participation by various communities. These prizes were typically not associated with competitions and other engagement programs. For example, Takoma Park, Maryland's Neighborhood Energy Challenge used branding efforts to incentivize energy efficiency, and offered a $2,000 prize to neighborhoods that are working on reducing energy.

E5 - Misc
These were unique efforts that includes affordable, high-efficiency passive houses project, energy reduction house parties, alternate transportation fair, community action/empowerment workshops, community gardens, monthly sustainability themes, and building benchmarking. For example, Madison, Wisconsin's Green Madison encourages residents to host Energy House Parties, where a “local energy expert” teaches guests about energy efficiency within the home. Or Fargo, North Dakota created a partnership with the architecture program at the University and local non-profits to design and build affordable, Passive Houses for low-income families.

2.2.2 Financial:
F1 - Incentives
This category includes financial programs to incentivize energy reduction but not tied to particular action items. Often these programs might be paired with with upgrades, retrofits and rebates. For example, Park City-Summit County, Utah’s Summit Community Power Works connects residents to state incentives, including the Utah Solar Incentive Program.

F2 - Upgrades, Retrofits, Rebates
Programs to pay for physical improvements to homes and replacement to more efficient appliances. For example, Aspen, Colorado’s Energy Smart Colorado hosts an application for Home Rebates to connect homeowners to programs that make energy-saving upgrades more affordable.

F3 - Weatherization
Improvements to increase the efficiency of homes; several programs specifically offer free weatherization for low-income renters and homeowners. For example, in Champaign, Illinois, the County Regional Planning Commission funds a weatherization program that prioritizes low- and moderate-income, elderly, and disabled applicants.

F4 - Renewables
Renewable energy including solar and wind power, is often purchased in co-ops or other community-based groups. For example, the City of Palo Alto, California is setting an example for its residents by installing solar energy for municipal buildings, creating the necessary infrastructure for solar long-term, and offering incentives for residents to install solar for electricity and water heating.

F5 - Loans, Financing
Financing programs to make weatherization, upgrades and renewable energy accessible to lower-income residents. For example, City of San Mateo, California offers financing options to those looking to install solar panels.

2.2.3 Assessments:
A1 - Assessments
Online and in-person assessments of home energy efficiency. For example, Anacortes, Washington’s, Anacortes Community Energy provides both an online dashboard for tracking home energy use and referrals to professional energy assessors.

A2 - Customized Advice, Energy Coaching, Plans
Individualized plans and advice for improving the energy efficiency of homes. For example, Bellingham, Washington's Bellingham Energy Prize offers an online assessment dashboard complete with individualized plans to improve energy efficiency in the home.

Once the activities were categorized, the cities were ordered by their current GUEP rankings and all activity categories that the cities pursued were recorded (Figure 1 & 2).
This preliminary analysis only includes the twenty cities that have current completed and verified data sets. The early conclusions of this work are drawn from this limited dataset. The energy use data of the thirty cities (Figure 2) is currently under review pending audits for incomplete information or anomalies. In addition, the cities are in the process of submitting an activities and investments report which will be more comprehensive and indicative of all the work undertaken by the various cities. Future analysis will benefit significantly from the final community rankings and by gaining access to the qualitative reports from the communities. This will be made available following the close of the competition in Fall 2017.

From the data currently available, of all the activity categories found for both ranked and unranked cities following are some of the preliminary findings. Generally, the top ten cities focussed more heavily on the financial and assessment categories rather than engagement type activities.

Of all the activity categories, home-efficiency assessments (A1) were most frequently utilized. 12 of the ranked twenty cities and 17 of the unranked thirty cities utilized home-efficiency assessments (A1). Following closely behind were Upgrades, Retrofits & Rebates (F2) and renewables (F4) among the ranked cities. In the unranked cities group, home-efficiency assessments (A1) were followed closely by renewables (F4) and Community education programs (E2) which were followed closely by Gaming and Competitions (E1), Weatherization (F3), Upgrades, Retrofits & Rebates (F2). In the top ten ranked cities, every city had an Upgrades, Retrofits & Rebates (F2) or renewables (F4) program and six of the ten cities had both programs.
Of all activity categories, Prizes (E4) were the least frequently utilized in ranked cities and the second-least frequently used activity in the unranked cities. Messaging/branding (E3) was the other least frequently used engagement activity among the ranked cities. Interestingly, among the ranked cities within the financial category Weatherization (F3) programs were least frequently used but upgrades, retrofits and rebate (F2) programs that included weatherization as part of a list of other efficiency-related upgrades was very frequent. Loans & Financing (F5) was the second least frequently used program within the financial category for both ranked and unranked cities. General incentive (F1) programs that are offered by entities other than the municipality could include federal or state incentives, were not as frequently emphasized in ranked cities or unranked cities as the local upgrades, retrofits and rebate programs that connected people to programs that pay for physical improvements.

Since these preliminary findings are based on a limited data set they are likely to adjust when the complete dataset is available. Although we have noted some general trends in the current data, there does not seem to be any clear and emphatic correlation between the number of activities or the types of activities that a city implemented and the GUEP rankings. When final data and activity reports are available, a correlation analysis will be conducted.

4.0. LIMITATIONS & CHALLENGES
Communities voluntarily participated in the Georgetown University Energy Prize (GUEP), and were therefore responsible for self-reporting on energy consumption and programs. This meant that the timelines and completeness of reports were subject to shifting priorities and resources in each community and would sometimes lag for weeks or
months beyond required deadlines. This created inconsistencies across any given reporting period and lead to GUEP being able to update data and rankings less often than desired.

In addition, the analysis in this paper was based on the best data available while the competition was still in progress. Because of this, thirty of the fifty communities had not submitted their complete and error-free energy consumption data, and therefore may receive revised rankings once their data is updated and completed. Moreover the activity analysis was based on publicly available reports because communities had not yet submitted their complete report on program activities.

5.0 FUTURE DIRECTIONS
Once the competition is complete, this extensive data set of community energy-use, activities and efforts and existing conditions can provide the grounds of multiple future research directions. Valuable research could be conducted in determining the most impactful activities or combinations of activities to achieve maximum energy-use reductions, carbon emissions reductions and financial savings correlated to independent variables such as community conditions. Community conditions could include issues such as political spectrum (congregational delegation distribution among the Democratic, Republican and Independent parties), economic markers (poverty, household income, income per capita), demographic make-up (race, gender, age, ethnicity, household size) and community agency due to housing types (owned, rented, single family, multi-family, age of housing stock). Additional information currently being gathered and organized for every city includes political spectrum history, income information, housing types and demographics. Future descriptive and inferential analysis to discover any correlations between activity type modifying variables, community conditions independent variables and the GUEP performance dependent variables will be conducted.

A future adjustment to the design of the Georgetown University Energy Prize or other such efforts would include additional periodic incentives or other similar mechanisms to ensure more timely and up-to-date data submittals to the program administrators. While some of the variability is to be expected given the broad and distributed nature of an innovation program like the GUEP, future programs need to address the difficulties that the communities are encountering in data collection and transmittal.

CONCLUSION
This preliminary overview demonstrates that there is significant opportunity for further analysis once the complete rankings and full programmatic data is available which should lead to useful assessments of what approaches lead to successful outcomes in different conditions. This analysis would reveal successful activity category combinations correlated to community conditions. This will provide immensely valuable information for the more than 8,000 small- and medium-sized cities and counties in the U.S. that are considering future programs. Any community-wide approach to a problem is necessarily complex, and needs to accommodate the varied conditions and needs of these communities.

ACKNOWLEDGEMENTS
This paper was supported by the research assistance provided by Paige Vance in identifying public sources of community activity and categorizations (Undergraduate Research Assistant, efargo, Brown University).

REFERENCES


ENDNOTES

1 See the official Competition Guidelines at https://guep.org/about-the-prize/ for complete details on the competition structure, community eligibility, definitions, data reporting, calculations, and evaluation criteria.

2 See https://www.guep.org/energydata/ for energy data reporting templates and instructions.

3 See https://portfoliomanager.energystar.gov for more information about how Portfolio Manager performs calculations, including weather normalization, and their conversion factors for “site” to “source” energy.
ABSTRACT: The projected impact of global climate change on community resilience places a significant proportion of the world's population in a precarious position. The increase in storm surges and sea inundation events create a poor outlook for small island nations in the South Pacific, decreasing habitability. Forced displacement and relocation is a likely future that many communities face in Small Island developing states, such as the Republic of the Marshall Islands. The impending landlessness faced by the Republic of the Marshall Islands calls to question the viability of the Marshallese culture and whether or not it can survive resettlement within another nation. As a freely associated state of the United States, there is a high probability that resettlement will follow the current chain migration of Marshallese into the United States.

This paper addresses the complexity of resettlement programs with cultural resilience in mind as we approach the design, development and planning of climate resettlement schemes. The study analyzes the cultural patterns imbued in the dialectic between culture and the built-environment of the Marshall Islands by employing a multi-sited ethnography across three communities in the Marshall Islands. Primarily qualitative analysis is employed to uncover deep-time cultural patterns that persist across time and space. These methods hope to develop a deeper understanding of cultural resilience in relation to the built environment in the Marshall Islands within a complex systems approach.

The goal of the research is to not only develop a language for building cultural resilience in resettlement programs, but also expand the development discourse to consider the agency of the built-environment in providing for more inclusive environments and the need for transformative action to be truly inclusive. Based on the positive attributes of deep-cultural patterns, they demonstrate a phenomenon that must be considered in any development project.

KEYWORDS: deep-culture, resilience, climate change, resettlement

INTRODUCTION
The projected impact of global climate change on community resilience places a significant proportion of the world's population in a precarious position; as sea level rise and sea surface temperatures change, there will be an increase of tropical storm frequency and intensity, which will significantly affect the ability of coastal zones to protect themselves from storm surges (Dasgupta et al. 2009). The increase in storm surges and sea inundation exacerbated by existing anthropocene environmental degradation create a poor outlook for small island nations in the South Pacific, decreasing habitability (Church, White, and Hunter 2006; Lilleør and Van den Broeck 2011; McGranahan, Balk, and Anderson 2007; Nunn and Mimura 1997; Pelling and Uitto 2001). Climate change is creating a particular urgency for small island populations to find solutions for mitigating vulnerability and build community resilience. The projected sea level rise over the next century, which ranges from a 0.5 to 2 meters (National Research Council (U.S.) 2010) will leave atoll nations - with peak elevations of 3-6 meters - almost entirely inundated by seawater (Spennemann 2006; Webb and Kench 2010). Forced displacement and relocation is a likely future that many communities face in Small Island developing states, such as the Republic of the Marshall Islands. The estimated sea level rise will inundate nearly the entire nation within the next century. The impending landlessness faced by the Republic of the Marshall Islands calls to question the viability of the Marshallese culture and whether or not it can survive resettlement within another nation.¹ As a freely associated state of the United States, there is a high probability that resettlement will follow the current chain migration of Marshallese into the United States.

The mass displacement of populations caused by global climate change is one of the most pressing issues we will likely face in our lifetimes. When a community's identity is rooted in a place, how does its culture survive environmental forced migration? This study seeks to uncover the continuity of culture in the built environment of the Marshall Islands and investigate the cultural patterns that continue to manifest themselves. By focusing on the vernacular habitat of the Marshall Islands I hope to demonstrate that these patterns are necessary in order to enhance both cultural continuity and cultural capital in resettlement programs in order to mitigate cultural degradation.

A common problem with resettlement programs is the tendency to overlook the complexity of the system, disregarding
the inherent place-based, social and cultural issues (Oliver-Smith and de Sherbinin 2014; Scott 1998). In order to properly approach resettlement, a process-based perspective needs to be implemented. By not sustaining cultural values that provide people with a sense of identity or investing in the enhancement of both tangible and intangible cultural capital, cultural systems may break down and lead to loss of welfare and economic output (Throsby 2014). In considering cultural resilience as an approach to sustainability, change is inherent as an adaptive strategy to disturbances; therefore, culture change does not necessarily mean the loss of culture, but “a creative space where new forms of cultural understanding (and practice) are developed in the dynamism that exists in cross-cultural engagement” (Wesson 2013, 108). Investing in efforts to maintain cultural patterns to reduce the stresses on the health, well-being, and security of the displaced populations will provide a mechanism for mitigating further vulnerability to more unpredictable events in the post-resettlement system. Since these mechanisms are culturally embedded, a sustainable approach must invest in whatever possible models contribute to the mitigation of any possible vulnerability to cultural patterns (Maffi 2007, 274).

This study develops insight into the implications of vernacular architecture within the discourse of climate displacement and resettlement planning and views the vernacular as a medium for analyzing cultural resilience. It is not to assume a desire for or maintenance of “traditional” architecture, but the evolution of the vernacular architecture that continues to support the inhabitants’ way of life. These concepts are an ever-changing and adaptive set of ideas that shape how the Marshallese engage with their built environment. The understanding of culturally supportive principles within the housing design of Marshallese will be essential for both developing more sustainable communities today as well as developing resettlement plans. The study takes a theoretical position that the persistence of a cultural pattern's relationship within the built environment demonstrates both the resilience of the pattern and a high value in cultural capital. Deriving from Jacka (2015), it questions how social transformation over time has limited or expanded the resilience of these patterns manifest in habitation. Through a study of the complex relationship between culture and the built environment of the Marshallese, I hope to expand the theoretical discourse on vernacular architecture and cultural resilience. My central hypothesis is that deep cultural patterns are embedded within the built environment, demonstrating a specific dialectical relationship between people and architecture. This research will bring a needed cultural perspective to critical social issues in sustainable architecture. The dissertation will also present design and planning principles for creating cultural resilience in forced displacement and resettlement projects.

1.0 HUMAN RESETTLEMENT
Resettlement should be seen as a development project, and therefore sustainability is a necessity in its approach (Oliver-Smith 2010). As scholars of resettlement programs have demonstrated, lessons advanced on development forced displacement and resettlement offer a vital perspective into understanding resettlement programs across all three forms of resettlement (Oliver-Smith 2009). Using varied definitions of “success” we may be able to reach an understanding on the role of sustainability in resettlement programs and how cultural supportive mechanisms might be seen as a necessity for sustainable solutions. In order to apply the model of cultural sustainability developed above to resettlement programs, it will be helpful to provide a brief overview of current resettlement models. The breadth of literature on displacement and resettlement is quite vast – especially with the rapid increase in forced displacement and resettlement, but the three most salient models are ‘impoverishment risks and reconstruction,’ ‘involuntary resettlement and sustainable livelihoods,’ and ‘inherent complexity.’ These models were developed by Michael Cernea (1998), Christopher McDowell (2002), and Chris De Wet (2006), respectively, and are commonly used to evaluate resettlement programs. Additionally, the work of Anthony Oliver-Smith has been invaluable in understanding post-disaster resettlement and implications inherent within the built-environment, such as quality of design, spatial organization, and appropriate housing (Oliver-Smith 1990).

1.1 Impoverishment risks and reconstruction (IRR)
Michael Cernea’s model has been widely accepted and used as a strategy in development forced displacement and resettlement (DFDR). He outlines eight risks to which people are subjected by displacement: landlessness, joblessness, homelessness, marginalization, social disarticulation, food insecurity, increased morbidity, and loss of access to common property resources (Cernea 1998). These risks represent the inherent vulnerability within the resettlement process, and the failure of a resettlement program to provide for vulnerability mitigation based on these elements will inhibit resilience and lead to loss of welfare during a second calamity (the first being the displacement) (M. M. Cernea and McDowell 2000; Oliver-Smith and de Sherbinin 2014).

1.2 Involuntary resettlement and sustainable livelihoods
McDowell (2002) combined Cernea’s IRR approach with Sustainable Livelihoods’ research in order to develop this methodological framework for research on resettlement. McDowell’s approach is mostly concerned with the socio-cultural component inherent in community disarticulation. “The unraveling of spatially and culturally based patterns of self-organization, social interaction, and reciprocity represents loss of valuable social capital that compounds the loss of both natural and human-made capital” (McDowell 2002). Anthony Giddens’ work on agency and the way behavior shapes the world provided important insights for McDowell. The complexity of these power relations made it clear that
an equilibrium stasis was unachievable in the forces that fundamentally shaped the people–environment relationship of displaced peoples. Implementing a transformative process, McDowell’s methodology seeks to understand the impacts of identified risks on livelihood, understand adaptation processes, understand institutional processes in re-settlers’ adaptation strategies, and focus on sustainable outcomes.

1.3 Inherent complexity
De Wet (2006) proposes an “inherent complexity” approach to development forced displacement and argues that:

there is a complexity in resettlement, which arises from the interrelatedness of a range of factors of different orders: cultural, social, environmental, economic, institutional and political – all of which are taking place in the context of imposed space change and of local-level responses and initiatives (p. 190).

This takes place simultaneously with pre-resettlement processes and post-resettlement processes. De Wet argues that the inherent complexity within resettlement programs requires open-ended, participatory processes rather than the predominantly economic and bureaucratic perspective. To overlook complexity undermines the success of resettlement program, negatively impacting the health, wellness, and security of the displaced population.

From these models, it is evident that establishing ‘success’ requires understanding the inherent complexities within a resettlement program and building resilience into the displaced population. Planning for complexity improves the chances for sustainable outcomes. As key components of the complex system, culture and its supporting elements are integral to resettlement planning and cannot be overlooked. Interlocking Wesson’s concerns with those of De Wet would require building an understanding of the cultural dynamics within a displaced population prior to resettlement planning, especially if that population had already faced displacement. These models are critiqued for being overly general and for focusing on narrow elements of the resettlement experience, which are mostly economic (Muggah 2000). In regards to the dynamics of a system constantly in flux, it is important to realize that even a successful resettlement program cannot return economic, environmental, social, or cultural norms back to their pre-resettlement state. Downing and Garcia-Downing (2009) argue that it is highly improbable that the everyday cultural patterns of a pre-displacement population may ever be recovered, let alone restored. The standard operational approach is not effective in dealing with an evolutionary process in which the interaction between social, cultural, economic, and environmental factors are constantly in flux; rather an open-ended, collaborative and participatory approach is necessary in order to achieve sustaining social and cultural processes over time (Oliver-Smith, 2009; De Wet, 2006).

2.0 THREE MARSHALLESE VILLAGES
2.1 Methodology
In order to develop a well-supported notion of cultural patterns that manifest in the built environment and persist through the evolution of culture, primary field research is layered with the analysis of archival data relevant to human habitation on the islands and the historical change to the built environment in conjunction with the archaeological record on human settlement of the Marshallese. The unit of analysis for this study is the land parcel called the weto (Figure 1), which stretches from the lagoon of an atoll to the ocean providing access to resources necessary for sustainable livelihoods; the weto allows one to understand the system of habitation that represents the cultural habitus.

Employing a multi-modal methodology, the study was conducted on three different villages in the Marshall Islands, consisting of Djarrit-Uliga-Delap, Majuro, an urban center; Laura, Majuro, a semi-rural village; and Namdrik atoll, a remote atoll. The selection was based on the different contexts, demonstrating theoretical replication (Yin 2009). The research design consists of data collection through ethnographic field study of selected villages, building and site surveys, and archival research on each village selected, consisting of historical development, family lineage, and
oral histories. The goal is to uncover the changes of the social and cultural significance given to spatial arrangements, material use, building design, and the integration of resource management within the habitation zone (the weto).

The field study in each village consisted of participant observation, interviews, building and land parcel surveys, and participatory mapping. The study primarily focused on two bwij (extended family) in each village and their corresponding wetos. The goal of the observations was to develop an understanding of the minutiae of daily life in regards to habitation and to begin to understand cultural and social norms associated with spatial relationships, the use of materials, and the production of dwellings. Observational studies of human spatial behavior demonstrate that such differences in accessibility determine how people are likely to distribute themselves in space; these observations uncover frequency of activity patterns. Twenty interviews were conducted to uncover meaning in space, form, materials, and processes and to understand how relationships to the land and dwellings have changed throughout an inhabitant's life. The building surveys consist of mapping the weto and measured building plans. These drawings were analyzed based on their components and the level of connection between spaces. The interrelationships, measure of access, depth, and spatial permeability are calculated and used to bring interpretations of social meaning of space. This data layered with the historic and current patterns of human activity helps to contextualize spatial significance. Lastly, participatory mapping allowed inhabitants to demarcate importance and meaning directly to their wetos and dwellings. This process helped to visualize resource use, the importance drawn to elements of habitation, and changes over time (McLees 2013). The process also builds common understanding on spatial distribution and status of resources, land use, and building use. Qualitative research software was used to code and analyze data, uncovering patterns and emergent themes related to the socially spatial patterns that continue support Marshallese culture across space and time.

2.2 Analysis
Over twenty core socio-spatial patterns have been uncovered that support the Marshallese way of life on the weto. Data analysis has not been fully completed for all of the data collected during the dissertation field work; therefore, it is a working list. Table 2 provides a matrix of these patterns as observed in each location.

Table 2: Working list of culturally supportive, socio-spatial patterns of the Marshall Islands

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Namdrik</th>
<th>Laura Village</th>
<th>Djarit-Uliga-Delap, Majuro</th>
</tr>
</thead>
<tbody>
<tr>
<td>The earth oven (um)</td>
<td>X</td>
<td>Present</td>
<td></td>
</tr>
<tr>
<td>The cookhouse at the center of the Bwij</td>
<td>X</td>
<td>-</td>
<td>XM</td>
</tr>
<tr>
<td>Alcoves for storage and cooking in the cookhouse</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>A space for chatting in the cookhouse</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Local resources used in construction of the cookhouse</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Three trees (pandanus, coconut, and breadfruit) providing sustenance and defining the landscape</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>A central ‘big house’ for the elders and children</td>
<td>X</td>
<td>XM</td>
<td>XM</td>
</tr>
<tr>
<td>A cluster of familial homes around the large house</td>
<td>XM</td>
<td>XM</td>
<td>XM</td>
</tr>
<tr>
<td>A place for resting under the shade</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>A place for keepsakes under the roof</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Houses for married couples without room for children</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Orienting the house along the lagoon</td>
<td>X</td>
<td>XM</td>
<td>-</td>
</tr>
<tr>
<td>Protection for the side of the house where the soul rests</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unhealthy housing sites at the ocean and</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
It is clear that the influence of the market economy to the Marshall Islands has greatly impacted the culture and its relationship to the land. The built environment of the Marshall Islands has gone from one that is designed for efficient subsistence strategies to one that commodifies natural resources. The change in the relationship to the land is recent and drastically altered the landscape since World War II as the occupation by the United States led to an acute period of acculturation in Majuro and Kwajalein (Hezel 1994). Figure 2 provides a depiction of changes across the spectrum of urban to rural environments in the Marshall Islands. Given the vast change that has overcome the Marshallese way of life and the connection between culture and its design of the built environment, there are socio-spatial patterns that continue to support core cultural elements. As Rapoport (1969; 1982; 1983; 2006) demonstrated the importance of the core culture in developing culturally supportive environments, the process of ‘syncretism’ and the maintenance of core culture patterns are manifest in today’s Marshallese built-environment. This analysis is not extensive given the ongoing nature of the research, but it does describe significant findings.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Marshall Islands</th>
<th>Marshall Islands</th>
<th>Marshall Islands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local materials used for construction of homes</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>The house as a symbol of power</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Dense but not crowded housing occupation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Taboos provide gradients of security</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Sacred ground where the chief’s house stood</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A coral spread to designate one’s land</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>A place for the canoe</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

X = pattern present, XM = pattern present but modified, - = not identified
The land tenure system in the Marshall Islands, which is through matrilineal inheritance, maintains its central role in the Marshallese culture. Although housing disperses across the weto, the identity of the bwij rests within the land it spurred. The density of housing on the weto is a result of population growth and to an extent the individualizing effect of modernization (Hezel 1994; Hezel 1995). On Lojolimen Weto, in downtown Majuro, housing is dense, but several traditional socio-spatial patterns persist, such as the concept of ‘one cookhouse per bwij’ and the grandchildren living with the grandparents under one room. Lojolimen emphasizes the implications of population growth more than that of individuality. As observed through the active participation with a family of Lojolimen, the ‘American’ three bedroom track house (see figure 3) had taken the form of the traditional ‘big house’. Rather than a clustering of small huts around a central cookhouse and the elder’s house, each bedroom housed a couple and the children slept in the living room. The kitchen of this house was adapted by the family, but maintained the symbolic identity and location of the cookhouse.

On the other hand, Likin Atbwe demonstrates the role of the individualizing effect has on the land use of the weto. Each house on Likin Atbwe is owned by a separate nuclear family within the bwij and often each nuclear family has their own cookhouse or has adopted the use of the western kitchen. The fact that core patterns, such as the ‘cookhouse’ and the ‘big house’ continue to manifest, demonstrates their resilience throughout the cultural evolution. Even as the physical representation of space or material changes, the symbolic identity persists. How these patterns might be implemented within the design of a resettlement program would be dependent on a predictive model of change induced during resettlement. Their transformation, depicted in figure 4, demonstrates what could be expected in a post-resettlement community. While the pattern fits within a typical western house, the use of space and density of occupants is in opposition to standard land use codes and ordinances in the United States. This alludes to the necessity of policy leading the charge in allowing for more culturally supportive environments of climate refugees.

In considering cultural resilience, change is inherent as an adaptive strategy to disturbance regimes; therefore, culture change does not necessarily mean the loss of culture, but “a creative space where new forms of cultural understanding (and practice) are developed” (Wesson 2013, 108). Based on Wesson’s argument, investing in efforts to maintain cultural patterns to reduce the stresses on the health, well-being, and security of the displaced populations will not sustain the pre-displacement culture, but will provide a mechanism for mitigating further vulnerability to greater stochastic events in the post-resettlement system. In so doing, we can provide mechanisms that will most likely alleviate the shock and allow elements of the culture to persist – dependent on their desires in the evolution of their cultural identity. Understanding cultural patterns as elements that help support the continuity and enhancement of cultural capital, it is clear that ensuring the continuity is a necessity to create sustainable development and sustainable resettlement schemes.
Figure 3: The plan and aerial view of a house in Lojolimen. On the house plan: 1 = kitchen/ cookhouse, 2 = bedroom, 3 = living room, 4 = shop, 5 = lanai.

CONCLUSION
The developing pattern language, which demonstrates supportive socio-spatial relationships across time and space, will continue to be tested through follow up surveys and interviews in order to corroborate evidence. It is the intention to develop this pattern language as a working framework for both current land use and development projects in the Marshall Islands as well as potential resettlement programs. As the patterns become a participatory knowledge source from Marshallese communities, it provides a way forward within a participatory process to building consensus toward the design, planning, and policy making of future resettlement schemes. In addition, it provides a methodology for all future climate change induced resettlement programs to learn from and aid in their own efforts. The analysis of the established patterns is being incorporated into architectural design guidelines, aiding Marshallese place making. The goal of this research is to provide the necessary evidence for developing both design principles and policy concerning resettlement procedures in order to support cultural continuity through migration and lead toward more resilient and inclusive communities for environmentally displaced populations. If deep-cultural patterns manifest in the built-environment of the weto persist through time and demonstrate a high value in capital due to their resilience, than these patterns demonstrate a phenomenon that must be considered in any development project. The great difficulty will be to see how effective an environment based on culturally supportive principles will actually be at both mitigating vulnerability and supporting cultural continuity. Communities in locations such as the Marshall Islands are rooted in place; they “live in space: heavy, resilient, untouchable, which ties down time and keeps it beyond...control” (Bauman 1998, 88–89). This is a challenge that will require broader analysis of multiple global case studies between trans-local spaces. Even in light of trans-local place-making, these studies will not shed light on the generative capacity of a population that will no longer have a place to return as these studies have just begun. When a communities’ ‘local’ will be no more and transnational ties are severed, what roots will grow and how will they be nourished?

REFERENCES


ENDNOTES

1 This has been debated extensively across publications, conferences, and summits (Campbell 2012; Dema 2012; McAdam 2012).

2 The Sustainable Livelihoods framework was developed as a tool to guide research in Asia and Africa to explore routes for sustainable livelihoods for poor people in predominantly rural agricultural settings (McDowell 2002).

3 It is apparent that McDowell's methodology must be influenced by Friedman's (1987) description of transformative theory in radical planning.

4 See Rapoport's writing on 'systems of systems' as related to the culture-environment relationship for an explanation on the importance of looking beyond the dwelling (Rapoport 1990).
ABSTRACT: Approximately one-fifth of the planet’s geographical area is characterized by hot-humid climates, while being inhabited by one-third of the total world population. The majority of continental areas have weather conditions outside the thermal comfort zone. This has resulted in considerable and consistent increases in the use of HVAC mechanical systems, with its associated energy costs and environmental impacts, which potentially nullify the benefits otherwise achieved by the energy conservation policies implemented by many industrialized countries.

Much can be learned from the study of historical buildings where sensitive design approaches were implemented with respect to natural ventilation strategies. An excellent example of a passive stack effect design employing skylights to take advantage of convective air flow is found in the Kalteyer House located in San Antonio, Texas. San Antonio is situated in Climate Zone 2A, hot-humid. The house under analysis is a three-story plus basement, single-family brick residence, designed at the end of the nineteenth century in Richardsonian Romanesque style by the architect James Riely Gordon (1863-1937). Here, the difference in temperature and pressure between two different zones of the house, enhanced by the presence of the skylight, creates naturally occurring convection air flows without the aid of mechanical systems. Natural ventilation can be an incredible resource for implementing passive cooling of buildings.

This paper aims to investigate how to maximize the potential offered by these passive design strategies by developing an understanding of how they have been historically implemented, specifically in the Kalteyer House, and then exploring their potential as a valid alternative for achieving thermal comfort in newly-designed residential buildings. The effectiveness of this passive-cooling strategy is determined through an in-depth case study analysis and critical understanding of the passive system designed by James Riely Gordon, evaluated through CFD software simulations to determine how to maximize the potential of stack ventilation, which is currently underutilized due to the advent of mechanical-cooling systems. The goal of the analysis is to achieve the best performance in terms of thermal comfort with the minimum amount of energy consumption, thus reducing the resulting environmental impact.

KEYWORDS: Kalteyer House, historic buildings, natural ventilation, hot-humid climate, software simulation

INTRODUCTION
Approximately one-fifth of the planet's geographical area is characterized by hot-humid climates, while being inhabited by one-third of the total world population. The majority of continental areas have climate conditions outside the comfort zone. This has resulted in considerable and consistent increases in the use of heating, ventilating, and air conditioning (HVAC) systems, as well as their associated energy costs and environmental impact, potentially nullifying the benefits otherwise produced by energy-conservation policies implemented by many industrialized countries.

Much can be learned from the study of historical buildings where sensitive design approaches were implemented with respect to ventilation devices, such as passive stack effect convection-related air flow employing skylights, a method utilized in the 1892 Kalteyer House located in San Antonio, Texas, designed by the architect James Riely Gordon (1863-1937), renowned for his design of numerous courthouses across the nation.

This paper will report on and identify lessons learned from an interdisciplinary project aiming at identifying low retrofit for historic architecture in Texas, built prior to the introduction of mechanical systems. The project is involving researchers from architecture history, historic preservation and sustainability and aims to identify sustainable strategies adopted in historic buildings in order to utilize them to implement cost effective retrofit strategies for energy use reduction, while enhancing the unique typological and construction features of historic structures.

The architect James Riley Gordon specifically addressed the design challenges of the Southern climate in his courthouse and capitol building projects. In his technical correspondence, Gordon writes: “It is not difficult in the South to keep comfortably warm during the winter, but it is a monster problem to keep cool during the long hot summer” (Gordon,
1890–1937). Not as well known is that his stack-effect design was also used in other building typologies, such as the residence under analysis. The case study under analysis, the Kalteyer House, may have been a proving ground for the architect’s climate-responsive design ideas, leading to the development of a new, more sophisticated courthouse typology, such as the one Gordon proposed for Brazoria County in 1894.

This study investigates, through CFD software simulations, the passive-cooling design features of the Kalteyer House with the objective of verifying their effectiveness. This design is characterized by a ventilating shaft corresponding to the entrance hall which utilizes passive stack effect convection-related air flow.

1.0 BRIEF OVERVIEW OF THE KALTEYER HOUSE HISTORY
The Kalteyer House is a three-story, single-family brick residence, designed in 1892 in the Richardsonian Romanesque style by the renowned architect James Riely Gordon (1863–1937). It is located in the King William Historic District, one mile southwest of the Alamo, in the city of San Antonio, Texas.

Design and construction of the house was commissioned by George Kalteyer for his family. George Kalteyer (1849–1897) was one of the city's most successful businessmen in the final two decades of the nineteenth century, during which the city of San Antonio witnessed a tremendous growth and a thriving economy, largely due to the introduction of the railroad to the city in 1877. The King William neighborhood was a logical location for the wealthy son of German immigrants to choose for a homestead.

The neighborhood, in fact, was named between 1868 and 1873 in honor of Wilhelm I of Prussia. (Burkholder et al., 1973); still sparsely populated in 1873 (1873 Augustus Koch’s Bird’s-eye View of San Antonio), in few years it transitioned to an aristocratic community (1887 Augustus Koch’s Bird’s-eye View of San Antonio). Large, multi-story, masonry houses appeared, beginning along the river-side of King William Street. An eclectic array of architectural styles were employed, typical of this revivalist period. Known for its large population of successful German immigrants, the King William neighborhood soon became San Antonio’s most exclusive suburb.

For his new home at 425 King William Street, Kalteyer had the choice of a handful of architects who were working in San Antonio near the end of the nineteenth century. Kalteyer chose James Riely Gordon who in 1892 was beginning to eclipse also the city’s most prominent architect, Alfred Giles. During the same period that he was designing the Kalteyer House, Gordon was also working on two of his landmark commissions: the Texas Pavilion at the Columbian Exposition in Chicago and the Bexar County Courthouse in San Antonio (Meister, 2011). He had already designed several courthouses around Texas, which are also part of this research project.

Between 1830s’ and 1870s’, domestic architecture becomes a central focus both in the ‘quest’ of an American identity and for the development of main cities. The stylistic and decorative research characterizing such process certainly finds an important reference in the work of Henry Hobson Richardson (1838–1886) who introduces in American architecture the Romanesque style. This style, however, is not intended as an imported style, but as a ‘composition method’, which takes in consideration construction features, drastically reducing decoration to the essential. (O’Gorman, 1987)
In the Kalteyer house, the reference to Richardson style is evident both in the use of masonry masses made of stone and brick, interrupted by arches, towers and wide roofs, and in the use of architectural forms associated with typological and technological innovations, such as indoor ventilation system shaping the home’s interior layout.

The house is characterized by a combination between the authority of classical order and the dynamicity of the asymmetric form of the main façade, expressed by the volumetric masses' variation on the upper level. The authority of classical order is expressed through the use of binate columns and tympanum crowning the entrance, the asymmetric form is developed both in plan and in the elevation of the main façade, where a large conical tower is anchoring the east corner, and a slender octagonal belvedere marks the opposite side. Polychromatic voussoirs of white limestone and red sandstone, set against the yellow brick walls, create a dynamic and dramatic contrast between materials, volumes, solids, and voids.

This combination of classical and dynamic forms intimately ties the work of Gordon to the one developed by the ‘masters’ of American architecture, such as Richardson, Sullivan and the early works of Wright. The house, beyond its stylistic features, incorporates original elements of the architect’s design philosophy, including attention to light, structural design, and mechanical systems, including heating and anti-burglar systems, considered at that time the most technologically-advanced.

As the twentieth century progressed, and the original residents of the King William neighborhood passed away, many of the homes, including the Kalteyer house, were converted to low-income apartment buildings. Following designation of the King William neighborhood as a historic district by the City of San Antonio in 1967 and as a National Register Historic District in 1972, numerous houses were returned to their former splendor, and King William Street once again became a fashionable address. The Kalteyer House was restored with attentive philological attention by Mr. Sidney Francis in the 70s.

2.0 TOWARD A NEW UNDERSTANDING OF HISTORIC BUILDINGS
2.1. The building as a ‘direct source’

The study of ‘indirect sources’ should be intersected with the analysis of ‘direct sources’, the latter represented by the structure itself, in order to achieve a critical understanding of the unique building’s feature and its potentials. Indirect sources include bibliographical and archival research, comparative analysis of building typologies, decorative elements and construction technique, briefly presented in the previous chapter. (Morbidelli et al, 2012). The consultation of primary sources, ie. the archival documents in the Alexander Archive in Austin, Texas, allowed the team to bring new light on the architect’s main design interests, through his writing. The building, as a ‘direct source’, provides ‘intrinsic data’, meaning all possible information that the structure may display (De Angelis d’Ossat, 1995), in this case specifically focused on climate-responsive strategies utilized by Gordon.

This phase included the following activities:

1) An architectural survey of the building: floor plan, sections and elevations were recreated, using as a starting point archival drawings (Gordon, Alexander Archive) which were drafted in the 70s, after the house complete restoration. These drawings, never completed, were made by architecture students as a training for HABS drawings execution. New measurements were taken with a disto Laser Leika, integrated with tape measures.

2) A visual inspection: this activity focused on the identification the relevant building features where climate responsive strategies were applied, such as orientation, openings, shading devises, construction techniques, etc., and lack of major prior retrofits. A description of the passive design characteristics is included in Table 1. The inspection also aimed to identify major energy efficiency problems or deficiencies including presently major energy-consuming systems such as HVAC, as well as potential issues in the building envelope.

Table 1: Passive cooling techniques used in Kalteyer house

| THERMAL MASS | Load bearing masonry brick walls. Wall thickness: from 12 inches to 16 inches. The thermal mass results in a summer lag time that improves thermal comfort in the afternoon. |
| STACK VENTILATION | Entrance hall performs the function of a ventilating shaft, with a skylight composed of two openable windows. This is supplemented by window openings from the side rooms, connected to the central shafts through transom windows. |
| CROSS VENTILATION | On first and second floor, doors around the central ventilating shaft are aligned. Transom windows on each door ensure cross ventilation even when doors are closed. |
| HIGH CEILING | High ceilings allow for air stratification. Ceiling height for first and second floor: 11 feet and 6 inches |
2.2. Review of relevant literature

Existing residential buildings are conventionally considered less energy-efficient than new structures, since they were erected before energy-efficient standards were imposed. Some leading national and international organizations in North America and Europe have become engaged with their governments on the debate on how historic structures can be considered more sustainable, overall, than new constructions. The English Heritage was one of the first organization to claim that some historic structures are inherently climate responsive, utilizing specific construction techniques and materials, like in the case of “many vernacular styles that have massive solar gains, thick walls and small windows” (Berthel-Bouchier, 2013, p. 139).

Therefore, performances of historic buildings can be improved also through a deeper understanding of how historic structures are inherently climate responsive, in the effort to fit the precise standards for evaluating energy efficiency and carbon footprint, such as the ones provided by the U.S. Green Buildings Council’s Leadership in Energy and Environmental Design (LEED) (Berthel-Bouchier, 2013).

For different climate regions, several studies have been conducted on identifying appropriate retrofit strategies for existing housing (e.g. Florian et al. 2011, Parker 2001, Burgett et al. 2013), while very few focused on the analysis of passive design characteristics of historic homes despite their historical, cultural and social significance, both in hot and humid climate (Rashed-Ali et al., 2015; Dupont, 2016) and hot dry climate.

In cases of hot and humid climates, available studies focus on contemporary homes, investigating retrofit potentials through the installation of radiant barriers such as the one conducted by the Florida Solar Energy Center (Parker et al. 2001), or the one by Pacific Northwest National Laboratory, PNNL, the latter covering a high number of case studies (51 homes in total) located in marine, cold and hot-humid climates which also included three homes in San Antonio (Chandra et al. 2012).

A simulation-based approach was adopted by Burgett et al. (2013) to identify retrofit packages for existing homes in hot and humid climates in general. In this context, the analysis of integrated climate responsive strategies in historic homes is a clear addition to the current effort of improving energy performance both of historic and contemporary house stock.

3.0 CLIMATIC CHARACTERISTICS OF THE CITY OF SAN ANTONIO, TEXAS

The city of San Antonio, Texas, is characterized by hot humid climate. The eastern third of Texas has a Subtropical Humid climate that is mostly typified by warm summers, the central third of Texas, where San Antonio is located, has a Subtropical Sub humid climate characterized by hot summers and dry winters. The variation of climate types in Texas is caused by the physical influences of the State being located (1) downwind from mountain ranges to the west, (2) proximate to the Gulf of Mexico and the southern Great Plains, (3) west of the center of the Bermuda high pressure cell, (4) at relatively a low latitude, and by (5) the transitions in land elevation from the high plains and mountains to the coastal plains. These influences on the weather particularly affect the moisture content of the air-define climate. (Larking and Bomar, 1983, p. 3)

Average relative humidity in San Antonio is higher than 50% all year long, with peaks of 70%. Therefore, perceived temperature is far outside the comfort zone. According to ASHRAE Standard 55, comfort temperature, measured at dry bulb, must be within 68°F (20°C) e i 78°F (25°C), with relative humidity between 40-80%. Despite this, an analysis of the San Antonio Climate shows that a strong potential exists for achieving thermal comfort in significant portions of the year using natural ventilation. Figure three shows a monthly temperature range distribution compared to the adaptive comfort range for the city, in which we can see that average daily temperature fall mostly within and around the comfort zone in the summer months.
4.0 STACK VENTILATION IN THE KALTEYER HOUSE’S ENTRANCE HALL

The Kalteyer House incorporates climate-responsive design principles that the architect was experimenting and applying in the several Texas courthouses which he designed and built from 1888 to 1892, such as the one of Aransas county (demolished), Fayette, Erath and Victoria counties (Meister, 2011). In these projects he developed buildings constructed of solid masonry which incorporated “ventilating shafts and tower combined” in the center of the building (Gordon’s Affidavit in Meister, 2011, p. 290-291). In the architect’s correspondence, we learn that Gordon believed “The greatest consideration should be given in our mild climate to ventilation;” therefore buildings can be “especially designed with reference to its peculiar fitness for this climate” (Gordon, 1890-1937, AAA).

The floorplan of the Kalteyer House is a centrally-organized typology developed around the entrance hall and elevated upon a brick foundation incorporating a basement. The entrance hall performs the function of a ventilating shaft, similar to those which Gordon created in his courthouses. From this space the main stairwell leads to two upper floors. At each level, a distribution space serves the rooms. Doors around the central ventilating shaft are characterized by the presence of colored-glass transoms which open to take advantage of cross ventilation.
The entrance hall lies beneath a large, stained-glass, operable skylight, which not only brings light into the space, but also expels the rising air, thus preventing overheating in the attic space “between the top story ceiling and the roof thoroughly ventilated” (Gordon, Alexander Archive). Such a system is “preventing any accumulation of hot air and rendering the top story apartment as comfortable as those of the other stories” (Gordon, 1890-1937, AAA). The stack-ventilation effect relies on convection and occurs when cool air enters a home on the first floor or basement, absorbs heat in the room, rises, and exits through upstairs openings. Pressure differences, in fact, create convection air flows, producing a partial vacuum, which pulls more air in through lower-level windows. This effect works efficiently in open-air designs with operable skylights, as applied in the house under analysis, or also with windows such as clerestories located near the top of the space. Gordon describes the central space designed for one of his courthouses as follows:

“[i]t acts upon the same principle as a fire place with good draft, that some of you have probably noticed draw a piece of paper up the chimney, except this is larger scale and during period that there is no breeze, by opening the outside windows and transoms, and opening some windows as much as little circulation of air can be created as is desirable...” (Gordon, 1890-1937, AAA).

Gordon also explains that:

“This shaft can be made to draw thousands of cubic feet of air per minute from the outside of the building through these chambers as up this shaft.... This is not an experiment as the many letters from those who have occupied the completed buildings embodying this system will testify. This is the most practical, simple, effective and inexpensive system of ventilation” (Gordon, 1890-1937, AAA).

Figure 6 shows a section through the house which illustrates how the ventilated shaft is surrounded by stairwell leading to upper floors, the skylight has the dual role of illuminating the space and creating convective air flows.

Figure 6 and 7: Diagrammatic section through the Kalteyer house (Author, 2016) and the Design Builder whole building performance model.

5.0 CFD SIMULATION OF NATURAL VENTILATION

5.1. Software Simulations and Proposed Configurations

To test the effectiveness of the natural ventilation design solution in the Kalteyer House, a whole building simulation model was created for the house in the Design Builder Software (see Figure 7). The CFD module in Design Builder was then used to simulate the comfort conditions in the central space in the house using several configurations representing different scenarios for the use of the shaft and side openings. In total seven configurations were simulated. A brief description of these configurations is included in Table 1.
Table 1: Description of the CFD simulation configuration performed using Design Builder.

<table>
<thead>
<tr>
<th>Configuration Number</th>
<th>Configuration Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>Baseline configuration, both fireplace and skylight are closed. No air flow.</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>Only skylight open, no major airflow expected due to lack of inlets.</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>Both skylight and main entrance open. Entrance provides cool air inlet while warm air is exhausted through skylight.</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>Both skylight and main door open. Chimney open and assumed to work as a solar chimney acting as a second inlet.</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>Both skylight and main door open. Side entrance is also open to take advantage of cross ventilation perpendicular to the plane of the door/skylight (see plan in figure 2).</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>Same as configuration 5 plus opening the chimney,</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>Same as configuration 5 plus opening a window on the first-floor level to test the impact of air flow from higher levels.</td>
</tr>
</tbody>
</table>

Figure 8: Diagram of air flows generated on each floor to create Configuration 7, the one showing best simulation results (Author, 2017)

The simulation was only conducted in the affected rooms including the central shaft space, the stairwell, and the first-floor rooms. The dependent variables generated from the CFD simulation included relative humidity, air temperature, radiant temperature, operative temperature and dry bulb temperature. Operative temperature is the temperature perceived by the occupants.

The simulation was conducted for representative days in the summer months (June, July, and August), and the dependent variables were calculated at the levels of the ground floor, third floor, and the attic (skylight cavity), which represent the spaces most affected by the influence of air flow. Air speed was assumed to be zero for configuration 1 and between 20 – 40 fpm for the other configurations.

5.2. Analysis of results
The summary of the simulation results for all configuration is included in Table 2. Table 3 shows an analysis of thermal comfort parameters under the conditions generated from each simulation generated using UC Berkeley’s Center for the Built Environment (CBE) online Thermal Comfort Tool conducted at the first floor level. The analysis assumed a metabolic rate of 1.1 met and a clothing level of 0.5 clo. From both tables, we can see that none of the configurations results in thermal comfort conditions that would satisfy the ASHRAE standard. However, the best results are achieved in configuration 7, where the skylight, entrance, side entrance, and first floor window are open. Also, a comparison between configuration 2, in which only the skylight is open, and configuration 7 shows the positive impact that having multiple inlets at different levels can have to improve the impact of the vertical shaft on thermal comfort. Table 4 shows a comparison between the average summer outdoor dry bulb temperature and relative humidity compared with those achieved indoor using configuration 7. With regard to the impact of the chimney, the results showed no noticeable impact for opening the chimney on internal comfort conditions.
Table 2: Average June, July, and August results of CFD simulation for all configurations and zone

<table>
<thead>
<tr>
<th></th>
<th>First Floor Zone</th>
<th>Third Floor Zone</th>
<th>Attic Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{db}$*</td>
<td>$T_{op}$*</td>
<td>RH***</td>
</tr>
<tr>
<td>Configuration 1</td>
<td>83.2</td>
<td>83.6</td>
<td>58.3</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>85.7</td>
<td>86.0</td>
<td>57.5</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>84.9</td>
<td>84.9</td>
<td>64.4</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>84.3</td>
<td>84.8</td>
<td>64.5</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>84.3</td>
<td>85.1</td>
<td>64.5</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>84.3</td>
<td>85.1</td>
<td>64.9</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>83.9</td>
<td>84.5</td>
<td>65.5</td>
</tr>
</tbody>
</table>

* $T_{db}$ = Average summer dry bulb temperature. ($^\circ$F).
** $T_{op}$ = Average summer operative temperature ($^\circ$F).
*** RH = Average summer relative humidity (%).

Table 3: Resulting thermal comfort parameters for all simulated configurations

<table>
<thead>
<tr>
<th></th>
<th>PMV*</th>
<th>PPD**</th>
<th>Thermal Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>1.25</td>
<td>38%</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>1.55</td>
<td>53%</td>
<td>Warm</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>1.45</td>
<td>48%</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>1.38</td>
<td>45%</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>1.43</td>
<td>47%</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>1.43</td>
<td>47%</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>1.12</td>
<td>32%</td>
<td>Slightly warm</td>
</tr>
</tbody>
</table>

* PMV = Predicted Mean Vote.
** PPD = Percentage of people dissatisfied.

Table 4: Average summer outdoor conditions compared with average results of configuration 7

<table>
<thead>
<tr>
<th></th>
<th>$T_{db}$ outdoor*</th>
<th>RH outdoor**</th>
<th>$T_{db}$</th>
<th>$T_{op}$</th>
<th>RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Floor Zone</td>
<td>90.9</td>
<td>67%</td>
<td>83.9</td>
<td>84.5</td>
<td>65.5</td>
</tr>
<tr>
<td>Third Floor Zone</td>
<td>90.9</td>
<td>67%</td>
<td>86.1</td>
<td>87.2</td>
<td>60.4</td>
</tr>
<tr>
<td>Attic Zone</td>
<td>90.9</td>
<td>67%</td>
<td>88.3</td>
<td>91.1</td>
<td>56.6</td>
</tr>
</tbody>
</table>

* $T_{db}$ outdoor = Average summer outdoor dry bulb temperature. ($^\circ$F).
** RH outdoor = Average summer outdoor relative humidity (%)

These results show a clear positive impact from the use of natural ventilation in the Kalteyer House. While it may be difficult for contemporary houses to completely rely on natural ventilation for cooling throughout the overheated season in a climate such as San Antonio, these results demonstrate the potential for passive cooling through natural ventilation to be used for at least part of the time, which could result in significant reductions in energy use, emissions, and utility costs.

CONCLUSION

This study shows that much can be learned from the study of historical buildings, where sensitive architect-designed environmental strategies were implemented with respect to ventilation devices in order to mitigate the problem of summer heat in hot climates. Environmental and climate-adaptive strategies have been used since antiquity, including
in Eastern building tradition as well as in some ancient hypogeaem or earth sheltered constructions. Analogous approaches have been also historically used in vernacular buildings in the hot and humid climate of the southern United States, with the adoption of architectural elements such as cupolas, wide central halls, dog-trot plans, etc., to enhance ventilation for cooling and, in some cases, de-humidifying the air. The archival and bibliographical research showed that passive cooling ventilation strategies were also adopted in 19th century architectural design, mostly considered by scholars only for its stylistic peculiarity. The architect James Riely Gordon specifically acknowledged in his projects and writings the issues related with the extreme summer heat characterizing Texas's weather, which resulted in the development of specific buildings typologies of courthouses. These typologies included 'signature plans' integrating ventilating shafts and combined towers to create stack ventilation effect, as well as solid masonry buildings to ensure high thermal mass.

Literature review also shows that the whole-building ventilation strategies in nineteenth century context were not only aimed at cooling. In addition to that, great emphasis was in fact given to providing healthy 'sanitary conditions', since the pivotal 1842 Edward Chadwick's report on health sanitary condition of working class (Frederick- Rothwell, 2015). This debate became international and involved not only architects but also experts in the newly created 'sanitary science' and can be well grasped reading professional discourses published in late 19th century American architectural journals (Frederick- Rothwell, 2015).

Further, the results of the CFD computer simulation reveals that the entrance hall of the Kalteyer house, which is characterized by a ventilating shaft, most effectively works when an air flow is generated through the opening of a door or window at the building lower level as well as windows at upper levels. Achieving the best results required keeping the skylight open. The simulation results also clearly show that in the case in which only the skylight is opened, no effective naturally occurring convection flows are created; therefore, no impact is achieved in terms of improving occupant thermal comfort.

The simulation results however show that only one of the created configurations, configuration seven, achieves notable improvements of environmental conditions, as defined in ASHRAE Standard 55, and that Gordon's passive cooling system is not able to reach contemporary comfort conditions during the hottest months of the year without the aid of mechanical systems both with regard to temperature and humidity. However, the improvement shown in configuration 7 still indicated a potential for passive cooling through natural ventilation to contribute to the cooling of the house and potentially reduce the need for mechanical cooling in some parts of the year. Given that cooling represents the largest residential energy end use in this climate, such a mixed mode system could lead to notable reductions in energy use, emissions, and utility costs. Such a system could also be very useful in low income situations in which utility costs represent a significant portion of the family's disposable income where even small reductions in utility costs can have a considerable positive impact.

This paper represents part of a larger investigation aiming to analyze the potential of passive cooling strategies used in the Kalteyer House. Other ongoing phases of the project include the following:

1. Empirically testing the effectiveness of the passive cooling strategies in the home through monitoring the internal environmental conditions that exist through a network of sensors and conducting experiments in which the existing mechanical system is turned off and different configurations of opening and closing doors, windows, and skylights are investigated. The conditions in the house will be monitored during the hottest period of the year, which will allow the research team to compare the simulation results and the monitoring data. In addition to validating the results, this will also allow for evaluating the effectiveness of the CFD simulation, which relied on average climatic data.

2. While the ventilation rates associated with strategic passive designs such as utilized at the Kalteyer House may effectively address issues of occupant comfort, there is a directly related secondary issue that will be addressed in another future study phase, which is: Indoor air quality (IAQ). In the era in which this house was designed and built, there were different concerns about the quality of air with respect to actual occupant health, which concerned 'hygiene' and 'healthy air' to fight infectious diseases considered as a real threat. Current norms accept the association between air exchange rates and IAQ. That being the case, investigators will include monitoring of common poor IAQ markers such as carbon dioxide, VOCs, gas and bioaerosols.

3. Additional simulations will be conducted to investigate how to jointly use passive cooling ventilating shaft and mechanical air conditioning system to reduce the HVAC energy consumption, both achieving comfort conditions and minimum energy use in the hottest periods, responding more favorably to the requirements of energy-saving policies.

ACKNOWLEDGEMENTS
Special thanks and gratitude to the present owners of the Kalteyer house, Gina Walter and her husband John Hughes, for giving us the opportunity to use their home as a case study. Thanks to Mr. Sidney Francis, who restored this building.
in the 1970s, for providing us important information on the transformations of the house throughout time and its energy performance. We also gratefully acknowledge: Nancy Sparrow, curatorial assistant of the Alexander Architectural Archive, University of Texas at Austin, for sharing with us Gordon's archival material and for her insight.

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Meredith Sattler
'California Polytechnic State University, San Luis Obispo, California

ABSTRACT: This paper examines relationships between conceptual and spatial boundary conditions as they produced knowledge, processes, communication, and frontiers at Biosphere 2 [B2]. B2 created a novel architecture, one that simultaneously addressed symbolic and molecular criteria. The architectural-apparatus of B2 was constructed as a laboratory to house a microcosm of Earth's ecosystem service provisioning processes for eight people, over two year intervals. Over 3,600 species were intentionally and unintentionally entangled within a 'Human Experiment' designed to test eco-technical applications for long-duration outer space colonization. Boundaries were essential to the project's design, construction, and enclosure experiment. They both facilitated and undermined the experiment's success architecturally, scientifically, and culturally while creating inherent tensions through the delineation of edges driven by conceptual boundary conditions, often determined utilizing Ecological Systems Theory and diagramming practices. In the case of B2, the primary boundary manifest as the physical bathtub-space frame building envelope which facilitated unprecedented potential for quantification and categorization of molecules in the gas phase. For B2, this boundary was considered necessary for scientific inquiry during 'The Human Experiment,' and produced intense design, construction, and maintenance challenges. Once complete and sealed inside, an edited and enhanced Earth, shrunk 30 trillion times, began to evolve. Through the demarcation and analysis of B2's boundary conditions and their dynamic qualities, which frequently demanded redefinition, this research unpacks relationships between architectural envelope conditions, transitional spaces, scientific theory, body/organism skins, and biogeochemical processes to reveal findings related to the entangled anthropocentric condition architectural occupies today.

KEYWORDS: Biosphere 2, Boundary Conditions, Anthropocene, Posthuman, Transhuman


In 1990, amidst saguaro cacti and roving bands of javelina, a hybrid construction crew of professionals and a unique group of visionaries raced against the sun's daily trajectory to assemble the tightest building envelope ever constructed. Biosphere 2 [B2] emerged as a stainless steel lined concrete bathtub with space-frame topper, which would enclose a 3.14 acre area containing approximately 7 million cubic feet of air, inorganic matter, and biomass [Dempster, 1999]. B2's first closure experiment, Mission 1, commenced at 8:00 am September 26, 1991 and terminated at approximately 8:20 am September 26, 1993. It:

...was designed to operate for 2 years with a crew of eight healthy ‘Biospherians' with the aim of supplying the entire food needed for the crew, maintaining a 200 m3 atmosphere with safe levels of trace gases, complete recycle of human and animal wastes, and recycle of water, and a minimum leakage of air... and if it failed any of these aims, to analyze the causes to improve the apparatus. [Allen + Nelson, 1999, 17]. Functioning simultaneously as a venture capital project for long-duration space colonization, a large-scale ecological laboratory, and a social-ecological experiment, in the end only two missions occurred out of the 50 conceived as a continuous chain of 2 year duration experiments.

During its enclosure missions, B2 operated as the tightest material boundary condition ever constructed at architectural scale. When sealed, it facilitated energetic and information exchange from the sun and digital communications, while exchanging less than 10% of its atmosphere with earth annually, [Dempster, 1994] compared to the Space Shuttle which exchanged 10% of its atmosphere with outer space daily. It created a microcosm of Earth, an energetically open but materially closed system that produced an evolving biogeochemistry that increasingly diverged from Earth's as the experiment progressed. Its interior can be thought of as a molecular economy composed of select components of our planet's matter, in liquid and gas phases, that produced accelerated biogeochemical cycling: “It's small enough that things happen fast...because it's so small, you could see immediate changes” [Alling, 2015].

B2's enclosure demarcated a novel boundary, one that facilitated the measurement of environment according to productivity, and human bodies according to health and toxicity, which the Biospherians' conceptualized utilizing Ecological Systems Theory [EST]. EST, with its quantified flows of energy and matter, shifted the project's units of measurement from surface area to the more refined unit of volume. This 3-D, 'quantum' condition, generated to test
the ‘The High Frontier’ of outer-space through the integrated process of instrument and experiment design, demanded new mappings of flows and devices for data collection and processing, novel hybrid eco-technical programs and infrastructures, and a unique culture of sustainable stewardship.

1.0 DEFINING BOUNDARIES, CREATING FRONTIERS

1.1. The Science of Ecological Microcosms

EST was largely developed in the late 1950’s, and once put into practice at the Odum’s labs and beyond, began to evolve. The first of its evolutions influential for B2, was originated by the Head of the University of Hawaii’s Exobiology Laboratory, Clair Folsome who was ‘bottling’ ecological samples from aquatic environments across the globe containing “… complete functional suite[s] of microbes together with [water and air]… inside a closed laboratory flask…” [Allen 1990] (Fig. 1). These ultimately became the diagram and model for B2 and its missions. Ironically, the first one was sealed in 1968, one year before Apollo 11 landed on the moon. Folsome’s inauguration of the science of closed ecological systems allowed him to quantify, to “…measure oxygen and carbon dioxide levels, study energy flows and visually observe changes” [Allen, 1990]. By doing so, Folsome not only furthered EST, but simultaneously propelled a long trajectory of the study of microcosms, dating back to the Ancient Greeks [Conger, 1922]. Many of these Buchner flasks are now located at the B2 facility and are still living dynamic microcosmic systems.

Based on Folsome’s observations, and EST, the Biospherians convened a series of conferences, which furthered the theory and practice of Ecological Microcosms, and simultaneously B2’s design. These became incubators for a number of scientists from a wide range of disciplines to further closed-ecological systems ideas such as Harold Morowitz, Walter Adey, and others. Morowitz, a biophysicist, served on B2’s Scientific Advisory Committee, and utilized B2 to test his theories related to the application of thermodynamics within living systems. Adey, an algal ecologist, built a variety of experimental aquatic ecosystem microcosms and mesocosms during the 1980’s and 1990’s at the Smithsonian Institute to test the most efficient photosynthetic systems on Earth. He was put in charge of designing the aquatic systems at B2.

In 1993, less than 2 years after Mission 1 began, Robert Beyers and Howard Odum, officially inaugurated their new scientific discipline by publishing a 500 page volume titled ‘Ecological Microcosms.’ The book spans theory and practice, utilizes EST diagrams to illustrate phenomena, and contains chapters on aquaria, stream microcosms, terraria and soil microcosms, wetland microcosms, ponds and pools, reefs and benthic microcosms, plankton columns, and thermal and brine microcosms. There are detailed technical drawings of these eco-technical microcosm apparatus along with an appendix entry devoted to “Experiments on the Closed Ecological System in the Biosphere 2 Test Module” [Beyers + Odum, 1993] (Fig. 2). Perhaps most significantly, their work explicitly linked ecological system boundaries to the environments/apparatus that contained them.

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**Figure 1:** Clair Folsome with one of his experimental ecospheres. Source: (Biosphere 2 archive, University of Arizona)

**Figure 2:** The Biosphere 2 Test Module, circa 1988. Source: (Biosphere 2 archive, University of Arizona)
1.2. Boundary in Ecological Systems Theory

The Biospherians had tacit knowledge of relationships between resources, productivity, and boundary necessary to choreograph long-duration colonization. They had spent years restoring degraded landscapes around the globe [Allen, 2009], which would later become the models for B2’s five wilderness biomes: rainforest, desert, savanna, marsh, and ocean. B2’s experimental aims produced a new type of enclosure, a new type of interiorized frontier, which demanded new forms of measurement. Early on the Biospherians’ identified the Odum’s Ecological Systems Theory [EST] diagramming as critical for accomplishing this measurement, necessary for actualizing their integrated vision. EST developed methods to trace and quantify flows of energy and matter through environments, not just representing them as taxonomies. Howard and Eugene Odum, the founders of EST, conceptualized environments as systems of energy flow, initially through ecological food webs. In their work, they traced ninety-nine percent of the energy pulsing through matter on Earth back to its source, the sun, and developed a universal measure of energy, the emjoule unit, which created a solar equivalency for all previous units of energy. The emjoule was utilized to specify and calculate energy moving through a system, which first required drawing a clear boundary around the system. Once an appropriate boundary was determined, the energy/matter relationships within that boundary were depicted utilizing three linked methods: a flow diagram which visualized all components in the system and their linkages, a set of equations that quantified the energy movement through time, and a graph of the equation which visualized the relationships between the flows through time.

Through the Biospherians’ visionary eyes, this process could not only describe the world, but could also facilitate its redesign. EST’s method of diagramming ultimately became the generative design tools of B2. It allowed for existing geographically-based biomes to serve as models for B2 biomes, not “…artificial simulacrum…based on statistically-determined collections of plants…” [Allen, 2009, 162] by facilitating methods for quantification of the ecosystem service provisioning of these landscapes, necessary for their long-term performance and production. It simultaneously became B2’s language of inquiry because it was easy for scientists previously unfamiliar with it to learn, and it served to erase disciplinary boundaries, to some extent, by converting them into energetic terms. In the end, it also produced results that the Biospherians living inside would later describe as ‘beautiful’:

We had the most perfect nutrition recycling system in that everything at some point went back into the soil. And by the time it was finished in ’91, already the biomes were taking form, and you could begin to see how they were going to look and they were starting to mature. So what we moved into in 1991 was a very, very beautiful thing, a very beautiful space [Silverstone, 2015, 10:25-10:55].

1.3. Envelope as Boundary

Because B2’s envelope was conceived and constructed as a materially closed by energetically open boundary condition built to operate as an experimental apparatus for 100 years, the quality of B2’s envelope engineering, materials, construction techniques, and post-construction commissioning were impeccable. Composed of an underground bathtub style liner of 3 mm thick ‘super’ stainless alloy Allegheny Ludlum 6XN which lines a concrete slab containing 2.5cm diameter sniffer tubes (installed behind each weld to monitor them for leaks). Capping this bathtub is a glazed space-frame skin composed of approximately 16,000m2 of double pane laminated safety glass sealed within steel tubes, set inside aluminum flame sprayed/powder coated space frames that are double sealed with approximately 30 km of silicone [Dempster, 1999].

Because B2 was so airtight and subject to fluctuating temperatures and humidity, it required additional mechanics in order to keep the laminated glass space frame skin from exploding during sun-filled desert days. So B2’s boundary also included the first variable air volume pressure relief structures of their kind, endearingly referred to as The Lungs. These domes are attached as appendages to the main structure. Each is comprised of a protective layer that houses a continuous airtight hypalon membrane weighted in the center by a 20 ton aluminum disc. The membrane/disc unit rises and falls as air expansion and contraction occurs, maintaining a relatively constant air pressure inside. The lungs facilitated a combined expansion capacity of approximately 43,000m3, adding about 30% additional volume to the structure when fully inflated. Depending on pressure differentials, as much as 0.5m3 per second of air would move between B2 and the Lungs [Zabel et al, 1999] creating a gentle breeze.

1.4. Boundary Defines Frontier

The history of the relationship between boundaries and frontiers in American culture is rich and entwined within B2’s conceptualization of boundary condition, resource management, and frontier. It can be traced back to the 1803 Louisiana Purchase, which almost doubled the American landmass overnight. The acquisition exacerbated problems that Americans’ east of the Mississippi had contended with for years: accurate surveying. Of all the methods employed, including triangulation, Andrew Ellicott’s proved to be the most accurate by employing an equal-altitudes telescope for star and moon observation [Linklater, 2007]. It was only through the view off the planet that precise Cartesian measure on the planet’s surface was established. (Ironically, the Biospherians’ view off the planet, to Mars, also reflects this clearer conception of the Earth from the vantage of outer space.) Years later, one of the architects of B2, Phil Hawes,
would re-contextualize this relationship between boundary and measure on the Earth's surface through understandings of waste in the environment. He wrote

A human in Earth’s biosphere cannot see to the boundary of the biosphere—or even the bounds of the biome or eco-region he or she is in. Biosphere 2 and even smaller ecosystems, such as the Biosphere 2 Test Module, put the boundaries of the whole and the relation of the parts into a clearly visible paradigm or model that hopefully delineates the ethics and necessity of an ecological lifestyle for inhabitants of a biosphere [Nelson, et. al, 1990, 66].

Both surveying [which is concerned with quantifying 2-dimensional surfaces, and B2, which is concerned with quantifying 3-dimensional volumes] utilize forms of visualization to conceptualize earth scales and processes within human scale. This act of visualization, pared with quantification, proved essential to the visioning and design of B2.

The Biospherians were not unprecedented in their contextualization of resources as contingent with other, three and four dimensional methods of quantifying the environment. The climate of western North America seems to engender similar conceptualizations despite the fact that pioneers of European descent often saw western lands as endlessly resourced during their westward expansion. Inevitably this proved devastatingly inaccurate. Even prior to Ellicott's time, select westerners had clear conceptualizations of the pressing issues unique to life on their side of the 100th parallel related to resource availability, and the disconnect between their landscape and the Rectangular survey overlaid upon it, that was developed in the East. When the first Americans of European descent arrived in Mexico, they found that Mexicans had adopted the Spanish tradition of measuring the land via fanega, “...a measure of about 2 bushels—meaning an extent which two bushels of wheat will suffice to sow” [Gregg, 1845, 152]. A measure of land based not on surface area alone, but on a relationship between surface area and agricultural productivity. Major John Wesley Powell's report from the field dealt directly with water resources in the West's arid environs,

...plea[ding] for adjustment of land laws to fit geographical conditions, explaining that in a region where water, not land, was the major resource, different regulations were essential for survival [Powell, et. al., 1879].

Even at the end of the century, Woodrow Wilson's lament in the Atlantic Monthly clearly demonstrates that that Americans had yet to learn the lesson:

We have left the manner of boundaries to surveyors rather than to statesmen, and have by no means managed to construct economic units in the making of States. We have joined mining communities with agricultural, the mountain with the plain, the ranch with the farm, and have left the making of uniform rules to the sagacity and practical habit of neighbors ill at ease with one another [Wilson, 1897].

1.5. Boundary Defines Enclosure

As the Western frontier's edge continued on its march, the Rectangular Survey's lines transitioned from an edge facing an unknown, to divisions between known entities which demarcated rectangular enclosures. When barbed wire arrived at the frontier in the 1880's which facilitated the physical manifestation of enclosure through the extrusion of fences that chopped the once open range. Fences removed resources from the common pool, re-casting them as private goods. This facilitated an inward turn, farmers and ranchers began to understand their properties as semi-autonomous, closed-loop productive landscapes, similar to their British counterpart, the Estate. But the homestead was more than a landscape of production, it was also a cultural core, and as the Western Pioneers turned inward they brought their values and habits with them.

Pioneers welcomed wild country as a challenge. They conceived of themselves as agents in the regenerating process that turned the ungodly and useless into a beneficent civilization [Nash, 1967, 43]

But the freedom of the ever expanding edge encountered the limit of the Pacific Ocean, which proved both a spatial and psychological limit. By the early twentieth century much of America's western land-grab was complete, and the violence of the frontier had largely turned its face inward, to a new frontier, the dense spaces of socio-economically hierarchied urban cores.

Post two World Wars and two decades of prosperity, the U.S. was anxious for a new, virgin frontier, one that would ultimately prototype B2. In September of 1962, from within Rice University's stadium, J.F. Kennedy cracked open that next frontier by claiming that

...what was once the furthest outpost on the old frontier of the West will be the furthest outpost on the new frontier of science and space. Houston...with its Manned Spacecraft Center, will become the heart of a large scientific and engineering community [Kennedy, 1962].
Thus the race to the Moon was launched, defined by the critical need for boundary layer between human life-support system and the violent void of outer space. While the short-term moon missions would be accomplished eight years later, they are relatively straightforward operations compared to the long-duration, remote space colonization that B2 was prototyping.

1.6. Living within the Diagram

Once fluency in the Odums' Ecological Systems methods was established, the Biospherians were choreographing the creation of their new oikos, their new house, with a host of ecologists, biologists, engineers, architects, and landscape architects collaborating on the design and construction of seven fully operational biomes. Within B2's autonomous eco-technical ecosystem service packed mini-earth arc, a new species of frontier was born, an applied science of non-geographically situated environments where chemical cocktails cycled rapidly. This, in combination with the ever-present gridded glass megastructure space frame produced transference and indeterminacy between interiority and Biosphere 1 'outside' [Lavin, 2004], and a dream-like alternate reality that chemically morphed space, time, and explicit boundary conditions somewhat analogous to the hypnotic quality of Folsome's sealed Buchner flasks. His self-organizing, sustainable ecologies not only furthered scientific inquiry, but also predated, and resonated symbolically with Apollo 17's first photograph of the sphere of the Earth surrounded by the void of space, which ultimately unleashed a new holistic paradigm. Folsome's flasks became functional models, and simultaneously symbols of Earth's materially closed system. Ultimately, they became the model for B2, the largest materially closed, energetically open mega-structure ever built.

With the conceptual model in place, EST's tripartite method of diagramming and budgeting ultimately became the primary generative design tool of the interior, which would later contribute to the production of a scripting of the behaviors of the building's inhabitants. Throughout the evolution of B2's eco-technical architecture and landscape, ESTs functioned as design predictions, as scientific depictions, as scripts, 'Rosetta Stones' of communication, and as signifiers of co-production. Largely, EST diagramming facilitated whole-systems thinking and interdisciplinary design across the range of experts working on the project.

Ultimately, because the Biospherians' inside during Mission 1 contributed extensively to the design process, this research argues that the knowledge they accumulated from the design phase significantly influenced their modes of habitation, environmental management, and research once inside. They had to tread between idealized conceptual mappings of EST energy/matter flows, and the realities of material frictions, and between cognitively dissonant modes of operation as posthumans and transhumans, which had significant ethical and procedural implications. These were particularly evident as they grappled with realizing anthropocentric motivations inherent in Vladimir Vernadsky's environmental ethic of Noösphere [Vernadsky, 1945], which the Biospherians' adopted as a guiding principle and diagrammed into their overall microcosmic system (Fig. 3).
EST also facilitated a more intimate knowledge of molecular and energetic exchange, which caught all of B2’s species within a cybernetic web of co-production and ‘unnatural’ sites of agency. The Biospherians’ were not completely unaccustomed to this habit of mind, their intentional community had a history of structured practices of tacit knowledge acquisition, largely based on theatrical performance, the rigorous production of crafts, and ecological restoration [Reider, 2009]. EST’s synergetic logic, methods, and nomenclature resonated with the Biospherians’ modus operandi, and further facilitated their deep engagement with the experiment through simultaneously visual, quantitative, and integrative modes of design, knowledge production, communication, and lived-experience.

2.0 BOUNDARY BLUR

2.1. Biospherian Co-Production: Bodies and Minds

The relation is the smallest unit of analysis, and the relation is about significant otherness at every scale. That is the ethic, or perhaps better, mode of attention, with which we must approach the long cohabitings of people and [other species]. [Haraway, 2003, 24]

Because the Biospherians had co-created the design and construction of B2, which they came to endearingly refer to as the ‘9th Biospherian’ once the Mission 1 crew of 8 was sealed inside, they leveraged an immense intellectual knowledge of their environment. While the rest of their team looked in from the other side of the glass, and through electronic communications, the Biospherians inside were experiencing unique embodied relations with the other species, and the larger biogeochemical cycling.

We could traverse the closed system, touch the space frame and cement floor, remember how the biomes were created, and visualize the entire world we lived and breathed for 2 years. This provided powerful insights about Biosphere 2 that would not have been fully possible if we did not have the opportunity to participate in its design and construction...Because of this, we were there to learn about the system we had created and let the complex nature of this coherent closed system teach us about its dynamic cycles. It was an unprecedented 2-year experiment between the observer and the observed due to the length and comprehensive design of the experiment. The observer was part of the experiment, the cooperative manager, observing it as part of a process [Alling, et. al., 2002, 74-5].

Simultaneously, as with many complex designed systems, the project was continually fraught with parallel tensions between alternate perspectives. In this case, they often manifest as disjunctions between ideological motivations.
and environmental realities. While the privileged view, described by Alling above, was deeply satisfying, the same EST diagrams, which facilitated this view through its inscription within the mind’s-eye of the inhabitants, ultimately influenced their behaviors. This created significant critical tensions related to the objectivity and ultimate validity of the scientific experiment.

We knew how Biosphere 2 was designed, where its boundaries reached, how finite its resources were, and in what ways our daily actions impacted this miniature world. In time we learned how to live with this evolving system, and become stewards of its well being. This experience brought a shift in consciousness, similar to the ones the astronauts experienced, we became part of this unique, manmade biosphere. Our health and well being was synonymous with the health of Biosphere 2. [Alling, 2015, 2:00-2:32]

The Biospherians were split between their embodied experience, the roles they were to play as scripted by EST diagram flows, and the objective mental space they were expected to maintain as scientists. As it became more and more difficult to disentangle the many roles the Biospherians assumed within the experiment, and the exhaustion resulting from intense manual labor on a low-calorie diet accumulated, the intellectual, emotional, and spiritual boundary-wall between the humanities and the sciences within them began to dissolve. With it, the Biospherians inside were stripped of their power as independent pioneers within their frontier, and within the scientific community they had worked so hard to assemble. They were increasingly subsumed under the control of their management, their Scientific Advisory Committee, and the media outside.

2.2. The Cyborg and Companion Species
This research argues that they had been conceived as, and had become cyborgs, but in the process had actually shifted into a more emotionally entangled relationship with the 9th Biospherian, thereby aligning themselves as companion species in addition.

Cyborgs are ‘cybernetic organisms,’ named in 1960 in the context of the space race, the cold war, and imperialist fantasies of technohumanism built into policy and research projects...Telling a story of co-habitation, co-evolution, and embodied cross-species sociality, [the Companion Species Manifesto] asks which of two cobbled together figures—cyborgs and companion species—might more fruitfully inform livable politics and ontologies in current life worlds. These figures are hardly polar opposites. Cyborgs and companion species each bring together human and non-human, the organic and technological, carbon and silicon, freedom and structure, history and myth, the rich and the poor, the state and the subject, diversity and depletion, modernity and postmodernity, and nature and culture in unexpected ways. Besides, neither a cyborg nor a companion animal pleases the pure of heart who long for better protected species boundaries and sterilization of care. [Haraway, 2003, 4]

Both the Biospherians and Haraway have concluded that “art and engineering are natural sibling practices for engaging companion species,” [Haraway, 2003, 22], to dramatic effect. But technocratically driven design doesn’t necessarily produce empathy and ethic, necessary for achievement of one of the ultimate goals of the Biospherians: to prototype not only eco-technical apparatus, but also manifest a culture of environmental ethics that:

...produced new understandings for artists, philosophers, scientists, explorers, managers...and even mystics to raise their disciplines to new levels of integrated complexity that can help create new cultures and strengthen old cultures...to transform Homo sapiens into a creative collaborator with biospheres, rather than a parasite weakening the host. [Allen + Nelson, Space Biospheres, 55]

During the missions, the Biospherians may not have fully understood the implications inherent in the creation of the deep relations [as simultaneously the smallest unit of analysis and as emotional entanglement] they were structuring. Not only were the mission's inhabitants:

“Biological organisms...becoming] biotic systems, communication devices like others. There is no fundamental, ontological separation in our formal knowledge of machine and organism, of technical and organic...one consequence is that our sense of connection to our tools is heightened.” [Haraway, 1984, 177-8].

But they were collapsing into cybernetic systems with their environments and the experiment, which rendered them blurry boundary objects that susceptible to increasing presence and exceedingly fragile states of existence. Tensions between landscape, labscape, demonstration, and domestic space inside B2 were palpable; a new species of internal frontier, visible from all sides within B2's glass space frame.

While this completely constructed synthetic environment produced a laboratory capable of generating a
Within B2's entirely synthetic space, it was impossible for the Biospherian scientists to "...remain stable individual entities that are separated out from other objects in the laboratory" [Knorr-Cetina, 2009, 146]. Instead, at any given time, some of their features may be coextensive with those of objects, coupled, or they might 'disappear,' as individuals altogether. Because of B2's undeniable "...reconfiguration of the natural and social order..." [Knorr-Cetina, 2009, 142], the space inside cannot just be understood as an improved natural order, or society, but must be seen as a highly controlled "...'upgraded' social order..." Knorr-Cetina, 2009, 146] within a laboratory context. The Biospherian's experiment was deeply entangled, in part because their Labspace existed somewhere between the programs of a large lab-bench, their life-support system, and their 'home.' Their rhetoric and representational strategies for multiple diverse audiences, (including themselves) were multivalent, ranging from quantitative analysis of sensor data to paintings to conceptual films, and very specific to their specific circumstance.

It is possible to unpack how components of their particular mix of species, technologies, bodies, and matter/energy evolved or co-created, and contrasted their localized condition of situated data collection with their more basic-science driven desires for universalizable data. While long-duration eco-technical space capsules may be reproducible and optimize in theory, in reality they are each very specific entangled environments, or superorganisms, that diverge once enclosed, and evolve into their own specific socio-technical ecologies. Knorr-Cetina describes how comprehensively this phenomenon operates within a scientific laboratory, where it appears there is less entanglement between scientists, environment, technology, culture, and experiment:

...ontologies of organisms and machines that result from the reconfiguration of self-other-things [are] implemented in different fields, the use of 'liminal' and referent epistemologies [are used] in dealing with natural objects and their resistances, strategies of putting socially to work through the erasure of the individual epistemic subject and the creation of social 'superorganisms' in its place, or the use of equipment as 'transitional' objects. [Knorr-Cetina, 2009, 158].

Ultimately at B2, this resulted in a new frontier of science, a techno-quantum space where objective measurement could not be qualified as such without a situational scaffold; a scaffold that was equally in danger of collapsing. Ecological systems diagrams, with their understanding of enclosure as a critical component of the energy budgeting process, inherently fold identifiable components of this situational scaffold into their forms of measurement, but only as long as their boundary conditions remain intact. Once "...the sign and the flesh are one" [Haraway, 2003, 17], the boundary dissolves, and the production of objective science is rendered impossible.

But is this a problem, or has it been just a less acknowledged reality of living while questioning all along? And what are the implications for the design of resilient, long-duration environments in the age of the Anthropocene, the Capitocene, and the Chthulucene? [Haraway, 2016]. Arguably, today we all operate as cyborgs, and are therefore subject to risks born of political mishandlings of agency in relation to indeterminacy, and their unintended consequences. As designers working from within entangled systems, tools like EST diagramming are powerful frameworks for mapping relations and locating leverage points within systems. But it is only at the point where one can see the system, by first constructing it, that one can then view how it falls short as the boundaries upon which it was based dissolve.

"Lacking symbolic mastery of the schemes and their products—schemes which they are, products which they do—the only way to which agents can adequately master the productive apparatus which enables them to generate correctly formed ritual practices is by making it separate.48 This is what the observer is likely to forget, because he cannot recapture the logic immanent in the recorded products of the apparatus except by constructing a model which is precisely the substitute required when one does not have [or no longer has] immediate mastery of the apparatus." [Bourdieu, 1977, 123]

A REHEARSAL OF THE ANTHROPOCENE?
The same year that Apollo II landed on the moon, John McHale’s “The Future of the Future” was published [McHale, 1969], which laid out a deterministic view of the technological path to space colonization. Less than a decade later, ‘Space Colonies’ had captured the American imagination as evidenced by the publication of “The High Frontier” [Gerard K. O’Neill] in 1976, and “CoEvolution Quarterly’s “Space Colonies” [Stewart Brand] appeared the following. The new frontier had been identified. Now it was just waiting for pioneers, in this case, to generate the territory from the void of space as three-dimensional envelopes containing human life-support systems. B2’s enclosure experiments prototyped that generation process, which has seen another recent uptake with SpaceX, Mars 1, and Bezos and Musk. While the colonization of the High Frontier has not proceeded as the predictions of fifty years ago forecast, B2’s experimental
apparatus has allowed us to draw more intelligent conclusions about our relationship to Biosphere 1 [Earth] and ourselves as co-constructive agents within its enclosure.

Yet enclosure created unique challenges for the eight Biospherians locked inside, who were not only the inhabitants and laborers that kept B2 systems operational, but also data collectors/analyzers in the traditional laboratory sense while simultaneously acting as sensor/actuator units themselves, feeding back into their dynamic environment. They became something more than just human, they became embodied flows, pawns, for better and worse, contained within a simultaneous ecotopia and dystopia of risk and external control, as we may expect other pioneers who follow their path might.

In certain respects, B2 can be understood as an early rehearsal of today's anthropocentric experimentation in sustainable and resilient performative architectural design. Our biosphere's (Earth's) current condition is operating very much as a semi-quantified experiment minus a separate control Earth, for comparison. With the advent of ubiquitous computing and smart buildings, we, like the Biospherians, have been subsumed into the cybernetic system.

“Clearly, cyborgs—with their historical congealings of the machine and the organic in the codes of information, where boundaries are less about skin than about statistically defined densities of signal and noise...cyborgs raise all the questions of histories, politics, and ethics that [other species] require. Care, flourishing, differences in power, scales of time—these matter for cyborgs. For example, what kind of temporal scale-making could shape labor systems, investment strategies, and consumption patterns in which the generation time of information machines become compatible with the generation times of human, animal, and plant communities, and ecosystems?” [Haraway, 2003, 21]

We have rendered ourselves fragile because we have destroyed the possibility of experimenting objectively, as if we ever had more than a false pretense of that possibility. There is no ‘other’ Earth that can be used as an experimental ‘control.’ Like the Biospherians, we are designers of the built environment designing and experimenting in situ, in real time. In the case of B2, this produced novel tensions between space as model, versus space as experiment, versus space as life-support. For us, unlike the Biospherians, we are not operating from within a largely command-control style of governance, and we have no globally agreed-upon coordinated script, despite the numerous intergovernmental summits on climate change of the last decades. This situation raises serious debates over the contexts [especially when they are understood to be entangled] of laboratory spaces, fieldwork sites, spaces of resource production, and spaces of habitation. This form of experimentation has proven highly problematic in relationship to scientific methods, and can render experimental results difficult to interpret, yet, historically it has played a significant role in the ecological sciences, and certainly within the design and engineering disciplines. Because of this, it may be possible to reconcile the situation, but not likely with methods we have historically deployed. If anything, it begs designers to become more versed across a broad range of knowledges, so that they might better understand boundary blur and its implications. Asking applicable questions that frame our overarching goals as environmental designers, while developing sophisticated abilities to design with their implications, may be the greatest service we can provide. In:

...understanding how things work, who is in the action, what might be possible, [we can better understand] how worldly actors might somehow be accountable to and love each other less violently. [Haraway, 2003, 7]

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REFERENCES


PEOPLE AND PROCESS IN ARCHITECTURAL PRACTICE
ABSTRACT: Digital workflows able to accommodate qualitative information are key to addressing issues of rigor, clarity and continuity in architectural programming. Technological advances have progressively improved the role that data can play throughout the design process, but current use of such technology relies almost exclusively on numerically defined quantitative information. This research investigates the relatively unexplored potential that current technologies offer for harnessing qualitative information throughout the design process, and lays a groundwork for new practices in architectural programming based on emerging human and environmental metrics coupled with digital capabilities. In this paper, programming and the flow of qualitative information is reviewed through literature, a series of interviews, and a case study of programming documents on one project. An analysis of these studies frames a proposal for a database-driven strategy to improve the handling of program information throughout a project's lifecycle. A discussion of the strategy's impact makes a case for better architectural information management practices, and sets the stage for future research and development at the intersection of programming, qualitative information, and building information modeling.

KEYWORDS: Programming, qualitative information, project lifecycle, building information modeling, database, workflow

INTRODUCTION
This paper is the result of a yearlong collaborative effort between the University of Minnesota School of Architecture and Cuningham Group Architecture (CGA) through the Consortium for Research Practices. The impetus for this work was the open question, “how are the qualitative characteristics of a building designated and tracked throughout the lifecycle of a design, and how could the rigor of this process be increased?”

The aim of this research is to investigate the relatively unexplored potential that software offers for harnessing qualitative information throughout the design process, and lays a groundwork for new practices in architectural programming based on emerging human and environmental metrics coupled with digital capabilities. To support this aim, the study was divided into two parts: (1) a review and primary investigation of the historical and current processes of programming with the objective of understanding the role qualitative information plays in the process; (2) a review of our findings in the context of emerging database options and currently available qualitative metrics to inform the proposition of a “living data” workflow strategy for integrating programming information into the full architectural lifecycle.

The investigation of programming practices (1) made use of a mixed methods approach which consisted of a literature review, a series of interviews, an analysis of program document structure and a case study of the documents produced while programming a specific project. The results of these investigations reveal differences in programmatic rigor across internal design studios specific to CGA, driven by needs specific to project type and professional attitudes. They outline how information is organized in a program document, and highlight a range of issues in the collection and synthesis of information over the course of one project's programming phase.

A workflow strategy (2) was proposed to enable more effective and rigorous tracking of qualitative information. The proposed strategy outlines an approach to programming which utilizes a central database as a repository for project information that can be used to track objectives and verify their incorporation into the final design. The workflow strategy is presented incrementally throughout this study, contextualized by the aspects of the mixed method review which informed it. The workflow proposition is not intended as a finalized solution, but rather a rough framework to inspire further development and increasingly refined approaches to managing and tracking the qualitative characteristics of a design. This approach would enable architects to clearly articulate the relationship between design decisions and client objectives, track their implementation and evolution over the course of design, and gauge their effectiveness in achieving project objectives.
1.0 ARCHITECTURAL PROGRAMMING AND PROJECT LIFECYCLE

1.1 Programming Literature Review

At the outset of this project a literature review was conducted to develop an understanding of the history of programming and its role in contemporary practice. The first known written architectural briefs began to emerge during the late 17th century, but it wasn’t until the mid–20th century that programming closely resembled what is practiced today (Cherry 1999). In the early 1960’s, a growing body of research conducted by members of the design methods movement produced a wealth of literature associated with architectural programming (Cherry 1999). The design methods movement widely embraced Kaplan’s Systematic Design Model, which placed a heavy emphasis on deductive reasoning (Groat and Wang 2013). This model’s structure of analysis, synthesis, evaluation can be seen reflected in the stages of programming outlined by practitioners of the time (Sanoff 1992; Peña 1977) and is still influential on some professional programmers and researchers today (Groat and Wang 2013; Hershberger 1999). More recently, design thinking has been modeled as a system of abductive decision making, in which acting within a critically derived frame of thought can lead to unanticipated conclusions (Groat and Wang 2013). The contrast between deductive and abductive reasoning is present in the discussion of how extensively design and programming should be integrated, a point of contention between some authors (Duerk 1993; Peña 1977; Robinson and Weeks 1984; Cherry 1999). Because both abductive and inductive methods of programming can be found in contemporary practice, the workflow proposition is designed with both philosophies in mind, preferring systems flexible enough to accommodate either approach.

Another commonality shared by many programming workflows was the introduction of feedback loops for evaluation (Groat and Wang 2013). In fact, the architectural process is frequently depicted with a cyclical diagram that feeds back on itself, where programming serves to instantiate the cycle (de Jong and van der voordt 2002). Drawing from several sources that outline the position of programming in the architectural process (Hershberger 1999; van der Voordt and van Wegen 2005; Peña 1977; Kumlin 1995), and AIA contractual documents AIA B101 and AIA B202, a diagram was developed which represented the contemporary architectural lifecycle (Fig 1 – black underlay and text).

In 1978, database tools became available to professional programmers, and were viewed as a significant improvement over the previous computational tools. While specific team members would need experience in writing code and a background in data science to work with database tools, it required less specialization than the previous file-based applications. As the early forms of spreadsheet software came on the market, architects eventually gravitated toward these tools, appreciating them for their ease of use (Reeder 1993). However, databases have progressed significantly since the early decades of the personal computer, and are more accessible today than ever before. A prime example of this is Microsoft Access, a Microsoft Office product which allows users to easily build an interface and structure for multiple types of data without needing any prior knowledge of SQL or other coding languages. While databases are rarely used for programming today, they are heavily relied on for tracking quantitative information in many contemporary practices. The primary software used to build and manage these architectural databases are Building Information Modeling (BIM) tools such as Revit. There are even tools on the market able to directly integrate quantitative program metrics into the Revit database, including dRofus and Codebook (dRofus 2015; CodeBook International 2016), while others have been developed which are capable of transferring information into and out of underlying BIM databases using formatted spreadsheets (CAD Technology Center, Inc 2016; Autodesk, Inc 2016).
1.2 Workflow proposal – process diagram

Figure 1: Database workflow overlaid on top of conventional project lifecycle

As our understanding of the role programming and building information play in the design process developed, a cyclical process diagram served as a tool to clarify discussion and chronologically frame the functions of our workflow proposition. An overlay of the diagram produced during the literature review was iteratively developed over the course of the research depicting the shifting role of the database at different phases of design, and the general flow of information at any given point in the process (Fig 1). There are two databases depicted in the workflow diagram; one in yellow that represents the building information in the form of a BIM; and the other in red that represents the proposed programming database. The two databases regularly interact with one another at critical stages in their development.

At the outset of a project, (shown at the top of the diagram loop in Fig 1) information will be detached from a central database (represented by the large red dot) existing independently of the specific project for use as a starting point in the programming process. As the program database progresses through the design process (follows along the loop), it will accumulate information specific to the project while sloughing the initial information which is no longer relevant to the project’s design goals. At specific points in the project’s lifecycle, new information which may be applicable to future projects can be exported back to the central database (thin red arrows returning to central database). Once the project progresses into design development the information that has been accumulated and refined in the program database can be used to validate the design and guarantee that the initially determined qualitative objectives have been addressed (two headed arrows between program database and BIM). A primary source of inspiration for this interaction between database and process comes from Zeisel’s diagram of the practitioner’s accumulation of architectural knowledge over time (Zeisel 1984). The proposed central database would function like an individual practitioner’s knowledge base, progressively accumulating information over time and leveraging new information and insights to drive decision making in future projects.

2.0 ORGANIZING INFORMATION
2.1 Programming document case study

To have a high degree of confidence that a database tool would be a good fit for the types of information being produced through the program process, it was critical to understand the actual documents that were generated, and what role qualitative information played in this process. On the company’s servers, information is sorted into file directories relative to project phase and content. Because not all programming workshops progress into a design commission, their files are kept in a separate directory. A case study was conducted on the documents contained in the programming file directory of one specific project that is widely considered by those at CGA to be an example of good practices. As shown in Fig 2 and 3, there were 557 items in the programming directory, and each was analyzed then catalogued for the research based on several characteristics. For the purposes of equally weighting file types, photographs were treated slightly differently than other items; as sets grouped by the date they were taken rather than individual files. Each
file’s date of creation, format of information, and type of qualitative information was recorded and graphed to gain an understanding of the documents being produced at different points in the programming phase's timeline and the how the types of information they contain relate to key events (Fig 2).

The documents were sorted based on qualitative information into one of three categories; tacit, explicit and none. The difference between tacit and explicit qualitative information is how specific characteristics are presented to a reader/viewer. Tacit qualitative information is defined as being communicated through a medium dense in content, but in which specific subject matter is not stated specifically. A common example of tacit information generated in the programming phase is an architectural rendering (one of the file types represented by light green in the diagrams). These are typically dense in information, but their interpretation and perceived subject matter can vary significantly between viewers. Explicit qualitative information is defined as being communicated in a manner that limits interpretation categorically, typically through written format. For instance, while the exact understanding of a phrase like “Well lit” could vary between two individuals, they are still thinking about the way a space is lit and how this is accomplished. If a well-lit space is shown in a rendering, one viewer may focus on the lighting while the other focuses on the human factors of the design. Qualitative information tends to be captured in an explicit format during programming workshops and client interaction. As the explicit information is synthesized, its format becomes increasingly tacit through graphic representations of the design.

Figure 2: Program phase document analysis timeline
Immediately of note from these results are the document formats which could easily be handled by a database system (Fig 3). Approximately half of all documents created during the programming phase of this representative case study project were a format that could easily be uploaded to and managed through a database system. Only two formats of the project’s files could be generated as outputs from a database, but since these are presentations and program documents, even partially automating their production could save on labor time for layout and graphic design.

This review of the programming process shed light on the sheer quantity of documents being produced, as well as the complicated file structure of the directory. Additionally, cycles of information collection and synthesis began to emerge within the timeline (Fig 2). During and immediately after community workshops immense amounts of information were collected, and the documents containing qualitative information were formatted to explicitly communicate their content. After program workshops synthesis through design would begin; fewer items were generated, and they primarily contained qualitative information in a tacit format that directly pertained to the design proposal. As the design progressed the initial information quickly became outdated, with the qualitative content existing primarily in the tacit representations of the design. Program documents (dense pdf booklets) were generated at the conclusion of the process which represented the outcome of the programming phase of design. These documents described the quantitative needs of each individual space, but the qualitative requirements consisted primarily of rendered floor plans and perspectival views of the design. Documents of this kind create only a snapshot of the project’s objectives and rapidly lose accuracy to the project’s goals, particularly regarding qualitative objectives which are not explicitly communicated.

### 3.0 ENGAGING IN PROGRAMMING

#### 3.1 Programming review – how practitioners view and practice programming

It is important that the proposed workflow be applicable to different programming approaches, as there are a wide range of practices which take place at CGA, and across the profession. Nine exploratory interviews were conducted with senior designers and principles at CGA whose role involves overseeing the programming phase of design to gauge the range of current practices within the firm. CGA is composed of multiple studios, each of which is focused on specific architectural markets. The practitioners interviewed represented four market groups; Grow, focused on education and worship; Heal, healthcare; Live/Work, mixed use development and corporate; Play, entertainment and commercial. These interviews were conducted through a series of 13 thematic questions, phrased to allow the subject to expand on the topic as they personally understood it. Each interview lasted approximately an hour. The questions were related to three primary areas of inquiry; overview of programming, types of information, and methodologies / strategies. The interviews made it apparent that no programming effort was identical, with variation in process from one project to the next. This frequently lead to answers which took the form “often programming is like ‘x’, but sometimes it’s more like ‘y’.” To catalog the indefinite nature of these responses, they were organized by strength of conviction/regularity (Fig 4). Indefinite qualifiers in a subject’s responses were sorted into three categories: often; sometimes; and infrequently. If a certain topic was viewed by a practitioner as irrelevant or was not referred to in a response, it was designated as not applicable.
The results of mapping the interview responses showed that the Grow studio conducted the most extensive programming efforts, implemented the widest range of strategies, and most consistently collected qualitative information in the form of “Vision, Values and Aspirational Goals.” The Grow group primarily designs buildings of the education or worship typology, frequently involving large groups of community stakeholders in the programming process. Grow also typically conducts programming efforts that are concurrent with design, placing an emphasis on designing through programming and engaging the community through a project’s conceptual development. The Grow group’s emphasis on qualitative information, and the extensive nature of services provided made their process an ideal context for prototyping the critical stages of the proposed database workflow.

3.2 Prototyping a database interface
The primary objective of prototyping a database-driven workflow is to illustrate how it would function from the perspective of those who would make use of it regularly. This prototype takes the form of “screenshots” and process documentation depicting critical stages in the workflow. The “screenshots” depicted in this document are not taken from a working database, but iterations with Microsoft Access attempting to build a structure for information currently tracked in a conventional program document was highly influential on the anticipated capabilities of the proposed database tool. An emphasis was placed on the role qualitative information plays in this process, as tools that can interact similarly with quantitative information are already on the market (CodeBook International 2016) (dRofus 2015). It is also our objective to illustrate that a data-driven workflow need not restrict creative decision making, and could fit naturally into existing architectural design processes.

The investigation began by sourcing various systematic perspectives on qualitative characteristics of design. The sources chosen were not intended as a comprehensive overview of qualitative design characteristics, but rather a first look at what types of information could be of value in the initial construction of a central database. These sources were 14 Patterns of Biophilic Design (Terrapin Bright Green, LLC 2014), WELL Building Standard (International WELL Building Institute 2016), Building Schools: Key Issues for Contemporary Design (Chiles, et al. 2015), Learning from Schools (Clegg 2015), A Pattern Language (Alexander 1977) and Poetics of Space (Bachelard 1964). Each varied significantly in clarity,
quantity of qualitative information and the ease by which metrics could be derived. The source identified as the most valuable to our prototyping process was *14 Patterns of Biophilic Design* as it contained a wealth of qualitative information which was clearly defined through research, precedent and metrics. Because of its direct applicability, *14 Patterns of Biophilic Design* served as the primary source of qualitative information in the prototypical workflow.

The first step in the database-driven workflow, outlined earlier in the lifecycle diagram, is to detach information from the central database. This first batch of information would be broad and general, made up of experiences and resources from numerous previous projects. This information contained in the project database could be browsed with an intuitive search function linked to meta data associated with each qualitative objective (Fig 5 - Left). The metadata used to search for objectives in Fig 5 are “Site”, “Place”, and “Environment”. The objectives would be organized into database entries containing full text description, precedent imagery and relevant post occupancy questions (Fig 5 - right). It would be in this interface where design objectives and their associated criteria can be established; Fig 5 represents an entry for “Visual Connection to Nature” which is one of the options available from the metadata search. If a relevant design objective or criteria are not available, the user would be able to generate their own custom content within the project database.

The project database would be used to export materials for the presentation and capture of client preferences which takes place during community programming workshops. Figure 6 depicts two examples illustrating how a database could be used to drive current program workshop strategies. The initial presentation shown on the left would be compiled from qualitative information contained within the project database. Shown on the right are images used in an exercise referred to as “dotocracy” in which client groups can place dots on images that resonate with their personal design sensibilities. If these images were output from a database, they could be associated with metadata and used to generate lists of qualitative characteristics the clients subconsciously favored. As design teams became comfortable with workflows leveraging data, new exercises and strategies could be developed to take advantage of the large quantity of information available.

![Figure 5: Database interface. Source: (All information and pictures in this figure are sourced from *14 Patterns of Biophilic Design*. (Terrapin Bright Green, LLC 2014))](image)

![Figure 6: Program workshop deliverables and exercises](image)

As the project progresses into schematic design, quantitative information from the database would be pushed to the BIM model as a method to automate repetitive or systematic modeling tasks (Fig 7 – Left). As the design develops,
information from the BIM environment would be pushed back to the database and used to cross check the status of the model against the initially determined design objectives. An interface inside the database tool (Fig 7 – Right) would compare metrics taken from the BIM directly with those in the program and inform the designer of any discrepancies. Documentation would be uploaded through this interface for metrics which prove difficult to track numerically. Just as with program workshop exercises, as the design team becomes more comfortable working with database tools, new methods could be developed which enable increasingly seamless transfer of data to the BIM and validation of this information inside the programming database.

![Figure 7: Validating database against design: process (Left) and interface (Right)](image)

In addition to the early outputs in the programming workshops, the database could be used to automatically generate a final program document (Fig 8 – Left) from the information it contains, and create graphic tools to help designers keep the initial objectives in mind as they work (Fig 8 – Right). These output documents would likely be one of the most immediate benefits of incorporating a program database into the architectural design workflow, as the generation of documents which replicate information contained elsewhere can be a time-consuming process.

![Figure 8: Database outputs](image)

**CONCLUSION**

This paper has outlined an approach to managing architectural information in which the qualitative could be tracked and validated in a manner similar to contemporary quantitative data. While this workflow would initially only reference a sparse database of information, over time it would accumulate the experiences and precedents of numerous projects and practitioners, becoming increasingly comprehensive. Through its wealth of information describing design concepts, the methods through which they can be achieved, and the overall success of these solutions, this database could serve as a reference book for architectural decision making. Its solutions would not be prescriptive for designers, but instead would provide general guidance, precedent and best practices regarding the success of design concepts. This workflow would enable a design team to make the best decisions possible to meet a project's specific constraints and accomplish the specific design goals established with the client.

Some inherent weaknesses of this study are derived from the time frame. Each exercise from the programming review could have served as its own yearlong exercise, examining with greater depth and specificity the nuances of its individual subject matter. To counterbalance this aspect of the mixed methods process, its relative speed and flexibility enabled the research to adjust and narrow toward collecting the information most applicable to addressing issues identified in previous exercises. The next
steps in this research would be to construct a functional prototype of the database tool being proposed, and test it in an experimental context. An issue we also recognize in the development of a database strategy of this kind is user preference and accessibility. Like any new technology or process in the design field these tools would require time, training and acceptance from current practitioners at all levels of a design team.

Living databases that contain qualitative objectives and the metrics aimed at meeting them could profoundly affect the future of the architectural profession. Practitioners would be able to articulate the progression of design concepts more clearly to their clients. Information about design concepts would be distributed ubiquitously across members of the design team, and associated with a wealth of references and precedent to guide a project's conceptual development. Datasets of previous design solutions would encapsulate generations of practitioners' production and intentions. These datasets could be used to drive computational design processes, and might one day be foundational in the development of computer learning in architectural applications.

REFERENCES


THE CAPTURE AND SYNTHESIS OF QUALITATIVE INFORMATION IN ARCHITECTURAL PROGRAMMING

Madlen Simon, Ming Hu
University of Maryland, College Park, Maryland

ABSTRACT: The authors survey design decision making in architecture and related design professions, setting forth normative practices and identifying important proposals for innovative methods to navigate the complex constraints of design problems. First the authors set forth conventional decision making methodology in the engineering and architecture design process. Then the authors survey typical decision making processes in related design fields such as industrial design, engineering design, and product design and identity their different approaches. The paper compares decision making strategies in engineering and architecture design. The authors conclude by analyzing strengths and gaps of systematic decision making methods in the context of architectural design. This literature review will lay the theoretical foundation for researchers in the area of architectural decision-making and evaluation. The authors will apply these findings to their study that proposes and tests an innovative design decision-making methodology that systematizes a process for evaluating early design proposals against client criteria.

KEYWORDS: design decision making, process, methodology

1.0 INTRODUCTION - DECISION THEORY AND METHODS IN DESIGN

Architectural design is the process by which the designer applies intellect, creativity, and knowledge to resolve a complex array of constraints into a solution that balances the Vitruvian ideals of firmness, commodity, and delight. The traditional design approach is characterized by deterministic problem solving, generally a loosely structured, open-ended activity that includes problem definition, representation, performance evaluation, and decision-making. A number of systematic approaches have been proposed to organize, guide, and facilitate the architectural design process. The main objective of these design thinking research studies is to discover a logical and rigorous path to a design that is acceptable to the architect, satisfies the client, and serves the needs of users. All approaches focus heavily on decision making, which is integral to the process, and an important element of nearly all design phases. In fact, the center of all architectural design approaches is decision making. However, architects and engineers typically do not consciously integrate decision analysis (modeling real-life choices involving uncertainties) and modeling strategic interactions into their design processes. But, strategic interaction among multiple stakeholders with uncertainty is critical in the architectural and engineering design cycle. In fact, systematic design decision making in architectural design process has been unclear, hard to understand, and therefore difficult to teach in architecture school. This paper will provide a foundational platform to understand how architects and related design professionals make decisions and to identify strengths and weaknesses in the process.

Design is a process involving constant decision-making. The decision process is influenced by sets of conditions or contexts; some are controllable, such as the business context, and some are uncontrollable, such as the market and economic conditions. The business context represents the long-term view of the developer/owner and is in general largely in the control of the developer/owner. Decisions such as project capital investments, real estate profit margin and future building upgrades, and sales marketing strategy are determined by the developer/owner. However, some aspects of business contexts, such as market share (which is influenced by competing design products), are somewhat uncontrollable. In addition, the state of the economy and market demands are not controlled by the developer/owner. Correctly assessing the context for making a decision is important because it dictates the level of effort and long-term impact. Decisions with long-term impacts are often irreversible after implementation; therefore, the decision-maker must seriously analyze the context and impact of alternatives before arriving at a decision. Whether the conditions are controllable or not, there is always uncertainty involved in decision-making. For example, in the field of product design, the uncertainty largely comes from the inputs, such as the completeness of and variation in product requirements and constraints established by the customers.

In general, in design development in the architectural context, the product could be a single building or multiple buildings; decisions are made at different levels under different types of scenarios. At a high level, decisions are made for scenarios such as team organization, product cost, work breakdown, and suppliers. At the mid-level, a decision involves issues such as design requirements, material selection, subsystems and components, and the manufacturing and fabrication process. At a low level, a designer determines the design objectives, forms and dimensions of the individual components, and so forth. There are many methods that aid in decision-making. Some of these methods developed...
decades ago are more ad hoc and incorporate relatively high levels of subjective judgment, such as decision matrix, in which weighting factors that significantly affect the decision are assigned by the designer. When these methods are used, they are generally applied to support more significant project decision-making at a high level. Methods developed more recently involve rigorous theory and mathematical frameworks in decision-making, such as utility theory and game theory.

2.0. CONVENTIONAL DECISION MAKING THEORY IN DESIGN

Two primary methods developed decades ago are commonly employed to aid design decision-making: programmatic decision-making approach versus instinct-driven approach. The two approaches present an iconic dichotomy existing in all different decision-making in design process. Within the programmatic approach, various methods are commonly used to aid designers in decision-making, such as a decision matrix (Shafer 1976), a decision tree (Shamim et al. 2010), quality function deployment (Akao 1994), and so forth. These methods are generally ad hoc and incorporate relatively high levels of subjective judgment, or so-called “designer's intuition.” An additional set of methods addresses variability, quality, and uncertainty in the design process, such as the Taguchi method (Otto et al. 1993), Six Sigma (Linderman et al. 2003), and so on. These tools are more analytical and are typically coupled to the processes used to produce products. Design theories also exist, such as Suh's axiomatic design (Albano and Suh 1994), that are less widely used but offer more rigorous analytical bases. Finally, certain other methods are used primarily in the fields of management science and economics, such as utility theory and game theory, which are explored in the current research for feasibility and applicability to support decision-making in design, mostly engineering and product design. Traditionally, architectural design has been viewed as an intuitive or subconscious thinking process.

2.1. Programmatic decision-making approach

2.10. Decision matrix method

Decision matrix techniques invented by Stuart Pugh (Pugh 1991) are used to define attributes, weigh them, and appropriately sum the weighted attributes to find a relative ranking among design alternatives. Note that, in practice, attributes are weighted as numeric figures based on a prescribed ranking system for individual design alternatives. In some contexts, such as design optimization, attributes are also called design objectives, which are to be maximized or minimized, or constraint functions, which must be kept within limits. In general, attributes are also referred to as design criteria or decision criteria. A basic decision matrix consists of a set of criteria options that are scored and summed to gain a total score, which can then be ranked. Importantly, it is not weighted to allow a quick selection process. An example of decision making with the design matrix is a case in which the design team needs to choose between two sites, A and B. in this case, there are nine attributes to be considered: visibility, accessibility, setting, environmental impact, neighbors, size, cost, schedule, and operation. Each attribute has a different weight in the value. The team will first score the two sites and then multiply by the weight to get the overall score, and the overall score could provide guidance for the team to make a decision.

Table 1: Decision-making Matrix (by authors)

<table>
<thead>
<tr>
<th>Issue</th>
<th>Site A</th>
<th>Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Value</td>
<td>Score</td>
<td>Total</td>
</tr>
<tr>
<td>Visibility</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Accessibility</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Setting</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Environmental Impact</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Neighbors</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Size</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cost</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Schedule</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Operation</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TOTALS</td>
<td>37</td>
<td>35</td>
</tr>
</tbody>
</table>
2.12. Decision tree method
The decision tree method is another way to evaluate different alternatives. This method is often used in evaluating business investment decisions, considering the outcomes of possible future decisions, including the effect of uncertainties. The strength of the method is that it allows an evaluation of the benefits of present and future profits against the investment. It is a useful technique when a series of decisions must be made in succession into the future. Every decision tree is a collection of branches connected to each other by nodes. A tree is constructed from the left starting with a decision node, and branches emanating from a decision node represent individual options. The right end of each branch must terminate in one of three types of nodes: decision, event (or chance), or payoff. Note that the event is also called the state of nature, which is in general out of the control of a designer. To illustrate the method, we consider the decision tree shown in Figure 1, which is concerned with deciding whether an architectural firm should carry out research and development for new life cycle assessment (LCA) software or a tool that can be quickly integrated into the design process and generate relatively reliable results to capture a potential market niche in the next 10–15 years. The firm has extensive experience in developing software. However, the firm has no direct experience with LCA tools, which could dramatically increase the firm's competitive edge. With preliminary research completed, it was found that a $4.0k investment is required upfront to develop new software. However, a $1.5K investment is needed to improve the current design process. The primary decision selection criterion for the firm is the front cost, so based on this decision tree diagram, the final decision the firm should make is to do nothing.

![Decision Tree for R & D project](image)

**Figure 1:** Design Tree for R & D project. Source: (Author 2017)

2.2. Instinct-driven approach
Creativity is the core of design as each architecture design proposal is uniquely tailored to meet a set of unique requirements, while in other domains, problem solvers seek solutions based on reason and evidence with an analytic approach. The relentless practice of this form of reason could trap us in the reason and cause the loss of creativity. This has become the main worry and mental block for architects to pursue the programmatic approach to design. Researchers have attempted to study the source of creativity to find out how creativity arises in many different situations: a solid and novel proof of a mathematical theorem comes from a mathematician's creativity; a beautiful painting or wonderful music comes from an artist's creativity; an innovative electronic gadget comes from an engineer's creativity, and a profitable stock trade comes from an investor's creativity. In the context of architectural design, we define creativity as an act of discovering design alternatives with components that meet objectives in ways previously unseen or creating new value with a new use of existing components. As Robert Clemen and Terence Reilly pointed out: "From a decision-making perspective, we need not be stuck with the alternatives that present themselves to us; in fact, good decision making includes active creation of new and useful alternatives. Moreover, the very process of decision analysis - especially the specification of objectives - provides an excellent basis for developing creative new alternatives" (Clemen and Reilly 2001).

In architectural design, alternatives are often generated through design iteration and “gut” feeling. Former general electric CEO Jack Welch describes “gut” as emotional response (Harvard Business Review 2014). “Gut” is relative to human feeling and associated response; “gut-decision” makers do not always make high quality decisions, however,
trusting intuition does have a certain place in creative activities. A cognitive approach suggests that creativity arises from a capability for making unusual and new mental associations of ordinary objects or concepts. Campbell suggests that more creative people are better at generating multiple alternatives (Campbell 1960). In architectural design concepts, the alternatives are design proposals. In Clemen and Reilly's book, they described the commonly used phases of the creative process as: preparation, incubation, illumination, and verification, which could be translated into the traditional architecture design process: conceptual design, schematic design, design development, and construction documentation. Clemen and Reilly's different creativity techniques include fluent and flexible thinking and idea checklist. Fluency is the ability to come up with many new ideas quickly. Flexibility, on the other hand, stimulates variety among these new ideas (Linderman et al 2003). And together they could be rooted in “guts.”

3.0. MODERN DECISION MAKING THEORY IN ARCHITECTURE DESIGN

Decision theory provides a rational framework for choosing between alternative courses of action when the consequences resulting from this choice are imperfectly known. Decision theory has been applied more to business management situations than to engineering or architectural design decisions.

The literature on design theory of architecture is diverse. Some studies discuss the design of games. M. Montola (Montola et al 2009) explores the aspects that concern game designers and provides a philosophical, solid theoretical, and aesthetic understanding of the genre. S. P. Walz (Walz 2010) analyses and designs games from an architectural standpoint, and this contribution could be particularly applied to an era when games extend into physical, designed space. Architectural design must include various attributes. O. Ma studies the relation between the architecture of platform manipulators and the accuracy of a manipulator and introduces various performance indices that would explicitly or implicitly affect the accuracy. These indices are considered functions during the configuration [Ma and Angeles 1991]. All existing studies use architectural design as a platform or infrastructure, but little research has examined the decision-making theory and mechanism in architectural design.

The design theory we have discussed so far has focused on a situation in which a single decision-maker needs to find the best possible decision among alternatives. A decision needs to be made by one decision-maker to produce maximum payoffs in a single or multiple attributes (or criteria) under a set of constraints. This one decision-maker could be a group of people. In many situations, however, the payoff of a decision made by an individual depends not only on what he or she does but also on the outcome of the decisions or choices that other individuals make. In architectural design, decision designs are often not made by a single designer or a single design team. Instead, multiple designers or design teams work on the design and are involved in design decision-making, with each designer or team being responsible for one or more design objectives and/or sub-systems. The design team could include architects, engineers, manufacturers, and clients. For example, an architectural design may focus on maximizing the view and solar shading efficiency of a window/wall system, while the goal of window manufacturing is to produce the component with the least cost in shortest time. Design decisions made by the architect in determining the geometric shape of the window wall of a curtain wall system may affect the cost and time of manufacturing the component and vice versa. In practice, some design decisions are made simultaneously at a specific time in a design phase, and some occur in sequence throughout the design process. With several designers (or design teams), each with his or her own objectives, the nature of the design decision can take several paths, and the resulting overall design may not be desired. This is because a single designer or team can theoretically do better and his or her decision could dominate, hence largely determining the performance of the overall product, which may or may not be desired.

Traditionally, architectural design decision-making and practice is learned through a project-based ‘studio’ approach. Designers explore design alternatives and their consequences through the linked activities of sketching, modelling, and discussion. Visual learning and decision-making based on visual analogies is an essential tool for designers and architects. Alexander proposed that analysis and synthesis are important steps to reach a design decision and need to be taken in that order [Alexander 1964]. On the contrary, Rittel and Webber thought that design problems cannot be fully described and are therefore not easy to analyze at the beginning (Rittel and Webber 1973). This could result in an architecture-specific design methodology that does not depend on the completeness of problem analysis before the design reaches a decision. This seems like design decision-making method practiced in real scenarios.

4.0. COMPARISON BETWEEN ARCHITECTURAL DESIGN DECISION MAKING AND OTHER DISCIPLINES

4.1 Decision-making in Engineering Design

“Design is decision-making,” according to S. Sivaloganathan [Sivaloganathan 2000]. Engineers are the decision-makers; the design process is important to make sure that newly designed products have improved quality, and more importantly, the design decisions will affect the environment and the safety of the society (Fathianathan and Panchal 2009, Hazelrigg 2012). Some studies in the literature have emphasized that decisions play an important role in concurrent engineering and that engineering design presents a utility-based decision support method for selecting an engineering design. A cooperative enterprise selection mechanism is designed and implemented in an allied concurrent engineering environment (Hatamura 2006). Hatamura points out that decision-making in engineering design is a
mental process of design (Sivaloganathan and Andrews 2000). The design decisions are important because they impact
the product quality and environment/safety of the society (Fathianathan and Panchal 2009) (Fernández et al 2005)
(Hatamura 2006). Hazelrigg claims that decisions play an important role in concurrent engineering and engineering
design, and presents a utility-based decision support method for design selection. Chen and research team (Chen et
al 00) designs and implements a cooperative enterprise selection mechanism for an allied concurrent engineering
environment. In the cooperative enterprise selection process, engineering activities and resources from different
enterprises (stakeholders) are integrated through some alliances. Hatamura (Sivaloganathan 2000) points out that
decision making in the engineering design is a mental process of design. A variety of researchers (Dixon 1966) (Ertas and
Jones 1996) (Jackson 2014) analyze incentives for decision making in engineering design process. Brickley and his team
(Brickley et al 2003) studies decision-making and its application within the structure of an organization.

Many decision-making methods have been utilized in engineering design. The Journal of Decision Making in Engineering
Design (Lewis 2006) provides insights on modeling preference, uncertainties, and validation, and illustrates examples of
effective application of decision-based design. Vadde and colleagues (Vadde and Mistree 1994) use Bayesian statistics to
model uncertainties for multilevel design. The principles of probability and statistics in realistic engineering problems
are studied by two research teams. (Ang and Tang 2006) and (Bandte 2000) study probabilistic multi-criteria decision
making (Tzeng and Huang 2001) in aerospace design. Multiple criteria decision support in engineering design has
also been studied in by Sen and Yang, (Sen and Yang 1998) who developed an integrated multiple criteria decision
support system with user interface and interactive decision making. Sen and Yang develop an optimization software
to assist in engineering design making. Fathianathan and colleagues and Ross (Fathianathan and Panchal 2009) (Ross
2003) propose that collaboration decisions should form a critical component in the modeling of collaborative design
processes. Vanderplaats (Vanderplaats 2001) studies numerical optimization techniques in the process of engineering
design, such as unconstrained/constrained functions, linear/discrete variable optimization, and structural optimization.
The response surface methodology is studied in Unal and his team's work (Unal et al 1996) as an approach to design
optimization. This proposal uniquely aims to integrate concepts from both descriptive and normative decision models
in engineering design while developing a framework to incentivize the decision makers towards strategic value
optimization.

4.2 Decision-making in Architecture Design

While decision making has been intensively studied in engineering in the last decades, it has not been exhaustively
studied in architectural design. (Lawson 1997) (Yi-Luen et al 1997) This might be due to the complexity of architectural
design; unlike engineering design or product design in which the scope and risk are well defined, there is more
uncertainty and risk associated with architectural decision-making. Ralph Keeney identified twelve factors contributing
to the complexity of decision-making which are adaptable to the architectural design context. The factors are: multiple
objectives; difficulty of identifying good alternatives; intangibles; long-time horizons; many impacted groups; risk and
uncertainty; risk to life and limb; interdisciplinary substance; several decision makers; value tradeoffs; risk attitude;
sequential nature of decisions. (Keeney 1982) Those factors all exist in architectural design and cause complexity.
Compared to engineering design, architectural design has overall high stakes, complicated structure and no overall
experts, and the need to constant justify decisions. A small amount of critical decisions in an early design stage might
result in severe environmental damage. For instance, the decision between building a project in a dense urban area or
suburban site might be made by clients with early input from architect and planner, prioritizing infrastructure cost,
resulting in tremendous and irreversible environmental consequences.

CONCLUSION

Conventional design approaches heavily involve decision making, which is integral to the architectural design process
and an important element in nearly all phases of design. To the best of our knowledge, this paper is the first to formally
provide an overview of decision making theory in architectural and engineering design, a necessary first step in an
ongoing research project aimed at proposing an effective decision-making process for architecture.

The critical question is what values and preferences the design is based upon. Multiple stakeholders are involved
in the architecture cycle, including designers, consultants, developers, regulators, project managers, contractors,
manufacturers, and end users. Although those decision influencers may have different (and often conflicting)
perspectives, values, and resources, they often jointly and subconsciously determine the effectiveness and success of
the design process through discussion, negotiation, and contracts. We acknowledge that through those interaction
processes, the stakeholders' preferences and frames of understanding (Goffman 1974) could be altered or transformed.
Architectural designers could use decision analysis to evaluate design options and make decisions. The methodologies
of decision analysis have been intensely studied; Grayson (Grayson 1960), Allison (Allison 1971), Moore and Thomas (Moore
et al 1976), Kaufman and Thomas (Kaufman and Thomas 1977), Keeney (Keeney 1982), Howard and Matheson (Howard and
Matheson 1984) provided wide evidence on various aspects of decision analysis methodologies.
Unlike engineering designers, architectural designers have not consciously integrated decision analysis (modeling real-life choices involving uncertainties) as a tool in design process. The largely intuition-based and creativity-driven approach is certainly critical in architecture design, where it does not conflict with a factors-driven programmatic approach. We could model real-life choices involving uncertainties based on decision analysis and modern decision theory that have been adopted in other disciplines. The dichotomy of brain versus gut is largely false; few decision makers ignore good information when they can get it. [Harvard Business Review 2014] The reason some decision makers need to reply on their intuition is either the relevant information is largely not available or they have not been trained to consciously use decision making tools following decision analysis methodologies. Since architectural design is composed of many decision making steps, teaching decision making methods and intentionally integrating decision making skills into the architectural curriculum could be critical in educating next generation design professionals.

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ARCHITECTURE (DISAMBIGUATION): MAPPING A RESOURCE-BASED DESIGN PROCESS SYSTEM

Ahmed K. Ali*  
*Texas A&M University, College Station, Texas

ABSTRACT: The process of designing and developing a building from conception to realization is indeed a sequence of creative and rigorous activities that combine the art of architecture with its scientific, engineering and financial aspects. Like other creative activities, the design process charts a path that is not always straightforward and, in fact, is likely to include multiple investigative sub-design procedures. Previous attempts to define the architectural design process have been vague and confusing to those in other disciplines. In this paper, we introduce a novel method of integrating system thinking into architectural design by mapping its processes in a standard modeling language. We present a decision-support framework using process mapping in order to incorporate sustainable building materials and resource reuse decisions into architectural design practice. We turned to other disciplines' knowledge bases, such as Business Information Technology (BIT), to develop a workflow system for the Design-Bid-Build (DBB) process. Mapping both current and the proposed design processes, including their activities, workflow, processes and decision nodes, was critical in defining roles, processes, and subsequent decisions. A literature review suggests that there are five types of design processes, which are somehow defined as linear, divisional, centralized, cyclical and investigative. However, no attempts have been made to map their processes using a systematic methodology. In this study, we utilized a qualitative methodology to capture the required knowledge from industry experts in resource-based design and then integrated our findings into a set of process maps to support the materials decisions of the architectural design team.

KEYWORDS: Architecture, System Thinking, Process Design, Resource-Based Design

INTRODUCTION

When asked what architecture would be like in fifty years and what we could anticipate in the interim, Louis Kahn simply responded, “You cannot anticipate.” Then, he recalled his meeting with a group of General Electric executives who presented him with a depiction of what a “spacecraft” would look like fifty years hence. Kahn listened carefully, then responded with conviction, saying:

It will not look like that, because if you know what a thing will look like fifty years from now, you could do it now. But you don’t know because the way a thing will be fifty years from now is what it will be. (Kahn and Ngo 1998).

Kahn relayed this exchange to a group of architecture students at Rice University in the spring of 1968. Nearly fifty years have passed, and Kahn’s statement remains valid today. Unlike Kahn, Ulrich Beck argued that the current era is defined by increasingly global problems, the mitigation of which ultimately require “anticipation” (Beck 1992). Whether we agree more with Kahn or with Beck, we realize the inherent difficulty in anticipating solutions for the complexities of the architectural discipline of tomorrow, especially given that we cannot even define our current design process. Like Kahn, we might not be able to completely anticipate the future of architecture in addressing increasingly global problems, but we might still find it valuable to attempt to redefine the complexity of our current architectural design process through its integration with common mapping language.

Literature searches for “architecture of complexity” led us to a foundational article with the same title, written in 1962 by Herbert Simon, then a professor of computer science and psychology at Carnegie Mellon University. His work focused on artificial intelligence, psychology, administration, and economics. Simon, in his article, argued that the “architect” of complexity uses hierarchy as the central structural scheme of a system. He defined four aspects of the architecture of complexity, as illustrated in Fig. 1: frequency in the form of hierarchy; the relationship between structure and time; the dynamic properties of hierarchy; and, finally, the relationship between the complex system and its description (Simon 1962). In his later book, The Sciences of the Artificial, Simon defined design as the process by which “we devise courses of action aimed at changing existing situations into preferred ones” (Simon 1969). Simon’s work, which heavily borrowed terminologies from the discipline of architecture (such as design, architect, architecture, structure, and hierarchy), leaves us wondering precisely to which domain he was referring: architecture or computer science? In today’s nomenclature, and as a result of the exponential growth of the information technology (IT) and information systems (IS) domains, understanding the terminology at it pertains to its underlying intent can be difficult.
In the last fifty years, the fields of artificial intelligence (AI), information technology and computer science have significantly repositioned these terms. For example, in IT, the term “architecture” refers to the system architecture; the term “design” refers to system design or process design, and “architect” refers to the system engineer. The enormous growth of big data, systems and information raises the following questions: How can architects cope with the increasing complexity of the built environment? How can architects move their design process from ambiguous to defined territories?

Figure 1: Simon's four aspects of the “architecture of complexity.” Source: (Author 2017)

1.0. THE DESIGN PROCESS AND THE ARCHITECT
To answer these questions, we must begin by acknowledging that architecture, as a discipline, is not solely a commercial transaction, a service activity, or a manufacturing process. It is neither an engineered system nor a mathematical model. Although the general public might perceive that architectural practice is nothing but a business providing services and products, this misconception doesn't take into consideration the artistic, scientific and creative essence of architecture. In this paper, we refer to architecture as the “physical built environment,” but also acknowledge the wide use of the term in reference to the components of a system for processing information. Inevitably, architects are now asked to navigate new knowledge domains that integrate the possibilities provided by the information age, and therefore, must seek to resolve the conflict that arises in the established practice of passing on traditional skills. As a result, the architect is under pressure to make buildings that are influenced by today’s information age. A distinction between being a process-oriented and a product-driven architect is explained in the book 101 Things I Learned in Architecture School. Frederick’s distinction of being a process-oriented architect characterizes certain qualities regarding the way one assesses design problems, makes decisions and implements solutions (Frederick 2007).

If we adopt Simon's definition of design as a “process by which we devise courses of action aimed at changing existing situations into preferred ones,” we are likely to have a foundational base for building a design theory. Design theory relies on human (or “tacit”) knowledge, because design thinking is outside the boundary of verbal discourse (Daley 1982). Under the scientific paradigm, where findings are presented as description, designers and architects find it very difficult to specifically describe what they think when they design, because design thinking is better expressed through the use of examples and by showing how design is done, rather than through merely describing the process. Here comes our dilemma in the realm of epistemology, which deals with little-objectified knowledge. Design knowledge pertains more to a knowing or a guiding intellectual capacity embedded in human actions and practices (Cross 2001). Therefore, while design knowledge might be difficult to describe, it is not inaccessible for research purposes. Friedman argued
that design knowledge grows in part from practice, and therefore, overlaps with design research (Friedman 2003). The cornerstone of our epistemology is the distinction between tacit and explicit knowledge, where the key to knowledge creation lies in the mobilization and conversion of tacit knowledge. Friedman uniquely defines the position of design relative to science. His view of theory-construction in design research as “design sets on . . . science’s three legs,” is illustrated in Fig. 2.

Figure 2: Friedman’s view of theory construction “design sets on . . . science’s three legs.” Source: (Author 2017)

1.1. Constructing a Design Theory
To provide the underpinning theoretical framework for why we are concerned with modeling the design process, we should explain how to construct a design theory. In this study, we primarily deal with prescriptive theory, while acknowledging the fundamental intuition of design as a creative activity, which cannot readily be mapped or prescribed. The work presented here is related to the overlapping territory between the two frameworks of theory. Friedman, in his work on theory building, stated that one should consider a process of forming “models” for the research problem and continue refining these models and repeating the process until one has the simplest possible model that demonstrates all the phenomena under consideration. Models, in Friedman’s view, can be simple representations of reality because a model is supposed to reveal the essence of what is going on and should be reduced to just those pieces that are required to be workable (Friedman 2003). The importance of modeling in theory construction is to visually clarify how things work (again, with similarity in the use of terminology to physical and digital modeling in architectural design). This leads us to the question of prescriptive theory, as prescription furnishes a sort of certainty that our experiences or thoughts are real, rather than mere byproducts of our imagination. Primarily, prescriptive theories seek to make truth a real, viable category rather than a relative term. If a prescriptive theory is true, then the ground of reality has been reached. In epistemology, a prescriptive theory is the most abstract and general theory; it is the theory that grounds all other theories. Some argue that all major scholars in epistemology have sought to lay out a theory of prescription to ground their theories (Östman 2005). Prescriptive theories are abstract, general frameworks for knowledge within which the individual can reach certain conclusions that cannot be proven in and of themselves. They are axiomatic; that is, the means of proving anything. So how could knowledge evolve from constructing a design theory through modeling? Thomas Kuhn stated that science undergoes periodic “paradigm shifts” instead of progressing in a linear and continuous way, and therefore, design also goes through a paradigm shift (Kuhn 1996).

1.2. Design Process and Process Design
Modeling a design process requires an understanding of the difference between design process and process design. A typical design process might be described as a linear sequence of events that has a starting point and an ending point, is often investigative and is sometimes circular, as new information takes shape. Design usually begins with a precise definition of the problem to be addressed, and also is concerned with decisions of taste, choice and sensitivity that rely on human value judgments. In contrast to a design process, a process design (or the design of a “process”) refers to the planning and structuring of the routine steps of a process apart from the expected result. In process design, processes generally are treated as a product of design, not a method of design. The term “process design” originated from the industrial designing of chemical processes and with the increasing complexities of the information age, consultants and executives have found the term useful to describe the design of business, as well as manufacturing, processes (Korber 2002). According to William Miller, design is defined as “the thought process comprising the creation of an entity, and it consists of many smaller processes” (Miller 2004). Sub-design processes are defined as detailed, smaller processes
that are linked in a network of precedent relationships. Models formation, as previously defined by Friedman, can thus be divided into two parts: a decision model, which is a structure of data elements and its mathematical relationships, as well as an information model that in our case could be the Building Information Modeling (BIM) database, which includes the parameters for the decision model (Ali, Badinelli, and Jones 2013). Like many other creative activities, the overall design process is linked to a path that is not always straight, and in fact is likely to include investigative sub-design processes. Some designers call this a “spiral” process because it has both a forward direction and a tendency for self-questioning along the way to ensure that it is going in the right direction. Literature suggests that there are the following five types of the architectural design processes:

- Linear: “Design process is a continuing sequence of basic linear steps” (Reekie 1972)
- Divisional: “Design process includes choosing the best solution out of several options of design solutions” (Jones 1992)
- Centralized: “There are no steps in the design process, everything is happening at the same time” (Lawson 2006)
- Cyclical: “Design process is a series of endless repetitive cycles” (Snyder 1970)
- Investigative: “Each step in the design process is based on a selective investigation process on options of ideas and solutions” (Kalay 1987)

Any of these design processes occur within a number of established project delivery methods known to the practice. The current trend is to move toward an integrated project delivery method; however, the traditional Design–Bid–Build process is still widely accepted as the industry standard. In the next section, we explain the workflow of the DBB and our attempt to model both the current workflow and our proposed workflow. We call the proposed workflow a “resource–based” design, which primarily deals with the catastrophic amount of solid, nonhazardous waste that accounts for nearly 40% of all solid waste generated by the building industry.

2.0. WORKFLOW IN THE (DESIGN–BID–BUILD) PROCESS

In this paper, we primarily focus on the most widely adopted project delivery process in practice, the traditional project delivery method known as Design-Bid-Build. We illustrate the current and our proposed resource–based design workflows in detail using two different modeling languages. We realized through research that incorporating decisions of resource reuse to the DBB method may require an early integration during the programming and pre-design phases. The overall traditional design process typically starts with a program, creative idea(s) and an estimated budget, and then proceeds through several levels of development. Traditionally, in practice, there exist seven phases of a typical project, starting from abstract information gathering and conceptual design to the precise construction documents, and then construction administration culminating with occupation (AIA 2007). The entire process is initiated through communication between a prospective client and an architect. At this time, the architect typically asks the client about the program or intended use of the proposed building, proposed budget for the project, location of the proposed project and expected time frame for completion. This information represents the primary critical inputs to the pre-design or programming phase. This information is mostly quantifiable, with variables such as program, size, budget, location and schedule. We will only present here mapping of the schematic design (SD) phase, as other phases of the process are documented in previous publications (Ali and Badinelli 2016).

3.0. RESEARCH METHODOLOGY

We utilized a qualitative, grounded theory approach using an inductive mode and an intensive, open-ended and iterative process that simultaneously involved data collection, coding (data analysis) and memoing as a method for theory building (Wang and Groat 2013). The author used a knowledge–capturing approach from a medium sample of experts involved in the area of architectural design with resource reuse, design for disassembly and building deconstruction. The knowledge–capturing process was developed through a multi-phase questionnaire, face-to-face interviews and structured Delphi focus workgroups. The knowledge captured was compared to the data extracted from the literature and case studies to form a consistency check. Findings from the qualitative analysis were evaluated through a triangulation method to test the validity of the proposed design workflow. The proposed framework in this study constituted an effort to collect, organize and present available knowledge on building materials and resource reuse in a readily usable form. The number of attributes and variables in the design process with used building materials was overwhelming; therefore, we used standard mapping language to streamline the paradigm shift within the typical architectural design process. The preferred solution ultimately was based on some trade–offs that the design team would have to evaluate and choose from; therefore, there was a need to weigh these trade–offs in a rational and explicit method in order to assist the design team by using the decision support framework. Some inputs to this framework emerged from personal interviews, analysis of selected case studies and online surveys, which helped in identifying some evaluative categories. Each category contained a set of variables that was considered and integrated into the framework.
3.1. Standard Modeling Languages
Following several attempts to map the design process using bubble diagrams (known as a conventional method in architectural design), we realized that a standard modeling language was essential to map the resource-based design process. It was critically important to follow a consistent, representational repertoire and to build a common understanding with the IT and IS disciplines. After studying the available modeling languages, we found that each has capabilities and limitations. We initially adopted the Unified Modeling Language (UML) in mapping the current traditional design process (DBB) and the activity diagram of the proposed building material reuse workflow. However, after investigating further, other modeling languages, such as the Business Process Modeling Notation (BPMN) appeared to address more details in the process. Literature suggests that process modeling should consist of static and dynamic elements. For static components of a system, especially the architecture and design of a system, there are design patterns. The dynamic aspects of a system are abstracted and captured as process patterns. Using patterns in the modeling of systems helps keep the design standardized, and more importantly, minimizes repetition in the system design. Events are used to communicate a relationship between a context, a problem and a solution, and bring in and reuse the previous modeler experience. An example of mapping the flow of activities in the DBB process that typically includes a sequence of activities and processes is shown in a UML map of the SD phase (Fig 3).

3.2. Unified Modeling Language (UML)
Initially, we selected UML language to map the current DBB process. UML is an easy language for non-IT professionals to understand. UML activity diagrams are simple to learn and are similar to flowcharts (Rhem 2006). They are graphical representations of a workflow of stepwise activities and actions with support for choice, iteration and concurrency. Activity diagrams are used to describe the business and operational step-by-step workflows of components in a system. Activity diagrams show the overall flow of control; they are constructed from a limited repertoire of shapes connected with arrows, as shown in Fig. 3. The most common representation symbols are rounded rectangles, representing activities; diamonds representing decisions; bars representing the start (split) or end (join) of concurrent events; and arrows that run from the start toward the end, representing the order in which activities happen. Decisions are represented as “nodes” where each decision would have information inputs. Decision needs should be specified as alternatives, decision variables, Key Performance Indicators (KPIs) and parameters. The component of the decision model is beyond the scope of this work.

![Figure 3: UML process design map of the DBB schematic design (SD) phase. Source: (Author 2016)](image3)

3.3. Business Process Modeling Notation (BPMN)
We used Business Process Modeling and Notation (BPMN) in revising the initial DBB design processes maps using UML. It is a graphical representation for specifying business processes in a process model. BPMN language allowed us to include more details in modeling, such as project phase, responsible stakeholder and a cross-referencing system similar to construction documents standards. In the revision of the workflow, a thorough review of all the boxes in the knowledge and data section was considered in a hierarchical structure. The specification of knowledge elements went from general to specific in a hierarchical method. A sample representation of BPMN map can be seen in Fig. 4, illustrating the SD phase.
4.0. BUILDING THE PROCESS MODEL

The resource-based design process that we propose is an effort to collect, organize and build relationships between activities, processes, knowledge, data and information in a standardized workflow language from start to end. The value-added component of resource reuse to the current DBB process needed to be seamlessly integrated into the process. The previously presented UML activity maps illustrated the captured knowledge from the literature and from the expertise of professionals (Ali and Badinelli 2016). Several project stakeholders and consultants are usually involved in the activities and processes related to design, demolition, procurement, and so on. Some of the process activities are performed concurrently and some, sequentially. The initial UML activity maps represented some of these relationships in the SD phase. The SD phase is presented on three detailed level maps based on the complexity of a project. First is Level 0, a traditional DBB process modified from UML to BPMN. Second is Level 1, with a new BPMN process, including preliminary resource reuse activities. Third, Level 2 has a new BPMN process, including detailed resource reuse processes (Fig. 4,5).

Figure 4: Resource-based schematic design process level 1 (map # SD2b). Source: (Author 2012)
CONCLUSION

Architecture as a discipline is known for its slow adoption of paradigm shifts, and architects typically are reluctant to drastically change their design process. In his book, *Complexity and Contradictions in Architecture*, Robert Venturi noted that the growing complexities of our functional problems must be acknowledged (Venturi and Museum of Modern Art (New York N.Y.) 1966). What we propose in this study is often what an architect thinks about while approaching the problem of building design. Nevertheless, he or she could be required to alter the design process to include, for example, resource reuse of materials. Process design offers a clear and systematic workflow that makes design decisions less ambiguous and brings the knowledge gathered for one project to the next without depending entirely on the tacit knowledge of the project’s designers. As noted by Herbert Simon, a structure's complexity or simplicity is critically dependent on the way we describe the structure. The architecture of complexity for the built environment can benefit from the architecture of complexity for information systems. The latter provides the backbone of the information flow to the architect and allows him or her to focus on the creative aspects of design. A structured framework such as the one we propose allows for the apparent integration of dynamic decisions, which includes the specific parts, linkages and networks of such a dynamic system. In a world where complexity has to evolve from simplicity, the hierarchy of systems helps in process disambiguation and synthesizes the architecture of complexity. We hope that architects will find this method beneficial for streamlining the nearly limitless parts of the design process. So, now we return to Ulrich’s question: How can we ensure that the same fate is not repeated for future generations?

The work presented in this study is an important step toward solving the problem of waste in the building and construction industry. The proposed decision support framework, which includes redefining the traditional design process to incorporate resource reuse, anticipates a major societal contribution of reducing 40% of the total solid waste stream. This paradigm shift requires changing our practice and perspective toward the environment, economics, and the social and cultural aspects of design. Without rigorous governmental restrictions regarding waste required of the AEC industry in building design and construction activity, waste reduction will remain a low priority. The lack of interest from the AEC industry due to the lack of information on BMR can be now mitigated by this proposed dynamic knowledge base and decision-making framework. The straightforward process of incorporating BMR to design is evident throughout this work and can be implemented with minimal unknown factors.

The resource-based design process, as a system approach, is dynamic, although we have presented it as cause-effect
relationships between activities, data and processes. Our mapping attempts to reorganize design practice. The decision support framework offers a holistic approach to the built environment. While defining the extent of the system and its parts anticipation for the architecture of tomorrow might not be possible, the current architecture of complexity is readable, rigorous and meaningful.

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IN SEARCH OF HEALTHY COMMUNITIES: A CONCEPTUAL FRAMEWORK FOR ENGAGING DEVELOPERS

Traci Rose Rider, PhD1, J. Aaron Hipp, PhD1, Margaret van Bakergem, MPH1
1North Carolina State University, Raleigh, North Carolina

ABSTRACT: As the U.S. continues to see rapid growth in urban areas, multifamily developers are providing rental units to house this population surge. Given that critical health outcomes including obesity, cardiovascular disease, diabetes, and cancers have been linked to the built environment, and provided the influence of home on community health and healthy behaviors, multifamily real estate must be an active participant in the health conversation.

While connections between housing and health have long been recognized, empirical evidence is needed to inform decision-making within the real estate industry to encourage their active engagement in developing healthy communities. Potential benefits regarding the real estate industry’s influence on community health are beginning to draw attention, including work by the Urban Land Institute (ULI), the Green Health Partnership, and the recent 2016 Health and Well-Being Module from Global Real Estate Sustainability Benchmark (GRESB). Regardless, a large gap in peer-reviewed research still remains.

This paper outlines the early stages of a research initiative exploring considerations for building a business case for private developer investment in projects engaging community health. The proposed framework suggests methods for integrating resources and expertise to create a holistic, mixed-methods business case to understand motivations, processes, and implementation mechanisms needed to develop practical strategies and create identifiable value based on health and well-being within multifamily developments. Items to be addressed include: (1) how and why developers might address health; (2) criteria for decision-making processes; (3) favored health strategies within projects; (4) economic factors, including discussions with financial lenders; and (5) considerations between different project types and locations based on local infrastructure and relevant housing and health policies. The resulting business cases would be able to inform municipal policies to encourage multifamily development projects that support creating a culture of health in communities, as well as incentivize or make the case to developers to incorporate health in their projects.

KEYWORDS: multifamily development; health; built environment; culture of health; real estate

INTRODUCTION
Multifamily developers in the United States have been slow to engage community health initiatives, and overall have not been incentivized to do so. As the U.S. continues to see rapid growth in urban areas, multifamily developers are eagerly providing rental units to house this population surge across the country. Freddie Mac estimates the number of renter households will increase by 4.4 million by 2025, with 306,000 multifamily units completed in 2015 (Freddie Mac, 2016). The cost of multifamily rental units is now 38% higher than the pre-2008 recession peak, representing over $5.1 billion in rent in 2015 nationwide (US Department of Commerce, 2016). Multifamily developers’ response to this growth affords a largely unconsidered opportunity for the real estate industry to positively impact the health and well-being of the community at large. One way developers can engage health is through the built environment, which is associated with both physical activity behaviors and health outcomes such as obesity, cardiovascular disease, diabetes, and cancers (Sallis, Floyd, Rodriguez & Saelens, 2012). A study of 6–11 year olds found that youth spend 47.2% of their day at home, accounting for 43.6% of their moderate and vigorous physical activity (MVPA) (Tandon, et al., 2014), while adults were found to spend 51.3% of their time within 125 meters of home, accounting for 20.7% of their MVPA (Hurvitz, Moudon, Kang, Fesinmeyer & Saelens, 2014). Provided the influence of home environments on community health and healthy behaviors, multifamily real estate must become part of the mainstream interdisciplinary research, policy, and practice conversation. This paper reviews the conceptual foundation and research aims for a grant received from the Robert Wood Johnson Foundation’s Engaging Businesses for Health project, an RWJF initiative managed by Academy Health. The project is in its early stages as it commenced in February 2017. A collaboration between North Carolina State University’s College of Design and Department of Parks, Recreation & Tourism Management in the College of Natural Resources, the funding seeks to ultimately establish a business case for the inclusion of health strategies in real estate to inform both policy and private investment.

1.0 BACKGROUND
While connections between housing and health have long been recognized by researchers and policymakers (e.g., ‘The
relation between housing and health; Public Health Reports, 1934), empirical evidence is needed to inform decision-making within the real estate industry to encourage their active engagement in developing healthy communities. The real estate industry is vastly complex and includes an array of decision-gates throughout the development process; so, in an effort to narrow the scope, this research particularly focuses on formative development conceptions for new multifamily projects. Literature addressing mechanisms that incentivize decisions to locate multifamily developments proximate to existing transportation, fresh food outlets, parks and greenways, and medical services, for example, remains nascent. Currently, incentives (i.e., financial, accreditation, and others) used in real estate decision-making are focused primarily on green building initiatives and policies, leaving the health impacts of real estate endeavors unmeasured and unconsidered – an economic externality (Trowbridge, Warden, Pyke, 2015). Translating the business value of these health-promoting features into actionable, project-level decisions for real estate industry stakeholders is therefore rarely implemented (Erickson and Andrews, 2011; Trowbridge et al., 2015). At the same time, potential benefits regarding the real estate industry’s influence on community health are beginning to draw attention, including work by the Urban Land Institute (ULI), the Green Health Partnership, and the recent 2016 Health and Well-Being Module through the Global Real Estate Sustainability Benchmark (GRESB) (Trowbridge, Worden and Pyke 2015; Bauer, Eichholtz, Kok and Quigley 2011).

ULI recently outlined developers’ motivations, intended wellness and health outcomes, the development process, and metrics of market performance for thirteen developments with wellness intentions - i.e., clean indoor air, physical/pedestrian activity through project design, support for bicycling, structured fitness activity, and social interaction (Kramer, Lassar, Federman and Hammerschmidt 2014). Performance metrics for one such development in Fayetteville, AR, indicated the inclusion of clean indoor air strategies and a community garden near the pool and social courtyard contributed to the fully leased status. Current rents for this development run 113 to 140 percent of pro forma estimates, significantly higher than comparable apartments in the area. Turnover has been 15 percent lower than the market average (Kramer, et al. 2014). Highlights like these are promising; however, these initial, engaged projects remain the exception, not the rule. A large gap in peer-reviewed research – especially from an interdisciplinary design, health, and real estate perspective - still remains. The prospect of private multifamily developers adopting a novel value proposition is not unprecedented. The green building industry, for example, provides a model that can help guide efforts to build a culture of health across the built environment system, including: practitioners, policy makers and financiers. The past two decades has witnessed the introduction and implementation of tools and practices within the green building industry to drive the adoption of sustainable built environment design and operation practices on a global scale (Trowbridge, Worden & Pyke 2016).

The Green Health Partnership, with funding from Robert Wood Johnson Foundation, consists of interdisciplinary researchers from the University of Virginia, U.S. Green Building Council (USGBC), and Global Real Estate Sustainability Benchmark (GRESB). Their aim is to create new market interventions, tools, and metrics to influence investment and design decisions in the community development sector where data related to health costs and benefits are largely unconsidered. Their publications address how, within the real estate industry, health impacts of transportation, community development, and construction continue to operate as economic externalities: unmeasured, unregulated, and unconsidered. For example, researchers looking to advance the design, construction, and operation of built environments – to both promote human health and protect the environment – were unable to garner needed attention to permanently shift markets due to lack of substance; very little information is available to describe distributions of practice and performance related to sustainable design in real estate, let alone health (Pyke 2012; Trowbridge, Pickell, Pyke and Jutte 2014).

Building squarely upon these notable efforts, our objective is to go further and develop a business case for private developer investment in projects engaging community health. Working specifically with developers interested in these initiatives, and attempting to implement them, we have direct access to information and data needed to establish a health road map for the multifamily developer industry. Our interdisciplinary project team will integrate resources and expertise to create a holistic, mixed-methods business case to understand motivations, processes, and implementation mechanisms needed to develop practical strategies and create identifiable value based on promoting a culture of health and well-being within multifamily developments. The resulting business case will also inform municipal policies to encourage multifamily development projects that support creating a culture of health in communities.

2.0 RESEARCH QUESTIONS
This project is designed to explore strategies and financial considerations used in decision-making by private multifamily housing developers that are early adopters in supporting community health through the built environment. Specifically, the following aims are proposed:

Aim 1: Determine how and why private multifamily developers consider and include community health strategies and health-related amenities in new projects.
Rationale: Privately-funded multifamily developers house 57 million residents in the US, making critical upfront decisions on the location of properties and health-related amenities available.

Research Questions:

1.1: How do private developers define health strategies, amenities, and potential benefit?
1.2: What strategies and amenities are being considered and included, and why, in the design and construction of multifamily development projects to support community health?
1.3: How do equity partners view these strategies as they consider investing, and how do developers communicate the business value of the strategies to these financial institutions?

Aim 2: Determine the actual and perceived costs and returns for private developers to include community health strategies and amenities, in both total dollars spent and added construction premiums per project.

Rationale: Exploring developers’ total expenditures and returns on investments through different contextual lenses will inform the business case as to how for-profit companies justify risks involved in the dollars spent in different communities on community health interventions.

Research Questions:

2.1: What are per item and total costs of including the identified health related strategies and amenities?
2.2: How do private developers understand and categorize, both conceptually and analytically, their returns on amenity investments, and how do they define the success of these investments?

3.0 METHODOLOGY

To understand the complexity of decision-making processes in multifamily development, particularly focusing on private businesses that have chosen to incorporate health initiatives in their projects, it is important to study specific cases in-depth focusing on the questions of How and Why. Yin proposes that a case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context” focusing on questions framed in How and Why (Yin 2009). Case studies have also been used extensively in “developing and testing strategies to collect...data...to design and implement interventions” as seen in RWJF’s Collection of case studies in the National Health Plan Collaborative (The National Health Plan Collaborative Toolkit 2008). With the goal of exploring how private businesses can best target their investments to increase community health, the case study approach will use primary and secondary data to inform the business case for leaders in multifamily real estate to invest in health across geographical markets.

3.1. Case study selection

Two multifamily development organizations were strategically approached to partner on this research based on their interest and engagement in establishing healthy communities in the Southeast region of the U.S. They represent two of the fastest growing population centers in the country: Crescent Communities (Charlotte, NC) and LIFT Orlando (FL). Five cases within these developers were selected based on location in the Southeast, and a focus on healthy community themes such as food and social equity. Four cases will come from Crescent Communities, a traditional for-profit real estate developer. Two selected cases are in Charlotte, NC, one in Nashville, TN, and one in Washington, D.C. Three cases are traditional for-profit, market rate multifamily communities for easily transferrable findings; one influential case is a social equity project addressing homelessness, providing unique insight to a specific social challenge through the investment of private funds.

LIFT Orlando, a market rate multifamily community in Florida and a Purpose Built Community, focuses on holistic community revitalization engaging a mixed-income housing strategy and community wellness services. This is a unique way of building community health, and could support a rich business case as a fifth example.

3.2. Data collection measures

To gather the primary data addressing the research questions of How and Why, a day-long, in-person session of in-depth interviews and data gathering will be held with Crescent Communities using comprehensive questions guided by USGBC’s LEED Pilot Credit program, which is aligned with RWJF’s Culture of Health, and GRESB’s Real Estate Health Assessment. Items to be addressed will speak to Aims 1 and 2, and include: (1) how and why the company addresses health; (2) criteria for decision-making processes; (3) favored health strategies within projects; (4) economic factors, including discussions with financial lenders; and (5) considerations between different project types and locations based on local infrastructure and relevant housing and health policies. The above steps will be repeated with LIFT Orlando via virtual meetings. After analysis of initial meetings, half-day follow-up meetings will be scheduled. Initial findings will be shared for feedback and remaining questions will be answered or clarified.
Secondary data will be gathered through a partnership with Trulia, the online residential real estate site for homebuyers, sellers, renters and real estate professionals. Trulia is providing unit pricing, demand, vacancy rates, and marketing for each multifamily development in the 58 cities with a population over 100,000. The properties will be stratified by whether or not the listing description includes key health features on-site (i.e., walking or biking trails, sport courts, access to public transportation, etc.). Unit pricing and vacancy rate data is available annually and retrospective to 2006.

3.3. Data analysis
Transcribed interviews will first be analyzed through a within-case analysis (Creswell 2007), with coding for themes by two team members, addressing research questions with respect to each particular case. Following the preliminary creation of codes, team members will modify coding and themes as necessary to ensure findings fit the research questions being addressed. A second round of cross-case analysis (Creswell 2007) will be completed analyzing themes across cases. Both rounds of coding will be reviewed with the full research and advisory teams. Descriptions, frequencies, and contexts of responses will be captured to enumerate common and less frequent health strategies and amenities, decision-making processes, economic considerations, market determination, and location of new developments. Results will be shared for discussion with participant developers.

Quantitative data gathered in Aim 2 will stem from financial pro formas received for the selected developments. These will include sources of funds, funding associated with tax credits, development timeline, and actual costs for community health components within specific developments. Analyses will include descriptive and frequency statistics as well as associations between health-relevant language, tax credits, timeline, costs and other investor benchmarks (i.e., capitalization rates).

Descriptive and frequency statistics will be developed with data from Trulia including health-related strategies and amenities, unit pricing, vacancy rates, and rental tenure. With data from 58 cities, inferential statistics will address health-related strategies and amenities and the outcomes of pricing and vacancy/tenure. City and census tract data will be included to control for spatial differences in demographics and socio-economic status.

3.4. Quality standards and verification
A Technical Advisory Group has been established to review and provide expert insight on the project, including representatives from: University of Virginia’s Green Health Partnership; GRESB; Delos, creator of the WELL Building Standard; Trulia; and professional designers in practice. These advisors have agreed to review the research plan, process, and findings. Additionally, quality standards of Credibility, Transferability, Dependability, and Confirmability will be addressed through measures including members’ checks with participants; triangulation of data between interviews, pro formas, and online listings; and the use of an audit trail documenting the processes by which data is collected (Guba 1981).

4.0. BARRIERS AND LIMITATIONS
This proposal has been designed to eliminate as many barriers and limitations as possible. However, the success of the research is dependent on the engagement and cooperation of the developer partners. By engaging these organizations early in the research design process, the proposal includes methods, data, and analyses that have been agreed to.

A barrier to case studies is the sheer wealth of data gathered to craft a holistic perspective of the issue being addressed. In exploring the methods for engaging private multifamily developers in community health, a variety of methods need to be used, including interviews, pro forma analysis, and data mining from national databases. Generalizability could be limited with only two developers, though the participants were approached based on being mainstream (Crescent) and unique (LIFT).

While the goal is to better understand the financial and strategic paths necessary to include health as an impactful and necessary consideration within the real estate process for multifamily developers, a long-term barrier will be establishing fundamental organizational transitions within the real estate industry toward a culture of health. This research represents the early stages of a burgeoning field of incorporating health and wellness into a measured component of the real estate process; efforts to adopt recommendations offered by this research may take time.

5.0. DISCUSSION
Research in the urban planning and public health fields have recognized that the design and operation of communities in which people live, work, play and learn can significantly influence health behaviors and outcomes. There has been considerable evidence supporting that built environments shape opportunities to integrate physical activity and other health behaviors into daily lives. However, it remains unclear if private sector real estate recognizes these critical relationships in their decision-making and implementation processes. Provided that real estate development, in its most basic form, is the continual reconfiguration of the built environment to meet society’s needs, and that the current state of chronic disease within the U.S. society has reached epidemic proportions, this project highlights how the intentional
implementation of healthy built environments will be increasingly reliant on the practices and choices of real estate developers. Further, the projected build-out of multifamily developments to accommodate population influxes within the southeast provides a well-suited housing type to deeply explore top-level decision-making with respect to the prioritization of healthy community design in development planning.

Termed as market transformation, this strategic process of market intervention has successfully removed barriers to and create incentives for built environment decision makers’ prioritizing energy efficiency on a broad scale (Trowbridge, Worden, Pyke 2016). The above research aims to explore how health promotion objectives can adopt a similar trajectory within the real estate industry. Our mixed methods study design will enable our team to not only uncover motivations and in-depth decision processes observed within the real estate stakeholder industry, but also apply quantitative techniques to develop the necessary financial evidence base to drive a market shift towards a culture of health. Identifying and defining opportunities for public health engagement within this process will be essential to drive progress toward the goal of creating healthier communities at a national scale.

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REFERENCES


ABSTRACT: The United Nations indicates that more than half of the world population now lives in the urban area. In urban environment outside of North America and Western Europe, one of their prominent characteristics is the prevalence of the informal settlements. They are a manifestation in the built-environment of experiences of modernity, which have shifted from the transitions from traditional into modern societies into integration into the globalized, post-industrial world, which included impacts of the economic, political, and cultural forces of late capitalism. This phenomenon possesses a multitude of social, economic, political, and environmental issues, in particular, in relationship to the presence of the urban underprivileged. The latter informs a particular way of constructing and ordering of space and form of cities. This paper reports the design research that the author and students have been performing in slums in Addis Ababa, Mexico City, Manila, and Mumbai. The research documents and analyzes first hand experiences in slums architecturally, then seeks the relationship to the local socio-cultural contexts. The design research aims to ask the question of how to interrogate contemporary spatial and formal practices in this context? How can we theorize these practices within the context of theory of modernity in architecture? It intends not only to offer the understanding of slums in descriptive or prescriptive fashions, but also to seek generative design principles that possess potentials as social catalysts.

KEYWORDS: slums, generative principles, modernity

INTRODUCTION
Ullrich Beck argued that modernity has shifted from the dissolutions of traditional societies into the transformations of the industrial societies themselves (Beck, 19-50). He pointed out that modernization brought about the increase and distribution of wealth. However, it produced risks and hazards as its consequences. Thus, the logic of modernity changed from the logic of wealth distribution in a society of scarcity to the negative logic of risk distributions. The dream of an emancipated, utopian society without economic and social disparities was replaced by a negative utopia of the distribution of risks. The process of modernization turned into a systematic way of dealing with its own hazards and insecurities. He alluded that history showed that wealth were accumulated at the top socio-economic classes, while risks were concentrated at the bottom tiers. This implied the social and political dimensions of risks, as they became means of the filtration of societies that would enhance the class stratification. Beck argued that eventually, risks would affect all parts of societies because of the systematic nature of modernity. Modernization became spatial, as risks were concentrated in specifically geographic areas (Beck, 19-50). This line of thought is particularly relevant to the urban realms in the Third World. Nowadays, the experiences of modernity for the third world has shifted from the transitions into a modern society from traditional societies into an integration into the globalized, post-industrial world, which included impacts of the economic, political, and cultural forces of late capitalism. Urban areas of the developing world manifest these experiences of modernity in the built-environment. This phenomenon possesses a multitude of social, economic, political, and environmental issues, in particular, in relationship to the presence of the urban underprivileged. The underprivileged inhabit informal settlements that made up a large part of the urban areas. As the urban areas in this part of the world experience rapid growth, so do the extent of their informal settlements.

1.0 DESIGN-RESEARCH ON SLUMS
1.1. Methodology
This design research was fifth-year theses in our institution that consisted of research in the fall semester and design studio in the spring. Each of these students involved came from different cultural backgrounds and they chose to work on slums from their respective upbringing. The methodology for this research was a series of descriptive and analytical mapping from general to particular levels. The intent was to understand the issue through visual means and to unfold the relationship within each level and across different ones. We started with the UN Habitat’s definition of slums that we articulated as architectural issues, based on framing architecture as spatial, formal, tectonic, programmatic, and performative factors. overcrowding and socio-economic exclusions illustrated the spatial and programmatic dimensions of slums, in which certain groups of people were concentrated in certain areas with real and invisible barriers. Tectonically, the construction and materials of structures signaled a part of a city as a slum. Lacks of services and infrastructures illustrated the performative dimension of slums. We diagrammed comparative photographic
examples of slums to understand their morphology, assuming the street as its basic elements. We analyzed properties including of the geometry of spaces, ordering system, scalar aspects, and properties of boundaries. The findings included that street and alleys created figurative profiles in figure-and-ground. The scales of space were mostly intimate, and they tended to be curvilinear. Programmatic features included the overlaps of public and private space, low degrees of separations of personal, family, and communal spaces, the porosity of these programmatic boundaries, and the distinction of spaces based on genders. We mapped both physical, visible and conventional infrastructures, such as water and electricity, and less visible ones, such as internet and mobile services. We noted that spaces in the slums were highly flexible and that inhabitants of slums were highly skilled in adapting their social and economic activities within their spatial and formal settings. Each student then researched demographic features and related economic factors of selected countries. We also researched typologies of vernacular architecture in respective country. Vernacular in this sense included contemporary houses, working on an assumption that the way people used spaces in slums was informed by spatial behaviors that were embedded in vernacular architecture. The findings provided a framework for the field studies to observe, collect, and document data and information. Besides site observations and documentation of spatial and formal features, they also observed daily activities in slums, including shadowing families.

In the design studio, we started with programmatic analyses of a swath of a street, mapping daily activities according to categories including economic or social and personal or collective activities. This analysis was based on the understanding of the ways the locals used space. We diagrammed and mapped activities as bodies occupied and moved around space and also the temporal scenarios in which bodies occupied spaces in different ways and locations in different times. We also diagrammed elements that facilitated activities and the roles of spatial boundaries relative to those activities. These activities diagrams fed the formal analysis, in which we translated them into a series of two- and three-dimensional forms. We also analyzed characteristics of materials in slums that tended to be rough and colorful and construction techniques that tended to be flexible, temporal frame structures. These findings informed in the iterations of the design research. The focus on activities on slums led students to propose interventions in terms of infrastructure that would support daily activities in slums. Each student's interests after engaging life in slums, such as provisions of education, economic and health services, informed the design intents. Students explored designs that integrated materials and techniques adapted from the slums. They then constructed artifacts for infrastructure out of materials commonly used in slums, using techniques and methods that inhabitants of those places used in their daily life.

1.2. Research and Observations
One student researched slums in Mumbai, India, starting with analyzing the morphology of Indian slums. He identified features such as small urban grains, clusters of small and large blocks, dense blocks with narrow streets and public open spaces around religious buildings. The street sections showed a vertical separation of commercial and industrial activities on street levels and residential purposes on upper levels. The street level tended to be permeable, creating a linear, continuous space that accommodated various activities. He identified verandah on a raised level as one of the

![Figure 1: Comparative studies of slums. Source: (Tolentino 2014)](image-url)
main features of vernacular architecture there. It provided a space for daily activities, including cooking, relaxing, social activities, as well as home-industries such as pottery and sewing. The study focused on Dharavi, considered as the largest slum in Asia, in which he noted that its central location had made the area as one of the most valuable land in the city. A particular characteristic of area was the predominance of small businesses and industries based on waste-recycling. The area was organized according to types of wastes that they processed, such as plastics, metal, and paper, and to the separations of areas for receiving, processing the waste and delivering recycled products. Inhabitants lived among these recycled materials, sleeping, cooking and eating in leftover space inside their shelters.

Another student studied Addis Ababa, Ethiopia, starting from researching low-cost housing programs to address slums in that city. However, these housing schemes failed to accommodate the needs for diversity and qualities of social and economic supports. She mapped the social organization of the societies along a successive system, starting with family units, which together would form an association. Several associations would integrate into a community unit, which in turn would create a larger unit called kebele, which served as the building blocks of a city. The family and the associations revolved around vernacular houses. She identified the courtyard in vernacular houses as the space around which social activities within the spheres of both family and associations would gravitate. In their evolutions, such as in the housing schemes, inhabitants would form a space that resembled this courtyard. She focused on Mercato, a large residential and commercial area in the city. She observed that types of commodities and programmatic hierarchy of buildings along the street created the logic of spatial organization in the neighborhood. Her findings included the spatial separations based on gender, social activities revolved around drinking coffee, and the prevalence of economic activities around the recycling of metal goods.

Figure 2: Analysis of slums in Addis Ababa. Source: (Moges 2016)

The research on slums in Mexico City mapped the distributions of slums that followed geographic features, with concentrations of slums on steep slopes, with easy access and close proximity to economic nodes. The student mapped different types of slum, the first of which was irregular settlements equivalent to favelas and barrios. The second type was inner city tenements or vecindades in which inhabitants repurposed big, abandoned houses. The third type was makeshift housing on the flat roofs of apartment buildings and the last was shanty housing occupying public land. Their morphological features included courtyard buildings with aggregated cells, which lent to flexibility and adaptability; an echo of characteristics of vernacular architecture. Narrow passages converging to one point with hard enclosure created a sense of claustrophobic space. Abandoned infrastructure morphed into mixed-use public spaces, such as corridors in vecindad. In the neighborhood, artisans with certain social status would occupy structures facing the street or units facing a courtyard in a communal dwelling. The student focused on Tepito, in which he mapped the interrelated networks that linked solids and voids and public institutions, including schools, sport, and healthcare facilities. The mapping also revealed the patterns of activities, including illegal activities within the area. Noting the prevalence of invisible infrastructure, the student established a survey through Facebook to gather inhabitants’ feedback of interventions that they would like to see.
The students identified Manila as a very dense metropolis with informal settlements covered much of the area. It was a multi-centered city, around which both formal and informal settlements were organized. The students characterized the small scale of spaces in the slums as oscillating between intimate scales for personal activities and oppressing ones where the sense of personal space disappeared. Each structure usually was built as a room that accommodated various domestic activities. The alleyways that connected these cells of space turned into highly flexible and active semi-public and public spaces. These alleyways were both semi-exterior and exterior space, accommodating both personal and communal activities. These spaces were defined by soft, porous enclosures that allowed for physical and visual connections. The properties of the enclosures created different degrees of the transformation of the alleyways into public spaces. Women and children were the primary users of these spaces, while men tended to work outside the slum. Women used these public spaces to perform both daily chores and home-based businesses. Slums dwellers modified these spaces throughout the day and night to accommodate their activities, each of which occurred at a specific time. However, they also observed public spaces other than the alleyways, such as basketball courts. These public spaces revealed the gender segregation, in which basketball courts tended to be a space for male. In the evening, men would gather in these spaces to watch television. Extended families were common in the slum neighborhood and they formed close-knit community. However, single persons were common, to which inhabitants rented out spaces inside their dwellings. Services, mainly electricity and clean water, were uneven. The structures were based on post-lintel system, a makeshift construction out of locally-sourced materials, including corrugated metal sheets, plywood panels, concrete blocks, and stretched fabric. A particular condition of Manila was the torrential rain that posed a constant threat of flooding, which in part informed the temporality of those structures.

Findings led to design-research that revolved around the notion of flexibility of space, the provisions of infrastructure to facilitate activities, and the explorations of materials available in local slums and of local knowledge and techniques. Infrastructure in this context means artifacts that would enable activities and a module that could be repeated and reproduced, forming a system within the slums. At the concluding phase, the design-research took form of a design-build project. In this line of thought, the Addis Ababa's case intended to capitalize on the tradition of gathering for coffee, stemming from the idea of combining the hearth for making coffee with other elements to facilitate transmissions of information and knowledge. This artifact would be deployed in such a setting, allowing the artifact to transform such a meeting into informational and educational events. The theme of the design was a portable classroom through an artifact that was flexible, able to fit anywhere within the slums, applicable to community scale, could be configured in multiple ways, and constructed out of recycled metal. The studies on Manila researched on the creation of a transformable artifact that could accommodate activities for women and children. This intent emerged out of the observations of the ways women combined their home-businesses with child-caring. The design was a transformable
device made out of modular, foldable panel. This unit would be of fabrics or flexible materials attached to a light-weight frames. Thus, the combined panels could form stalls for women for their economic activities or classrooms for the children. The second project for Manila stemmed from the observations of the need of defining space to accommodate activities and needs for women. The main argument was that although women played a crucial role in life inside slums, even more so compared to those outside slums, their existence was often neglected. The focus of this research was on investigating the construction of surfaces with atmospheric qualities that would accommodate and highlight women's needs, along the trajectory of exploring the possibilities to transform plastic bottles into an atmospheric fabric. This line of thought aimed at efforts to translate sophisticated technology, such as parametric design, into low-key technology in working with the materials.

Figure 4: Proposal for Manila (left) and Addis Ababa (right). Source: (Tolentino 2014, Moges 2016)

1.3. Literature on Slums
According to Mike Davis, slums emerged along with the process of industrialization, with slums sprang around manufacturing industries in nineteenth century cities (Davis, 1-69). However, current slums, mostly in the third world, exemplified a process of urbanization without industrialization. They were a result of agricultural deregulations and fiscal policies, which created surplus of labor in rural areas. The lack of employment and the disappearance of networks of social safety forced this surplus of labor to migrate to cities. However, cities in the third world evolved without the growth of manufacturing industries. As a result, the migration of the poor to the city led to the proliferation of the informal economic sector, accompanied by the spread of informal settlements. Along this line, Rao argued that the growth of cities in the developing countries stemmed from the belief of cities as the engine of modernity (Rao, 671-2). However, they failed to stimulate the development of the rural area. In this vein, Davis charted the typology of slum, including squatting or occupying land without secure tenure, the filtering down of housing to the poor, street housing, invisible renters, and urbanization of the edges (Davis, 27-49). Further, he stressed the spatial consequences in which the poor had to live in dangerous, unhealthy locations, exposing them to hazards from toxic industries or to encroach on environmental reserves, such as riverbanks. The risks of these settlements were exacerbated by the inability of cities to provide proper infrastructure. In this sense, this form of urbanization revealed the urban inequality in formal and spatial terms. However, Rao noted that for Appadurai and Chatterjee, slum demonstrated the emergence of a space with new strategies of self-governance, rather than a space managed by the government (Davis, 125-47). Nevertheless, Rao noted Ananya Roy who countered that these participations did not necessarily challenge the treatment of cities as mega-projects by government and big businesses (Rao, 679-80). In this line, Lefebvre stressed that a city should always be for human (Rao, 681). Hence, he argued for the right to the city as a collective right that could be achieved through participation and engagement. This argument related to Lefebvre's broader argument that space is not an abstract entity. Instead, it is the location of social relations, the design of which, in turn, affected social and political behaviors. This argument informed the notion of everyday urbanism that highlighted the diversity in urban spaces and the notion of strategic and tactical use of urban space (Crawford, 6-11). The former referred to ways authorities prescribed the use
of urban space, such as in the zoning and land use codes, while the latter referred to ways in which urban inhabitants used urban space, going about their daily life and navigating around the prescription of urban space.

In dealing with slum, Rao called for architect to change the roles of design from a tool of interventions to a tool of innovations in order to further the critical understanding between cities and their inhabitants (Rao, 683). This call found an echo in Teddy Cruz, who pointed out to the critical project of the avant-garde in art and architecture, in which work in architecture has become self-referential and autonomous in order to achieve critical distance (Cruz, 205–16). This critical distance was a form of resistance, allowing a design work to serve as a form of critique. Cruz instead challenged architects to reverse the position in order to engage the world, which he called radical proximity. Along the line, Goodbun, Till, and Iossifova have reframed the context of conditions such as slum in terms of scarcity, in which they challenged designers to ask the effects of scarcity on the production of the built–environment (Godbun, 10). Till and Schneider argued that one of the issues was the tendency to address scarcity in terms of lack, failing to recognize the opportunity for a critical engagement with existing conditions (Till, 38–43). They suggested to use architectural intelligence to engage existing conditions, relating social and ecological factors with the physical design. Examples of these strategies included reusing and redistributing available materials and resources, avoiding the use of costly materials, and matching local skills with needs.

CONCLUSION

The values of this design-research lies in the way students recognized the limits of architectural interventions in complex and multilayered socio-cultural, economic and political situations. They started with a vision of addressing slums through massive interventions, such as public housing. However, this process led them to discover distinctions between top-down and bottom-up approaches, along with opportunities and limitations of each. As the process turned to revolve around the notion of bottom-up approaches, the intent of learning from local knowledge emerged as the main motive. It brought about the notion of humility in the design process, in which we tried to learn from particular contexts rather than imposing our ideas. Visits to slums always led to the sense of overwhelming desperations. However, by calibrating the focus to everyday, small-scales potentials, students recognized opportunities for architectural interventions in the face of structural conditions. The design explorations turned to investigations of infrastructural interventions, rather than a specific building type, that aimed to facilitate the use of space. They also turned to low-key technology in order for the project to be carried out locally as an opportunity to incorporate inhabitants as agency. As such, we intended to produce designs that would allow active participations. As a capstone project, this process gave opportunities for a process that progresses from global to local contexts and eventually to constructed architectural artifacts.

Beck urged to frame to notion of modernity as a reflexive process, to apply rationality to examine risks and hazard as the consequence of modernity. Extending this notion to the third world, slums exemplified the experience of modernity as an experience of risk and hazard, in which ordinary people were forced to face them in daily life. We sought to read these experiences through basic architectural lenses to identify opportunities in formal, spatial, programmatic, tectonic and performative terms. Our design–research sought to capitalize on findings that came out of close readings of slums. We saw the flexibility of spaces and the resilience of the inhabitants as a starting point to develop possible generative design principles. We sought to set a way to develop deep understandings and awareness of contexts and to learn from local resources, knowledge, and practice, while referring back to some fundamentals in architecture, including basic formal properties. The findings informed us on possibilities to engage and negotiate conditions on site to propose design responses through small interventions that would empower them, capitalizing on lessons learned from sites.

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Mike Davis, Planet of Slums, 2006, New York: Verso


ENDNOTES

1 UN-Habitat, State of the World’s Cities Report 2007/2007, 21. UN Habitat defined slums as an urban area with a lack of one or more features including protecting, durable housing, sufficient living spaces for more than three persons, easy accesses to water, adequate sanitation and basic services, the security of residential tenure, and adequate structures. It included the unhealthy living condition, hazardous locations, high density and overcrowding and a high level of poverty and social exclusion.
ABSTRACT: The Docking State Office Building, a 12-story state office building immediately adjacent to the historic capitol building in Topeka, Kansas, was completed in 1957 as one of the region’s earliest examples of tall, curtain wall glazed modern architecture. The Docking’s glass curtain wall was innovative for its time, and the design exhibits an elegant composition of stone planes and glazed skin.

In recent years, the Docking Building has been thrust into limbo, with competing plans to demolish, renovate, or sell the building stalled in government gridlock. Problems with the building’s systems and glass facades have been cited in arguments to demolish the building. This paper examines the building’s current and potential energy performance on a typical tower floor, analyzing the original curtain wall’s thermal resistance and ability to use daylight. While it is believed that the building needs gutted and reskinned to be saved, the paper asserts that the original environmental hypothesis of the building is sound.

KEYWORDS: Curtain wall, envelopes, simulation, historic analysis

INTRODUCTION
The Docking State Office Building, completed in 1957 and designed by Kansas Architect John A. Brown in 1954, is more than simply a facsimile of other glazed office buildings. While currently threatened by demolition and deterioration, research presented here argues that the Docking’s original thesis of broad, glazed walls and open floors is not only worthy of preservation, but remains tenable today given contemporary understanding of daylit office buildings and energy efficiency.

Architecturally, the Docking references the U.N. Secretariat Building, a monumental glass and stone-clad tower designed by Oscar Niemeyer and Le Corbusier and completed in 1950. Following the Secretariat by only a matter of years, Docking’s architectural expression was still quite avant garde in 1957 and consistent with a paradigm described by Korn [translated in Yeomans 1998]: “…a new structural concept where all load-bearing elements are kept within the core of the building, leaving the outside wall to be nothing but a wrapping to enclose and allow light to penetrate.” Like the Secretariat, the Docking building makes a statement by contrasting the lightness of a glazed curtain wall with crisp, stone-clad planes at its end walls – as opposed to wrapping the building homogeneously with glass. While the Secretariat stands monumentally against the Hudson River in New York, the Docking’s 14 stories offer a more complex volumetric composition where two intersecting tower wings, a slightly projected stone-clad core, and a stretched three-story base come together to frame the southwest corner of the state capitol grounds (Figure 1).

The Docking’s aluminum and glass skin was improvised from scratch as many early curtain wall systems were, with manufacturers “kite-flying” largely untested ideas on paper (Yeomans 1998). The Docking’s aluminum and steel curtain wall were manufactured by the Benson Manufacturing Company of Kansas City, Kansas, whose prior business was in beer kegs. Thermopane, a pioneering manufacturer of double-glazing, provided double pane glass units (Griffin 2011). In the opaque portions of the curtain wall, Foamglas insulating blocks were used for their thermal efficiency and fire resistance.

Early glass buildings also presented significant environmental control problems. Reynor Banham credits Corbusier and air conditioning pioneer, Willis Carrier, side by side with the urban revolution marked by the U.N. Secretariat – a building only feasible because of huge fan rooms forcing air through heating and cooling induction units at the harsh perimeter environment (Banham 1969). The Docking’s original approach was similar, yet different, using perimeter fan coil heating and cooling units instead of the remote fan rooms as in the Secretariat or most other tall glazed buildings at the time: these fan coils powered air flow and introduced fresh air locally at every unit.

Architecturally, the Docking made a powerful, forward-looking statement in a humble Midwestern capital city. Inside, the building’s luminous and sweeping views of a capital city are complemented with beautiful original finishes that include carefully-selected stone, tile, and crisp aluminum ceilings. Fully occupied, the Docking hosted 1,500 workers in
various state agencies while also providing an underground link to the capitol building.

![Docking State Office Building](image)

**Figure 1**: The Docking State Office Building soon after it was constructed. (Source: Kansas Historical Society)

1.0 THE DOCKING BUILDING TODAY

1.1. Current Conditions

Sixty years after it was constructed, the Docking faces the prospects of either a costly renovation or implosion. Like other pioneering glass towers, its once-high-tech glass skin is entangled in larger questions about the building’s viability. The U.N. Secretariat, for example, was ‘reskinned’ during a major renovation costing $2.3 billion (Gonchar 2012) and the 1952 Lever House in New York, had its glass skin replaced as part of a $60 million renovation in the 2000s (Stephens 2003). These buildings used single glazing systems that experienced widespread leaking and glass breakage. Aside from the decades-old sealant, the Docking’s 60-year old façade appears to be in reasonable condition with little visual evidence of serious problems.

Comfort and energy consumption is another matter, and the ‘poor’ condition of official assessments cite poor performance of the original 1957 mechanical, plumbing, and lighting systems (Carlson 2007). Through the building’s history, issues with comfort and energy use are evident. In 1965, forced air HVAC was added to each floor to supplement the struggling 2-pipe fan-coil units at the perimeter of the building (Steele 2016). According to building operators, complaints about comfort and the building’s appearance grew as the building aged (Steele 2016); archival photos over various years show fabric curtains and blinds mostly closed, day and night.

By 2014, officials began publicly discussing the implosion of the building and state agencies were moving out (Marso 2014), leaving the building nearly vacant today. Most recently, estimates to extensively gut and reskin the building have grown to $84.5 million (C-J Editorial Board, 2016), while the state has ‘mothballed’ the building (Figure 2) rather than finance a costly demolition. While comfort and energy problems fit the stereotype of a recklessly glazed modern tower, this research examines the possibility that the risky – but innovative skin – may not be the root of the building’s troubles. We know today that building performance is complex, the sum of many factors. If the Docking’s fundamental design is sound, less expensive modifications may be able to update it to the efficiency and environmental quality of a modern building – or even a high-performance building, something of significant value for the State of Kansas.
1.2 Description of the Wall Systems

The Docking Building is composed of a three-level base, with nine subsequent levels of ‘tower’ above, with an addition elevator machine level and penthouse level at the top. Two floors of underground mechanical space house boilers and chillers providing heating and cooling for six other major buildings in the capital complex. In total, of the roughly 368,000 square feet of building area above grade, 60% resembles the typical tower floor examined in this study (Fig. 3). On a tower floor, approximately 70% of gross wall area is curtain wall, with opaque spandrel panels giving the tower a window to wall ratio (WWR) of 33%: nearly compliant with the 30% minimum of current energy code (International Code Council 2014).

Apparantly late in construction documentation, details were produced to bid the curtain wall system as an alternate, though earlier designs showed conventional masonry infill walls with ribbon glazing. Subsequently, the $4.5 million construction contract was awarded to a company who errantly bid the curtain wall alternate at a modest savings, but who admitted the company would “not relish” sourcing the more complex and exotic façade (No Author, 1954). Without surprise, construction didn't reflect the originally improvised details with enamelled steel skinned Foamglas panels for opaque sections of the curtain wall. Instead, the spandrels were solid granite (Figure 4) backed up with fireproof (and insulating) Foamglas block knee walls at the glazing sills. Glazing used Thermopane double glazed glass units with ¼” clear glass and air infill. Typical of early curtain walls, thermal breaks in the aluminum frames and mullions are absent. Structural loads are transferred to the building structure with continuous steel angles and tees. Though the
sashes are bolted and sealed today, the drawings specified push-out awning windows for all glazing, worsening thermal performance.

The remaining end walls and exterior core walls (30% of wall area) are masonry block clad with limestone. No insulation in these masonry walls appears in the detail drawings, except for limited areas that placed thin fiberglass sheets in alcoves with fan coil units.

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**Figure 4:** Shown are the details for a spandrel panel, glazing unit, and kneewall. The FCU surround is not shown in the detail at right, which was used for THERM analysis. At right, the spandrel is drawn as solid granite, and the knee wall is 2” FoamGlas block, representing the as-built condition. (Sources: Kansas State Office Building Construction Drawings; CAD drawing – author)

### 1.3 Mechanical Systems

By the 1950s, it was well established that aside from heating and cooling, commercial mechanical systems had to provide fresh ventilation air as well – one may imagine the ventilation problem in an office floor where over a hundred people are simultaneously smoking cigarettes. The Dockings peers, such as the U.N. Secretariat, distributed preconditioned ventilation air from central fan rooms where it received final heating and cooling in occupied spaces and, especially, in induction units along the climate-sensitive glazed perimeter (Banham 1969). Rather than use the more complex system of fan rooms and induction units for HVAC, the Docking attempted to use fan coil units (FCUs) exclusively for heating, cooling, and ventilation; a typical office floor has 84 FCUs, with an estimated 1,010 units in the building. Located at the base of each window (seen in Fig. 2) the FCUs brought in exterior ventilation air directly via a 2” by 24” duct connected to perforations in the floor-level curtain wall mullion on upper floors. Though this intake had a damper, for most of the building's life these intakes were probably left open [Steele 2016].

Environmental control by the FCUs posed several problems. The two-pipe water delivery system for the FCUs delivers hot or cold water to the units but not both, with the availability of hot and cold water determined uniformly for entire facades. A thermostat at each FCU controls water supply, while fans on the units operate continuously. Early in the Docking's life, it became clear that the FCUs could not provide all of the HVAC needs of the building and forced air was introduced in 1965, adding an air handling unit to each floor to service the central zones of office space.

### 1.4 Interior Components

The original perforated aluminum ceiling system used 48” two-lamp fluorescent fixtures throughout the office spaces. The ceilings have been largely preserved over time, while the original lighting fixtures were upgraded from T12 to T8 lamps and ballasts. The original beige vinyl floor tile was covered by dark carpeting in many offices and woven curtains were replaced by venetian blinds. More significant interior changes came when open plans were divided with floor-to-ceiling partitions on several floors, introducing private offices and other rooms against the perimeter.
2.0 EVALUATION AND ANALYSIS

2.1 Ventilation Rate
A ventilation test measured the outdoor ventilation rate of a typical FCU with the dampers open, as they were presumed to be for most of the building’s life. The measured rate of unconditioned outdoor air was quite significant, at 102 CFM per FCU. For a floor of 84 units, the total ventilation rate would be approximately 8570 CFM, or 2.34 air changes per hour. Based on an average of 125 occupants per floor (as reported in Carlson, 2007), the code-required ventilation rate for a typical floor would be 2059 CFM, the equivalent of 0.56 air changes per hour – about one fourth of the ventilation rate from the FCUs. Fresh air is also provided by the air handling units in 1967 forced air system, further increasing the ventilation rate beyond what is necessary.

2.2 Lighting Loads
The second issue evaluated lighting loads. Each roughly 20 foot by 20 foot bay in the office space is illuminated by 12 original two-lamp luminaires with retrofit T8 ballasts and lamps that consume approximately 54 watts each; the original 1950s era lamps consumed 89 watts (Westinghouse 1946). With the T8 retrofit, the lighting power density (power per unit area) is 1.61 W/ft^2 for a typical tower floor. By today’s standards – 1.0 W/ft^2 for ASHRAE 90.1 and 0.82 W/ft^2 for IECC 2015 – the lighting energy use in the building is high. This is significant because the heat gain from lighting energy increases cooling loads.

2.3 Daylight Analysis
The potential to use daylight in place of electric lighting was evaluated using analysis software (DIVA with Rhino). A typical tower floor was modelled with the complete exterior building mass in place to accurately shade, reflect, and obstruct sun and sky light. Curtains and shades were omitted from the model. Daylight evaluation used three methods: point-in-time illuminance with a cloudy sky, point-in-time illuminance per the LEED v.4 daylight credit (clear sky and sunny conditions), and climate-based simulation where the zone was evaluated through a typical year of sky conditions using Topeka climate data (following LEED v.4, USGBC 2016). The IESNA recommended office illumination levels were considered during this process, including 300 lux for task lighting (at desk surfaces), 150 lux for general lighting, and 75 lux for lighting in computer task areas.

Early daylighting design principles borrowed from Europe didn’t consider direct sunlight. In cloudy sky conditions, the illumination in the Docking is evenly distributed, though relatively low; an average of 38.3 lux across the daylight zone, and 10.3% of the floor area within the useful range of 75 and 150 lux (Fig. 5). If the floor’s reflectance is changed to 0.50 (versus the estimated 0.20 reflectance of dark carpet) much more daylight reaches the interior: an average of 88.1 lux is achieved, 33.5% of the floor area is between 75 and 150 lux, and 18.3% of the floor area reaches the recommended level of 150 lux for ambient office lighting (Fig. 6).

Figure 5: Illuminance levels throughout the typical floor, analysed with RADIANCE software and DIVA. The sky condition was overcast, and the model including the building volumes above and below. (Source: Author)
Figure 6: RADIANCE visualizations in a typical floor, without blinds. The image at left shows the existing floor, a dark carpet; the image at right shows a more reflective floor like that originally used in the building. The sky condition for the simulation was overcast. (Source: Author)

Next, a point-in-time illuminance analysis was done using a clear, sunny sky on Sept 21st at 9am and 3pm. The criteria for the current LEED v.4 daylight credit stipulate 75 to 90% of the floor area must be illuminated between 300 and 3000 lux: the lower end representing task lighting and the upper end representing a threshold where glare would become problematic. Results from the simulation show only 15.2% of the floor area in the 300 to 3000 lux range: too low to quality for the LEED credit. However, reasonable window sizes and deep surfaces around the windows result in only 7.9% of the floor at risk for glare.

The climate-based simulation sought the amount of floor area where daylight would satisfy the 300 lux threshold (sDA300) for half of the occupied hours, while also measuring high solar exposures (ADE1000). The daylit floor area, defined in the LEED glossary, is a “regularly occupied” area where people “spend time...seated or standing as they work” (USGBC 2016). Thus for this analysis, the center bays were excluded in the daylit area as non-daylit circulation and support zones. Given this interpretation, the climate-based simulation results showed 47.2% of the daylit zone fulfilling the LEED sDA300 criteria: very close to the 50% minimum. Additionally, the ASE1000 simulation returned a 0%, satisfying that portion of the LEED credit.

2.4 Building Envelope Thermal Resistance

The thermal resistance of the curtain wall system was analysed with two-dimensional finite element analysis (via the computer software THERM) to determine and average the varying thermal resistances of glazing units, aluminum frames, granite panels with a variety of backing conditions, and their respective intersections. Following the simulation described for ‘site built fenestration products’ in the THERM NFRC User Manual (THERM 2013), analysis results from different typical curtain wall bay sections (shown in Figure 7) were averaged using an area-weighted method to produce ‘total product’ U-values. The U-values from simulation are shown in Table 1, with a typical bay averaging a U-value of 0.515 Btu/ F°*ft^2*hr. The energy code mandates a minimum fenestration U-value of 0.38 Btu/ F°*ft^2*hr for region 4. Thus the thermal resistance of the curtain wall as an aggregate is not terrible by today's standards, but the effect of the aluminum mullions and frames is striking, increasing conductivity of the glazed areas by 44%.

Figure 7: A typical curtain wall bay was divided as shown for determining an area-weighted average of the various conditions in the curtain wall. These averages are shown in Table 1. (Source: Author)
Table 1: (Source: Author)

<table>
<thead>
<tr>
<th>Component</th>
<th>% of Ext. Wall Area, Typ. Tower Floor</th>
<th>U-Value Btu/ F°<em>ft^2</em>hr</th>
<th>R-Value F°<em>ft^2</em>hr/Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Glass, double-pane IGU, clear glass¹</td>
<td>-</td>
<td>0.476</td>
<td>2.10</td>
</tr>
<tr>
<td>Window (glass, edges, and frames)</td>
<td>33%</td>
<td>0.796</td>
<td>1.27</td>
</tr>
<tr>
<td>Upper Spandrel</td>
<td>18%</td>
<td>0.297</td>
<td>3.37</td>
</tr>
<tr>
<td>Column Spandrel</td>
<td>7%</td>
<td>0.238</td>
<td>4.20</td>
</tr>
<tr>
<td>Lower Spandrel</td>
<td>15%</td>
<td>0.214</td>
<td>4.67</td>
</tr>
<tr>
<td>End Walls and Exterior Core Walls</td>
<td>25%</td>
<td>0.48</td>
<td>2.1²</td>
</tr>
<tr>
<td>End Walls at base of glazing, insulated</td>
<td>2%</td>
<td>0.22</td>
<td>4.6²</td>
</tr>
</tbody>
</table>

¹Additional properties used for the glazing units: SHGC = 0.704, Tvis = 0.786, SC = 0.809
²Determined by summation and R-values of referenced materials.

Thermal resistance values for the end walls were determined by summation. In-situ observations with a heat flux sensor and thermal camera support the hypothesis that these walls, making up nearly as much exterior wall as the glazing, lack insulation. In summary, while the window areas (combining glass and frame effects) are the weakest components of the envelope, the better-insulated spandrels cover more wall area.

2.5 Annual Energy Simulation

Once ventilation, lighting, and envelope thermal characteristics were studied, the energy use of a typical tower floor (Fig. 3) was evaluated using EnergyPlus, with simulation inputs originating from the Grasshopper plugin Archsim and weather information for Topeka. The building volume above and below the floor were modelled to accurately shade the zone, and thermal properties from Table 1 were used in the simulation. The existing ventilation volume and lighting loads, derived from calculations discussed earlier, provided conditions for the initial baseline simulation along assumptions described in Table 2. Simulations were conducted with the floor as a single zone and without shading devices.

Following the initial simulation, a series of simulations were conducted in sequence to study simple modifications to the typical tower floor aimed at decreasing energy use. These variations are summarized in Table 2, presented in an order from least presumed cost to implement. The impact of these modifications to annual building energy use is shown in Figure 8, where results are displayed in terms of Energy Use Intensity (EUI, in annual energy units per square foot of floor area).

The first modification following the base simulation adjusted set points to the ASHRAE Standard 55 PMV Model, a prevailing climate-based comfort model. Lighting loads were then reduced to 0.40 W/ft², representing the daylight as primary space lighting with low-energy lighting used for task lighting. The next simulation (number 3 in the sequence) reduced the infiltration rate from 2.34 to 1.1 air changes per hour (ACH). This number was derived from work by Emmerich et al which asserts that buildings like the Docking (over ten stories and double glazed) can be re-sealed to achieve infiltration rates of 3.3 cm² per m² of exterior wall area; using a reduction factor of 50% for a tall building (cited by Emmerich) and 10 mph of wind velocity, an infiltration rate of 0.55 ACH is reached. To this value, the 0.56 ACH minimum infiltration rate discussed earlier may be added to reach 1.1 ACH of approximate ventilation and infiltration. Further simulations were conducted with increased thermal resistance at the spandrels and end walls – using the equivalent of 1.5 inches of added polystyrene insulation to those assemblies. Lastly, a simulation was done with low-E glazing replacing the clear double pane glazing units.
### Table 2: (Source: Author)

<table>
<thead>
<tr>
<th>Set Points¹ (H/C)</th>
<th>Lighting Loads W/ft² [W/m²]</th>
<th>Ventilation Rate</th>
<th>End Wall R-Value h<em>ft²°F/Btu [K</em>m²/W]</th>
<th>Spandrel U-Value Btu/h<em>ft²°F [W/m²</em>K]</th>
<th>Glass U-Value¹ Btu/h<em>ft²°F [W/m²</em>K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base - 0 70°F / 75°F [21.1°C / 23.9°C]</td>
<td>1.61 [17.3]</td>
<td>2.34 ACH</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td>See Table 1</td>
</tr>
<tr>
<td>1 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>1.61 [17.3]</td>
<td>2.34 ACH</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td>See Table 1</td>
</tr>
<tr>
<td>2 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>0.40 [4.3]</td>
<td>2.34 ACH</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td>See Table 1</td>
</tr>
<tr>
<td>3 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>0.40 [4.3]</td>
<td>1.1 ACH</td>
<td>See Table 1</td>
<td>See Table 1</td>
<td>See Table 1</td>
</tr>
<tr>
<td>4 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>0.40 [4.3]</td>
<td>1.1 ACH</td>
<td>9.6 [1.69]</td>
<td>See Table 1</td>
<td>See Table 1</td>
</tr>
<tr>
<td>5 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>0.40 [4.3]</td>
<td>1.1 ACH</td>
<td>9.6 [1.69]</td>
<td>0.10 [0.568]</td>
<td>See Table 1</td>
</tr>
<tr>
<td>6 68.5°F / 80.1°F [20.3°C / 26.7°C]</td>
<td>0.40 [4.3]</td>
<td>1.1 ACH</td>
<td>9.6 [1.69]</td>
<td>0.10 [0.568]</td>
<td>0.263 [1.49]</td>
</tr>
</tbody>
</table>

1 No temperature setbacks were used.
2 Glazing in the base simulation was double pane glazing with properties as listed in Table 1. Glazing for simulation 6 was double pane, low-E glazing with a SHGC of 0.373 and VLT of 0.444

### Additional Configuration Notes – All Simulations:
- Plug and equipment loads were 0.75 W/ft²²
- Occupancy was 125 people
- A typical office schedule of all-on, 8a to 6p, M-F was applied to lighting, occupancy, and plug and equipment loads
- Final EUI was based on ideal loads and did not model or simulation HVAC systems. For load conversion to energy consumption, the cooling COP was 2.7 and heating AFUE was 0.80.

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**Figure 8:** The resulting EUI of from various simulations, compared to median commercial EUI as estimated by Energy Star Target Finder. Simulation 6, using Low-E glass, increased EUI to 52.3 kBtu/ft² thus is not shown. (Source: Author)
CONCLUSION
At the end of this detailed analysis, it may be argued, with evidence, that the basic architectural premise of the Docking State Office Building is quite sound. More importantly, its innovative curtain wall may be absolved as the source of energy and comfort problems. As results in Figure 8 demonstrate, efficiency gains from reducing lighting loads via daylighting may be greater than adding insulation to the curtain wall. Further, reskinning the building with Low-E glass appears to increase energy usage overall. Rather than an expensive reskinning, the Docking can take advantage of minor modifications (and preservation) to become an impressively efficient, passive office building – matching the performance of more advanced contemporary buildings. It should be no surprise, as the Docking fits the basic recipe for many of today's high performance commercial buildings: a resilient, high mass structure; narrow, open, and daylit floor plates; and appropriate amounts of double-pane glazing. One might contemplate the time and resources spent on new buildings pursuing benchmarks like Energy Star; the Docking offers this possibility for what could be a fraction of the cost.

Rather than pointing fingers at the Docking's facades, managing the building's ventilation and infiltration rate and more appropriately utilizing its open floors offer the biggest energy gains. With reduced cooling loads associated with daylighting and using existing fan rooms and duct spaces, it may be possible to retrofit the building to use modern forced air systems, distribution, and controls without the need for perimeter heat. Several sensible approaches can improve comfort while retaining the existing curtain walls. Modern window treatments can both admit diffused natural light while mitigating thermal issues. Primary work areas should take advantage of the open plan and occupy the perimeter daylit zones; though areas immediately next to windows, where comfort problems would be most acute, should be left to circulation or common. The center of the floorplate should be used for private offices and other rooms, rather than the obstruct daylight at the perimeter with these rooms. Interior partitions, if they are necessary, can be transparent to admit daylight.

Moreover, this paper serves to demonstrate a process of analysis and evaluation that may be used to counter vague criticism seizing upon comfort and energy problems of modern buildings. Such buildings may have more than historic significance – like the Docking, these buildings may also have latent environmental efficiency and environmental value, if the buildings are evaluated thoughtfully. The Docking Building is, in fact, an excellent work of architecture – not just for its modern lines and beautiful materials, but for the functional, modern, and elegant work environment it created for important state employees. It may be true that its 60-year-old systems need upgrading, that its limestone is stained with age, and the state has moved out of the building – but the building's purpose and potential as a modern office building hasn't expired at all. In many ways, the Docking Building was ahead of its time in bringing in natural light and using a long-lasted, serviceable curtain wall as its cladding: a soundly designed and built building that in many ways is superior to even today's buildings.

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REFERENCES


Steele, George (Deputy Director, Facilities Operations - Engineering and Operations, Office of Facilities and Property Management, State of Kansas) interview during building walkthrough with author, December 2016.


ABSTRACT: This inquiry explores the architectural habits that a priory prioritize building-scaled efficiency over effectiveness at alternative scales to define a building’s performance. These habits, while good intentioned, undermine the architect’s agency to act on the non-linear, non-isolated networks that shape our design contexts. When operating on complex adaptive systems one cannot assume that by making an individual processes more efficient the effect on the larger system will be increased efficiency. In fact, often when a process is made more efficient in isolation, the net effect on the system, as a whole, is an increased inefficiency. Performance dictated by the energy efficiency of an individual building-scale is ineffective when optimizing performance within the realities of non-isolated systems. The shortsightedness of architects focused myopically on building efficiency has yielded a serious performance defect when considering buildings in aggregate.

As an alternative to the isolating influence of efficiency this inquiry explores the design of strategic (sub) optimizations; architectures that yield agency and energy efficiency to reinforce critical moments of feedback that optimize the system at an alternative, and often much larger, scale. The concept of “free agency” in architecture refers to a practice allowed to operate outside a building’s envelope; on that intends to prioritize the “building” as (sub) component within larger, trans–scalar, design interventions. In this context, the architect manages and synthesizes an increasing amount of expert knowledge of which they are not expert. The architect, as non-expert, is ideally suited to make associations between dissimilar forms of expertise that represent potential design interventions that transcend spatial and temporal scales. These concepts are explored through a set of (sub)optimized design inventions focused on ecologic and energetic feedback loops between forested management practices, wood processing, and wood construction in North-Central Minnesota.

KEYWORDS: Architectural Practice, Non-Isolated Thermodynamic Systems, Wood, Forest Management, Construction

INTRODUCTION
In 1973, Horst Rittel and Melvin Webber coined the term wicked problems, referring to questions that lack definitive descriptions and problems whose solutions serve a pluralistic societies with differing goals. They have no stopping point, are one off, have no ultimate test to measure success, are not true–false, lack describable lists of problem variables, etc. Rittel and Webber wrote specifically about the problems faced by policy makers working on planning projects that affected large-scale, long-term change within the built environment (Rittel & Webber, 1973). This inquiry holds that wicked problems are also architectural norm. What follows is a strategy to engage the unwieldy, trans–scalar, open-ended, wicked problem of building through a framework of (sub) optimization.

The underlying position behind an architecture of (sub) optimization is a “building” is not the appropriate scale of optimization for building. It offers architects a critical discontinuity intended to disrupt current definitions of building performance that preference material optimization and energy efficiency as its primary drivers. Performance understood in this way relies on an increasingly restricted system’s boundaries to “predicatively” model the “performance” of a building. This habit, of restricting boundaries, limits an architect’s agency to the scope contained within a building’s envelope and occludes the architect from operating on larger-scaled, more powerful, energetic systems (Moe, 2014). These boundaries provide neither a realistic representation of the matter or energy predicted, nor a useful account of the actual flows of matter and energy moving through the systems modeled (Winsberg, 2010). By excising variables that complicate quantification, these habits yield a “high performance” architecture defined by the incremental improvement of operational deficiencies. This view of performance reinforces checklist-based rating systems that at best represent a limited range of metrics for defining “high performance” architecture.

1.0 OPEN AND CLOSED SYSTEMS
From a systems standpoint buildings consist of energy, concentrated into matter, organized into specific materials, arranged through a logic into systems that prescribe their arrangement as construction units, to formations that provide spaces that serve social or environmental purposes. This characterization of a building is based on Odum’s concept of transformity (Fig. 1), which describes the relationships between quantity and quality as energy is transformed across a
Characterizing a building in this way allows it to be understood as a thermodynamic system; and to understand its connectivity with social, cultural and technical systems that exist well beyond the boundaries of its envelope. There are three basic states of thermodynamic systems: (1) isolated systems, which allow neither energy of matter to transfer through its boundary; (2) closed systems, which allow energy, but not matter, to pass through its boundary; (3) non-isolated systems, which allow both energy and matter to pass through its boundary (Fig. 2).

When looking at the variables we use to define the context of buildings, cities, and/or environments (historical, cultural, social, economic, ecologic, energetic, material, etc.) an irrefutable similarity is often overlooked. Namely, that all these formations behave as non-isolated thermodynamic systems. Kiel Moe describes open systems as relative to architecture in the following way:

"By open - a more technical way to identify a system as non-isolated - I mean that buildings and cities are open to energy and material exchange between their system and their surroundings. This is an absolute, irreducible, and uncontestable reality that must be the basis of any non-modern agenda for energy in architecture in the future." (Moe 2014, p. 20)

The universal fact that we design in the open context should shape the techniques we use to qualify the flows of energy that travel across our built environments. Modern design practices, however, do the opposite. They align with reductive methodologies that seek to dissect and isolate objects from the larger systems of which they are subcomponents (Mans & Yamada, 2015). These methods tend to understand a system through analysis of its isolated
parts and then reassemble it as a singularly legible object. While practices that isolate complex systems are temporarily needed, they should remain temporary. Finite analysis, which isolates and abstracts variables of non-isolated systems to simplify and understand them, should reintroduce this simplified analysis back into the proper non-isolated context. Not doing so results in a false understanding of the system in general. (Moe, 2014)

**Figure 2:** Thermodynamic System States (Author, 2017)

1.2. Energy efficiency and system boundaries

In reality, the buildings, cities, and environments we create exhibit non-isolated behaviour; formations all depend on the exchange of energy and material with the larger systems that they are a part (Prigogine & Strengers, 1984). These exchanges are non-linear, and often catalytic, with tipping points and thresholds that are unpredictable. However, the approach taken by most architects when operating on these formations is to isolate and simplify – to design within a pseudo reality. How is it, given our non-isolated reality that the default approach to building performance is to minimize the amount of energy cycled through the building, i.e. to isolate it? This logic contradicts both common sense and basic theory. This type of architectural agenda is based on the 1st law of thermodynamics, where by definition, energy can neither be created nor destroyed (100% efficient). If buildings were isolated systems, they would be inherently efficient, which of course they are not. A more productive architectural agenda focuses on the quality of energy as it degrades across a system (Moe, 2016). This approach is based on the 2nd law of thermodynamics and is focused on the production of entropy within a system and the quality of exergy (usable energy) entering and leaving a system (Moe, 2013). This distinction has a significant impact on an architect’s agency when dealing with wicked problems. Architecture conceived of as an isolated system reinforces habits to reduce existing deficiencies through continuous improvement; whereas, architecture conceived of as a non-isolated system reinforces habits to reconsider the original architectural problem and to design a discontinuous solution for it.

1.3. Ineffective efficiencies

This characterization of architecture, based on transformity and the articulation of architecture as belonging to a non-isolated system’s state, expands the range of variables that an architect can consider when establishing a solution for a wicked problem. Key to recognizing an extended system boundary is acknowledging the role of an individual building as a (sub) component within the “at large” system under design consideration. Just as system-state affects agency, system-scale impacts our approach to wicked problem. Scale determines the specificity with which we view a system, and affects our perception of that system. Zooming out, Bataille asserts that, “On the Surface of the globe, for living matter in general, energy is always in excess; the question is always posed in terms of excess” (Bataille, 1988,21). In other words, as a whole, our terrestrial eco-system receives far more energy than it can effectively use. On the other hand, zooming in, poverty manifests when we constrict our system boundaries and find ourselves isolated within
a context scaled to a (sub) component level of our much larger terrestrial eco-system. Bataille would describe this isolated system’s boundary as a framework for a particular economy. Within this (sub) component context - a context of poverty - it seems logical to base decisions on optimization because of the limited access to resources at this scale of the systems design.

However, this form of optimization is fundamentally ineffective. It solves for deficiencies within a limited context as opposed to solving to reposition oneself within a context of resource excess. When operating within a trans-scalar system it cannot be assumed that by making deficient processes more efficient, it will increase the overall efficiency of the system at large (Ackoff, 1991). In fact, most often when singled out process is made more efficient in isolation, the net effect on the system, as a whole, is an increased inefficiency (Kay, 2002). Improving the performance of the large-scale systems requires that we (sub) optimize at the (sub) component level. This means that buildings can, and should, be (sub) optimized to improve the performance of large-scaled urban, ecological, economic and/or cultural systems.

1.4. Effectiveness over efficiency
Shifting optimization regimes from efficiency toward effectiveness is the final agency altering adjustment in this (sub) optimization strategy. It represents a transition from design aimed at affecting the smallest amount of harm, toward designs aimed at affecting the largest amount of positive change. Ackoff states that, “In designing a system, the primary criterion the designer uses in changing the structure or the behaviour of part of the system is not the effect on the efficiency of the part but the effect on the effectiveness of the whole system” (Ackoff, 2003, 81). The fundamental difference between efficiency and effectiveness is rooted in the content of a design question and whether the question asked, is asking the right thing. Ackoff describes it in the following way, “To do the wrong thing right is to do it efficiently but not effectively. Effectiveness is evaluated efficiency. Therefore, effectiveness is obtained only when the right thing is done right.” (Ackoff, 1995, 45). Ackoff uses the example of continuous improvement in the automobile industry over the last century. Improvements are rampant in handling, safety, mileage, towing capacity, etc. but none of these “improvements” negate the large-scaled impact the automobile has had on pedestrian systems, urbanism, and pollution. The continuous improvement of the automobile’s efficiency generates enough momentum to support automobile designers to continue asking the wrong question. Substitute “building” for “automobile” within Ackoff’s example and a similar set of problems persist, namely that an isolated focus on individual building efficiency does not address the performative challenges of the larger environments in which we live.

1.5. Free agency
Misguided adherence to energy efficiency and material optimization has caused architects to ask the wrong question at the wrong scale with the wrong performance goals in mind. An “agent”, by AIA definition, act in the owner’s interest, providing professional services for compensation (AIA, 2007). From a contractual point of few, (sub) optimization at the building scale, the scale to which an architect is typically contractually obligated to act as an agent for their client, could present a contractual conflict if the client is not directly feeling the “effectiveness” of the design solution. An architect operating as a free agent would require both a different kind of client as well as a different kind of practice. As enablers and organizers of social capital, architects provide value and services to communities beyond the design of a building have the potential to leverage local assets as a vehicle for economic development. Communities are complex socio-economic systems nested within even larger socio ecologic systems. This research deploys a material sub-optimization strategy geared toward the discovery of novel local economic development strategies. The urban theorist, Jane Jacobs, referred this kind of strategy as "import replacement" which drives financial activity, jobs, innovation and city focused wealth (Jacobs, 1985). This focus on local material production and consumption of materials extends the architect’s agency to specify construction materials for projects based on the ecological, economic and social implications of local extraction, processing and use (Hutton, 2013).

2.0. PRACTICING FREE AGENCY
The strategies outlined above are being explored through a construction logic design project that (sub) optimizes material efficiency at the building-scale to enhance local economic performance at the community-scale and forest habitat resilience at the regional landscape-scale, in North Central Minnesota. These ideas build on an initial (sub) optimization project, similarly focused on wood utilization, in New England, located at the New England Forestry Foundation headquarters in Littleton, Massachusetts (Mans, 2017).

2.1. Minnesota Made Transitional Nail Cross-Laminated Timber (nCLT) Panels
The project looks to leverage existing nCLT technology to improve and diversify market-utilization of under valued and/or high risk (pest or fire prone) species such as Oak, Maple, Ash, Pine and Tamarack, as well as low-quality and small diameter lumber, through the structural properties of cross lamination. Given the quality of material, and the structural limitations of nail lamination, the panels are materially inefficient at the building-scale when compared to more traditional glue cross-laminated timber (CLT) panels made from structurally graded softwoods. However, by exploiting this inefficiency the panels become more effective at larger scales: (1) improving local wood markets, (2) generating local economies, and (3) improving the resilience of Minnesota forest resources.
2.2. Improving Local Wood Markets

Response to existing wood markets in Minnesota, the project was designed not to create direct competition with currently highly-utilized species (i.e. aspen), but instead focused on the less used species listed above to develop a more "diversified portfolio" for Minnesota's wood economy. Panels are being designed to incorporate a multitude of species (both hard and soft) and the initial commercial market that product hopes to supply are industrial equipment mats. This is in part due to the current acceptance of mass timber construction in Minnesota and in due to the reality of producing a high enough quality product to meet structural standards for CLT panel products in early production with (sub) optimized materials. Equipment mats are a low quality gateway to a much more robust forest resources utilization plan that will provide material for emerging mass timber construction markets - a strategy deployed by Smartlam, a CLT manufacture in Columbia Falls, Montana (Tudhope, R., 2016). By positioning our project between existing industrial and emergent construction markets we position ourselves on the front edge of nCLT technology where we can deploy the applied knowledge gained through repeated manufacturing to tap more value added markets. The design is optimized to addresses specific land-use and economic needs of Aitkin County as well as fire management programs for the Chippewa and Lake Superior National Forests.
2.3. Generating Local Economies

Minnesota boasts over 15.5 million acres of timberland, covering over a quarter of the state's total area. Timberland is defined as forested land that is productive enough to produce a commercial crop of trees and is not reserved from harvesting by policy or law. Minnesota's timber resources are incredibly heterogeneous, characterized by the USDA through sixteen distinguishable forest types (USDA, 2014). The settler economies of the state were founded on the timber industry, and the current condition of Minnesota's vast timber holdings is a result of a historical decisions made around the economy of wood products. Economic opportunities in Northern Minnesota are limited, with wood being one of the few sustainable natural resources readily available. The development of systems that leverage local material and labour, while less efficient in both processing and material utilization, improve effectiveness at the community-scale when compared against more efficient remote systems that leverage centralized economies of scale and are higher material quality. In many rural communities the design of systems that generate local economies, as opposed the design of buildings that require capital investment, is more effective at affecting positive change. This project anticipates successful production to generate eight (8) new jobs. The improved production capacity of our local manufacturing partner not only allow them to make a value added products, it also makes the company more resilient to market shifts and helps secure the long-term employment of its existing employees.
2.4. Improving the Resilience of Minnesota Forest Resources

The project’s initial production goal is to process 5,000,000 board feet of wood annually, and anticipates extracting approximately 22,000 tons of stumpage from forest lands each year. We hope to source a quarter of our first year’s material, roughly 5,000 tons, from the Chippewa and Superior National Forests, and to increase this percentage moving forward once relationships are established and the quality of the material is better known. The utilization of low quality and small diameter material in our value added timber panel also increase the effectiveness of forest professionals in fire management at the regional landscape-scale. Without viable wood markets it is not commercially feasible to proactively manage forest lands.

Once we transition production toward longer-lived building panels, our products will effectively operate as carbon sinks. Assuming carbon constitutes approximately 50% of the dry mass of trees and an average density of 40lbs/ft³ for the wood processed into our products, we will sequester approximately 4,150 tons of carbon each year. The Decentralized Design Lab Minnesota (DDL MN), a design-build workshop at the University of Minnesota, is exploring how a (sub) optimized panel system could work. The project focuses on leveraging the structural advantages of mass timber panels to improve the utilization of both heavy timber and balloon framing materials. Three variations of this system will be constructed and tested at the Anoka Heritage Lab in Hugo, MN in the summer of 2017. These structures are programmed as portable learning shelters for the Anoka County Parks and Recreation department and for the local YMCA.
CONCLUSION
(Sub) optimization operates as a critical discontinuity intended to disrupt current definitions of building performance. Shifting optimization regimes from efficiency toward effectiveness is critical if we are to address the wicked problems attached to the built environment. For this to happen we need to acknowledge that the architecture, cities, and landscapes we design are non-isolated systems. In addition, we need to consider the scale of the system we are attempting to improve and position our design interventions as (sub) components within this larger system. A building can no longer be the sole scale of response to the question of building. Lastly, we need to consider the differences between efficiency and effectiveness to insure that we are asking the correct questions. These principles have helped to guide the Minnesota Made Transitional Nail Cross-Laminated Timber Panel project as well as DDL MN in shifting their architectural agency toward creating systems that can effectively improve local markets, local economies, and local ecologies.

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Students involved in DDL MN 2017: Alexander Greenwood, Claire Hoffman, Trevor Kinnard, Brittany Lindsay, Martin Preuss, Anthony Rabiola, Jianrui Shen IV, Tyler Snell, Christopher Sticha, Virginia Tyson, Allen VanDien, Samuel Busman, Muna El-Taha, Kyrsbanor Hynmiewta, Goldielyn Lopez, Elizabeth Schmiesing, Nathaniel Tollefson, Thomas Vogel
REFERENCES


ABSTRACT: Donald Schon coined the notion of wicked problems that are too complex to be broken down into their component parts prior to offering solutions. He noted that wicked problems faced by large organizations and social structures have increased in light of technical advancements, and have been challenged by expertise in which knowledge is distributed among disparate individuals and institutions (Schon, 1987).

Architects utilize intuition and creative leaps fostering a notion of architect as genius, and a model in which architects provide leadership and orchestrate specialist consultants. Owner initiated pressures on budget and schedule, increased systems performance expectations has challenged this model while internationally recognized firms have come to rely on collaborations with engineering firms such as ARUP to provide sophisticated integrated designs. A gulf has formed between firms that can forge, afford, and manage these relationships, and those that cannot.

In the face of performance goals warranted by environmental and social needs, can architects as a group achieve emergent designs without relying on collaborations with elite engineering consultancies? If so, how can intuition be complemented increasing efficacy and performance? Opportunities for optimal solar and daylighting performance increase when performance factors are considered and buildings correspondingly shaped early in the design process but architects have limited time to validate design decisions before committing to actions.

Considering the importance of knowledge, a paucity of studies exist that validate how form has impacted the performance of modern architecture. More importantly, existing studies fail to acknowledge relationships and tradeoffs between different factors where value is added in design. This paper utilizes results from a study of a Marcel Breuer design for a college residential hall where tradeoffs between solar performance and composition are considered. The analysis expands on methods of analyzing seminal buildings that have been traditionally available, but do not provide sufficient perspective on building performance.

KEYWORDS: Performance, Knowledge, Representation, Analysis

INTRODUCTION

Building technology advances over the last couple of centuries have fostered faster growth of non-architect building design specialists including engineers and manufacturers who provide design-assist. Architects are challenged by demand for complex buildings and higher performance since verification of performance requires significant effort and cost. Evaluation of design outcomes is complicated by varied site conditions, programs, available technologies, and aesthetic traditions that warrant being considered. Many design outcomes such as views elude quantification and are intertwined with other actions.

In order to integrate design objectives with form, architects must identify design problems prior to, and after proposing solutions which require evaluation. Architects can gain assistance of non-architects with analyzing problems and forming solutions, but they have to recognize the importance of, and be able to integrate supplemental perspectives. Incorporating outside expertise early in the design process typically lies outside of budget expectations, and works against the highly personal nature of building design which is speculative and places a significant demand on intuition because building problems can't be exhaustively researched prior to action.

Intuitive problem identification by architects is complimented by rigorous analysis late in the design process when engineering systems design is solidified and performance benchmarks are verified. However, objective verification is typically implemented when it is too late to realistically integrate performance objectives into building form. For example, opportunity for optimal solar and daylighting performance increases when performance factors are considered, and buildings correspondingly shaped early in the design process. Digital tool are available to facilitate performance analysis, but the efficacy of these tools is limited by the knowledge available to frame problems and evaluate output.
This paper focuses on methods architects use to make decisions during the design process in light of the complex nature of the design process and limits on time, labor, and knowledge. Inherent in the process is consideration of alternate solutions requiring a weighing of the implications of particular solutions which ultimately lead to compromises as different proposals address underlying problems with different degrees of effectiveness. A dormitory designed by Marcel Breuer that includes ornamental shading projections is studied using digital representation technologies not available in 1950 when the building was designed to better understand the implications of design decisions. Central is the weighing of information normally processed intuitively, by integrating data and images in a manner that would be too tedious to factor in Breuer’s time.

1.0 BACKGROUND
The subject building (Fig. 1) was featured in Solar Control & Shading Devices by Aladar and Victor Olgyay which was published in 1957, an era when energy was scarce and mechanical cooling had yet to be expected new institutional buildings. The Olgyays’ overtly featured the energy impacts of shading devices but subtlety made the argument for the ornamental benefit of shading devices which would help justify their cost. (Olgyay & Olgyay, 1957) In this light, positive energy benefits of shading devices and their additional cost of are rationalized.

When the Olgyays’ study was published in 1950’s, the positive and negative impacts of light and views on building performance could be considered, but the energy impacts of artificial illumination could not accurately be framed in conjunction with shading devices and views, and are seldom recorded as prime drives of architectural form in institutional buildings. Prior to the development of analytical software, designers and evaluators had to perform arduous calculations to estimate heat gain and loss in a building, and even the most advanced techniques such as those advanced by the Olgyays’ were crude compared to modern standards.

Part of the difficulty of linking daylighting performance to energy use includes tools available for complex calculations; another is reconciling science based outcomes with visual instruments, traditionally employed by architects. Until recently, most solar analysis was performed crudely, incorporating basic inputs such as solar path diagrams, climate data, and drawings. Use of shading diagrams for prototypical or specific site related conditions are more reliable than a similar analysis performed intuitively without the benefits of diagrams, but ultimately the output of daylighting, and more specifically energy analysis, is numerical.

Arduous analysis early in the design process, when it is most effective, has historically been difficult and expensive. Now digital simulations allow for observation of changes in basic daylighting performance and energy performance early in the design process permitting time to shape a building when it is least costly. Even with current digital tools, however evaluating images as well as data is challenged by a multitude of factors including diffusion of factors across different modes of representations. As a result, a designer has to mentally integrate the different forms of feedback. Although designers ultimately utilize intuition and personal judgment, objective feedback bolsters existing capabilities as opposed to displacing them altogether. Analysis tools do not make decisions for designers, nor do they capture nuanced design considerations that experienced designers can process.

2.0 ROLE OF INTUITION IN DESIGN
Proposing appropriate solutions in light of vague problems is one of the mysterious talents that architects develop and hone throughout a career. The process by which architects pose solutions is personal and can include inspiration from sources external to the stated problem. Speculative solutions that are ill suited to relevant problems are risky in a practice environment in which architects have to act quickly and address many complicated issues including code, budget and material constraints. Early process solutions lack detail reflecting considerations not easily extracted due to their lack of representation, requiring verbal or written supplement to satisfy lay individuals or skeptics. More realistic and detailed representations of a design come later after larger decisions have been committed to.

Fundamental early phase representations of proposals are not easy to evaluate testing the intuition of the designer although parameters can be checked against standards including codes. Because of the fundamental nature of early phase output, architects traditionally have critiqued work at this stage themselves with some input from clients to check solutions against their expectations. More objective informed feedback of design proposals has historically come at the later stages of the design process from engineers after the engineers have contributed enough information to the design to facilitate verification through calculations or more recently digital analysis. This analysis is particularly important to verify compliance with codes and performance benchmarks.

Reliance on intuition allows architects to cut through complex problems by honing in on problems they can identify readily and offering solutions unencumbered by incomplete knowledge of underlying problems. Although intuition is personal, it is highly dependent on a sufficient knowledge base to be effective. Without sufficient knowledge, an architect cannot recognize and isolate important problems that need to be addressed. Architects also gain knowledge about issues related to specific problems they are engaged with through a combination of analysis and reflection of
represented solutions. (Lawson & Dorst, 2009) Project specific knowledge helps guide future design moves, and is bolstered by ability to contextualize knowledge.

According to Nobel Prize winning psychologist Daniel Kahneman, there are downsides to intuitive analysis that rest with two mindsets that drive human thinking. The two modes which are intuitive and analytical, do not operated simultaneously. The intuitive mind which functions quickly, operates without consciousness, and cannot perform computations. The analytical works much slower and requires more energy, is more objective, and less susceptible to deceiving itself. (Kahneman, 2016) The difficulty of reconciling intuitive and analytical thinking supports the notion that architects limit use of statistics because it cramps intuition. Kahneman advocates finding ways to make it easier to performing analytical functions while not dismissing the importance of intuition, a challenge central to architects ability to better understand and address complex problems.

2.1. Balancing Intuition and Information
Although architects cannot discard intuition completely and rely on machines or algorithms to address complex design problems, they can utilize computation to complement capabilities they already possess. One of the preconditions of including alternative methods of evaluating design during the design process is developing data that does not require an exceptional expenditure of energy to process. Similarly, part of the process of making this possible is increasing the reservoir of available perspectives on building performance through study of accessible forms of precedent. Historically this study has been static and limited in perspectives provided through traditional media such as plans, sections, elevations, and perspectives.

When evaluation of architecture involves environmental conditions, particularly solar, shading studies of elevations, sections, and plans are challenged by the changes that motion throughout the day and seasons renders on building performance. Most often when shading diagrams are developed, they are limited to key elevations where shading strategies are under consideration. This contributes to a problem of perspective across time. It also contributes to a problem of perspective of the actual impact of the sun toward heat gain, how insulation factors into performance, and how internal heat loads complement thermal gains.

Efforts to develop media that demonstrate effects of heat gain and loss in buildings has resulted in limited success. More often than not these diagrams involve superimposing heat flow arrows over building section drawings. Heat flow diagrams and shaded elevation and sections do not relate to local climate conditions that play a significant part in the effectiveness of passive and active building design strategies. Recently progress has been graphically grounding the building in a specific location/context by placing an aerial plan of the building under a sky dome with sun paths for the different seasons. Example includes site diagrams in Learning from Modernism, which included a shadow cast by the building. (Bone, 2014)

Limits to graphic feedback exist without numerical feedback and narrative. Numerical feedback is particularly pertinent to energy performance as measures for performance can be found in quantities of energy utilized and available light. Statistics can be compared to benchmarks or used as project specific reference points for changes in building performance difficult to capture with traditional graphics. Significant meaning can be derived from analyzing data and statistics, but data as a design tools has been largely limited, with the exception of dimensional criteria provided by clients or code.

The appeal of data has been tempered by the relative ease of reacting to drawings and models as opposed to numbers during the design process. When the final result is assessed visually, the value of data, no matter how significant is diminished. Visualizing data is particularly challenging because deriving meaning of the data is less suggestive of future design moves than review of design speculations. Ultimately data is not what is presented to clients as a final product. Architects also perceive as data constricting, preventing creativity, and inserting impersonal judgement. However, by using data for comparatively as opposed to against benchmarks, knowledge gained can contribute to creativity, optimization, and justification.
3.0 THE BUILDING

The Ferry Cooperative is a residence hall (Fig. 1) which opened in 1951 at Vassar College in Poughkeepsie, a small city abutting the Hudson River approximately 80 miles north of New York City. Breuer adopted the concept of a bar elevated over a perpendicular bar from a design intended for a nurse's home at Long Beach Hospital, located on Long Island, which was never realized. (1) The 146 foot long elevated bar contains residence rooms flanking a double-loaded corridor with communal baths located near the center and a central stair connecting a lower mass perpendicular to the bar, housing communal space including a kitchen. The open area under the elevated bar that is not enclosed is not programed. The upper bar points due north and south resulting in bedroom windows oriented to the east and west.

Relief from the flat brick surfaces of the building is provided by a ribbon of window and wood laminated panels that run along the upper level, and a segmented corrugated metal canopy above the ribbon at the roof line. The canopy (Fig. 2) is the architectural point of interest for this study since it was featured in Solar Control and Shading Devices, and is an expressive element equating to ornament in older buildings. The lower level storefront window is set back on the south exposure and not on the south exposure demonstrating that Breuer was actively working to acknowledge the effects of the sun.

The Ferry Co-op is significant as the first modern building on Vassar’s campus and the fact that Marcel Breuer is one of the most accomplished and celebrated architects of the period tracing his history to the Bauhaus in Germany. Additional virtues of the building are its compactness and economy of material. Although it can be grouped with other buildings of the era reflecting a utilitarian aesthetic, the Ferry Co-op demonstrates, primarily with its ornament that modern buildings can reflect order, elegance and defy monotony.

4.0 DIGITAL MODELLING

A digital model (Fig. 3) of the building was created to serve as a basis for energy and daylighting analysis, as well analytical drawings. Fundamental building characteristics were modeled in Revit based on a survey of available construction documents produced by Breuer’s office and a field visit made to verify exterior conditions which confirmed that the current building was consistent with original documents. Energy and daylighting analysis was performed in Safaira, a computer program that allows for rapid adjustments of building assembly properties providing opportunities to change material parameters and limiting model changes to building forms. As a result of the analysis process, material properties including insulation were specified in the analysis engine and not derived from the model. This also
allowed for modeling to consider contemporary material standards and original material properties to be applied to the same model geometries. Fine details such as pipe rail used to stabilize the shading devices were omitted from the model.

Figure 3: Revit Model. Source: (Author 2016)

4.1. Existing conditions vs. No shades
An initial analysis was performed to determine effectiveness of shading devices by comparing results run for the existing building with results with the shading devices removed. The primary purpose of the exercise was to determine how effective the shading devices are by measuring the difference between results. It was expected that the annual energy intensity of the building without shading devices would be greater without shading devices than with, but the feedback pointed to the shading devices having an adverse effect with respect to energy consumption with energy use being 0.17 percent higher with the shades vs. without. (Table 1) The first step confirmed that intuition can be misleading and that the original designers would not have had a fair chance of confirming the impact of shading devices with tools available around 1950.

With exhaustive analysis, the architect might have been able to anticipate points of excessive heat gain, but would not have been able to anticipate the heating potential of the sun as well, the impacts of the sun in the transitional seasons, and the effects of lighting. Poor performance of the shading device pointed to the northern location of the building which is heating dependent, has a very small cooling season, and is overcast for much of the heating season. Horizontal shades on the east and west sides of the building block sun that is desirable at the peak of spring and fall when the sun is still high enough to be impacted by horizontal projections on these elevations but heating is needed. Also, the horizontal projections have a continual negative impact on daylighting driving up electrical use. The initial feedback of poor sunshade performance opened up two paths for improving the performance of the building. One path involved changes in the shading devices and the other changing the aperture size.

4.2. Increased Glazing
Windows were added to the upper level east and west facades in different edits to the model to test if additional sunlight would reduce the energy intensity of the building. Tests for additional glazing did not result in improved energy performance with energy use increasing by 5.62 percent when opaque panels were replaced with glazing. (Table 1) Additional widows did result in increased daylighting autonomy to a factor of slightly over 2. The primary factor attributed to the reduced energy performance with additional glazing is that additional glazing on the east and west facades could not offset thermal loss in this climate. The primary benefit of additional glazing would be psychological which were benefits lying outside of factors considered for this study with the exception of the visual impacts of building form.

Shading adjustments were tested, including removing horizontal shading devices from one side of the building and adding vertical shading devices to the edges of the windows slightly interrupting the ribbon effect. Models with horizontal shading on the east, and west side only, showed distinct results, pointing to the heating effect of the sun during the transition seasons. Horizontal shading on the east side did not contribute to improved performance but the shading on the west did. Visual results of this feedback were factored into final recommendation for improvements in the building design. With the horizontal shading device on the east of the building proving a liability, vertical shading devices were tested on both the east and west sides of the top building mass. Deep vertical louvers also contributed...
to negative energy performance and were shortened until an 8 inch projection from the face of the building provided positive energy results. (Table 1)

**Table 1:** Table of energy use for different design scenarios. Source: (Author 2017)

<table>
<thead>
<tr>
<th>Model</th>
<th>EUI [annual]</th>
<th>Existing insul.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contemporary insul. standards</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Existing condition</td>
<td>716,865</td>
<td>952,795</td>
</tr>
<tr>
<td>No shading</td>
<td>715,745</td>
<td>951,204</td>
</tr>
<tr>
<td>Existing added glazing</td>
<td>749,023</td>
<td>1,006,307</td>
</tr>
<tr>
<td>Vertical shading east and west</td>
<td>715,382</td>
<td>950,525</td>
</tr>
<tr>
<td>Horiz. shading west, vert. east</td>
<td>716,347</td>
<td>951,871</td>
</tr>
</tbody>
</table>

**5.0 REPRESENTING DAYLIGHTING**

Interest in the potentials of the sun to illuminate building interiors has increased with focus of the downsides of over reliance on artificial lighting, which includes heat-gain across the seasons. The shortest dimension across early modern buildings such as the Ferry Co-op Residence Hall were narrower than buildings built after central cooling systems became typical eliminating the need for operable windows and cross ventilation. These planning ramifications, features of a building that would support natural ventilation and their operational benefits are difficult to recognize with typical architectural representations. The clearest way to represent the impact of daylighting for a building is to utilize a metrics such as **Daylight Autonomy**.

Although performance metrics are gaining currency with architects, their fundamental numerical nature makes them difficult to reconcile with traditional graphics. As a result visualizations have become an important complement to the statistics allowing the mathematical representation of building factors to be understood against plan and section drawings. Most of these representations involve gradients applied over building plans or sections. The Ferry Co-op Revit model was used to generate a gradient plan in Sefaira for existing and modified schemes. Graphic and numerical output did not register notable changes in daylighting with the exception for the schemes in which additional glazing was added resulting increased energy use.

![Figure 4: Detail elevation from east with vertical shading at 11:30 am summer solstice. Source: (Author 2016)](image)

**5.1. Visualizing Shading**

Shading studies superimposed on elevations and perspectives has been part of the tradition of architectural representation with use dependent on the particular styles of the period. In the early years of solar design, physical models were also commonly used to simulate natural conditions and gain feedback on design proposals. With the emergence of digital modeling, simulation involving varied solar conditions can occur without building a physical model, permitting economic comparison of design alternative. Computer generated shading studies also benefit from comparison to data incorporating contextual information relating shading strategies to performance implications.

Graphic visualizations also support design that factors in the shading implications from an aesthetic perspective, something for which Breuer is noted. For purposes of this study shading across the major facades were studied to better comprehend the effects of the sun on the building geometry and to evaluate the visual interest of shading. The Revit model was used to generate shading studies for all elevations (north, south, east and west) at the major seasonal high points at three times throughout the day. Visual comparisons of the same elevation across time provided grounded feedback on what the shading devices were doing and the impact of resultant shadows. (Fig. 4)
6.0 RECONCILING ENERGY AND COMPOSITION
Although the original shading strategy for the Ferry Co-op did not contribute to an overall positive thermal performance, the shading devices provide aesthetic value by providing visual relief to flat facades, and casting shadows on the building façade that are dynamic across the day and year. The latter characteristics that are part of the architect's reservoir of design outcomes are important and are difficult to demonstrate during design. They also require continual observation to appreciate after the building is completed. The impacts of thermal performance and visual impact of the sun on a building façade can both be reconciled by design intuition within limits, without resorting to measured analysis and visual demonstrations that account for time.

Based on modeling alternatives, vertical shading devices (Fig. 5) were found to be a more effective response to solar conditions based on the fundamental building geometry and orientation of the case study building. Like horizontal shades, vertical projections also cast shadows on building facades and are a viable and alternative to horizontal shading with respect to creating visual interest and interrupting the monotony of flat building surfaces. Because horizontal shades are effective on the west face of the building and not on the east, and the west side of the building faces central campus, eliminating the horizontal shades on this face would have a significant impact on the original vision. Adding vertical shading on the east side of the building and eliminating the horizontal would lead to improved energy performance, while contributing to shadows, and not undermine the design on the west face of the upper level. Ultimately, the aesthetic merit of vertical shades is an architectural judgement that cannot currently be rendered through computational analysis or reduced to data.

CONCLUSION
Based on available knowledge and initiative, notable architects in the 1950's implemented design strategies aimed at satisfying compositional objectives with forms intended to mediate the impact of the sun. As this study demonstrates the results of past design efforts did not necessarily lead to performance outcomes which appear to be accomplished. In this case, perception of positive outcomes was reinforced by inclusion in a book featuring solar shading strategies. Rather than uncritically celebrating works by master architects by selectively identifying positive characteristics, and omitting design shortcomings, opportunities to understand fuller implications of design decisions are missed tempering capabilities of sorting through complexity. Considering how form can be improved advances the available knowledge reservoir and efficacy of architects to make decisions independent of engineers.

REFERENCES

ENDNOTES
1 Long Beach Hospital is credited as precedent in the project narrative accompanying drawings for Ferry Co-op as part of the Syracuse University Marcel Breuer digital archives.
ARCHITECTURE MATERIAL AND KNOWLEDGE FLOWS AND MANAGEMENT
NEXT GENERATION BUILDING TECHNOLOGIES:
A DIFFERENT PATH TOWARDS COMMERCIALIZATION

Matthew Gindlesparger¹, Jefferson Ellinger²
¹Philadelphia University, Philadelphia, Pennsylvania
²University of North Carolina, Charlotte, North Carolina

ABSTRACT: As the global human population expands, so do the bounds of the built environment. Advances in building technology are reactionary to the myriad of negative impacts buildings have on our global ecology: poor indoor air quality, inefficient envelope assemblies, and an unsustainable paradigm of energy use are just some of the numerous examples. There are many technological advancements that have the potential to be disruptive in the building industry, but the path towards commercialization of these technologies is often unclear and interrupted by the slow pace of product development and deployment in the construction industry. Sole source entities will not be able to develop and deploy these disruptive technologies without transdisciplinary collaboration and clear pathways for commercialization. This paper looks at an example of a next generation building technology moving to commercialization, beginning as an interdisciplinary collaboration in the academy within departments of architecture, science, and engineering. The project has become a reality by advancing the production of the system by working explicitly with architecture firms, manufacturers, and clients on real building installation projects. The technology is a modular plant wall system that improves indoor air quality (IAQ) in buildings by utilizing plants as a biomechanical filtration system that interconnects to a building’s HVAC system. Potential benefits include reduced energy consumption, HVAC equipment requirements and the improved well-being and productivity of building occupants. This project could only be completed with full collaboration of industry and the academy. The proof of concept could only be developed where multiplicities of expertise can be found – biologists, designers, engineers, horticulturalists, etc. The proof of operation could only be tested in a full building scale integration where architects, contractors, manufacturers, regulatory agencies, etc. can be fully integrated into the execution and hold agency over the outcomes.

KEYWORDS: Indoor Air Quality, Building Technology, Testbed

INTRODUCTION

In the classic model, buildings designed by architects have always been one-off experiments where form, material, structural innovation and/or programmatic relationships were developed and deployed. These buildings effectively became test beds to explore what are classically understood to be within the domain of the architect. However, the modern era of buildings requires significantly more consideration to include a wide range of building metrics. This new paradigm requires we instantiate new ways to create buildings and space to include the health and wellbeing of occupants. This re-emerging territory for the architect opens up the possibility for a new intellectual or innovative claim. Reyner Banham in his book Architecture of the Well-Tempered Environment offered a critique (or apology in his words) of the discipline as having evolved into such a “narrow-eyed aesthetic vision” that other agencies (plumbers and consulting engineers) would have to assume the responsibilities of maintaining building services dedicated to health and well-being. With the global pressures now weighing more wholly on the built environment there is an opportunity for architects to once again take the lead with respect to innovation within the built environment of advanced environmental systems. Models of practice and project delivery however have such a firm foothold that finding the economic territory to enable this kind of innovation is extremely difficult unless resources from outside agencies can be leveraged to advance research. Developing working relationships not only across disciplines but between enterprises (industry, services, and academy) is perhaps the only way to truly advance these issues in a holistic way.

This suggestion should not preclude the architectural endeavor from continuing to innovate in those historically significant domains where the discipline has continued to stake a claim but rather by incorporating building performance as a design challenge as well could produce similar innovations for comfort, well-being and building environment in addition to those familiar domains of inquiry.

A significant challenge with developing next generation technologies at the building scale is that ultimately the testing and characterization of these technologies is only possible at the scale and complexity of the building, rather than the confines of the lab or studio. The discipline of architecture is well equipped to understand these scalar relationships and how to navigate through those challenges once the parallels are drawn to traditional design processes: identifying the problem, developing a concept or hypothesis and outlining a working method or technique to get to the results. However, with implementing new technologies there are new workflow hurdles that must be understood. The building
façade is an example of innovation occurring across disciplines on large projects and efforts in this area are better understood as it is more common to challenge this technology. Leveraging preliminary simulation models before building full-scale mock-ups and assemblies that can be empirically tested and using the results to scale the system performance within a reasonable estimate is an example of how the process can effectively advance systems. However, typically this experimentation occurs within the territory and under the financial umbrella of the façade manufacturer as they are taking both the liability and the bulk of the compensation for that assembly. The question is how can architects move beyond the skin and instantiate this kind of innovation where aesthetics may not be the primary driver, as is typically the case with the façade and drive design experimentation across the systems that fully integrate with a design challenge?

1.0 MODEL FOR NEW BUILDING TECHNOLOGIES: BUILDINGS AS TEST BEDS

1.1. Research to Practice – Commercializing Entity

There is a long-standing relationship between academia, practice, and industry sponsored projects, exploring new ideas for buildings. Evidence of this can be seen in schools of architecture across the world, where students and faculty explore discrete design problems of the built environment with varying degrees of emphasis based on program and curriculum of the institution, faculty research and pedagogical agendas, and industry support/collaboration. These studies can vary in scale and complexity from discrete explorations within a classroom, to long term projects such as the US DOE Solar Decathlon. Too often however the fruits of these endeavors are siloed to academic publications and industry headlines. To engage in translational research and move ideas into buildings requires a more complex set of relationships than asking academia to explore a particular design problem; thermal performance in building envelopes or air quality in buildings for example. Very few building owners, contractors, or architects would be willing to simply adopt some underdeveloped idea for a new building technology without some assurances of safety, functionality, etc. In short, none of the existing stakeholders would be willing to take on the liability of an untested technology.

One example model for a successful path towards commercialization that addresses this issue of liability can be found at CASE RPI, the Center for Architecture Science at Rensselaer Polytechnic Institute. CASE leverages academic programs and research agendas along with a partnership with Skidmore, Owings & Merrill LLP (SOM) to develop and propose application of new building technologies in the context of complex building projects. The model relies on initial development of ideas including fundamental research, prototyping, initial testing, characterization, and product development within the academic environment, then through the formation of a separate commercializing entity to move the technology further forward for application in buildings. The commercializing entity assumes liability for the product, takes on further design and development, then manufactures and oversees the product and projects including long term studies of installations as test-beds whenever possible.

1.2. Key Stakeholders

It is a gross oversimplification to assume that any research project that can be initiated in academia and moved further with some new commercializing entity is immediately equipped to start delivering new building technologies to the building industry. The complexity of project delivery methods requires buy-in and vested interests by multiple stakeholders just to get to the point of agreeing to adopt a new building technology in a building, let alone delivering the product and long term testing and characterization to fully recognize the potential or failings of new building technologies.
Building owners and operators must be fully committed to adopting new technologies and be willing to take on the potential role of the lost leader. This critical stakeholder needs to have a vested interest in adoption of new technology, and fully support the initiative in both the short and long term. This role requires the longest commitment aside from the commercializing entity. The owner must be willing to support the integration of the technology into the building, procurement and installation of the technology, and for maximum impact the long-term monitoring and impact feedback of the technology to the project. There must be a strong relationship between the building owner and all project stakeholders to insure adequate coordination and delivery.

Architects and engineers must be willing to challenge traditional norms of project delivery and detailing to accommodate the requirements of new technologies. Contractors must be willing to install products that may be unfamiliar. Just as the building owner must be committed to integrating new technologies, architects and engineering consultants must be accommodating of new technologies and be willing to coordinate with relevant building systems. Without rigorous coordination, starting at the project outset, the potential impact of implementing new building technologies can be significantly compromised.

The commercializing entity has the challenge of coordinating all of these entities, accommodating the immediate, short term, and long term goals of delivering the project, and post-occupancy evaluation of new building systems to fully characterize potential impact at a building scale. The commercializing entity must be pro-active about managing project expectations and organizing stakeholders. Additionally, for long term characterization and understanding of potential impact, the commercializing entity must commit to the long term oversight of project installations, negotiating for long term access and monitoring of technologies.

1.3. Meeting the Needs of the Project and the Product
A large part of the interfacial role between commercializing entity and the rest of the key stakeholders draws parallels with the role of the traditional architect, with the complex problem of balancing the requirement of a particular project, and those of the new building technology/test bed. The typical architectural model that has historically driven the one-off design as a kind of “test bed” for intellectual ideas about space and planning; however, there was almost never any consideration for a post-occupancy evaluation to measure the successes or failures other than awards and publication. It is critical that specific investment be made to plan what the short and long term testing methodologies will be post-occupancy and how those efforts will be carried out. Is this work completed as an independent assessment, or through a specific sub-contract that may be connected to the technologies ongoing service and maintenance?

One critical step that the commercializing entity must take on is the identification of specific codes and regulations that allow the product to be accepted in a building such as structural, material, MEP codes, and labor regulations. To successfully deploy a test bed framework requires specific tests, certifications and coordination of architectural, structural, and MEP systems within the building to ensure that the system is allowed to operate as intended.

2.0 AMPS CASE STUDY: EXECUTION, DELIVERY, AND FEEDBACK LOOPS
2.1. The Problem – Improving Indoor Air Quality
IAQ has been identified as the fifth most important chronic health hazard nationally (Mendell, et al., 2002). Air quality in buildings can be directly related to occupant well-being and worker productivity (Clausen et al., 2011). Contemporary HVAC systems, specifically focusing on ventilation rates prescribed by ASHRAE have been the solution for most IAQ
problems. Those benefits can be easily undone with dirty filters and a lack of HVAC system maintenance (Wargocki et al., 2004). The AMP System proposes a solution to the dilemma of ASHRAE standards which require potentially unhealthy outdoor air intake into building HVAC systems. By leveraging bio-remediation as a means of filtration, return air, which has limited re-usability, is revitalized and can be re-distributed. Fresh air, created from within the building could significantly offset or even replace make-up air requirements mandated by ASHRAE. Without long-term results from building scale demonstration of this concept, ASHRAE standards will be the predominant design guideline for ventilation rates and air quality in buildings.

2.2. The Solution – Building Integrated Green Wall Biofilters

The next generation building technology discussed in this paper leverages plant-based air remediation strategies in which the air cleaning capacity of plants is amplified by mechanically moving air through the root structures of the plants as it is introduced into building ventilation systems. This technology was first demonstrated by NASA biologist Bill Wolverton in the development of the NASA bio-home (Wolverton, et al., 1989). Since the NASA demonstration, variations on green wall biofiltration strategies have been developed for building integrated bio-filtration systems, most notably the Nedlaw (Darlington System) Group in Canada.

Active biofiltration systems that are fully integrated into buildings can provide commercial/institutional building types with dramatically improved indoor air quality (IAQ), while most likely reducing energy consumption and HVAC equipment requirements. The United States Department of Energy identified the Active Modular Phytoremediation System (AMPS) as a potentially energy saving system that simultaneously improves air quality in a report on potential energy saving technologies for residential HVAC systems (Goetzler, et al. 2012). In addition, the biomechanical hybrid systems seeks to improve worker productivity and the general well-being of building occupants by enhancing IAQ and the spatial quality of interior environments through the introduction of large scale landscape, leveraging the concept of biophilia (Kellert & Wilson, 1995).

2.3. Active Modular Phytoremediation System (AMPS)

The Active Modular Phytoremediation System (AMPS) is a plant based wall system that leverages the entire plant systems towards the end of improving indoor air quality. The initial concepts for the AMP system were developed, tested and prototyped at CASE/RPI, leveraging the resources of academe and the potential for application in real architecture projects through the relationship with SOM. The AMP System proposes to significantly improve upon the air cleaning capacity of precedent systems by leveraging a proprietary soil matrix and a modular system designed to alleviate many of the maintenance and life-cycle challenges that current systems pose for building-integrated applications.

Plants, cultivated in a specialized growing media are placed in the air stream of a building’s HVAC system on the return air side where air is cleaned and re-distributed on the supply air side of the HVAC system. Plant support systems such as water, nutrients, and lighting are integrated into the systems controls. A modular approach allows for: scalable deployment, easy installation, and more discrete control of water distribution and system maintenance.

Performance benefits of the AMP system include:

- Enhanced oxygen levels and carbon dioxide absorption.
- Significant reduction of volatile organic compounds (TVOCs); e.g., Greater than 85% single pass formaldehyde reduction demonstrated in prior tests. (Aydogan, Montoya, 2011)
- Potential reduction in outside air requirements using active phytoremediation technology
- Tremendous potential benefits to general well being associated with the introduction of natural vegetation and improved indoor air quality, including reduced illness and absenteeism.
- Introduction of bio-diverse vegetation systems that have the potential to dramatically boost human immunity
- Modular design offers scalability for a wide range of installations and reduced maintenance

The first building scale installation of the AMP system was deployed at the New York City Public Safety Answering Center II (PSAC II), developed through the partnership with SOM, the concepts of the AMP system had been developed and tested at CASE/RPI with enough confidence to develop the AMP system further into a commercialized product. In 2013, Fresh Air Building Systems LLC (FABS) was formed as the commercializing entity to design for manufacture, and fully develop the AMP system for delivery into building projects, with the first large scale installation of the AMP system being fully installed and commissioned at PSAC II in 2016.

2.4. Delivery – PSAC II Zone Scale Installation

FABS was contracted by the New York City Department of Design and Construction (DDC) to deliver and install approximately 700 square feet of AMP system modules into the new Public Safety Answering Center II in the Bronx NY which was going to be the new 911 call center for NYC. The building is a high security 24/7 facility with minimal access to natural daylight and a potentially high stress work environment. The AMP system installation is positioned
on the main floor along a primary corridor, so is widely visible to everyone who works in the facility. The system includes a modular cassette system, with integrated water, nutrients and artificial lighting. The system is connected to the building’s HVAC system to ensure optimal system performance and benefit to building occupants including improvements to general well being associated with the introduction of natural vegetation and improved indoor air quality (Mendell, et al., 2002) particularly in a building with limited windows and access to exterior views.

One of the major challenges of designing the system for the building was the overall size of the building versus the output capacity of the AMP system installation and the total amount of fresh air required for the building versus what can be produced. To maximize system impact, the fresh air output of the AMP system was distributed to specific rooms and the return (dirty) air from those rooms is delivered to immediately in front of the AMP system for cleaning and re-distribution. Because of the resultant HVAC system configuration, the efficacy of the system can be easily monitored and characterized post-occupancy as a test-bed.

2.5. Feedback – Maintenance and Monitoring
Once the AMP system was fully installed and operational at PSAC II, the long-term monitoring and characterization of system performance began and to date, is ongoing. Despite being designed to minimize recurring system maintenance, plant systems require some attention and maintenance. This presents a unique opportunity and mechanism to gather data about the short and long term performance of the system installation within the building. As part of regular system maintenance, FABS contracts with CASE/RPI to sample various aspects of system performance including air quality and plant health. While there is an emphasis on early efforts to collect data about the system, because there will be some recurring maintenance of the system as long as it is in existence, it presents a unique opportunity for long term testing.

CONCLUSION
The partnership and collaboration of the many stakeholders has resulted in the successful installation of a proprietary HVAC filtration system into a fully occupied building that potentially changes the way indoor air quality is understood. Research will continue through a myriad of data collections to continue to prove and improve the function of the system. The success of this project was the result of continued buy-in from all key stakeholders throughout the project. It was initiated by a unique collaboration between industry and the that enabled the incorporation of research into an occupied building. The commercializing entity (FABS) solicited buy-in from the architect and client, then leveraged lessons learned from research in academia which was supported through research grants, those not typically available to a for profit architecture firm. It is precisely this transdisciplinary arrangement, between architect, client, and academia, with access to grants and transfer of knowledge to a newly formed delivery entity that has allowed this particular project to succeed.

There have been many advances to the built environment that have been made without architects involvement but, as a discipline charged with advancing the built environment, it is imperative that architects take a leadership role in the advancement of next generation building technologies and building integration represented by the AMPS system. The discipline of architecture fully understands the entire scope of project delivery and is positioned to facilitate the kind of coordination necessary to integrate research into building projects. However, because most project schedules do not allow for the open-ended process of scientific and experimental research it is difficult to incorporate it into the typical workflow from the inception of a contract to execute a building project. The academy is set up with the kind of infrastructures and support to take on the open-ended research within their operations. This means that the research must be initiated without a specific project driving constraints but be ready to adapt to the particular constraints of the project that emerges when the research is nearing commercialization. In order to negotiate these complexities, the suggestion here is that there needs to be more formalized relationships between academic units and architecture firms to help advance the building technologies to meet the news demands for human health and well being so as to advance outside of a single project delivery.

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DEVELOPMENT OF A SIMPLE HOT BOX TO DETERMINE THE THERMAL CHARACTERISTICS OF A THREE-DIMENSIONAL PRINTED BRICKS

ABSTRACT: With the rapid advancement in the application of innovative computational tools, in particular, parametric design, algorithmically-driven built forms have shown promise in the building industry as evidenced by the exponential growth of three-dimensional printing of building components over the past several years. With the promise to simplify construction, lower cost, increase speed and responsible use of natural resources, encourage recycled material use, and increase design flexibility, parametrized 3D printing represents a credible alternative to current construction practices. To date, the focus of research has been on printing techniques, materials, and structural performance, but many of the promised benefits and opportunities have remained largely unrealized. One of the topics that have received little attention is the study of the thermal performance of the 3D printed walls and envelope components. This paper describes the design and application of a small Hot Box Apparatus developed specifically to test the thermal performance of small and highly detailed samples produced in our labs. Based on several initial experiments, authors discuss in detail the testing procedures, the instrumentation, and the conditions of the tests. The discussion includes errors encountered and elaborates on their sources and how we addressed them in the two experiments that are the basis of this paper. The results revealed that the obtained values from the hotbox were within the acceptable margin of error found in similar laboratory tests. Data collected from testing a rigid polystyrene board of known thermal characteristics were used to estimate parameters used in the determination of the thermal resistivity (R-value) of the ceramic wall. Initial results the R-value of ceramic assembly were promising because of the ability to embed different shapes and sizes of air pockets in the wall. Recommendations include improving the performance of the Hot Box and instrumentation to increase the accuracy of the measurements.

KEYWORDS: Hot Box, Conduction, 3D Printing, Thermal Performance, Ceramic wall

INTRODUCTION
Driven by an explosive advancement in the application of innovative computational tools, in particular, parametric design, algorithmically-driven built forms have shown promise in the building industry. This is evidenced by the exponential growth of three-dimensional printing of building components over the past several years (Berman 2012; D’Aveni 2013; Docksai 2014). With the potential to simplify construction, lower cost, increase speed and responsible use of natural resources, encourage recycled material use, and increase design flexibility, parametrized 3D printing represents a credible alternative to current construction practices. To date, the focus of research has been on printing techniques, materials, and structural performance, but many of the promised benefits and opportunities have remained largely unrealized (Wu et al. 2016). One of the topics that have received little attention is the study of the thermal performance of the 3D printed walls and envelope components. Therefore, the primary objective of this study is to develop a small Hot Box to assess the thermal performance of 3D printed ceramic wall with an embedded semi-enclosed air spaces.

With the advancement of mechanical refrigeration in the early twentieth century, concern for thermal insulation quickly followed. Many of ASTM standards were developed by the National Institute of Standards and Technology (NIST) formerly known as the National Bureau of Standards. The first hot plate Hot Box Apparatus built by NIST in 1912. However, only after 1916 Dickenson and Van Dueson defined the standard terms, types of experiments, and provided accurate estimates of heat flow coefficients for air spaces and many insulation materials (Zarr 2001). Today the majority of tests are conducted on one of two Hot Box designs. The first configuration is the self-masking with a controlled guard chamber surrounding the metering box or the chamber (Figure 1). The second configuration uses ambient conditions as a surrounding guard. The metering room of this design uses highly resistive materials to heat flow. Figure 2 shows a calibrated Hot Box design with the specimen inserted in the middle separating the metering (hot) chamber from the climate (cold) chamber. This design is simpler but suffers from the potential for significant errors in the calculations due to the heat flow to the outside and though flanking.
Talk about Hotboxes, their designs, uses, and standards.

1.0 THE 3D PRINTED BRICK
In 2012, a 3D printed ceramic brick was developed to test the printing technology use at the scale of architecture and within the limitation of the printer dimensions (Figure 3). Each unit was made of stacked layers of 1/16 inch thick liquid ceramic slip cast recipe (Peters 2013). These units could be stacked and joined together to form a composite wall with air gaps and an interwoven perimeter (Figure 4). This design has attracted the attention of the design community and was awarded for its innovation and creativity. However, the brick as designed has potentially favorable thermal characteristics that could be studied and further enhanced. These are 1) ceramics have high thermal resistance, 2) each unit contains several enclosed air chambers, 3) the brick lining is thin and long, reducing the potential for thermal bridging. The objective of this research is to measure the thermal characteristics of the 3D printed wall and compare it with current construction assemblies.
The apparatus used to empirically determine the overall heat transmission of the ceramic wall assembly uses a calibrated design. The two-chamber are insulated with the specimen to be studied inserted in between. One of the chambers is heated, and the energy flow is metered while the second chamber is kept at a lower temperature. According to the American Society for Testing Materials, the apparatus is used to establish the minimum requirements to help the determination of steady state heat flow when exposed to controlled laboratory conditions (ASTM 2014; American Society for Testing Materials 2013). The apparatus is usually large and expensive (Seitz & Macdougall 2015; Schumacher et al. 2013). As a result, they are only located in national laboratories and large commercial testing facilities. The intent of this paper is to describe the development of a small, portable and inexpensive hot box for use in small laboratories commonly found in architecture and construction programs.

1.1. The Small Hotbox
The research team built an insulated plywood box measuring 20.5 x 8.0 x 11.25 in (Figure 5). The inner walls of the box are insulated with 2" thick expanded polystyrene. A second internal layer of plywood is attached to the inner wall. The metered chamber which we refer to as the hot chamber's inner walls is covered with aluminum foil. When locked, the two chambers are completely isolated from the outside wall. Only a few sealed holes connect the temperature sensors and the heating element power source and controller (Figure 6). The tip of the heating element is covered with aluminum foil on the wall side to avoid heating the wall through radiation.
The climatic chamber which will be referred to in this paper as the cold chamber is chilled with ice water that is pumped directly from a container outside the box (Figure 7). The water is continuously pumped from the ice and water filled container into the foils inside the cold chamber throughout the experiment.
1.2. Instrumentation
Temperature data were obtained using Hobo data loggers (Figure 8 & Figure 9) connected to external probes. The Hobo data loggers were calibrated before the initial laboratory tests. They were used to measure the instrumented wall hot and cold surface, as well as the air temperatures of the hot and cold chambers. The sensor probes were attached directly to the wall surface and covered with aluminum foil to protect the probe from reflected radiation from any potential heat source. The data loggers were setup to measure the temperature at the four locations inside the box, as well as the ambient temperature in the testing room. Temperature data was collected and recorded every minute for the duration of the experiment.

![Hobo data loggers and temperature probe](image)

Figure 8: Hobo data loggers and temperature probe

The heating element was built from parts originally designed for a 12v, 40 W Power Resistor heating element for a 3D printer (Figure 6). Setting the controller at a particular temperature causes the heating element to operate until the sensor reaches the designated level. The controller then switches on and off to provide only the heat needed to maintain that desired temperature. The heat input equals the power transmitted while the switch is in the on position. The team assembled an Arduino data logger configured to monitor the switching periodicity by measuring the power in milliamps (mA) with a timestamp and record it to MicroSD card.

![Calibration of the Hobo Sensors before testing](image)

Figure 9: Calibration of the Hobo Sensors before testing

1.3. Wall assembly
A wall was constructed from modular ceramic bricks, each measuring 2.0 x 8.0 x 1.9 inches. Each of these walls is comprised of five blocks stacked vertically to form a 2.0 x 8.0 x 9.5-inch wall with vertically discontinuous oblong-shaped voids 2.3 x 1.0 x 9.5 inches. A second identical wall was built to test the more complex two-wythe wall configuration with a 2" air gap in between.
The wall was located in the middle of the hot box, and foam insulation was applied to seal the gaps between the assembly and the box’s internal surfaces (Figure 7).

2.0 THE EXPERIMENT
Several initial experiments were conducted to test the hotbox, sensors and their locations, and to calibrate the testing protocols.

2.1 Experimental Protocol
- Each test took five hours.
- Each Hobo measured the temperature and recorded it every minute.
- Sensors were attached to the wall surfaces and kept in the middle of the hot and cold chambers without touching any surfaces.
- The heating element was shielded.
- The temperature in the hot chamber was set to 140 F.
- The ambient temperature was monitored every minute.
- The heating element switching monitor was connected, and light that switches on and off signified the switching periodicity of the controller. The measurements frequency was 1 Hz.
- The water pump chilled the cold chamber.
- A person was present during the tests at all times to monitor any sudden changes and notices an anomalous reading due to an error.
- Two experiments were conducted; The first one used a 2” rigid insulation board of a known R-value. The second experiment, we tested the ceramic wall (Single Wythe configuration)

2.2 Determine Steady State Condition
After completing the tests, data was collected and analyzed using a python script developed by the team. One of the objectives of data analysis to determine the steady state condition. This was achieved by calculating the temperature difference between the hot and cold surfaces and plotting over the duration of the experiment (Figure 10).

Figure 10: Temperature difference between the hot and cold surface in the single-wythe wall configuration

Temperature difference data was analyzed using a curve fitting algorithm. As a result, an exponential association (growth model) function was derived from fitting the data. The equation was used to determine the approximate temperature difference at which heat flow through the assembly reached steady state condition (Figure 11).

The best fitting curve for all experiments including the initial test was:

\[ y = a(b - e^{-cx}) \]

By solving for the first derivative \( \frac{dy}{dx} = 0 \), the solution of the derivation determines the approximate time it takes the temperature difference to reach the steady state condition (Figure 11).
2.4 Determining rate of Heat flow (Q)

Determining the heat input was accomplished in two steps; the first was to determine the times it takes the assembly to reach steady state conditions. An Arduino-based sensor was developed and deployed to count the number of times the heating element controller switched on and off. The time was recorded every time the event was counted (Figure 12). Periodicity data was added, and hourly power usage was estimated.

The time it took the temperature difference between the hot and cold surface of the wall to reach steady state condition ($\frac{\partial y}{\partial x} = 0$) was about 90 minutes for the single-wythe experiment. The hourly rate of heat input after 90 minutes of the experiment 35.4 Btu/hr (sensor was on 26% of the time). On the other hand, the heating element was switched on for about 25% of the time while testing the 2" rigid insulation allowing for about 34.2 Btu/hr to be input in the hot chamber. Data of this phase of the analysis was used to determine the total heat input to the hot (metered) chamber or $Q_{heater}$ input (Figure 13).
3.0 DETERMINATION OF THE R-VALUE

![Diagram of thermodynamic solution system for Hot Chamber](image1)

**Figure 13:** Establishing the thermodynamic solution system for the Hot Chamber

![Diagram of Hot Chamber](image2)

**Figure 14:** Estimating the Conductance Shape Factors of corners and edges

After reaching steady state condition, the following relationship should persist:

\[-Q_{\text{heater input}} + Q_{\text{wall loss}} + 2Q_{\text{flanking loss}} + Q_{\text{specimen loss}} = 0 \text{ or:}
\]

\[Q_{\text{specimen loss}} = Q_{\text{heater input}} - Q_{\text{wall loss}} - 2Q_{\text{flanking}} \quad (1)\]

Where:

- \(Q_{\text{heater input}}\) = Time weighted power of heating element in volt-ampere (VA)
- \(Q_{\text{specimen}}\) = Conductive heat flow through the specimen in BTU/hr.
- \(Q_{\text{wall loss}}\) = Conductive heat loss through Hotbox surfaces of the hot chamber in BTU/hr.

Using the specimen of known thermal characteristics (2" Rigid Rigid insulation), we were able to estimate \(Q_{\text{flanking}}\). However, because of the temperature at the rigid chamber did not change between the rigid insulation and the ceramic wall experiments, we applied a function proposed by Yuan (Yuan 2001) to estimate the change in flanking due to change in specimen thickness (eq. 2):

\[\Delta Q_{\text{flanking}} = 0.0005(L_{\text{specimen1}} - L_{\text{specimen2}})^2 - 0.1114(L_{\text{specimen1}} - L_{\text{specimen2}}) + 6.0332 \quad (2)\]

The estimate of \(Q_{\text{flanking}}\) of the ceramic wall was used to estimate \(Q_{\text{specimen}}\) in equation (1).

The \(R\)-value or the overall Thermal Resistance \(R_{\text{specimen}}\) was calculated using:

\[R_{\text{specimen}} = \frac{\Delta L_{\text{ambient}}}{Q_{\text{specimen}}} \quad (3)\]
Where:

\[ R_{\text{specimen}} = \frac{\text{Total Thermal Resistance}}{\text{BTU/hr}} \cdot \frac{\text{ft}^2 \cdot ^\circ \text{F}}{\text{hr}} \]

\[ A_{\text{specimen}} = \text{Surface area of the wall, ft}^2 \]

\[ t_{hs} = \text{Wall surface Temperature in hot chamber} \ ^\circ \text{F} \]

\[ t_{cs} = \text{Wall surface Temperature in cold chamber} \ ^\circ \text{F} \]

\[ Q_{\text{specimen}} = \text{Net Heat Transfer, BTU/hr} \]

The resulting \( R_{\text{specimen}} \) of the ceramic wall was 2.13 hr.ft\(^2\).°F/BTU.

4.0 DISCUSSIONS OF THE RESULTS

The discussion on the results of this study is focused on the lessons learned from the various experiments that took place and the experience with resolving the different issues that faced the team.

4.1. The Hotbox

Although the results are preliminary, the lessons learned from the exercise were invaluable to the team. A general comparison between preliminary laboratory measurements and the expected outcomes showed a margin of error within limits presented by other similar studies (Desogus et al. 2011). While some of the error sources in the determination of the R-value can partially be attributed to the heat loss beyond those estimated through the Heat Box walls and flanking, other uncertainties were inherent in the equations used (Asdrubali & Baldinelli 2011). Additional sources of errors are the mechanism used to determine the heat input through counting the periodicity of the controller switching. The small size of the hot box introduced additional levels of uncertainty caused by the relatively large heat loss through corners and edges.

The use of a small hot box, however, showed promise because of our potential ability to deploy it to test new configurations proved invaluable. The box was easy to set and test and inexpensive to operate. With larger wall sections, we will build a larger hot box on wheels to facilitate its movement from one space to another especially in an education setting where locating the apparatus in a permanent space may not be possible.

4.2. Limitations of the study

The most significant limitation facing the team is the lack of the relatively expensive heat flux meter. Without it, the uncertainty caused by the elaborate calculations based on estimates of box wall performance was larger than predicted. In addition, the team had to estimate the flanking based on the use of specimen materials of known R-values. However, with the variation in the temperature difference between the hot and cold surfaces, flanking estimation was impossible.

4.3. Planned future work

- Design and calibrate a larger hotbox
- Purchase and use a Heat Flux Meter

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ABSTRACT: Concrete Lattice seeks to challenge our normative association with concrete building construction by developing a lattice system of prefabricated units using Glass-Fiber Reinforced Concrete (GFRC) as the primary material. Lattice systems are porous, lightweight, and deployable; terms that are not typically associated with concrete structures. The design of parametric units rather than linear components, typical of lattice systems, highlights issues of assembly in precast building systems using integrated components. While design workflows and CNC fabrication aided in efficiently manufacturing the units, the assembly is post-tensioned during the construction process to limit the amount of scaffolding necessary. Our goal was to address the gap between design and production by exploring the development of complex lattice systems and using digital design tools to streamline the production of units to be deployed on site. The design of our Concrete Lattice through prototyping and fabrication highlights the value of design research for design studio learning.

The complexity demonstrated through this project argues for the use of computational design in both informing design decisions and managing the myriad contingencies involved in the production of a novel structure. Complexity in this respect addresses not only formal and experiential concerns, but also structural and manufacturing processes. Our Concrete Lattice makes explicit the role digital technology plays in the integration of design, engineering, and fabrication. While this discourse is not new, our design aims to take full advantage of lessons from precedents and offer a unique project uncharacteristic of what we have come to expect from concrete as a material.

KEYWORDS: concrete, lattice, digital fabrication, formwork design, computational design

Figure 1-2: (left to right) Final installation of Concrete Lattice structure at Taubman College's Liberty Research Annex. Detail of integrated post-tensioning connection.

1.0 INTRODUCTION
This paper expands upon the work produced in the graduate thesis design studio led by Assistant Professor Tsz Yan Ng at the Taubman College of Architecture + Urban Planning, University of Michigan between 2015-2016. This course was jointly taught with Assistant Professor Wes McGee, whose seminar, Advanced Digital Fabrication, is linked with the
thesis section to provide students the opportunity to fully explore novel techniques in digital fabrication.

As a yearlong, terminal-year design thesis course, the fall semester seminar is structured to provide the conceptual background for the development of disciplinary questions and the technical skills both in terms of computational design and in casting concrete. The exercises in the seminar introduce relevant historical and contemporary precedents as well as techniques for mold making through different design approaches. This includes “part to whole” assemblies, mix composition, techniques and processes for manipulation at various states of curing, and experimental processes previously prohibitive, but now possible through the use of Computer Numeric Control (CNC) fabrication techniques. The design studio in the winter term provides the opportunity for individual groups (in teams of two) to explore a trajectory of investigation involving design research, prototyping, and the production of a final design at full scale. As the title of the course suggests, issues of labor are investigated to address the inherent gap that exists in the industry for building in concrete – where the skilled intellectual labor of concrete mix development and formwork design is separate from the pure manual labor necessary to produce formwork for casting. This gap is reconsidered in light of new fabrication technologies, informing a more direct relationship between the various aspects of architectural production.

Figures 3-6: (left to right) Fabrication techniques explored for this project include CNC routing, robotic rod bending, waterjet cutting, ZUND cutting, jig manufacturing, and cast units of Concrete Lattice

1.1 Background

Many precedents served as inspiration for developing various aspects of Concrete Lattice. Extending from the work of Maciej Kaczynski in his 2013 project, Crease, Fold, Pour (Kaczynski, 2013); our use of Polyethylene Terephthalate Glycol-Modified (PETG) for formwork is similar with regard to how it utilizes folding for formal and structural potentials (Figure 04). Folding techniques highlight both formal aesthetics and structural performance of specific origami patterns. The work deviated from Kaczynski’s by moving away from a cast-in-place structure to working with a set of self-similar precast units as a comprehensive building system. The advantages of precast units include the possibility of disassembly/reassembly and the ability to install the project within a short period.

This project also takes cues from research in masonry compression-only systems explored by Philippe Block (Block & Ochsendorf, 2008) and from variable-volume systems such as La Voûte de Lafreure by Matter Design (Clifford & McGee, 2014). As precedents, these projects provided the framework to explore computational design processes where form is integrated with performance, optimized with material and structural considerations.

Figures 7-10: (left to right) Inspiration from spatial net structures, biomimetic geometries, and precedents of concrete lattice structures: Crease, Fold, Pour by Kaczynski (2013) and the MuCEM by Rudy Ricciotti in Marseille, France (2013)

The geometric design of this lattice system explores a “part to whole” assembly derived from a diamond cellular structure. Algorithmic design techniques were explored concurrently with biomimetic precedents found in nature. The diamond cell can produce a few variations of the base geometry, from rhomboids to hexagonal struts, and these are typically found in spider webs, turtle shells, and microscopic structure of soap bubbles. A similar geometric study was performed in the exploration of the lattice system through spatial nets, which take cues from spider webs but evolve outside the symmetrical pattern (Figure 07). This research stems from the paper Spatial Nets: The Computational and Material Study of Reticular Geometries, which experiments with reconfigurable jigs to produce volumetric nets (Askarinejad & Chaaraoui, 2015). The theoretical principles presented in this project – of reconfiguration, slender
materials, and space creation, were inspiration for the diamond lattice form with the adjustable jig as a necessary component for the casting process.

The use of concrete necessitates an understanding of compression-only systems. From the hanging chain models of Antoni Gaudi to the experiments and research of Frei Otto (Otto & Rasch, 1995), these principles have been tested and explored by architects seeking to extend the boundaries of the discipline to produce novel designs with optimized structural performance. As new software techniques have become available, we are now able to perform these tests digitally as simulated models. This project explored catenary logics using Kangaroo, a physics-based plug-in for Grasshopper, which informed the structural performance through interactive simulation and optimization of the variable units. While digital simulation is possible, many iterations of physical prototyping were still necessary to identify issues of material behavior of both PETG molding processes and GFRC casting.

2.0 PROCESS & FABRICATION
During the seminar phase, we began by collectively developing a base knowledge of material properties for concrete and casting techniques through different approaches of formwork design. These early experiments were performed alongside broader exposure to construction systems, which for this project, was focused on precast units that are typical to the building industry. Our goal for the design studio semester was to redefine the notion of the units, with a set of parameters that could produce manageable variations, be mass-produced, and deployed as a structural system. Additionally, as a team of two people, the scope of realizing the project within a short period after the prototyping and design phase was a challenge compared to more traditional design studios that does not require full-scale realization.

2.1 GFRC mix
There are four key ingredients in concrete: portland cement, aggregate, water, and air - the latter being a product of the chemical reaction between cement and water that also produces heat. In addition to a fine aggregate like sand, glass fibers of various lengths were introduced into our mix design for added strength and to resist cracking. Fiber reinforcement provided a critical advantage over steel for this project because of concerns for weight, workability, and cost. A polymer admixture was also used to reduce the water to cement ratio, enhance flow during casting, increase strength and bonding of the cement, and yield a smoother, non-porous cast surface. The ratio of these ingredients to one another is critical to ensure a smooth casting process and the desired resultant form.

2.2 Prototype testing
Fabrication and making were critical aspects of the ambitions for Concrete Lattice, thus prototyping at multiple stages of the design process charged us with identifying and solving problems as issues arise. The most significant component of the prototyping process beyond the concrete mix is the design and fabrication of the mold. We settled on PETG to have the most control over the lattice unit’s form, and to build the formwork with an inexpensive material that could be cut using a two-dimensional CNC knife-cutter (ZUND) and folded into 3-dimensional molds. (Figure 11).
a singular system capable of casting well over ten unique unit types (Figure 12). For the final lattice, we constructed six wooden jigs (enabling concurrency in production), cut from CNC routed plywood, and waterjet cut steel parts to secure the connection points on the ends of each unit. Within the singular jig system, steel collars, unique to each unit type, were used to accurately position the node at the top of the cast. In order to save time and material, the process was optimized to account for the various collar types needed in each casting session.

Figure 12: Axonometric of the PETG formwork in the reconfigurable jig system. Steel plates are at each node to ensure precise positioning of adjacent units.

2.3 Parametric design
In designing the units and their aggregation as an architectural system, we used the Rhinoceros modeling software and its parametric plug-in, Grasshopper, to develop a base unit with constraints in multiple dimensions. This parametric study allowed for precision in terms of aggregation and for the design of different combinations, creating varied typologies of spatial enclosures.

The individual unit inspired by biomimetic geometries is a cellular structure of a diamond lattice. For casting purposes, this diamond unit was split in half, creating compressive nodes at the ends of the linear elements where they meet. A steel collar fixes the position between the two ends along with other steel plates that hold the converging ends at the base of the jig. Node locations were controlled via the computational model to achieve a compression-only solution that would result in the least amount of shear stresses at the connection points.

The parameters of each unit were determined by its height, width between the joints, and the position of the legs at the base of the jig. The actual values were determined after a careful study using the Grasshopper plug-in, Kangaroo, which evaluated the desired curve of ten feet in height and ten feet in section. (Figure 13). Separate catenary curves were found for the inside and outside layers of the lattice geometry. These affect the individual unit parameters, adding a layer of complexity and asymmetry to the section of the half vault.
2.4 Final construct
While the fabrication of parts and their corresponding labels were made efficient by the Grasshopper script, the PETG formwork assembly process was time consuming given the human labor involved. Similarly, during installation, labor in post-processing each unit and the final assembly of the 42-unit lattice construct (Figure 14) consumed more time than the casting schedule. The scaffolding used was a minimal set of dimensional lumber struts, one at each major node with a specially routed module to cradle at the joint. The process for post-tensioning each unit during assembly minimized risk of collapse, scaffolding costs, and labor - especially for disassembly and re-assembly of typical scaffold structures.

3.0 COMPLEXITY & CONTROL
Our Concrete Lattice demonstrates that complex geometry in precast systems can be fabricated, assembled, and managed efficiently during construction within a short amount of time. Moreover, the installation was never meant to be permanent. With this consideration in mind, the system had to account for the logistics of assembly and disassembly as part of the design criteria, adding another layer of complexity to the overall process. The issue of time limitation, while posed as a challenge, was an integrated pedagogical tool. Most design-build pedagogy emphasizes the full-scale construction while responsibility for the afterlife of the project, from maintenance to disassembly, falls on someone else. By inserting the criteria of the logistics of deconstruction, systematic thinking in the life-cycle process forced the project to be more comprehensive and innovative as an architectural system. This enabled the project to consider the role of adding intelligence to the building process as part of the design thinking. As such, this work highlights not only the importance of design research through making as a pedagogical framework for exploring innovative designs via computational tools, but also the integration of construction logic as a form of design thinking in any built work. In gaining control of this logic, it enables designers to command the building process more effectively rather than builders dictating and determining one's design based on conventional processes.

By implementing a systemic logic early on, this project advocates for parametric scripting programs in the design of complex architectural systems, especially those at the intersection of design and construction. An understanding of the capabilities inherent to the variable lattice system led to advanced development and increased the layers of complexity achievable in the project. In this respect, Concrete Lattice demonstrates a novel solution to concerns of experiential and formal value, and simultaneously strives to match the performance of standard structural and manufacturing processes.

3.1 Computational feedback
Concrete Lattice was developed through iterative development in Grasshopper, looking at typical lattice systems and applying them to surfaces. Early on, the use of catenary curves simulated in Kangaroo, allowed us to control loading due to gravity throughout the system. By breaking down the diamond lattice, we arrived at the structural cross unit,
variable in multiple dimensions. Based on casting procedures, the lattice unit was split at the central node and a detailed script was designed for the precast unit. A separate code was also designed for the exploration of global forms when the units are aggregated, which led to the design of our final vault form. The process of prototyping enabled us to test the physical challenges that come with casting, which is much harder to predict with simulation software. As such, the feedback between prototyping and computational design informed many of the design decisions. With a high level of predictability, the design was optimized for structural performance while accounting for tolerances at critical moments to aid in the production of the final form.

3.2 Details and connections

Usually when one speaks about concrete architecture, it is reinforced concrete that is being referred to. For Concrete Lattice, despite the maximum use of glass fibers for reinforcement, two 3/8” rods had to be inserted to account for tensile strength along the linear extensions. Using an industrial robot, the rods were robotically bent and set in place inside the PETG formwork with tab connections to position the rebar at the proper depth. The bending system in use was developed as part of an ongoing trajectory of research at the University of Michigan (Pigram, et al, 2012).

An additional steel component was needed and became both an integrated part of the cast and a major node of connection in the assembled design. A ¼” black steel pipe was buried below the cast line of the split unit and was used to connect to its pairing unit, forming the cross geometry. The pipe was pre-drilled to receive the connecting elements for the post-tensioning system. The tensioning cables were integrated into the lattice design by running parallel to the legs; two on the outside at the single leg and one cable down the center of the split legs, producing another layer of asymmetry in the overall design (Figure 15). While cable turnbuckles provide a method for adjustments during assembly, they also proved useful for disassembly. These component parts were neither an afterthought nor a reason to deviate from the catenary form, but simply about efficiencies in cost and time.

3.3 Aggregation logic

This project imagines a broad range of variations and possibilities for how our innovative lattice system could enclose space. As mentioned, the parametric code of the basic diamond lattice could be adjusted to create units that when aggregated, produce diverse spatial forms (Figure 16). These typologies include spiral arrangements, thicket, vault, and branch logic. In the final vault design, slight adjustments had to be made to accommodate restrictions inherent in the unit, specifically in the length of legs and the width of the collar node. As the driving force for the vault design, the catenary curve was carefully studied and the vault iterated digitally to match multiple guiding curves. Nonetheless, small deviations from the perfect curve were necessary based on the parameters of the unit.

Figure 15: Image looking up below the lattice structure highlighting the compression-only connection at the wall and the network of post-tensioning cables.

Figure 16: Typologies based on unit aggregation with spatial considerations. Left to right: spiral, thicket, vault, and branch.
4.0 FURTHER INVESTIGATIONS
While the unit serves as a model for the scalar versions of itself to proliferate, the parameters of each unit also determine how it can aggregate. The particularities of each context will affect the spatial design, and therefore the unit. Three contextual situations were considered in the design variations study: a high alpine refuge, a shelter in an open field, and an urban pavilion. Additionally, sensors could be integrated between the units to provide direct feedback and adjustments between the compression and the tensioning system. When one area loosens, other parts of that system or its connected counterpart could respond to changes automatically. To enclose the full vault structure, a layer of folded skin could be added to provide shelter, responsive to lighting and weather conditions (Figure 17).

Figure 17: Axonometric diagrams of the lattice system assembled as a full vault with layers of componentry: from post-tensioning to flexible skin.

Any built work must negotiate social, economic, and natural environments by engaging the opportunities and constraints inherent in its context. As traditional building systems are designed and manufactured, contextual and environmental conditions are often accounted for in materials used, the building’s orientation, or specialized weather barrier systems. Concrete Lattice imagines the entire form and make-up of the system adapting as necessary, and projects a future reality for building systems that can respond more readily to their environments.

5.0 CONCLUSION

It is this lack of mediation between design and production that is being reformulated with integrated digital design and fabrication processes: drawings and models are no longer used to represent design ‘intent’; rather, they are used to communicate precise information on how to fabricate and with which material.

-Scott Marble, “Imaging Risk,” 2010

The experience of participating in a design studio that includes research and fabrication, provided an opportunity to learn not only how to close the gap between two divorced aspects of architectural production – that of design and construction – but to also do so in an integrative manner. In architecture, specialized computational tools and software have been developed by many practices - such as Gehry Technologies and SHoP - to link design directly with the production of architecture (the construction and building of) as a seamless process. In doing so, the architect gains better control of the outcome by closing the loop between design and fabrication. Closing this gap in the building construction process offers not only the opportunity for the architect to experiment with more innovative designs outside the constraints of industry standards, but also simultaneously reduces construction costs by allowing for a more efficient fabrication process. These workflows between design and fabrication are gaining traction in how we practice as architects. Firms such as Diller, Sciofidio + Renfro (for Broad Museum, Los Angeles), Snohetta (for SF MOMA façade, San Francisco), and Rudy Riccioti (for MuCEM, Marseille) have already employed such processes in their projects. While smaller in scope, the thesis studio’s pedagogical framework exposes this integrative process for architectural production by allowing the students to explore the full range of processes involved for this type of production.

By promoting this methodology for innovation in the building industry, Concrete Lattice advances our notion of precast units - with a set of parameters that produce manageable variations - that can be mass-produced, and deployed as a structural system. This project and the thesis studio at large also highlight the benefits of fabrication and technology for emerging designers at the academy. Exposure to advanced digital tools and workflows has helped to enhance architectural education and promote experimental designs among graduates seeking work that deviates from the traditional path.
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ABSTRACT: Parametric modeling and assembly of curved surfaces can be difficult for students to grasp due to complex computational workflows that rely upon higher mathematics. Using readily available materials and 3D printed components, a kit for parametric curved surfaces can initiate students into this field of contemporary design using a tactile approach. Software templates then enable the students to create a digital model of their initial physical model. The paper presents an example kit for Tactile Experimental Parametrics. It describes the concept, the parametric models of the fittings, the printing process and tools, the parametric modeling of the assemblies, and example designs produced by the students. The software tool for modeling was Autodesk Revit, and the 3D printing was done with an XYZ Print desktop printer. Workshops were conducted at Harbin Institute of Technology with students in the upper levels of the architecture program.

KEYWORDS: parametric, modeling, toy, learning, workshop

INTRODUCTION
Arguably no longer a trend, the modeling and fabrication of curved surfaces has become a common part of many architectural curricula and a response by architects that is no longer surprising. However, many students have difficulty grasping concepts that are critical to the craft behind designing and manufacturing such surfaces and may have similar difficulty conceptualizing a form. Working in a digital medium with unfamiliar ideas is an abstract activity that can lead to creative blockage. The chosen solution is often to vary a design that a student has seen before or use a “canned” script or process with predictable results or predictably unpredictable results (Doyle and Senske 2016). There can be a tendency to stop at an elementary solution that is quite beautiful, but does not exemplify much creativity. Even a commercially designed, massive structure such as the Metropol Parasol in Seville is conceptually little more than a gargantuan studio project using a wooden egg-crate assembly. There is a need to help students move beyond elementary and rote solutions, and develop “deep learning” that enables them to apply fundamental concepts in new and novel situations (Doyle and Senske 2016).

There are lessons that are best learned in physical exploration just as there are lessons that are best learned in digital exploration. However, by combining the two modes of exploration, there is an opportunity to “bridge the divide between digital and tactile design” (Snoonian and Cuff 2001). Much of the digital fabrication pedagogy that has arisen in the last twenty years has implicitly adopted this agenda, although often without a clearly stated pedagogical objective. Nevertheless, “Design education and digital technology education continue to be seen as separate loci of learning, separated by pedagogical gaps and teaching mindsets” (Doyle and Senske 2016, 192). The investigation described in this paper explores design of curved surfaces through tactile experimentation with a veritable physical toy to reveal fundamental issues and a range of possibilities. A digital representation of the toy then reinforces how the physical can be represented as a digital model. The use of digital tools of parametric modeling and 3D printing are necessary to produce the instruments of the investigation, but are not the investigation itself. The goal of the investigation is not to make something with “wow” appeal in an academic setting, but to help students to understand essential concepts in designing and building curved surfaces at an architectural scale.

A secondary motive is to increase students’ knowledge of Building Information Modeling and specifically Autodesk Revit for creating digital models of curved surfaces and fabricating them.

1.0 CONCEPTUALIZATION
The spline is a key concept in describing a free-form curve to the computer, and the skin made by sweeping and blending splines is the recurring method for describing a surface. Nevertheless, when such an architectural idea is elaborated into something at the scale of a building, the smooth, liquid forms must be fractured and faceted, usually into flat or singly curved panels, and then supported with fittings, struts, and columns in assemblies of primary, secondary, tertiary, and even quaternary structural elements. Explaining the set of parts and elements and teaching students to design them is a challenge to their patience. Students often do not recognize or acknowledge the devotion, intellectual effort, and time that is necessary to design and fabricate a complex form. Teaching the concepts and techniques using
didactic methods and tutorials can take many sessions and consequently the ability to model curved surfaces may be perceived as a specialization for an elite few designers. Many students give up and resort to conventional and “canned” solutions.

Students may also fail to finish fabrication projects because they have not learned fundamental principles of manufacture and assembly. The precision necessary in fabricating curved surfaces is a challenge for many students who are accustomed to building cardboard models where they can cut to fit. The notions of tolerances, use of physical connections rather than glue, impact of thickness of materials, and exploitation of deformation of a material are some of the tangible, physical realities that are difficult to grasp in a purely digital medium. Students often build a physical prototype that fails before they can respect the principles that govern design and manufacture.

1.1. Building toys
The insight of this research derives from personal childhood experiences. A few decades ago, digital or virtual play was non-existent but tactile play was omnipresent. Children had many building toys:

- Wooden blocks
- Tinker Toys
- Lincoln Logs
- Meccano sets
- Erector sets
- Lego blocks
- Girder and Panel sets
- Plastic kits of ships, airplanes, military vehicles, automobiles
- Balsa and tissue airplane models

These toys taught basic ideas in masonry, log, and steel construction, and introduced hierarchical assemblies involving foundations, columns, beams, plates, joists, trusses, shear walls, panels, fasteners and connectors. They involved press fits, mechanical fasteners such as nuts and bolts, and glued joints. However, none of them (except the plastic kits and the balsa and tissue airplanes which constrained modeling to a single instance) allowed for creating complex, doubly curved surfaces. Although Tinker Toys impose a hexagonal geometry, most of the tools rely upon rectangular geometry with a distinct dimensional module. One may criticize these childhood toys for normalizing design ideation into a presumption of rectangular forms. A toy for curved surfaces could be an interesting addition to the panoply of building toys, subtly presenting and integrating different concepts and patterns that are particularly relevant to contemporary architecture.

1.2. Toys first
Teaching fundamental concepts in curved surfaces using a building kit turns the current digital fabrication process on its head. First, students would use the kit to build something with their hands. In theory, this tactile activity will actuate their experience, heighten their perception, whet their appetites for learning, and ground their memory. This is followed by digital modeling to represent the assembled toy, engaging abstract thinking as well as simple acquisition of skill with the software. From the digital model of the toy, the student is challenged to design something new by employing the newly learned principles and techniques in creative ways. Production of a final physical assembly from the digital model closes the loop and engages the students as designers to create new surfaces, panels, connectors, and structural elements.

The use of a toy encourages experimental play while reinforcing concepts and skills through a combination of tactile and digital exercises. The process leads inevitably to an early success, as the student assembles the toy to make something intentional and in some ways surprising. We use the term Tactile Experimental Parametrics to describe “toys first” learning that sequences playing with a toy, modeling it with the computer, producing a new custom toy, and repeating to refine the design idea.

1.3. Devising the toy kit
The conceptualization of this experiment involved a search for commonly available materials that could be appropriated for use in a building kit toy. A pegboard is a “found” material that establishes a field of datum points, while dowels provide the third dimension to locate points in 3D space. Representing the spline requires a linear material with flexibility to accept changes in shape yet stiffness to produce curvature. After trying string, copper wire, grass trimmer string, and other materials, 1/4” irrigation tubing proved to have the proper material characteristics for representing a spline in 3D physical space. Paper, cardboard or other readily available and easily cut materials can be used for panels. The connectors are the critical part of the system and join the simple linear and planar materials to make complex forms. 3D printing of connectors could enable the toy to work. Joker Kit is a first experiment in using this learning method. It consists of irrigation tubing, dowels, pegboard, fittings,
and playing cards. Two kinds of 3D printed fittings are provided: a connector to clip a length of tubing to a support dowel, and a connector to attach a card to the tubing. Dowels may be cut to various lengths and inserted into the holes in the pegboard. The playing cards are another found material that is a module with an attractive stiffness in a comfortable size scaled to fingers. They may be used whole or may be cut with scissors to special shapes. The fittings provide overlap and slack to allow the tubing to be moved up and down and the cards to be supported even after sliding in and out. Panels can be applied using overlaps and gaps, or cut by hand or with a laser cutter to precise dimensions.

Producing the kit required designing the connectors and cutting other elements to appropriate sizes for a desktop toy. The pegboard was cut to 45 cm by 61 cm (18 inches by 24 inches) as a reasonable field for building a modest model. The dowels were cut to various lengths ranging from 7.62 cm to 30.48 cm (3 inches to 12 inches) to allow designers to position 3D points at various heights. Slots cut into the ends in a way similar to those in a Tinker Toy dowel facilitate a tight press fit into the holes in the pegboard or into the connector at the top of the dowel.

Figure 1: Joker kit parts.

2.0. MODELING COMPONENTS

Printing the two connectors requires modeling the connectors in a 3D modeling environment. Anticipating use of press fits that can resist modest force to pull the two elements apart, it was advantageous to use a parametric constraint-modeling tool to enable experimentation with dimensions. Autodesk Revit has adequate capabilities to support modeling the connectors and was used for modeling. Many other tools, such as McNeel Rhino, Autodesk 3D Studio, or Autodesk AutoCAD, could be used.

2.1. Dowel cap

The connector to join the dowel to the tubing is referred to as the “dowel cap”. It is a cylinder with a void cylinder subtracted from one end to form a recess to receive the dowel. Both cylinders are parameterized to allow experimentation with the tightness of the fit of the dowel into the cap and the strength of the wall of the hollow cylinder. The top of the cap is a hook to hold the tubing in place. It also is parameterized along several dimensions. The opening of the hook was varied to reach a comfortable press fit of the tubing into the hook, relying on deformation of the tubing to force it into place and then rebound of the tubing so that it does not easily pop out of position. The thickness of the hook in both directions affects the cross section to allow control of the strength of the hook. Too little material and it will break easily. Too much material and the effect is coarse and the use of materials is inefficient. The opening of the hook must have sufficient slack to allow the tubing to pass through the hook in an upward or downward direction.

2.2. Panel connector

The connector between the tubing and the playing cards is referred to as the “panel connector”. Similar to the dowel cap, the amount of material and size of the openings must allow press fits to the tubing and to the playing cards. A slight clamping action is desirable to hold the playing cards. Also, the panel connector is designed to allow the panels to slide close to the tubing or away from the tubing to account for the variability in size of the panels necessary for suggesting a curved surface.
2.3. Production
The dowel cap family and the panel connector family were placed into separate project files. Each was then saved as an ACIS file, imported into AutoCAD and then saved as an STL file. Alternatively, an addin for Revit is available for saving an STL file directly from Revit. The STL file was then imported multiple times into the 3D printing software, in this case, XYZ Print. Printing two dozen connectors required about twelve hours.

A designer should understand that quality of modeling affects the ability to print the STL file. A fundamental concept is the physical reality that two solids cannot exist in the same place at the same time. Sloppy modeling may intersect various solids, producing something that looks right but is physically impossible. An STL file may then require extensive repair to produce a printable representation. If the user takes the time to subtract volumes where two solids intersect, the model can be perfect and require no repair in the STL representation. The solid modeling approach provided in Revit encourages creation of high quality models that make perfect STL files. Neither of these connectors required any repair to the STL files to permit printing.

2.4. Playing with the toy
Putting together toy assemblies proved irresistible and the kit was tested by building modest assemblies. Dowels are easily cut to new lengths. Tubing is easily to cut to new lengths and to shape to new forms. Playing cards may be cut to new shapes. No glue is required, allowing the model to be reconfigured rapidly and the designer to explore alternative design ideas.
3.0. DIGITAL MODELING OF ASSEMBLIES

To facilitate learning how the concepts translate into the abstract world of digital modeling, the second stage of the assignment requires students to model the physical model with the digital tool. The process of digital modeling was worked out to provide students with step-by-step instructions. In a simplistic approach, each element in the toy can be modeled as an element in the digital tool (Autodesk Revit in the case of this experiment). However, there is no need for the digital model to be identical to the toy assembly. Instead it can inspire a more sophisticated and refined design that overcomes some of the limitations of the toy and adapts it for the full size of an architectural work.

3.1. Simplistic model

For the simplistic approach, the several components are each modeled as families in Revit. The pegboard is easily modeled as a Generic Model rectangular extrusion with a grid of holes subtracted. Dowels are modeled as an extruded Generic Model family with a parameter to determine the height. The dowel cap family can be reused from the one used to produce the 3D prints, as can the panel connector family. Dowel locations on the pegboard and dowel lengths in the physical model determine points in 3D space that control splines. The tubing can be modeled as a Generic Model Adaptive family with a line controlled by adaptive points and a cross section of the tube swept along the line. The playing cards can be modeled as simple extrusions of the rounded rectangle shape. If the card were modeled using the Generic Model family, it could only take on a rigid planar form. By using the Generic Model Pattern Based family, the card will tolerate warping out of plane, behavior that is more accurate to the playing card or to real-world panels.

This simplistic model makes use of a variety of Revit families with various behaviors. The Generic Model family provides for simple parametric modeling of dimensions using a single placement point. The dowel cap family and the panel connector family are mildly complex Generic Model components. The Generic Model Adaptive family provides for multiple placement points in non-planar 3D space. The Generic model Pattern Based provides adaptive behavior constrained to a standard pattern, in this case a warped rectangle.
3.1. Abstract model of architecture
If the toy model is recognized to be an abstraction or study for determining some more refined design, then modeling the assembly takes on a more creative dimension. The pegboard and dowels can be understood as merely the expedient pieces for placing points in 3D space. A different foundation can be designed. The tubing is merely an expedient physical embodiment of an abstract spline curve. To ease construction, it could be rationalized into straight segments or circular arc segments. The connectors, likewise are merely toy parts that do not need to correspond to the assembly in a building. The playing cards are also expedient panels used to suggest the surface. Panels in a real building may need to take on unique triangular or irregular shapes.

Given this understanding of the toy assembly, as merely an abstract model of an architectural built surface, digital modeling can proceed in new directions. The splines can be blended to make a surface. The surface may be divided in various ways, allowing for faceting of the surface to be achieved in various ways. Mullions, struts, stays, beams, girders, and columns may be designed to make something realistic. The next iteration of physical modeling can produce a new custom kit that has greater fidelity to the ultimate building, but is still made of plastic, wood, acrylic and other model-building materials. Ultimately, the BIM representation can drive production of steel, glass, aluminum, and other construction materials that could be used in full-size mock-ups or fabricating the components of an actual building.

3.2. Facet production

- As the student explores tessellation and faceting of a surface, production of irregular panels is a challenge. Autodesk Revit can be used to produce the panel cut sheets. The process is clumsy because it relies on a long list of procedures, but it does not involve programming or scripting:
  - Label the panels with an identifier;
  - Extract key dimensions from the panel family using reporting parameters;
  - Produce a schedule of the panel dimensions and labels;
  - Save the schedule as a CSV file;
  - Using the CSV file, produce a spreadsheet file in the proper format for Revit Lookup tables;
  - Produce a flattened panel family that reproduces a labeled panel using parametric dimensions;
  - Drive the flattened panel family from the spreadsheet of dimensions using a Lookup table;
  - Place the flattened panels in a new Revit project on a plan view, varying the label to look up each set of dimensions;
  - Add the view to a sheet in Revit.
  - Save the sheet as a DWG file;
  - Send the DWG file to a laser cutter, 3-axis milling machine, or water jet cutter.

4.0. WORKSHOP
The method was tested in a ten-day workshop in May 2016 at the Harbin Institute of Technology. A group of students were selected from upper level undergraduate and graduate students in architecture programs. Students were already adept with using Revit, but had little or no experience with adaptive components and parametric form making.

Figure 6: Use of lookup table to control parameters of a panel family.
The first class period focused on an exercise to use the Joker kit to create a physical model of an architectural curved surface. Subsequent class periods provided review and discussion of the forms and instruction in how to model them in Revit. Students were then shown additional Revit commands for dividing surfaces with patterns, building adaptive components for connectors and panels, and production with 3D printing and laser cutters. They were challenged to design a public canopy, such as a train station shed, a bus depot, or a public park covering.

![Figure 7: Products of the workshop](image)

Students' products demonstrate success in using the Joker kit, and some degree of inventiveness in the original composition. The student teams used conventional triangular faceting for surfaces, but used a variety of support systems, including concentric bulkheads, beams with finger-like facet supports, and curved beams. One team modified the dowel cap by physically cutting it to a new shape, while another team redesigned the cap to support rectangular beams.

**CONCLUSION**

While the conduct of a single workshop is certainly not conclusive evidence in support of the method, it suggests that the exercise is at least adequately described for implementation, with promising pilot study results. Tactile Experimental Parametrics may not only aid a designer in thinking about the specifics of an assembly and the contours of a structural shell, it may also help a student to understand concepts in mathematics, form, and modeling. Tactile Experimental Parametrics helps students break down complex physical forms into designable and buildable assemblies. The lessons learned cluster into three categories:

Mathematical and geometric concepts

- Cartesian field in 3 dimensions (the pegboard and dowels)
- 3D splines and control points (the dowels and irrigation tubing)
• Blended surfaces (the playing cards between the tubing)
• Surface normals (pins on the playing cards)
• Relative coordinates

Materials and fabrication

• Tolerances (the connectors)
• Panel deformation (the playing cards)
• Friction fits and material deformation (the connectors)
• Flattening facets (the Revit workflow using Lookup tables)

Architecture and assembly

• Hierarchical structural systems to collect loads and transmit them (the Joker kit)
• Adaptive points and elements (the Revit model of the Joker kit assembly)
• Inventing and managing a complex workflow (assembling a Joker model, flattening facets, devising a new kit, designing an architectural curved surface)

By engaging tactile play, the Tactile Experimental Parametrics is intended to ground the concepts, make them tangible rather than abstract, and reinforce memory. The approach may be effective in other levels of education for teaching mathematics and geometry, including kindergarten and primary school, secondary school, as well as college-level instruction.

The exercise could be executed using other digital tools or could provide other lessons in modeling, fabrication and assembly. Other 3D surfacing paradigms could be implemented, such as NURBS, constructive solid geometry, mesh modeling, and topological mesh modeling. As executed, the exercise had a secondary objective of fostering facility and confidence with a BIM tool. It effectively conveyed to students that Autodesk Revit is capable of representing complex, curvilinear shapes that may be easily modeled through a parametric approach.

Bloom's taxonomy has been suggested as a useful way for architectural educators to structure courses for identifying learning objectives (Doyle and Sensek 2016). The Joker exercise works through the entire Bloom's taxonomy of learning. Basic concepts are presented as discrete and abstract knowledge. Comprehension is aided through a tactile exercise of assembling the Joker kit. Application comes from modeling the physical assembly as a Revit model. Analysis and evaluation occurs when students assess the Joker kit and Revit model for adequacy in an original design. Creation is the final outcome of designing and fabricating an architectural work.

It has been suggested that designing with computer tools has become so common and normal that our era should be seen as a "post-digital" era (Kolarevic 2008). However, there is danger in the post–digital situation that cultural forgetfulness discards the information and knowledge that enabled us to arrive at this point. The "digital native" may not understand the tools that are employed with such facile skill, and thus be unable to produce new ones (Doyle and Sensek 2014). This experiment represents a "post-digital" effort to get back to understanding the roots of computational design. The design of the curved surface is not an end in itself or an expression of the delight in using new tools to make new things, but a carefully formulated exercise meant to foster and reinforce learning of targeted architectural knowledge. This investigation is essentially a "post-digital" study that treats the digital as both instrument of study and focus of study, but not the end of study (Swackhamer 2011). Learning to design with computers is inseparable from learning to design in the 21st century.

REFERENCES


INVESTIGATION OF THE RELATIONSHIP OF THE THERMAL COMFORT PERCEPTION BETWEEN THE LOCAL AND WHOLE BODY SEGMENTS IN A WORKPLACE ENVIRONMENT

Qi Wang', Joon-Ho Choi', Marc Schiler', Douglas Noble'

1University of Southern California, Los Angeles, California

ABSTRACT: Traditional air-conditioning methods maintain temperatures in a whole room at a constant level, and much work has been done to assess and improve the thermal comfort and sensations of people in a workplace environment. This study endeavors to identify the relationship of the thermal comfort perception between the local and whole body segments in a workplace environment. A total of 20 human subjects were tested in the University of Southern California's climate chamber to determine their physiological parameters and subjective perceptions of environment. Ambient temperature was documented during the tests, while the human subjects were exposed to a warm, cool, or neutral environment. Based on these tests, correlation and stepwise analysis are applied to identify the relative thermally sensitive skin areas, their contribution rate to the overall thermal sensation, and potential skin area combinations that have high correlation with overall thermal sensation. Results show that local thermal sensations are high correlated with the overall thermal sensation, the thermal sensation of arm is particularly strongly correlated with the overall thermal sensation with the reference to the Pearson R value of 0.918. Besides, with different genders and BMIs, there exists a sensation difference even in the same environment temperature. The study also identifies the different impacts of local thermal sensation while predicting the overall thermal sensation by applying data driven model.

KEYWORDS: Thermal sensation, Thermal comfort, Thermal environment

1.0 INTRODUCTION

People spend most of their time indoor, it has been proven that Indoor Environment Quality (IEQ) can significantly influence human mood and working productivity (Fisk 2000). IEQ can be determined by many factors, including indoor environment conditions such as temperature, lighting, humidity, glare, and air quality (ASHRAE 2016). Thermal comfort is one of the significant factors that highly correlate with the satisfaction of IEQ. But research from Huizenga shows that in only 11% of the 215 surveyed buildings in different countries, 80% or more of the occupants are satisfied with their thermal comfort in building (C. Huizenga 2006). Considering people's extreme dissatisfaction with the environmental quality in the interiors, a method that uses local body areas to predict the overall thermal sensation may give the designer practical and accurate way to evaluate the thermal environment of the building.

The traditional thermal sensation model is based on the thermal equilibrium of heat input and output. Researchers tried to combine four environmental factors (temperature, humidity, air speed, and mean radiant temperature) with thermal sensation. In 1970, P. O. Fanger proposed the equilibrium of heat input and output of the human body (P. O. Fanger 1970). In 1989, the researcher Wyon proposed the concept of “Equivalent Homogeneous Temperature” (EHT) to evaluate the non-uniform environment in a car based on the combination of thermal manikin and five years of vehicle environment research. (Wyon 1989).

Some researchers studied the local thermal sensation in different environment conditions. Edward Arens and others in the Center for the Built Environment (CBE) studied the thermal sensation and comfort in different uniform environments including slightly warm, warm, cool, and cold environments. The result from their study showed that the thermal sensation of the breathing zone tended to be warmer than the sensations of other body parts like head, neck, and face in cool and cold environments. (Edward Arens, Partial- and whole-body thermal sensation and comfort 2006). Some researchers studied the correlation between local thermal sensations and the overall thermal sensation. Humphreys measured temperatures of 2000 fingertip and collected the overall thermal sensation data in different thermal conditions. He proposed that a combination of hand temperature and environment temperature can predict the overall thermal sensation well (M.A. Humphreys 1999). Researcher Danni Wang studied finger temperature and the combination of air and finger temperatures to predict the overall thermal sensation. He found that the skin temperature range of fingers was narrow when compared to that of other local skin temperatures in cool conditions. This indicated that the skin temperature of the finger is a significant sensitive indicator of the body's thermal sensation and comfort in cool conditions (Danni Wang 2007).

Gender is one of the significant factors that can influence thermal sensation in similar thermal environments (JoonHo
In recent years, researchers also investigated the gender differences in thermal comfort (W. Pasut 2015). The researcher Karjalainen (Karjalainen 2012) found that females are more sensitive than males when the environment condition is cool. Other researchers also investigated sensation of male and female in different environment conditions. It has been proved that there is only small overall thermal sensation difference between the genders in neutral or slightly warm environment conditions, but females tend to feel cooler when the environmental temperature is relative cool (KC 2002).

Researchers also use machine learning approaches to predict thermal demands based on skin temperatures. Researcher Changzhi found that by using the support vector machine (SVM) model, thermal demands can be well predicted based on the local skin temperatures (Changzhi Dai 2017). Although the thermal demands can be well predicted in this model, other machine learning methods such as decision tree or Artificial Neuro Network are not used to predict the thermal demand or sensation.

2.0 OBJECTIVE
The purpose of the study is to understand the correlation between overall thermal sensation and local thermal sensations. At the same time, accuracy estimation to predict the overall thermal sensation is also evaluated. The potential use of some local skin spot to predict the overall thermal sensation can be achieved based on the method of correlation analysis, step-wise analysis, and the application of data-driven algorithm.

3.0 METHOD
A method to investigate how local skin temperature and local thermal sensation correlates to human thermal response is proposed. The workflow of the proposed method can be divided into three steps: chamber arrangement, data acquisition, and data analysis (Figure 1).

![Figure 1: Overall workflow of proposed method](image)

The human subject tests were conducted in the University of Southern California's (USC) experiment chamber. The experiment chamber is in basement of Watt Hall. As shown in Figure 2, the chamber is 4.0 meters long, 2.8 meters wide and 2.4 meters high. The temperature of the environmental chamber was regulated by two air conditioners and four portable heaters. Four diffusers were distributed uniformly beside the desk. One of the challenge for the project was to identify a program that could efficiently collect environmental data in the chamber. The Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software was used in this project to achieve the purpose.
A total of 20 volunteers (10 males, and 10 females) participated the experiment, the overall demographic information is shown in Table 1; they were all college students from the University of Southern California. All subjects selected were in good health and had no background information about the thesis topic.

Table 1: Demographic information about subjects

<table>
<thead>
<tr>
<th>Age</th>
<th>BMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>23.8</td>
</tr>
<tr>
<td>St. Dev</td>
<td>2.668</td>
</tr>
<tr>
<td>Underweight ≤ 18.5</td>
<td>Normal weight ≤ 24.9</td>
</tr>
<tr>
<td>20–25</td>
<td>26–30</td>
</tr>
<tr>
<td>Female</td>
<td>8</td>
</tr>
<tr>
<td>Male</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
</tr>
</tbody>
</table>

The experiment carried on for around 80 minutes, which consists of 60 minutes in the environmental chamber and 20 minutes’ rest outside the chamber, the detail of the experiment procedure is shown in Figure 3.

Figure 4 is a photograph of a subject wearing sensors in a calm condition. Based on thermoregulation models of thermal sensation and physiological response (J. K. Choi 1997), the seven local spots were forehead, neck (at the back), back (upper back), chest, arm (upper arm), wrist, and belly. The subjects could engage in some simple activities such as reading a book or listening to soothing music.
Figure 4: Photograph of a subject wearing sensors in a calm condition

Subjects' local and whole body thermal sensations and comfort were surveyed by the questionnaire. Thermal sensation and comfort data from different parts of the subjects' body and from their whole body were documented every five minutes.

4.0 DATA ANALYSIS
4.1 Overall and local thermal sensation analysis
Figure 5 shows the interval plot of local sensation votes under neutral overall thermal sensation (0). When the overall thermal sensation is neutral, the sensation level of different body parts is around zero. The local thermal sensation of the wrist is close to neutral (p < 0.05). The sensations of forehead, back, chest, and belly are warmer than neutral (p < 0.05), while the sensation of the arm (p < 0.05) is cooler than other locations on the body. This phenomenon indicates that in the condition of neutral overall thermal sensation, the sensations in the breathing zone and head region are more likely warm; the sensation in the trunk is more likely cool.

Table 2 shows the Pearson correlation between the overall thermal sensation and local thermal sensation. Each local thermal sensation had a very strong correlation (Pearson R > 0.8) with the overall thermal sensation (p < 0.05). The thermal sensation of the arm was particularly strongly correlated with the overall thermal sensation with the reference to the Pearson R value of 0.918; the forehead sensation also had a strong correlation with the Pearson R value of 0.871. The thermal sensation of the belly showed a relatively low correlation with the overall thermal sensation (Pearson R = 0.82, p < 0.05).
Table 2: Pearson correlation between the overall thermal sensation and local thermal sensation

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Neck</th>
<th>Back</th>
<th>Chest</th>
<th>Belly</th>
<th>Wrist</th>
<th>Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson R</td>
<td>0.871</td>
<td>0.869</td>
<td>0.842</td>
<td>0.865</td>
<td>0.820</td>
<td>0.85</td>
<td>0.918</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
</tr>
</tbody>
</table>

Table 3 shows the stepwise analysis of the local thermal sensation and overall thermal sensation. As shown in Table 5.2, thermal sensation of the forehead had a strong correlation with overall thermal sensation. The first step of the stepwise analysis focused on the arm with an R-sq value of 84.3%. Forehead sensation combined with that of the arm had the R-sq value of 86.8%; the Δ R-sq value was 2.5% in total. With the combination of the thermal sensation of seven local bodies, the R-sq value could up to 88.1%. By combining the arm and the forehead, the R-sq value could be 84.3%, which is close to 88.1%.

Table 3: Stepwise analysis of the local thermal sensation and the overall thermal sensation

<table>
<thead>
<tr>
<th></th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm</td>
<td>.968</td>
<td>.000</td>
<td>.684</td>
<td>.000</td>
</tr>
<tr>
<td>Forehead</td>
<td>.417</td>
<td>.000</td>
<td>.309</td>
<td>.000</td>
</tr>
<tr>
<td>Chest</td>
<td>.217</td>
<td>.000</td>
<td>.1697</td>
<td>.000</td>
</tr>
<tr>
<td>Wrist</td>
<td></td>
<td></td>
<td>.1271</td>
<td>.000</td>
</tr>
<tr>
<td>R-sq</td>
<td>84.3%</td>
<td>86.8%</td>
<td>87.4%</td>
<td>87.7%</td>
</tr>
<tr>
<td>Δ R-sq</td>
<td>-</td>
<td>2.5%</td>
<td>0.6%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

4.2 Demographic factor analysis
In total, 20 subjects were divided into two groups: six subjects were in the low BMI group (< 20 kg/m2) and 14 subjects were in the high BMI group (≥ 20 kg/m2).
As shown in Figure 6, The indoor temperatures of both high and low BMI groups increased consistently when the overall thermal sensations change from −3 (cold) to 3 (hot). In the sensation level of −1 (slightly cool) and +1 (slightly warm), the environment's temperature experienced by the high BMI and low BMI groups were similar. The biggest temperature difference occurred when the overall thermal sensation level was neutral (0).
As shown in Table 4, all body locations in the low BMI and high BMI group showed a very strong correlation with the overall thermal sensation. The low BMI group showed a higher correlation than the high BMI group with the reference to most body locations (forehead, chest, belly, wrist, arm). The Pearson R difference was not significant while considering the local thermal sensation of the neck, back, and chest. It is worth noting that there existed a relatively high correlation difference of the forehead between the low BMI (Pearson R = 0.906) and the high BMI (Pearson R = 0.853) group.

Table 4: Correlation analysis of the overall thermal sensation and local thermal sensation by BMI

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Neck</th>
<th>Back</th>
<th>Chest</th>
<th>Belly</th>
<th>Wrist</th>
<th>Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low BMI Pearson R</td>
<td>0.906</td>
<td>0.863</td>
<td>0.832</td>
<td>0.869</td>
<td>0.854</td>
<td>0.892</td>
<td>0.937</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>High BMI Pearson R</td>
<td>0.853</td>
<td>0.874</td>
<td>0.848</td>
<td>0.866</td>
<td>0.816</td>
<td>0.832</td>
<td>0.909</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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</tr>
</tbody>
</table>

In total, 20 human subjects (10 male and 10 female subjects) were tested in the experimental chamber. As shown in Figure 7, the thermal sensation level of both male and female subjects increased continuously. The thermal sensation of male subjects increased from –2 (cool) to +3 (hot), while that of female subjects increased from –3 (very cool) to +3 (hot). There was no male subject who felt cold during the test; this indicated that in very cool conditions, the male feels warmer than female. When male and female subjects had the same thermal sensation level (except +3), the mean environment temperature for male subjects was lower than that of female subjects. When the overall thermal sensation was hot (+3), the environment’s temperature for male subjects were higher than that of female subjects. This indicted that in very warm conditions, male tends to feel warmer than female.
As shown in Table 5, female subjects showed a higher correlation than male subjects with the reference to these body locations: forehead, back, and arm. The local body thermal sensation of the belly in the female group showed a relatively low Pearson R value, which means that the sensation of the belly was not highly correlated with the overall thermal sensation. Although the Pearson R value was different in the male and female group, the difference in the value was not significant.

Table 5: Correlation analysis of the overall thermal sensation and local thermal sensation by gender

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Neck</th>
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<th>Chest</th>
<th>Belly</th>
<th>Wrist</th>
<th>Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearson R</td>
<td>0.834</td>
<td>0.879</td>
<td>0.806</td>
<td>0.857</td>
<td>0.817</td>
<td>0.846</td>
<td>0.902</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearson R</td>
<td>0.871</td>
<td>0.838</td>
<td>0.840</td>
<td>0.842</td>
<td>0.781</td>
<td>0.822</td>
<td>0.914</td>
</tr>
<tr>
<td>p-value</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

4.3 Estimation of the overall thermal sensation by the local thermal sensation
To estimate the overall thermal sensation, this paper takes the subject’s physiological status (gender and BMI) and environment temperature as the baseline attributes and combines the local thermal sensation in different spots as the changeable attributes. The data-driven algorithm decision tree (J48) is used to estimate the accuracy (Correctly Classified Instances) of the prediction result and uses the ten-fold cross validation method for the test option. As shown in Table 6, The accuracy is at a relatively low level while not considering the environment temperature in the baseline attributes. The arm had maximum accuracy (75.77%), and the neck had minimum accuracy (68.71%). Although the forehead had the highest accuracy when the environment’s temperature, the BMI and gender in baseline attributes were considered, the accuracy was not the highest without considering the environment’s temperature.

Table 6: Accuracy of using baseline attributes (BMI, gender, environment temperature) and single local thermal sensation factor to estimate the overall thermal sensation

<table>
<thead>
<tr>
<th></th>
<th>Forehead</th>
<th>Neck</th>
<th>Back</th>
<th>Chest</th>
<th>Belly</th>
<th>Wrist</th>
<th>Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (gender, BMI, environment temperature)</td>
<td>98.58%</td>
<td>98.02%</td>
<td>98.44%</td>
<td>97.19%</td>
<td>98.05%</td>
<td>97.73%</td>
<td>98.05%</td>
</tr>
<tr>
<td>Accuracy (gender, BMI)</td>
<td>72.93%</td>
<td>68.71%</td>
<td>73.65%</td>
<td>71.46%</td>
<td>69.28%</td>
<td>74.13%</td>
<td>75.77%</td>
</tr>
</tbody>
</table>

5.0 RESULT AND DISCUSSION
The study aimed to enhance the researcher’s understanding about the relationship of the thermal comfort perception between the local and whole body segments in a workplace environment, the relationship between the local thermal sensation and the overall thermal sensation was statistically analyzed with consideration for an individual’s physiological factors (e.g., gender, BMI). The results from the correlation analysis of the local thermal sensation and overall thermal sensation showed that all the local thermal sensations have a strong correlation level with the overall thermal sensation. The stepwise analysis showed the exact combination order of local thermal sensations (arm, forehead, and chest), which were most correlated with the overall thermal sensation. Based on the correlation analysis, local thermal sensations are highly correlated with the overall thermal sensation (Pearson R > 0.8). By conducting stepwise regression analysis, the first step (arm) can have a high R-sq value of 84.3%. When the baseline attributes are gender, BMI, and the environment’s temperature, the local thermal sensation in one spot that has the highest accuracy (Correctly Classified Instances) comes from the consideration of baseline attributes and forehead (98.58%). When the baseline attributes are gender and BMI, the sensation of arm has the maximum accuracy (75.77%).

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ABSTRACT: Open-plan offices seem to be more common these days in comparison with enclosed private configurations. This layout is commonly assumed to ease communication, teamwork and interaction between coworkers and increase workspace satisfaction while enabling airflow and passive design strategies. However, there has been little attempt at quantifying pros and cons in terms of occupant satisfaction in open-plan office layouts. The research seeks to identify overall satisfaction/dissatisfaction of occupants in different office layouts, and to determine the differences between occupants' reported office layout and other reported factors. These factors include gender, age, view, working hours, visual comfort, and thermal comfort. The survey study was sent to occupants in office buildings (n=1,026) that are located in mixed-humid climates. The results show that the highest satisfaction ratings were reported by occupants in enclosed offices and open-offices with low partitions. The results also show that the open-office spaces with high partitions had lower satisfaction appraisals in comparison with lower partitions across 7 IEQ factors except 'view'. In addition, between open-plan offices, satisfaction with 'quality of light' and 'thermal condition' slightly increased as the height of partitions decreased. These findings enhance our understanding of occupant satisfaction by indicating that increasing partition height contributes to higher dissatisfaction among office workers.

KEYWORDS: Overall satisfaction, Office layout, Mixed-humid climate, Open-plan office, Survey study

INTRODUCTION
Oldham (Oldham, Cummings, and Zhou 1995) defined the office layout as “how the arrangement and boundaries of workspaces are laid out”. In the 1950's, a team from Hamburg, Germany formulated the idea of the open office for the purpose of better communication. In recent years, we have faced a transition in the form of office layouts from cellular or private offices to different types of open-plan offices. In 2011, Matthew Davis (Davis, Leach, and Clegg 2011) reviewed over one-hundred studies about office spaces. He compared open offices with standard offices and concluded that disadvantages (decreased productivity, damaged creative thinking, and declined satisfaction) of open offices undermined the benefits (increased communication between coworkers). Open offices may be better depending on certain ages and specific work types. A considerable amount of literature has grown around the theme of understanding how the physical environment in office buildings affects occupant satisfaction. Previous research has established that the negative impacts of an open-plan office on occupants perception can decrease satisfaction (Brennan, Chugh, and Kline 2002, Sundstrom, Herbert, and Brown 1982) and increased distraction (Kaarlela-Tuomaala et al. 2009). Another study by (Kim and de Dear 2013) compared enclosed private offices and open–plan offices in terms of various IEQ factors. The results showed that enclosed offices had better performance than open-plan offices in most of IEQ factors. A study by (Liang et al. 2014) examined the difference between conventional offices and green offices. He found a significant difference between the mean satisfaction score of green and conventional offices. Another study (Danielsson and Bodin 2008) identified the impact of different office types on worker job satisfaction by considering age, gender, and job rank. The results showed that the workers in shared room offices and cellular offices had the highest job satisfaction. Recently, study by (Choi, Aziz, and Loftness 2010, Schiavon et al. 2016) investigated the impact of occupant gender and age on thermal satisfaction in office layouts and the study revealed that females are more dissatisfied with thermal condition than males. The goal of this study is to assess the parameters that impact the overall satisfaction of different office layouts. First, this paper identifies the overall occupant satisfaction/dissatisfaction of different office layouts. This study also explores the importance of various IEQ factors in relation to the occupants' overall satisfaction. The following research questions are addressed in this paper:

1. Do different office layouts affect an occupant’s overall satisfaction in terms of various IEQ factors?
2. Is the importance of various IEQ factors different among occupants in office layouts?

1.0 METHOD
1.1. Occupant survey
The questionnaire used for this study was sent by email to building occupants to assess the occupants’ satisfaction ratings for various IEQ aspects. These aspects include thermal comfort, visual comfort, overall workspace satisfaction,
and the office layouts. Occupants in three office buildings completed a set of anonymous questionnaires. To measure the building occupants' satisfaction level five-point scale ranged from very dissatisfied/strongly disagrees (scale 1) to very satisfied/strongly agrees (scale 5) was used. Table 1 summarizes the questionnaire items used in the analysis for this study. The survey typically takes five minutes for a participant to complete. Background information about occupants such as the participants' demographics, the type of work they are engaged in, the time spent at the workspace, the workspace layout, and the type of work they are doing is collected at the beginning of the survey. Depending on the availability, floor plans of the surveyed building were collected in order to better understand the building's spatial characteristics and space allocations.

**Table 1: List of questionnaire items employed for the analysis**

<table>
<thead>
<tr>
<th>Category</th>
<th>IEQ items</th>
<th>Survey questions</th>
<th>Rating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal comfort</td>
<td>Thermal satisfaction</td>
<td>I am satisfied with the thermal conditions in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td>Visual comfort</td>
<td>Quality of light</td>
<td>I am satisfied with the QUALITY of light in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Access to daylight</td>
<td>I am satisfied with ACCESS to natural daylight in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>View</td>
<td>I am satisfied with the VIEW from my office.</td>
<td>1–5</td>
</tr>
<tr>
<td>Ability to Control</td>
<td>Temperature</td>
<td>I am satisfied with the ABILITY to alter the temperature in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Electric lighting</td>
<td>I am satisfied with the ABILITY to alter the electric lighting to meet my needs.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Blinds and daylight</td>
<td>I am satisfied with the ABILITY to alter the blinds and daylight source to meet my needs.</td>
<td>1–5</td>
</tr>
<tr>
<td>Source of dissatisfaction</td>
<td>Temperature</td>
<td>In general, how satisfied are you with the temperature in the workspace where you spend the most time?</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Too cool</td>
<td>Generally, I am TOO COOL in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Too warm</td>
<td>Generally, I am TOO WARM in my office workspace.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Lighting condition</td>
<td>In general, how satisfied are you with the overall lighting conditions in the workspace where you spend the most time?</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Too bright in the morning</td>
<td>I find my workspace too bright in the morning.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Too bright in the afternoon</td>
<td>I find my workspace too bright in the afternoon.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Too dark in the evening</td>
<td>I find my workspace too dark in the evening.</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Glare</td>
<td>My computer screen has a glare on it</td>
<td>1–5</td>
</tr>
<tr>
<td></td>
<td>Unnecessary lighting</td>
<td>I feel as though there is unnecessary lighting in my workspace.</td>
<td>1–5</td>
</tr>
</tbody>
</table>

This study was performed in August in three office buildings located in North Carolina and Virginia. All of the buildings in the current dataset were serviced by centralized HVAC systems and in some levels equipped with Under-floor Air Distribution System (UFAD). From 5031 questionnaires, a total of 1026 individual responses were obtained with the average response rate (i.e. number of completed questionnaires divided by number of email invitations sent) of 20%. Survey respondents' personal characteristics such as age (20 or below, 21-30, 31-40, 41-50, and 51 or above), gender (male and female), and work characteristics (type of work, time spent at workspace) are described in Table 2. The
The majority of the participants were in open-plan office layouts (87.4%) compared with enclosed office. 31% of participants have age range between 41 and 50 years, 54.4% engaged in a typing or reading role (40.7%), and 51.8% worked in the same workspace between 1 and 5 years. The office layouts were classified into four categories: (1) Enclosed private office (private and shared with other people) (2) Open office (cubicles with high partitions), (3) Open office (cubicles with low partitions), and (4) Open office with no partitions. The workspace characteristics (office layouts) and the number of survey samples within each office layout category are listed in Table 3. Among the different configurations of open-plan offices, low-partitioned cubicle is the single most popular office configuration (54.3% of the total occupants). A small fraction of the survey respondents occupied private offices and shared single-room offices (11.5%).

**Table 2:** Characteristics of the respondent samples (total n=1026).

<table>
<thead>
<tr>
<th>Personal characteristics</th>
<th>Description</th>
<th>Sample size (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Female</td>
<td>511</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>511</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>Age</td>
<td>20 or below</td>
<td>6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>21-30</td>
<td>145</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td>31-40</td>
<td>284</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td>41-50</td>
<td>318</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>51 or above</td>
<td>252</td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td>I prefer not to answer</td>
<td>21</td>
<td>2.0</td>
</tr>
<tr>
<td>Work category (type of work group)</td>
<td>Reading, seated</td>
<td>418</td>
<td>40.7</td>
</tr>
<tr>
<td></td>
<td>Writing</td>
<td>23</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Typing</td>
<td>558</td>
<td>54.4</td>
</tr>
<tr>
<td></td>
<td>Filling, seated</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Filling, standing</td>
<td>6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>17</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Lifting/packing</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Time of working in workspace occupied</td>
<td>Less than 1 year</td>
<td>432</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td>1-5 years</td>
<td>531</td>
<td>51.8</td>
</tr>
<tr>
<td></td>
<td>5+ years</td>
<td>63</td>
<td>6.1</td>
</tr>
</tbody>
</table>

**Table 3:** Number of survey responses in different office layouts

<table>
<thead>
<tr>
<th>Office layout</th>
<th>Number</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosed Office: private and shared with other people</td>
<td>118</td>
<td>11.5</td>
</tr>
<tr>
<td>Open Office: cubicles with high partitions (5 feet or higher)</td>
<td>181</td>
<td>17.6</td>
</tr>
<tr>
<td>Open Office: cubicles with low partitions (lower than 5 feet)</td>
<td>557</td>
<td>54.3</td>
</tr>
<tr>
<td>Open Office: workspace in open office with no partitions</td>
<td>159</td>
<td>15.5</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td>1026</td>
<td>100</td>
</tr>
</tbody>
</table>
1.2. Data analysis
Regarding the data, analysis measures have been taken. First, the mean satisfaction level of each IEQ factor (Table 2), except category of source of dissatisfaction, in four different office layouts was investigated. Also, the percentage of dissatisfied occupants who voted 1 and 2 on the five-point scale was estimated. This average shows the number of potential complaints in comfort studies. Second, separating those who were significantly dissatisfied assessed the importance level of dissatisfaction for each subcategory on lighting condition and thermal condition, which is done by analyzing IEQ factors under category “source of dissatisfaction”. For this purpose, the number of occupants falling into score 1 and 2 were counted. The influence of each subcategory was examined in all office layouts in order to find out the most influential factor on lighting and thermal dissatisfaction. Third, multiple regression analysis was used to predict the level of effectiveness of various IEQ factors in relation to the occupants’ overall assessment on their workspace. For this purpose, 7 IEQ factors under thermal comfort, visual comfort, and the ability to control in Table 1 were considered as independent variables and the overall satisfaction was considered as the dependent variable. Therefore, the relative importance of the 7 IEQ factors can be estimated by regression coefficients to determine overall satisfaction in different office layouts.

2.0 RESULTS
2.1. Occupant satisfaction with different aspects of IEQ
Figure 1 compares the average score of occupants’ overall satisfaction of the IEQ questionnaire items based on the five-point scale from very dissatisfied (1) to very satisfied (5) in four different office layouts. Closer inspection of the graph shows almost all IEQ factors in visual and thermal comfort categories achieved the satisfaction rated higher than neutral level by occupants in different office layouts. In contrast, occupants in all office layouts were dissatisfied with all IEQ factors in ability to control. Among 7 IEQ factors in Table 1, satisfaction with ‘quality of light’ received the highest overall workspace score in all four different office layouts. On the other hand, ability to alter the temperature received the lowest satisfaction score from occupants in all different office layouts. In terms of visual comfort, open-offices with low partitions outscored the other office layouts across ‘view’ and ‘natural light’. Also It is registered as the second highest satisfaction score for ‘quality of light’. Open-offices with high partitions received the lowest overall satisfaction score in almost all IEQ factors, except ‘view’. Interestingly, the noticeable differences between open-plan offices with low partitions and open-plan offices with high partitions appeared in ‘access to natural light’ and ‘view’. Between open-plan offices, satisfaction with ‘quality of light’ and ‘thermal condition’ increased as the height of partitions decreased. Satisfaction with all IEQ factors in the category of ability to control was almost similar in for open-plan offices. In general, open-plan offices with high partitions reported the lowest occupant satisfaction across 6 out of 7 of the IEQ factors. In all four layouts, occupants expressed slight satisfaction with ‘quality of light’, while ‘thermal condition’ and ‘ability to alter the blinds and daylight’ were more neutral.

Survey respondents who fell into the lowest two points (1 and 2) on the five-point satisfaction scale counted as the percentage of dissatisfied. The percentage of dissatisfied with each IEQ factor was shown in Fig. 2. In general, the most interesting aspect of this graph was the low dissatisfaction rates of most IEQ factors in all four different office layouts. Enclosed offices showed lower dissatisfaction rates than open-plan offices (except for ‘visual comfort’) while
no significant differences were found between different office layouts. Open-plan offices with low partitions were reported at almost the lowest level of dissatisfaction among three open-plan configurations across all IEQ factors except for ‘quality of light’ and ‘thermal condition’. In addition, occupants in open-plan offices with low partition were more satisfied across all IEQ factors compare to open-offices with high partition. On the other hand, the highest levels of IEQ dissatisfaction were recorded in ‘ability to alter temperature’ which is considerably higher than other IEQ factors. More than half of the occupants in enclosed offices and about 60% of occupants in open-offices with no partitions reported dissatisfaction with this factor. The percentage of dissatisfaction for occupants of open-plans with high partitions was relatively higher than other open-office layouts in IEQ factors under categories of visual and thermal comfort.

Fig 3a and 3b compared the relative importance of different factors and their influence on thermal and lighting dissatisfaction in four office layouts. A number of factors reported by occupants were identified to address the most influential factor on lighting and thermal dissatisfaction. Further analysis showed that no significant differences were found between different IEQ factors in terms of lighting dissatisfaction. The major source of lighting dissatisfaction in open-offices with low partitions were ‘unnecessary lighting in workspace’, followed by ‘workspace too bright in the morning’. In terms of thermal dissatisfaction, occupants in all types of office layouts tend to be more dissatisfied with ‘too cool workspace’ rather than ‘too warm’. Dissatisfaction with ‘too cool workspace’ was almost doubled compared to ‘too warm workspace’ in all office layouts.

Figure 2: Percentage of Dissatisfied for IEQ questionnaire items by office layout configurations

![Graph showing percentage of dissatisfied for IEQ questionnaire items by office layout configurations](image)

Figure 3: Source of dissatisfaction of a) lighting and b) temperature in different office layouts

**2.2. Relative importance of different IEQ factors**

Multiple regression analysis was examined separately on survey responses from the layouts to determine how the relative importance of different IEQ factors changes under the different spatial configurations. The four regression models explain the variance in outcome variables for both genders between 38% and 47%. As Table 4 illustrates, the regression coefficient is used to examine the importance of individual IEQ factors and the influence they have on the
occupants’ satisfaction. Although insignificant regression coefficients are presented in the charts and the table, they are excluded from the analysis. Based on Table 4, a radar chart was created to visualize the various IEQ priorities of the four office layouts in Fig. 4 (included both significant and insignificant regression coefficients). For both gender, ‘quality of light’ (b = 0.21 for enclosed offices), ‘view’ (b = 0.25 for open-office high partitions and b = 0.25 for open-office with no partitions), and ‘thermal satisfaction’ (b = 0.24 for open-office with low partitions) have the strongest relationship with occupants’ overall satisfaction (Fig. 4). However, the relative importance of ‘view’, ‘thermal condition’ and ‘quality of light’ varied between the different office layouts. While view ranked as the most important factor for occupants in open-offices with high partitions (b = 0.25), it appeared as the least important factor in enclosed offices (b = 0.15). Thermal condition had a relatively higher impact on open-offices with low partitions (b = 0.24) and open-offices with no partitions (b = 0.21) on occupants’ overall satisfaction. That indicated that its relative importance to the overall office satisfaction decreased as the height of partitions in open-offices reduced. Similarly, thermal condition was more important for those in open-plan offices with low partitions than occupants in other office layouts. Quality of light had a bigger impact on occupants’ overall satisfaction in open-plan offices with low partitions than open-plan offices with no partitions.

Fig. 5 was created to visually compare the importance of various IEQ factors in different office layouts on overall satisfaction between different ages, genders, types of work, and time spent in the workspace. Although Fig. 5 illustrates both significant and insignificant regression coefficients, only significant ones are analyzed and reported. As shown in Fig. 5a and 5b, there are a number of remarkable differences between IEQ factors and their influence on female and male overall satisfaction. ‘Thermal condition’ factor had the highest influence on female overall satisfaction in enclosed offices (b = 0.32) followed by open-offices with low partitions (b = 0.30). However, this was the least influential factor on male overall satisfaction. View, quality of light, and access to natural light had the highest impact on male overall satisfaction. Moreover, ‘view’ had the biggest impact on male occupant overall satisfaction in open-plan offices with no partitions (b = 0.31). In the other words, thermal comfort was the most significant issue for females’ overall satisfaction; However, visual comfort had the most influence on males’ overall satisfaction.

**Table 4:** Implicit importance (estimated by regression coefficients) of 7 IEQ factors in relation to occupant overall workspace satisfaction for both genders

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Enclosed Office: private or shared with other people (R² = 0.46)</th>
<th>Open Office: cubicles with high partitions (R² = 0.38)</th>
<th>Open Office: cubicles with low partitions (R² = 0.47)</th>
<th>Open Office: workspace in open office with no partitions (R² = 0.45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfy with the thermal conditions</td>
<td>0.16**</td>
<td>0.14**</td>
<td>0.24**</td>
<td>0.21**</td>
</tr>
<tr>
<td>Satisfy with the quality of light</td>
<td>0.21**</td>
<td>0.10</td>
<td>0.22**</td>
<td>0.18**</td>
</tr>
<tr>
<td>Satisfy with access to natural daylight</td>
<td>0.07</td>
<td>0.06</td>
<td>0.14**</td>
<td>0.10</td>
</tr>
<tr>
<td>Satisfy with the view</td>
<td>0.15*</td>
<td>0.25**</td>
<td>0.16**</td>
<td>0.25**</td>
</tr>
<tr>
<td>Satisfy with the ability to alter the temperature</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Satisfy with the ability to alter the electric lighting</td>
<td>0.00</td>
<td>0.10</td>
<td>0.01</td>
<td>-0.09</td>
</tr>
<tr>
<td>Satisfy with the ability to alter the blinds and daylight</td>
<td>0.16*</td>
<td>0.11</td>
<td>0.08*</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Note: Dependent variable: Overall satisfaction with workspace. Significance level: **P < 0.01, *P < 0.05.
Fig. 4: Relative importance of IEQ factors estimated by regression coefficients in four different office layouts for both genders

Fig. 5c, 5d, 5e, and 5f show the relative importance of 7 IEQ factors in relation to the occupants' overall satisfaction between four different age groups and their workspace. The relative importance of all IEQ factors varied between the different age groups in four office layouts. In general, among all IEQ factors, ‘view’, ‘quality of light’, and ‘access to natural light’ showed the strongest relationship with occupants’ overall satisfaction within various age groups. In open-offices with no partitions, ‘thermal condition’ (age 21-30) ‘view’ (age 31-40 and 51 or above) had the highest influence on occupants’ overall satisfaction. Interestingly, in open-plan offices with high partitions, ‘view’ was the most influential factors on overall satisfaction of occupants between the age of 21 and 50. The factor of ‘thermal condition’ was strongly related to overall satisfaction of occupants between the age of 31 and 50 in open-plan offices with low partitions compared to the other office layouts. As mentioned in section 2, the majority of occupants engaged in reading and typing in various office layouts. Further analysis between the two types of the work in all four office layouts indicated that although ‘thermal condition’ had the highest impact on occupants’ overall satisfaction for typing, ‘quality of light’ was the most influential factor for reading (Fig. 5g and 5h).
Figure 5: Relative importance of IEQ factors estimated by regression coefficients in four different office layouts for a) male, b) female, c) age (21-30), d) age (31-40), e) age (41-50), f) age 51 or above, g) type of work (reading, seated), h) type of work (typing).

DISCUSSION AND CONCLUSION

Overall, this study identified that occupants’ responses on different IEQ factors varied among office layouts (enclosed private and shared, open office with high partitions, open office with low partitions, and open office with no partitions). According to Fig. 1 and Fig. 2, occupants in open-office with low partitions were remarkably more satisfied with visual comfort (except ‘quality of light’) than occupants in the other three office layouts. In contrast, open-offices with high partitions received the lowest mean satisfaction score and highest percentage of dissatisfaction in almost all visual comfort factors except ‘view’. This is because of the lower partitions are, there is more access to light. In the other words, it seems that the height of partition can contribute to better visual satisfaction. Between open-plan offices, satisfaction with ‘quality of light’ and ‘thermal condition’ slightly increased as the height of partitions decreased. Even though the mean score for all IEQ factors under the categories of visual comfort and thermal comfort were slightly above the neutral line on the satisfaction scale, all IEQ factors in the category of ability to control were mostly rated as dissatisfied. Further analysis showed that feeling too cool in the workspace was the main cause of occupants’ thermal dissatisfaction. The level of importance of different IEQ factors inferred by multiple regression models revealed that the impact of ‘quality of light’, ‘view’, and ‘thermal satisfaction’ had on overall satisfaction were relatively large. One of the
goals for designing open-plan offices is to introduce more light in the workspace so open office occupants tend to have more sufficient light than those in enclosed or private offices. The results indicated that 'view' had a highest impact on occupants' satisfaction in open-plan offices with no and high partitions and open-offices with high partitions compare to other offices. This similarity between open offices with no and high partitions in terms of 'view' was because open-offices with high partitions are located near the windows. For this reason, open-offices with high partitions had a better access to views than other types of open-plan offices. This study has identified that the relative importance of thermal condition to overall office satisfaction increased as the height of partitions in open-offices decreased. Relative importance of occupants' overall satisfaction differs not only by gender but also in how long they are working in the building. We found notable differences between the magnitude and the type of individual IEQ factors influence on female and male overall satisfaction. Thus, thermal comfort tends to have greater influence on female overall satisfaction than male. The relative importance of visual comfort on male overall satisfaction was higher than females. These results are in line with previous studies (Choi, Aziz, and Loftness 2010). For example, in open-offices with low partitions ‘thermal condition' had the highest influence on female overall satisfaction (b = 0.30) but it was the least influential factor on male overall satisfaction (b = 0.10) as access to natural daylight had the highest impact on males. It supports the literature that females are more sensitive to thermal conditions than males. In terms of work category ‘thermal condition' had a higher influence on occupant satisfaction for those who mostly typed, but 'quality of light' was the most influential factor for those who mostly read. Interestingly, ‘access to natural daylight' and 'view', which were the most influential factors between genders and age group, had the lowest impact on the work category. This study provides valuable information on the effect of different office layouts on overall occupant satisfaction in terms of various IEQ factors. The findings of this study could enhance our understanding of the importance that various IEQ factors have among occupants in office layouts.

ACKNOWLEDGEMENTS

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REFERENCES


ABSTRACT: This paper explores thermal and energy performance of double skin facades (DSFs) in different climate types, specifically focusing on three typologies: box window, corridor type and multistory DSFs. These systems were investigated and analyzed to answer the question of how the different DSFs perform in comparison to each other, as well as a typical curtain wall (single skin facade used as a baseline), in a multitude of climate applications. The utilized research methods included two-dimensional heat transfer analysis (finite element analysis) and energy modeling. Heat transfer analysis was used to determine heat transfer coefficients (U-values) of all analyzed facade types. Results indicate that there is little variation in thermal performance of the different DSF types, but that all DSF facades would have significantly improved thermal performance compared to the baseline single skin facade. Energy modeling was conducted for an office space, which would be enclosed by the analyzed facade types. Individual energy models were developed for each facade type and for 15 different climates, representing various climate zones and subzones. The results were analyzed to compare energy performance of DSFs and baseline single skin facade, as well performance of DSFs in various climate types. The results indicate significant differences between the DSFs and single skin facade, but less variations between the different typologies of investigated DSFs. Moreover, the results show what would be the effect of DSFs in different climate types on energy performance, heating, cooling and lighting loads.

KEYWORDS: Double skin facade, energy efficiency, energy consumption, energy use intensity, climate types

INTRODUCTION
Double skin facades (DSFs) are an emerging type of building facades, aimed to improve thermal performance of glazed envelopes. Different from conventional single glazed facades' configuration, DSFs consist of three distinct layers – interior glazed wall system, ventilated air cavity, and exterior glazed wall system. The ventilated air cavity serves as a thermal buffer between interior and exterior glazed wall. Basic DSF types are box window facades, corridor facades, shaft box facades, and multistory facades (Aksamija, 2013). The physical behavior of the DSFs depend on the typology, as well as ventilation mode of the air cavity and material components. Ventilation mode can include natural ventilation, mechanical and mixed mode.

There is significant research available relating to the thermal and energy performance of DSFs in temperate and colder climates, while less research is available for warmer climates. A previous literature review was conducted, which systematically reviewed and compared 55 research articles focusing on energy performance analysis of DSFs in temperate climates (Pomponi et al., 2016). The study analyzed the energy consumption of multiple DSF types, in a variety of temperature climate types. Energy savings for heating and cooling were compared across different DSF types, but the study could not verify the impact of DSF types on energy consumption for lighting. Additionally, studies that systematically investigate thermal and energy performance of DSFs facades in all types of climates currently do not exist. Studies that also investigate different typologies of DSFs and their energy performance are currently not available. Therefore, this section reviews available literature and results of previous studies, which typically focus only on one climate type.

For example, Gratia and Herde looked extensively at DSFs in a temperate climate, analyzing behavior for various sun orientations, and how applying the DSF affected heating and cooling loads (2007). Energy performance and analysis, specifically for heating, cooling and ventilation energy usage, was also included in a study comparing DSF to other facade alternatives for a specific building application in central Europe (Gelesz and Reith, 2015). The authors simulated box window DSF and its single glazed alternative, and the results indicate that DSF can reduce energy consumption by 7% on average. In addition, closed cavities have overheating problem even on the coldest days in south orientation (Gelesz and Reith, 2015). For hot climate areas, summer ventilation for DSF leads to increased cooling loads (Eicker et al., 2007). Zhou and Chen looked at applying ventilated DSF in hot and cold climate zones in China (2010). Wong et al. studied the performance of DSF in Singapore by using energy and CFD simulations (2005). Through CFD simulation and comparative analysis, horizontal and vertical ventilation schemes were evaluated for double skin facade in Mediterranean climate (Guardo et al., 2011). Brandl et al. studied the airflow characteristics and temperature profile of multifunctional facade elements through comprehensive analysis and comparison by using CFD models, and the results...
identified that the ventilation effects of side openings can help decrease cavity temperature (2014).

Since there is lack of research that systematically compares energy performance of different types of DSFs in all climate types, this research study focused on addressing this gap in knowledge.

1.0 RESEARCH OBJECTIVES AND METHODS
The objective of this research was to investigate energy performance of different types of DSFs (in relation to single skin glazed facade, and based on differences between individual DSF typologies), in all climate types. Research questions that were addressed include:

• What is the effect of different types of DSFs on energy consumption for commercial office spaces in all climate types?
• How do openings affect the energy performance of DSFs?
• How do DSFs influence the heating and cooling loads in different types of climates? What are the energy saving potentials for different DSFs?
• How is energy consumption for lighting impacted by different types of DSFs?

Figure 1 shows the basic properties of these different types of facade systems. Box window DSF consists of horizontal divisions between different levels, as well as vertical divisions and an air cavity between the two glazed surfaces. Corridor type DSF has horizontal divisions between different levels, but air can freely move within the air cavity within each individual level. Multistory DSF does not have any horizontal or vertical divisions, and air can move freely between different levels within the air cavity. In all DSF scenarios, a curtain wall with double insulated glazing unit was placed on the interior side of the facade, while a single lite of glass was placed on the exterior side. Each of the DSF models was tested in three variations: without openings and with openings (holes and with vents). Scenarios without openings were used to simulate “air curtain” air flow type, which would trap air within the air cavity and create thermal buffer between the exterior and interior environment. Vents and holes were used to simulate scenarios where the air cavity would be open to exterior environment, to allow natural ventilation of the cavity. Vents were modeled as continuous horizontal openings on the exterior, with metal grilles that would be able to open and close, depending on the season. Scenarios with holes were modeled as continuous horizontal openings, but without grilles (these would remain open throughout the entire year). Since the components of these different DSF types are different, it was expected that their physical behavior (effects on energy consumption) would be different.

All DSF facade systems used 1 in double low-e IGU with argon gas fill on the interior side of the facade, and 0.5 in single tempered glazing on the exterior side. Single skin facade consisted of 1 in double air low-e IGU. The framing members for the typical curtain wall and the interior layer of the DSF included aluminum mullions. The outer layer of the DSFs did not include aluminum framing members—the assumption was that structural silicone would be used for glazing, and that the structural support for the exterior skin would be provided by point-supports and cables. For the box window DSF, the assumption was that the horizontal and vertical division panels between floors and individual windows would be constructed out of aluminum. For the corridor type DSF, the assumption was that the horizontal division panels between floors would also be constructed out of aluminum.

2.0 HEAT TRANSFER ANALYSIS
The heat transfer analysis utilized a 2D finite element analysis method, using THERM and WINDOW modeling software programs. THERM was developed by Lawrence Berkeley National Laboratory (LBNL), and it is widely used for thermal analysis of facade systems. WINDOW was also developed by LBNL, and it is interoperable with THERM. It can be used to calculate optical and thermal properties of glazing systems. THERM calculates conductive heat transfer, considering interior and exterior environmental conditions, and the conductive properties of air and materials in the facade.

Figure 1: Diagram showing investigated facade types, basic components and airflow patterns.
assembly.

The different analyzed facades (single skin, as well as different types of DSF) were initially drafted as 2D sections in CAD, and then imported as an underlay in THERM to develop thermal analysis models. THERM relies on detailed 2D representations of all components and materials, placement of appropriate materials and definitions of material properties, as well development of boundary conditions that represent exterior and interior environmental conditions. Simulation inputs for environmental conditions were determined based on the NFRC 100-2004 Standard, with exterior temperature of -18°C (0°F) and interior temperature of 21°C (70°F). The results were evaluated to determine relative thermal performance of investigated facade types and compare the calculated U-values.

### 3.0 ENERGY MODELING

Energy modeling was performed in Design Builder, and geometry models were created in Revit. The geometry models were imported into Design Builder, where inputs for energy modeling were defined and simulations were performed. The methodology for energy modeling consisted of building individual models for each type of investigated facade, which would enclose a commercial south-oriented office space. Each type of DSF had three variations (without openings, openings-holes, and openings-vents), which resulted in ten models being simulated for 15 different climate types (totaling 150 energy models), representing all climate zones in the U.S. Table 1 shows representative cities that were chosen for energy modeling.

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>City</th>
<th>State</th>
<th>Zone</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Miami</td>
<td>Florida</td>
<td>Very hot</td>
<td>Moist</td>
</tr>
<tr>
<td>2</td>
<td>Houston</td>
<td>Texas</td>
<td>Hot</td>
<td>Moist</td>
</tr>
<tr>
<td>3</td>
<td>Phoenix</td>
<td>Arizona</td>
<td>Hot</td>
<td>Dry</td>
</tr>
<tr>
<td>4</td>
<td>Memphis</td>
<td>Tennessee</td>
<td>Warm</td>
<td>Moist</td>
</tr>
<tr>
<td>5</td>
<td>El Paso</td>
<td>Texas</td>
<td>Warm</td>
<td>Dry</td>
</tr>
<tr>
<td>6</td>
<td>San Francisco</td>
<td>California</td>
<td>Warm</td>
<td>Marine</td>
</tr>
<tr>
<td>7</td>
<td>Baltimore</td>
<td>Maryland</td>
<td>Mixed</td>
<td>Moist</td>
</tr>
<tr>
<td>8</td>
<td>Albuquerque</td>
<td>New Mexico</td>
<td>Mixed</td>
<td>Dry</td>
</tr>
<tr>
<td>9</td>
<td>Salem</td>
<td>Oregon</td>
<td>Mixed</td>
<td>Marine</td>
</tr>
<tr>
<td>10</td>
<td>Chicago</td>
<td>Illinois</td>
<td>Cool</td>
<td>Moist</td>
</tr>
<tr>
<td>11</td>
<td>Boise</td>
<td>Idaho</td>
<td>Cool</td>
<td>Dry</td>
</tr>
<tr>
<td>12</td>
<td>Burlington</td>
<td>Vermont</td>
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<td>Moist</td>
</tr>
<tr>
<td>13</td>
<td>Helena</td>
<td>Montana</td>
<td>Cold</td>
<td>Dry</td>
</tr>
<tr>
<td>14</td>
<td>Duluth</td>
<td>Minnesota</td>
<td>Very cold</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Fairbanks</td>
<td>Alaska</td>
<td>Subarctic</td>
<td>-</td>
</tr>
</tbody>
</table>

In all of the simulated models, four floors were modeled so that the multistory DSF could be accurately simulated. Each floor was 40 ft deep, 40 ft wide, and the floor-to-floor height was 10 ft. All of the DSF types had an air cavity of 2 ft.

The inputs for occupancy loads, system loads, equipment loads, lighting and ventilation were based on ASHRAE 90.1 energy code and recommendations prescribed by ASHRAE 189 standard (ASHRAE, 2014; ASHRAE 2013). Operating schedule was based on a typical office space operation (weekday schedule from 8 AM to 6 PM). The HVAC system consisted of a packaged heating/cooling pump with DX coils, and natural gas used for heating. The results were calculated for all models, where total annual energy consumption was determined for each individual scenario, as well as the heating, cooling and lighting loads. Also, Energy Usage Intensity (EUI) was determined for all scenarios. The following section discusses the results in detail.

### 4.0 HEAT TRANSFER ANALYSIS RESULTS

U-values were calculated for conventional curtain wall, as well as three investigated DSF types, and Figure 2 shows thermal gradients within DSF assemblies. Table 2 shows the results, indicating the relative thermal performance of each investigated facade type. All DSF types have much lower U-value than a standard curtain wall, indicating that these facade types would have improved thermal performance. The differences between different DSF typologies are relatively small; however, multi-story DSF would have the smallest U-value, followed by box window and corridor type DSF. Nevertheless, the significant difference between U-values of DSF types and conventional curtain wall suggests that all types of DSFs would provide savings in heating and cooling loads due to improved thermal performance.
5.0 ENERGY MODELING RESULTS

Energy consumption for heating, cooling and interior lighting were calculated, as well as the EUI, for all investigated facades and design scenarios. Figure 3 shows the EUI for all facade types (without openings) in all climate types. Table 3 shows the amount of energy savings as a percent, for each type of DSF, across all climate types. Almost all DSF types performed better than the base case, a single skin conventional curtain wall. The DSF types without openings resulted in similar savings within the same climate zone. In all climate types, the box window DSF performed better than the other DSF types. Box window with vents performed better in warmer climates, while the box window with vents performed well across all climates. Hotter, drier climates saw the greatest energy savings (2B Phoenix: 30%), while humid climates saw lower savings compared to dry or marine climates in the same zone (2A Houston: 19%). Box window saw the greatest variation in savings within the subtypes (without openings, holes and vents), while multistory saw the least variation in savings.

Table 3 shows the energy savings for lighting for all DSF types and climate types. Lighting usage has increased across all facade and climate types. Locations in lower latitudes saw the worst performance, due to higher sun angles. Locations in higher latitude saw better performance due to lower sun angles. The corridor DSF type with vents was found to be the worst performer in all but two climate zones. The corridor DSF type with holes was found to be the best performer in four of the warmer climate zones, while the box window with holes was the best performer in 11 out of 15 climate zones. For all three DSF types, holes generally performed the best while vents performed the worst.

With the exception of climate zone 3C, warmer climates saw less energy savings in cooling than colder climates, as shown in Table 5. Humid climates also saw less energy savings compared to dry or marine climates in the same zone. In all but one zone (4A), the box window with vents was the best performer, while the multistory with holes was the worst performer across all climate types. Climate zone 3C saw similar savings to zone 8.

Warmer climate zones saw greater energy savings in heating, while colder zones saw the least savings (with the exception of zone 5A), as shown in Table 6. Zones 1A saw the greatest variation in savings (89% to -73%), while zone 8 saw the lowest variation (31% to 38%). The best performing DSF types were corridor with holes, and box window with holes. The worst performing DSF types were corridor with vents, and box window with vents.
Figure 3: Results of energy modeling, showing EUI for all climates and investigated facade types (DSF without openings).
Table 3: Amount of energy savings in EUI as a percentage for investigated DSFs, compared to single skin facade type.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Corridor</th>
<th>Box Window</th>
<th>Multistory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wo/ openings</td>
<td>holes</td>
<td>vents</td>
</tr>
<tr>
<td>1A (Miami)</td>
<td>14%</td>
<td>13%</td>
<td>15%</td>
</tr>
<tr>
<td>2A (Houston)</td>
<td>14%</td>
<td>14%</td>
<td>15%</td>
</tr>
<tr>
<td>2B (Phoenix)</td>
<td>25%</td>
<td>23%</td>
<td>27%</td>
</tr>
<tr>
<td>3A (Memphis)</td>
<td>17%</td>
<td>16%</td>
<td>17%</td>
</tr>
<tr>
<td>3B (El Paso)</td>
<td>23%</td>
<td>21%</td>
<td>25%</td>
</tr>
<tr>
<td>3C (San Francisco)</td>
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<td>21%</td>
<td>23%</td>
</tr>
<tr>
<td>4A (Baltimore)</td>
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<td>13%</td>
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<td>24</td>
</tr>
<tr>
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<tr>
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</tr>
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<tr>
<td>8 (Fairbanks)</td>
<td>21%</td>
<td>22%</td>
<td>20%</td>
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</table>

Table 4: Lighting energy consumption for investigated DSFs, compared to single skin as a percentage.

<table>
<thead>
<tr>
<th>Zone</th>
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<th>Multistory</th>
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<td></td>
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<tr>
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<td>2A (Houston)</td>
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<tr>
<td>8 (Fairbanks)</td>
<td>-27%</td>
<td>-19%</td>
<td>-35%</td>
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Table 5: Cooling energy savings for investigated DSFs, compared to single skin as a percentage.

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<td>vents</td>
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<td>55%</td>
<td>68%</td>
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Table 6: Heating energy savings for investigated DSFs, compared to single skin as a percentage.

<table>
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<td>vents</td>
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<tr>
<td>7 (Duluth)</td>
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<td>28%</td>
</tr>
<tr>
<td>8 (Fairbanks)</td>
<td>31%</td>
<td>33%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Figure 4 compares heating, cooling and lighting loads for all investigated climate types and facades.

Figure 4: Results of energy modeling, showing energy usage for all climates and investigated facades.
CONCLUSION
The purpose of this research was to investigate energy performance of different types of DSFs in all climate types. The research addressed several aspects: 1) energy performance of different types of DSFs (box window, corridor type and multistory); 2) the effects of openings on the energy performance of DSFs; 3) energy performance of DSFs in different climate types; and 4) the effects of DSFs on heating, cooling, and lighting loads. Research methods consisted of heat transfer analysis for calculating U-values and modeling energy consumption for a south-oriented office space in 15 different climate types, which would be enclosed by the investigated facades. The base case considered single skin facade, consisting of a standard curtain wall.

Results of heat transfer analysis show that investigated DSF types have much lower U-value than a standard curtain wall, indicating that these facade types would have improved thermal performance. The differences between different DSF typologies are relatively small; however, multi-story DSF would have the smallest U-value, followed by box window and corridor type DSF.

Results of energy modeling showed that all DSF types would improve energy performance compared to the base case scenario (standard curtain wall). Variations in DSF design had a significant impact on the energy performance of the investigated types. However, the energy savings vary depending on the climate type and DSF type. The box window DSF type with openings (holes and vents) was found to be the best performing across all climate types. Multistory DSF with holes was found to be the worst performing for EUI across all climate types.

All DSF types saw increased energy consumption for lighting, due to the geometry of the facades. As expected, southern climates saw greater energy usage due to high sun angles, while northern climates performed better than southern locations due to lower sun angles. In heating-dominated climates, cooling loads are significantly reduced (40-70%), while cooling-dominated climates have lower savings (25-40%). In cooling-dominated climates, heating loads are significantly reduced (50-90%), while heating-dominated climates have lower savings (30-40%). The results of this research systematically compare performance of different types of DSFs in terms of energy usage across all climates, and provide an insight how these advanced facade types would affect lighting, cooling and heating loads compared to conventional single skin facade.

REFERENCES


ABSTRACT: New building construction is often a source of indoor air pollution due to the large amount of volatile organic compounds that are emitted from newly manufactured building materials as well as field applied coatings, sealants and adhesives. One major concern has been the release of formaldehyde (HCHO). High levels of HCHO exposure has been linked to negative health effects such as irritation of the skin, eyes, nose and throat, neurological effects, increased risk of asthma and possibly the development of cancer. The United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) rating system attempts to encourage through voluntary action sustainable building design and construction practices. LEED recommends a whole building flush-out procedure and indoor air quality assessment to occur for all new construction to help reduce indoor air pollutant concentrations. The LEED version 4 rating system procedure requires that 4267 m³ of outside air to be supplied to the interior for every square meter of floor area. This research explores the effectiveness of the flush-out procedure and the inferred limits to the amount of off-gassing materials that can be included in new construction. The project used a first order emission decay model to iteratively determine the maximum allowable source emitting areas that could be present at the start of the flush-out procedure and still meet recommended concentration limits for formaldehyde from two engineered wood products. Modeling included residential, school and office scenarios to determine a range of allowable source areas (0.25 m² to 1.60 m² per unit of floor area). These results varied with changes in air exchange rates, material emissions characteristics and ceiling heights. In most cases the modeled indoor air concentration of formaldehyde was calculated to be below the recommended limit when using typically expected source areas in each of the three scenarios.

KEYWORDS: indoor air quality, flush-out, formaldehyde, LEED, modeling

1.0 INTRODUCTION
1.1 Flush-out
New building construction is often a source of indoor air pollution due to the large amount of volatile organic compounds that are emitted from newly manufactured building materials as well as field applied coatings, sealants and adhesives. One major concern has been the release of formaldehyde (HCHO). High levels of HCHO exposure has been linked to negative health effects such as irritation of the skin, eyes, nose and throat, neurological effects, increased risk of asthma and possibly the development of cancer (ATSDR 2008). The United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) rating system attempts to encourage through voluntary action sustainable building design and construction practices. LEED recommends a whole building flush-out procedure and indoor air quality assessment to occur for all new construction to help reduce indoor air pollutant concentrations. The LEED version 4 (LEEDv4 2013) rating system procedure requires that 4267 m³ of outside air to be supplied to the interior for every square meter of floor area.

1.2 Recommended Limits
To evaluate the effectiveness of flush-out procedures for indoor air quality LEEDv4 sets a maximum indoor air concentration of 27 ppb (33 µg/m³) for formaldehyde at the end of the flush-out period that can be measured using a time-weighted average sample (ASTM D5197-09). The National Institute for Occupational Safety and Health (NIOSH) states a recommended exposure limit (REL) of 20 µg/m³ (NIOSH 1997) and the California Department of Public Health in their 2010 Standard Method for Testing and Evaluation of VOC Emissions (CDPH method v1.1) has a recommended limit of 9 µg/m³. Typical outdoor air concentrations of formaldehyde are cited in the literature to be lower in rural settings and higher in urban settings with concentrations ranging from 1 to 68 ppb (USDHHS 1999). One study provided an average across all outdoor areas as 8.3 ppb (10.2 µg/m³) (Shah and Singh 1988).

1.3 Formaldehyde Sources
Flush-outs are intended to reduce indoor air pollutant concentrations by bringing in fresh air and exhausting pollutant laden building air that can have exceptionally high concentrations in the first few weeks after material installation due to elevated emissions rates that often occur with newly manufactured building materials and furniture (NPI 1999, Xiong et al. 2011). New building construction often utilizes recently manufactured engineered wood products that contain VOCs such as formaldehyde that are used in the manufacturing process to bond smaller wood pieces into
larger wood products (Salthammer et al. 2010) such as particleboard (PB) and medium density fiberboard (MDF). These wood products often continue to off-gas VOCs for an extended period of time and are a concern regarding long term indoor pollutant concentrations. Some studies researching the time varying aspect of these emission rates have been performed for both short term and long term decay rates. These studies have experimentally documented higher emissions rates of formaldehyde at the beginning of newly manufactured engineered wood products that have had good correlation with first order decay models (Brown 1999). Although second order and double exponential decay models exist they appear to mainly correct long term emission rates well past the time period that would be used for a building flush-out. Other emission rate models for formaldehyde instead of being directly time dependent are dependent on the indoor air pollutant concentration. They utilize the assumption that increased indoor air pollutant concentrations create a back pressure effect that reduced the emission rate (Guo 2002 and Mathews et al., 1987). Since the intent of a flush-out is to reduce the concentration via high air exchange rates the back pressure model may not be well suited since at high air exchange rates, the resultant low pollutant concentrations should reduce back pressure and thereby produce an increase of emission rates over time rather than a decrease. Thus, to take into account higher initial emissions expected in new construction this project implemented a time varying solution using a first order decay emission model.

Typical engineered wood such as PB and MDF can be readily found in new construction products such as doors, cabinetry and furniture that are most often installed at the end of the construction period to reduce the chance for damaging finishes. Although many other wood products are used in the construction process many of these are subsequently covered by other construction materials and the exposed surface area of these wood products are not generally in contact with the majority of the indoor air. Thus, this project examined PB and MDF as the primary element for wood based HCHO emissions in new construction.

2.0 METHDOLOGY
2.1 General Solution

This project studied the time varying solution of formaldehyde concentrations due to emission from PB and MDF installed in new building construction. Using $\lambda$ as the air exchange rate ($h^{-1}$), $EF$ as the emissions factor ($\mu g/m^2 \cdot h$), $A$ as the exposed surface area of the source emitting material ($m^2$), $C_{out}$ as the ambient outdoor formaldehyde concentration ($\mu g/m^3$), $V$ as the volume ($m^3$) and $C$ as the indoor air formaldehyde concentration ($\mu g/m^3$), the equation for the change in formaldehyde concentration with respect to time can be expressed as shown in Eq. 1:

$$\frac{dC}{dt} = \lambda C_{out} + EF \times \frac{A}{V} - \lambda C$$

If sources and losses are grouped as $S(t) = \lambda C_{out} + EF \times \frac{A}{V}$ and $L(t) = \lambda$ then the equation can be more simply written as shown in Eq. 2:

$$\frac{dC}{dt} = S(t) - L(t)C(t)$$

By multiplying Eq. 2 on both sides by an integrating factor, $\mu(t)$ where $\mu(t)L(t) = \mu'(t)$ this can be solved as a first order differential equation with the general solution form shown in Eq. 3:

$$C(t) = \frac{\int \mu(t)S(t)dt + c}{\mu(t)} = \frac{\int e^{\mu(t)}S(t)dt + c}{e^{\mu(t)}}$$

Where $c$ is the constant of integration which can be determined via an initial value problem.
2.2 Decay Rate
Brown stated the first order decay model for the emission factor as shown in Eq. 4:

\[ EF = k_1 M_0 e^{-k_1 t} \]

[4]

Brown provided results from experiments for particle board and MDF to derive the emission factor parameters \( k_1 \) and \( M_0 \). Where \( k_1 \) is the decay rate and \( M_0 \) is the total emittable mass of pollutant per unit area of product surface at \( t=0 \). Taking an average of these parameters from Brown’s three MDF experiments such that \( k_{1,MDF} = 0.00062 \text{ h}^{-1} \) and \( M_{0,MDF} = 650,000 \mu\text{g/m}^2 \) and from the three particle board experiments such that \( k_{1,PB} = 0.0014 \text{ h}^{-1} \) and \( M_{0,PB} = 346,867 \mu\text{g/m}^2 \) the average parameters are used in modeling the emissions of formaldehyde in new building construction. By substituting the first order decay model of \( EF \) into the time varying solution the expanded general solution is determined as shown in Eq. 5:

\[ C(t) = \frac{\int e^{\psi(x)} (k_1 M_0 e^{k_1 t}) dx + C}{e^{\psi(t)}} \]

[5]

2.3 Flush-out Duration
The LEEDv4 indoor air quality assessment criteria requires that 4267.2 m³ of outdoor air be supplied per square meter of gross floor area and uses the CDPH method for testing and evaluating VOC emissions from indoor sources. The duration of the flush-out procedure is directly related to the air exchange rate by:

\[ T_r = \frac{V}{V_f \epsilon k} \]

[6]

Where \( T_r \) is the time duration (in hours) required to meet the volume of air required (\( V_r = 4267.2 \text{ m}^3 \)) at a given air exchange rate and unit volume (\( V_f = \text{the one square meter of floor multiplied by the ceiling height} \)). Dimensions including ceiling heights of reference spaces are provided in the CDPH emission testing method. By using the first order decay model parameters and applying \( V= V_f \) an initial value problem can be formed with the assumption that \( C(0) = C_{out} = 10.2 \mu\text{g/m}^3 \) to determine the constant of integration. Having found the constant of integration all parameters of Eq. 5 are known and by setting \( C(T_r) = C_{\text{max}} = 33 \mu\text{g/m}^3 \) the maximum allowable area of source emitting material can be determined.

2.4 Iterative Solver
Calculation of the allowable areas was accomplished using an iterative numerical solver coded in MATLAB R2013a that started with an initial guess for the source emitting area parameter, solved for the indoor air concentration for time steps starting at \( t=0 \) to \( t=T_r \), and then strategically adjusted the area parameter so that the indoor air concentration at the end of the flush-out procedure would be equal to \( C_{\text{max}} \). Air exchange rates were then incrementally increased starting at 0.5 \( \text{h}^{-1} \) up to 16 \( \text{h}^{-1} \) and the iterative procedure for finding the maximum source area was repeated at each air exchange rate. The range of exchange rates selected was meant to reflect values that could be achieved given a wide range of mechanical ventilation capabilities. Although an air exchange rate of 16 \( \text{h}^{-1} \) is very high and unreasonable for a residential scenario, commercial laboratories are often designed to have the capacity to perform 8 to 12 air changes per hour. Fig. 1 provides a flow chart of the steps used in the MATLAB code.
Figure 1: Four-step flow chart of solver used to find allowable source area.

2.5 Scenarios
The CDPH (2010) emission testing method includes three scenarios for indoor air quality modeling. These are a standard school classroom, a standard private office and a new single family residence. Although multiple parameters exist for each of the scenarios, only the ceiling heights are needed to update Eq. 5 to solve for the maximum allowable area of source emitting material. The school classroom and single family residence scenarios both have ceiling heights of 2.59 m and the private office scenario has a ceiling height of 2.74 m. The scenarios also include standard product quantities such as the area of doors and millwork that are typically expected in these spaces and may be sources of pollutant emissions. By selecting the quantities that are related to MDF and particle board and dividing them by the floor area in each scenario the maximum allowable source areas can be compared to the source areas that are expected.

3.0 RESULTS & DISCUSSION

3.1 Air Exchange and Source Areas
Table 1 shows the maximum allowable source emitting area that can be present at the beginning of the flush-out procedure such that at the end of the flush-out period the concentration will be less than or equal to the maximum permissible limit of 33 µg/m³ for each of varying air exchange rates. It is important to note that for each scenario the results are shown per square meter of floor area. Thus, although the floor area of the CDPH new single-family residence scenario lists a 211 m² floor area and a 547 m³ volume the analysis and results presented attempt to volume normalize the results. It is apparent in Table 1 that higher air exchange rates allow for larger areas of source emitting materials to be present while still meeting the maximum permissible level at the end of the flush-out duration.

Fig. 2a is a line plot of Table 1 values and shows a relatively linear relationship between air exchange rates and allowable source areas when using MDF. Fig. 2b is the same data as Fig. 2a except plotted with the x-axis on a log-scale. Fig. 4 is a line plot of air exchange rates and allowable source areas when using particle board. Because the office scenario has a larger volume of 2.74 m³ per square meter of floor area compared to the school and residential scenarios (V=2.59 m³) the office scenario has higher allowable areas starting when air exchange rates are above 3/h. This difference though is relatively small and would be expected given the minor change in volume. Fig. 3a is a line plot of the indoor air formaldehyde concentrations over time for the first four air exchange rates analyzed. Fig. 3b is the same data as Fig. 3a plotted with the x-axis on a log-scale. The curves of these plots appear to be consistent with expectations given the first order decay model for the emissions factor. As the air exchange rate increases though the curve becomes much more linear. In addition, the maximum concentration and duration of the flush-out procedure are greatly reduced as air exchange rates increase. Fig. 5 is a line plot of the indoor air formaldehyde concentrations over time for the first four air exchange rates analyzed with particle board as the source of emissions.

Table 1: Maximum Allowable MDF Source Emitting Area for each air exchange rate and CDPH model quantities

<table>
<thead>
<tr>
<th>Air Exchange Rate, h⁻¹</th>
<th>Source Area, m²</th>
<th>Residence</th>
<th>School</th>
<th>Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td>0.35</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Modeling the Effectiveness of Flush-Out Procedures...: Chung 513
<table>
<thead>
<tr>
<th></th>
<th>CDPH quantity per</th>
<th>m² of floor</th>
<th>m² doors</th>
<th># desks</th>
<th>m² millwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.4235</td>
<td>0.3027</td>
<td>0.1695</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2a: Maximum MDF area versus air exchange rate.

Fig. 2b: Log-scale version of data from Fig. 2a
3.2 Model Scenario Quantities

Table 1 also includes per m² of floor area estimates of PB or MDF sources that would be present in each scenario. These are derived from the CDPH typical quantities listed in each model scenario. These values which were listed in the CDPH method as whole room or whole house quantities have been divided by the scenario floor areas to try to normalize the data for easier comparison and evaluation.

If a student desk with chair can be assumed to have approximately 0.3 m² of exposed PB or MDF (AIA 2007) then 0.3027 desks x 0.3 m² = 0.091 m² and thus for the office and school scenario the low expectation of PB and MDF in the space means that formaldehyde emissions for PB and MDF are not an issue in meeting the maximum permissible concentration and in fact all air exchange rates allow for higher areas of PB and MDF to be used in those two scenarios. This is not the case for the residential scenario where air exchange rates of less than 4/h will produce maximum permissible areas for PB and MDF that are below the expected areas due to a large number of engineered wood products used in residential doors and cabinetry.

When comparing the allowable areas for PB and indoor air concentrations of formaldehyde as a result of PB emissions the short-term concentrations are much higher than those when modeling MDF. The emissions factor decays more rapidly for PB and thus allowable sources areas were larger for PB (compared to MDF) for low air exchange rates and allowable source areas were smaller for PB for higher air exchange rates where the point of inflection appears to occur at approximately 8 air changes per hour.

CONCLUSION

This project sought to determine the effectiveness of flush-out procedures using the LEEDv4 requirements. Using high air exchange rates of 4 per hour or more appear to generally succeed in bring the air pollutant level below the recommended limit by the end of the flush-out duration. Since this study only focused on particle board and MDF
other sources such as paint, adhesives and sealants could contribute to the overall source emissions of HCHO and alter the allowable source areas. Using a first order decay rate emission model appears to show that low air exchange rates (below 4/h) which are typical for residential construction could significantly reduce the allowable source material areas. This might be of particular concern since it is in the residential scenario that there is a larger expectation of engineered wood products that could emit HCHO that are exposed in the form of millwork, cabinetry and doors when compared with school and office scenarios.

REFERENCES


ABSTRACT: The sustainable paradigm in architecture emphasizes concepts of conservation like limitation and efficiency, yet the ecological processes reveals a world founded upon abundance and functional complexities. Why are materials like urban wood waste treated so differently from those in the forest? This paper investigates the terms and narratives that have come to shape the language of wood used by the architectural profession (architectural wood) and forest scientists (ecological wood) and proposes a synthesis based on the concept that ecological benefits depend on an abundance of materials. The two perspectives about wood arise from distinct but related historical and contextual variables that reveal an opposition to one another. This raises questions about whether a designer can realize deeper ecological solutions while maintaining current constructs of architecture. The research in architectural wood looks to contemporary construction methods as well as the historical evolution from the forest to human product. The investigation shows how architectural thinking favors the structural language of “strength” and “efficiency,” as well as the avoidance of key ecological functions prevalent through terms such as “pests” and “decay.” Materials are favored for their linear and human functions, and once exhausted, are discarded and removed from the architectural process. Ecological wood is defined by forest science research in coarse woody debris. The research in ecological wood revealed concepts of redundancy and terms associated with decomposition, disturbance and legacies. These processes are favored by a multitude of species for their complex latent properties and serve various ecological roles simultaneously. The fundamental differences in language reveals deep barriers that may discourage ecological collaborations. The conclusion proposes to elevate the concept of ecological abundance by responding to architectural design gaps revealed through ecological research. The response aims to construct and prepare a more collaborative design language between designers and scientists.

KEYWORDS: Ecology, Wood, Sustainability, Disturbance, Language

INTRODUCTION

The current discussion about material and ecology is largely about its conservation – to limit use, to offset resources, and to reuse. The importance to conserve and even preserve forest lands overshadows the truth about resource availability – we seem unable to purge it fast enough from our urban places. A Forest Service analysis reveals that about a quarter of the timber residues in the U.S. amounted to waste in the urban setting (about 62.5 million metric tons). As it relates to the architectural field, “construction and demolition” totals about 52% of the urban waste, and if one accounts for all the related wood products such as furniture, cabinets, etc. then it rises to 76% (47.7 million metric tons) (Bratkovich, 2014). About half of this wood is turned into biofuel, mulch and engineered woods, while roughly half is sent to the landfill. In one sense, there is too much wood in the environment.

In response, organizations such as USGBC LEED and the Mass Timber movement promote long-established sustainable views on material conservation and emphasize issues like embodied energy, renewable sourcing and reducing waste. Additionally, there is an ambiguous implication that offsetting human use will provide more resources for other ecological beings and processes. What is evident is that wood in the urban setting is largely limited to human use and there is little clarity about how it could be used otherwise. The existing abundance of wood in urban places seems to suggest an opportunity if designers could open their material up to a world beyond people. If sustainability represents a kind of transformation from a linear method to a “Cradle to Cradle” loop, then perhaps there exists a construct that encompasses the multitude of ways non-humans and their processes might inspire an abundance of new “loops” (Fig 1).
Wood is a unique object to study amongst building materials. Lumber is not a mixture or recipe like concrete or steel, but a borrowed object from a particular and existing place. The arborist and writer, William Logan, recounts how the early foresters/shipbuilders began their process in the woods where “imagination had to find the ship’s actual materials” (Logan, 2005). Wood is found, and its physical properties are discovered, which represent only parts of the object’s possible characteristics. Concrete is invented with a purpose to take on particular forms, cures quickly and embodies great compressive forces. These engineered properties favor the language of specialization and linear application. Compare this to wood, which also allows for the emphasis of structural properties, but due to its organic quality also offers itself as food, energy and shelter for other organisms and ecological benefits. All materials return to the earth, but few so readily to reengage with the ecological system like wood.

The following analysis reveals the evolution and reasons as to why architects and ecologists have developed two directly opposing perspectives about the nature of wood (Fig 2). First, the investigation draws from historical origins and the cultural accretions that have defined wood for the architect. Next a comparative inspection about wood in the forest will similarly focus on use and waste and will draw from forest science research to establish language and values. The two narratives aim to define broad but distinct trajectories, rather than acute or specific one-to-one comparisons. The conclusion will suggest new applications that arise from gaps and opportunities in each narrative.

Figure 2: Trajectories Diagram

1.0 ARCHITECTURAL WOOD

1.2 Value and Design Language of Architectural Wood

A narrative sharing the modern values about architectural wood begins in the North American forests at a time when the western settlers, particularly in the mid-nineteenth century, were first conquering the unknown “wilderness,” while the world was transformed by industrialization. The timber historian Ralph Andrews emphasizes the “lament and hunger” the pioneers experienced, which contrasts the rhetoric from transcendentalist and environmentalist thinkers like Thoreau, Muir, and Leopold that would come later to pine the disappearing wilderness and build the modern sustainable stage (Andrews, 1968).

Andrews describes how there was no need for forest “management” because nature was something to be tamed and even naturalists at that time, “only saw beauty in the forest... (and) at first considered them inexhaustible” (Andrews, 1968). The advent of the circular saw, machined nails, sawmills and platform framing along with an exploding population were all instrumental in highlighting woods use as a building material (Sturges, 1992). Wood’s rapid commodification created greater distances between wild places and the places they were marketed and sold. These three key qualities:
inexhaustibility, technology and commodification remain embodied in the essence of today’s architectural wood. Technology and commodification seem self-evident, but inexhaustibility is less so, but remains important to design. Although old-growth forest resources have dwindled greatly enough to expose quality-loss, formally protected forests continue to be extracted, engineered woods offer less dependence on high quality woods from old forests, and silviculture as a method to maintain “renewable resources” has only protracted the idea of the “inexhaustible.”

Standardization happened early in this process to support the commodification of wood. For example, US forest service cites that dimensional lumber arose from the need for a “common understanding between the mill and markets” created by the increasing distances of rail or water transportation (Smith and Wood, 1964). Efficient delivery and mass production sustained the perception that resources were inexhaustible, even though forests were diminishing. Technology helped the industry to stay ahead of production by extracting more lumber efficiently. Consider that a “2x4” today still remains as a ubiquitous element both in form and in quantity. The succeeding World Wars accelerated the need for standards and engineered variants that could be stronger and lighter. This desire and dwindling forest resources propelled the creation of engineered woods. The population explosion from post WWII housing would systematize most of the modern language of architectural wood (Ore, 2011). So what does that language share about today’s perception and how does it echo the history of post industrial efficiency and inexhaustibility?

“Good architecture starts always with efficient construction,” echoes a familiar Meisian proverb as an embodiment of modern architecture (Konstantinidis, 1964). For wood this means structures and constructions are safe, strong and predictable – so there is no need to use more than needed. Words such as cantilever, load factor, gravity, strength, maximum forces, allowable stresses, strong, stiff, efficient, bend, capacity, deflect, directional, etc. are typical of textbook architectural descriptions associated with the human benefits of wood (Iano, 1999). These descriptions satisfy, in more definite terms, a basic professional creed in architecture to ensure the “health, safety and welfare” of the public. Such doctrines are achieved by a slurry of words that neatly categorize wood into its most significant structural elements. Wood construction seems to be overshadowed by ingenuity of steel and concrete, but ironically, wood seems to be the root metaphor for both elements and construction methods. Wood offers a more plentiful vocabulary that pertains to the location in an assembly; one thinks of terms such as purlins, rafters, girders, beams, sills, plates, and so on. These are then augmented with connection words such as mortise and tenon, pegged, bolted, spline, laminate, tongue and groove, notched, drilled, nailed, hangers, straps, anchors, wedged, braced, and the thousands of variations of existing joints that provides a safe and predictable product. It is the malleability of wood that ensures the potential for more words, even as new tools such as CNC machines help to define new ways of engaging it.

One of the most important qualities of the architectural language is its propensity to reject the ecological processes of decay. A fundamental architectural textbook on construction methods points to the avoidance of wood products that have “discontinuities” and “distortions,” with obvious prudence (Allen, 1999). These concepts shape negative sentiments about wood by defining them as “peppered with defects… (it) can split… warp… give splinters… decay and harbor destructive insects” (Allen, 1999) These dismissive qualities of wood are sensible conceptual barriers to reinforce safety. However, their presentation as apriori truths also implies that using “poor” qualities of wood might also suggest poor, amateurish designs, which sets up professional barriers for creative exploration.

The modern architectural wood language sustains the tension between humans and environment. Forests are still conceived as inexhaustible because so much is hidden and materials are extracted and discarded without regard to its other non-human benefits. The construction language favors those qualities that extract out the “wild” parts of wood for the benefit of structural efficiency. Such language originated from the a particular relationship with the natural world and it continues a trajectory away – an “anti-” sentiment – from the environmental processes (Fig 3).

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Figure 3: Architectural Wood Post-industrial Trajectory

2.0 ECOLOGICAL WOOD
2.1 Value and scientific language of ecological wood

The field of forestry and ecology offer a description of wood in natural systems through the science of coarse woody debris (CWD). A biodiversity guidebook defines CWD as, “sound and rotting logs and stumps that provide habitat for plants, animals and insects in the source of nutrients for soul development of material generally greater than 8 to 10 cm in diameter” (Stevens, 1997).

Colloquial descriptors for CWD include “dead-wood” or “waste” and as their negative connotations might suggest, they are both ecologically and culturally misunderstood as useless objects. However, since the late seventies, CWD research
supports emerging new theories about the benefits of disturbance and waste. The more recent acceptance in science to redefine wood from a thing of disease to an object of benefit is due to a shift in perceptions about ecological health and complexity. World Wildlife Fund (WWF) notes:

For generations people have looked on deadwood as something to be removed from forest, either to use as fuel, or simply as necessary part of ‘correct’ forest management...breaking up these myths will be essential to preserve healthy forest ecosystems and the environmental services they provide (Dudley, 2004).

The changing values in the forest are in line with the shifting paradigmatic values about ecological systems in the last century – from static to a more dynamic, “chaotic,” “complex” way to understand the world (Worster, 1994). Most notable is the dialog between ecologist like Eugene Odum and Henry Gleason who challenged different models of ecological systems. Odum advocated a world of balance and equilibrium which long dominated twentieth century thinking about forest ecosystems, while Gleason’s more controversial “individualistic concept” favored the organism autonomy and a world in less balance (Clements, 2000). As work like Gleason’s became more validated, a growing number of researchers began to study processes like deadwood in the forest differently, from one that disrupted balanced systems in negative way, to one that offered benefits through those disturbances. Embodied in the language of CWD research are distinct terms that contrast the concepts of “balance” and “equilibrium.”

Some CWD term include: death, disturbance, decomposition, mortality, uprooting, disruption, decadence, legacies, old-growth, complexity, exclusions, diversification, fragmentation, leaching, collapse, settling, seasoning, disease, failure, distribution, regeneration, debris, catastrophe, habitat, nutrients, dynamic, accumulate, etc.¹ The terms focus around the concepts of entropy and death. All waste is utilized and cycled, which present a different kind of efficiency. It is achieved through structural diversity and the ability to connect generations in order to maintain historical continuities. These transitional states also reemphasize the simultaneous, multi-uses of CWD and are crucial background agents in important ecological concepts such as “biological legacy.” The Dictionary of Forestry defines the term as:

a biologically derived structure or pattern inherited from a previous ecosystem – note biological legacies often include large trees, snags, and down logs left after harvesting to provide refugia and to structurally enrich the new stand (Society of American Foresters).

A key structural quality of CWD is its role as a complicated background figure. It is functional scaffolding for the many interacting species, but more importantly its contribution is to link ecological time and place (Fig 4).

![CWD complicating a old growth forest riverine system in H.J. Andrews Experimental Forest, photo by author](image)

**Figure 4:** CWD complicating a old growth forest riverine system in H.J. Andrews Experimental Forest, photo by author

In terms of management of these systems, a set of prominent research ecologists explains that “structural attributes of forest stands are increasingly recognized as being of theoretical and practical importance in understanding and managing forest ecosystems” (Franklin, 2002). Significant reasons for this development include structure providing a
clearer way to identify difficult to measure “surrogate functions,” such as productivity. The inclusion of CWD research (i.e. dead trees) with “live trees” is significantly providing a more dynamic understanding of forest structure and therefore ecosystems.

Much like the architectural world, CWD research also identifies many terms through structural and spatial qualities and applications. Some examples include limbs, trunk, elevated areas, loose bark, food source and sites, root wad, perches, cavities, hallow, protected areas, nesting cover, thermal cover, lookouts, low soft areas, resting areas, storage, burrows, humus, etc. (Maser, 1979). And it is likely that continued observation will generate even more. Many of these terms embody simultaneously functional and formal qualities, i.e. lookouts, thermal cover, etc. Each term also describes objects with multiple intermixed functions – with ephemeral uses. A “perch” can also be a “cavity” as well as “nutrients” and even “humus” for the forest floor. Organisms like the woodpecker, a keystone specie, can intercede the process, as a “primary cavity excavator” by creating spaces in CWD that “are critical for life history needs of other species of birds and mammals.” The resultant occupants, who depend on these places are described as “secondary cavity users” (Bevis and Martin, 2002).

Modern understanding of ecological wood embraces the concepts of excess and decay and depends upon the concept of inexhaustibility. These material elements seem to be stored in a form of beneficial purgatory between resource and waste – as an ecological storage bin. Abundance and redundancy help to ensure biological diversity and successional legacies when disaster strikes. Although large pieces of wood have influence, more often, smaller pieces scattered, working collectively, can have more significant impact on landscape processes. CWD presents a more complete picture of wood and also reveals the gaps that architectural wood embodies. These contemporary understandings about wood offers to draw architects toward a more ecologically collaborative synthesis (Fig 5).

Figure 5: Architectural Wood Trajectory toward Ecological Processes

3.0 BRAIDED WOOD
It was the inexhaustibility or abundance of resources that fueled the invention of the architectural wood through technology and commodification. Abundance is also the key bridge back to ecological processes, and therefore the notion to conserve materials, as emphasized by the sustainable paradigm, may further remove this connection. Landfills are proof that abundance can be unsustainable, however, the process of creating abundance may be the ironic foundation for an ecological transformation. Such insatiable consumption of materials has the potential to also sustain unlimited ecological – non-human – habitats. However, sustaining ecological abundance depends on designers integrating and elevating complex ecological processes like decay as an acceptable material aesthetic.

Table 1: Sample of Opposing Languages of Wood

<table>
<thead>
<tr>
<th>Element</th>
<th>Architectural Wood</th>
<th>Ecological Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>Architects + Urban Designers</td>
<td>Ecologists + Scientists</td>
</tr>
<tr>
<td>Example</td>
<td>(Lumber)</td>
<td>(Coarse Woody Debris)</td>
</tr>
<tr>
<td>Terms Used</td>
<td>Life, new, strong, durable, light, thin, powerful, sleek, easy, simple, balanced, hard, lasting, harmony, grace, stable, static, indestructible, clean, uniform, flawless, beautiful, load factor, gravity, strength, max forces, allowable stress, stiff, efficient, bend, capacity, deflect, directional, etc.</td>
<td>Death, disturbance, decomposition, mortality, uprooting, disruption, decadence, legacies, old-growth, complexity, exclusions, diversification, fragmentation, leaching, collapse, settling, seasoning, disease, failure, distribution, regeneration, debris, catastrophe, habitat, nutrients, dynamic, accumulate, salvage, heterogeneity, etc.</td>
</tr>
</tbody>
</table>

One way to breach this topic for the profession and collaboration is to have awareness of these embedded differences (Table 1). A recognition of these conflicts should better prepare and identify the ecological insufficiencies of design or approach. It may inspire unique design questions and barriers that help to disrupt standard practice toward ecological thinking. For example, how does one use lumber to create places for food to accumulate or to provide shelter from predators? Where and how can I site the building in order to enhance soil biology?
A more structured application might begin by listing the research findings about ecological wood as generated from researchers (Fig 6) (Stevens, 1997). Each potential strategy is described here as an “expanded thread,” and offers a practical way to encourage ecological abundance. We can then situate the architectural design language within an array of other possible threads. The prior narration about architectural wood reveals how the current profession largely occupies one dominant thread – a linear movement from resource to landfill. The sustainable paradigm has expanded some practical “green” threads with a promise to “sustain” human benefits. The proposition here is to further expand ecological opportunities through the contribution of forest science – ecological threads. Designer working toward a more braided outcome will also naturally work within linguistic threads and frameworks familiar to ecologists. The desire is to promote a more purposeful and direct collaboration that magnifies the expertise of each discipline, rather than isolating them (Fig 7). A braided project that is able to draw from a more diverse and abundant set of threads provides resiliency through redundancy and has the potential to sustain social relevance as well as economic well being.

**Figure 6**: The Expanded Threads to an Ecological Braid

The architectural theorist Brook Muller writes about the role of metaphor and ecological thinking as “extending outward to the unfamiliar leads to intimacy of shared ethos and generation of new metaphorical scaffolds” (Muller, 2014). The braided metaphor is a scaffold to make more concrete a shared ethos that environmentally conscious designers strive for, yet often times run into limitations. A dip into an authentic ecological world through the lens of our common building materials is, unfortunately, strangely unfamiliar and unrecognized. It raises many questions about what potential habitats can be brought together with such structures and how this may challenge more traditional architectural responses. What are the professional and regulatory challenges for architects to integrate “habitats” for non-human species and processes? How does architectural education reimagine a world of decay and abundance in terms of sustainability? How might the recognition of non-human ecological processes in materials change other parts of the design language, such as studio, structure and construction? What are the best methods to braid ecological threads so they promote the highest level of collaboration and benefit?

**Figure 7**: Braided Mediation
REFERENCES


ENDNOTES

1 Many of the CWD terms identified throughout this paper can be found in the following overview article. However, other terms were all also collected from CWD papers cited throughout this paper. Stevens.
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²Nanjing Tech University

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¹University of Massachusetts Amherst

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⁵University of Oregon

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