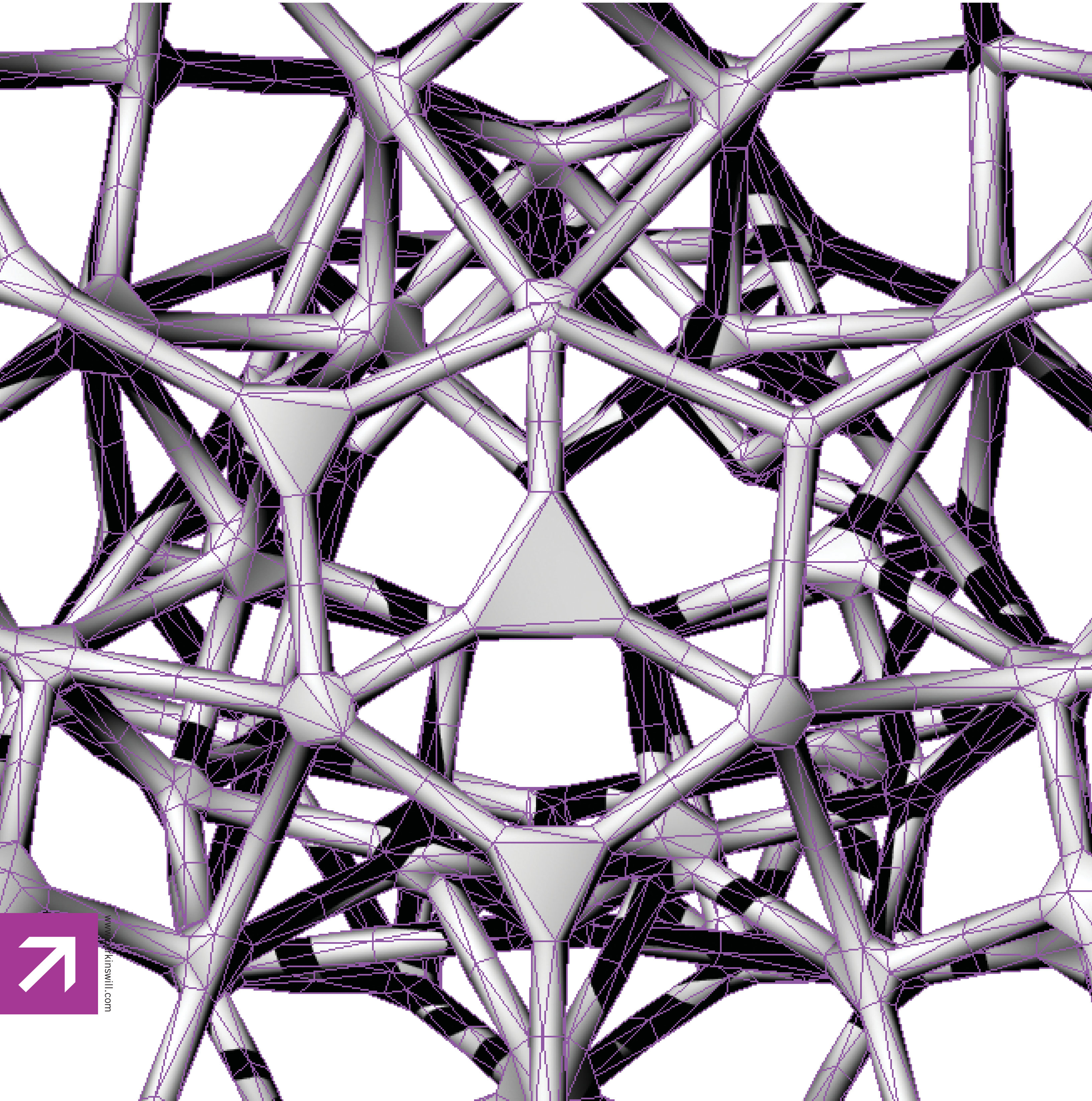
PERKINS+WILL

Research Journal

2016 / VOL 08.02



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Acknowledgements: *We would like to extend* **our APPRECIATION** *to everyone who contributed to the research work and articles published within this journal.*

Perkins+Will is an interdisciplinary design practice offering services in the areas of
Architecture, Interior Design, Branded Environments, Planning + Strategies and Urban Design.

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JOURNAL OVERVIEW

The Perkins+Will Research Journal documents research relating to the architectural and design practice. Architectural design requires immense amounts of information for inspiration, creation, and construction of buildings. Considerations for sustainability, innovation, and high-performance designs lead the way of our practice where research is an integral part of the process. The themes included in this journal illustrate types of projects and inquiries undertaken at Perkins+Will and capture research questions, methodologies, and results of these inquiries.

The Perkins+Will Research Journal is a peer-reviewed research journal dedicated to documenting and presenting practice-related research associated with buildings and their environments. The unique aspect of this journal is that it conveys practice-oriented research aimed at supporting our teams.

This is the sixteenth issue of the Perkins+Will Research Journal. We welcome contributions for future issues.

RESEARCH AT PERKINS+WILL

Research is systematic investigation into existing knowledge in order to discover or revise facts or add to knowledge about a certain topic. In architectural design, we take an existing condition and improve upon it with our design solutions. During the design process we constantly gather and evaluate information from different sources and apply it to solve our design problems, thus creating new information and knowledge.

An important part of the research process is documentation and communication. We are sharing combined efforts and findings of Perkins+Will researchers and project teams within this journal.

Perkins+Will engages in the following areas of research:

- Market-sector related research
- Sustainable design
- Strategies for operational efficiency
- Advanced building technology and performance
- Design process benchmarking
- Carbon and energy analysis
- Organizational behavior

EDITORIAL

This issue of Perkins+Will Research Journal includes four articles that focus on different research topics, such as relationships between interactive urban mapping and community health, robotic fabrication, relationships between perception and space, and impacts of climate change on energy and thermal performance of facade systems.

"Health Indicator Mapping: A Methodology for Visualizing Community Health" presents use of Geographic Information Systems (GIS) for visualizing urban context indicators that influence community healthcare practices. The article presents literature review, determines factors that relate to the built environment and healthcare practice, and shows how GIS can be used to visualize these factors and their effects on community health. The article presents a specific case study, a public hospital in Atlanta, and how interactive mapping has been used to determine factors that influence performance of this healthcare facility.

"Automated Robotic Fabrication for Temporary Architecture: Rethinking Plastics" discusses digital fabrication processes for temporary structures, composed of biodegradable plastics. The objective of the research was to investigate robotic fabrication methods, specifically targeting bioplastics. The article discusses material properties, fabrication techniques, structural properties, and a case study. The case study presents design and robotic fabrication methods for temporary pavilions in London.

"Crafting Architectural Experiences: Exploring Memory Places" discusses the importance of imaginative perception in architecture, and relationships between quality of space and human experiences. It is grounded in theoretical explorations, and extensive literature reviews. It also presents four specific case studies, which discuss design strategies, spatial qualities and human experiences of these buildings. It concludes with suggestions for translating ideas into creation of impressive architectural spaces.

"Climate Change and Performance of Facade Systems: Analysis of Thermal Behavior and Energy Consumption in Different Climate Types" presents thermal and energy performance of various facade systems under current and future climate conditions. The study utilized thermal and energy modeling of conventional and thermally improved facades. Thermal modeling was used to compare relative thermal performance of investigated facades, and energy modeling was used to simulate energy consumption of an office space in fifteen different climate types. Current and future climate conditions were considered. Results show the impacts of climate change on energy performance, and show that the energy usage is increased for all exterior wall types and almost in all climates.

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01.
HEALTH INDICATOR MAPPING:
A Methodology for Visualizing Community Health

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ABSTRACT

The U.S. healthcare industry is changing and shifting its focus toward prevention and community health. Geographic Information Systems (GIS) and interactive mapping can help healthcare clients visualize problem areas in their communities and help answer questions about how best to improve community health with limited financial resources. This research project reviewed existing literature to determine what aspects are related to community health. The literature suggests that levels of income and education, employment and health insurance status, as well as access to transportation and food, are all related to community health. The research methodology was to create a GIS map using publicly available and open-source data to visualize these community health indicators using Grady Memorial Hospital in Atlanta, Georgia as a case study. This work provides a detailed a road-map for future projects to enable teams to implement health mapping data.

KEYWORDS: healthcare, GIS, mapping, data analysis, community health, health indicators

1.0 INTRODUCTION

The U.S. healthcare industry is in a process of transformation. The WWII era fee-for-service payment model is generally blamed for excessive costs, and new models of "paying for performance" ushered in with the Affordable Care Act (ACA) in 2010, are driving a paradigm shift in models of care delivery. ACA accountability standards address disease prevention and population health, and service delivery is adjusting to lower-cost, community-based settings[1].

This study focused on health mapping, and utilized Geographic Information Systems (GIS) tools. The objective was to provide a panoramic view of community health, benchmarks for success, and recommendations on next steps to meet system-defined goals. This research helps identify which indicators are the most relevant and actionable metrics for specific communities, as well as where we can find this information.

The urban design practice at Perkins+Will has developed a healthcare mapping protocol, which includes mapping zip codes of patient origins for hospital visits in Baton Rouge and mapping pre-existing indexes, such as the Community Needs Index[2] for a potential hospital project in Las Vegas. This type of mapping helped clients understand data through visualization. However, these examples were developed from data that illustrated trends at a macro level, and the analysis was not robust or localized enough to help clients and urban designers to draw accurate and insightful conclusions about the population health of a particular community.

To generate the type of mapping that enables insight at more specific scales, it was necessary to define the questions that we should be asking, and determine the data resources. This research first reviewed existing literature to determine which five to six indicators are considered to be the most effective and actionable benchmarks of a community's population health.

The research methodology was to create a GIS map to visualize the community health indicators identified in the literature review. Then the researcher identified where one could find publicly available and open-source data that correlated to these community health indicators. Finally, Grady Memorial Hospital in Atlanta, Georgia was used as a case study to illustrate how a map could be created to visualize different aspects of community health.

2.0 CURRENT SITUATION IN HEALTHCARE

To understand the questions and the data types, we analyzed larger context of issues facing healthcare providers and the communities that they serve. Figure 1 gives a national level view, showing that health care costs are rising. In 2011 healthcare was 17.7 percent of the Gross Domestic Product (GDP) and in 2040 it is projected to be 34 percent[3]. Per person, the U.S. spent $1,066 in 1960, $8,650 in 2011, and is projected to spend $13,000 in 2020[3]. The average U.S. life expectancy is one of the lowest compared to other developed countries, and we have by far the highest per capita spending per person. All of these factors combined indicate that it is critical that the U.S. addresses both mortality rates and health care costs.

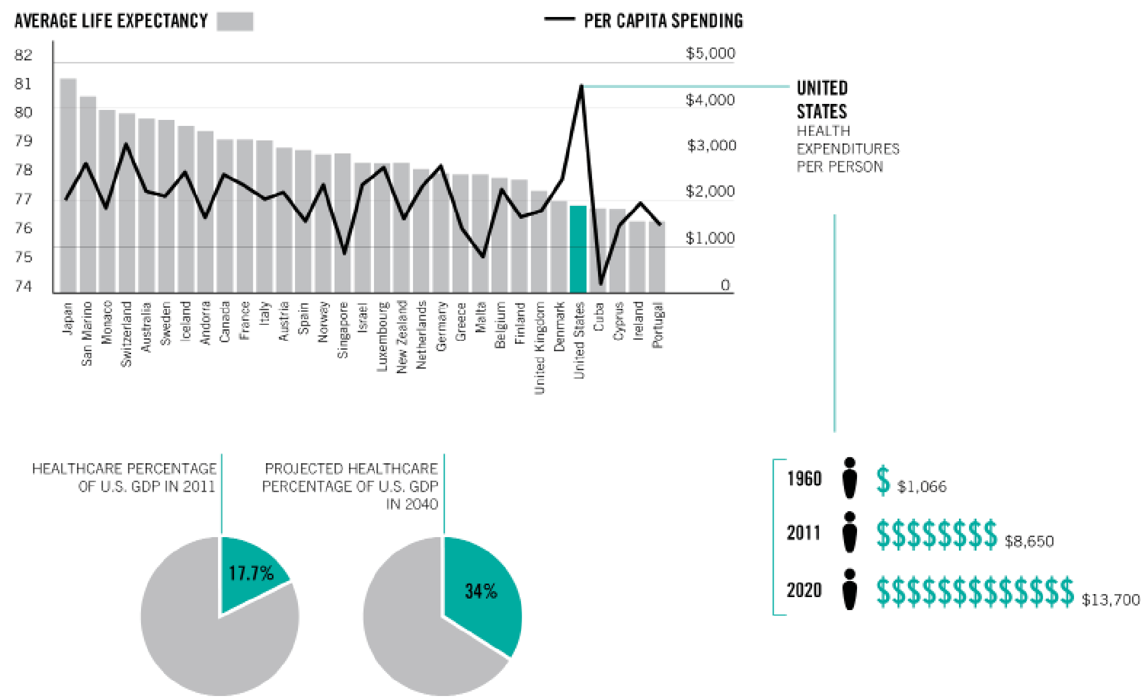

Figure 1: Rising healthcare costs[3].

There are areas that can be targeted to reduce both costs and mortality rates. Figure 2 shows the leading causes of death, juxtaposed with the most expensive medical conditions.

Heart disease tops both lists with a cost of $107 billion per year and a mortality rate of almost 600,000 per year[4]. Injuries, mainly acquired in traffic accidents, are the second most expensive category with $82.3 billion per year. Cancer is third, with $81.7 billion per year and second in mortality rate with 576,691 per year. Third in mortality rate is lower respiratory diseases with 142,943 per year.

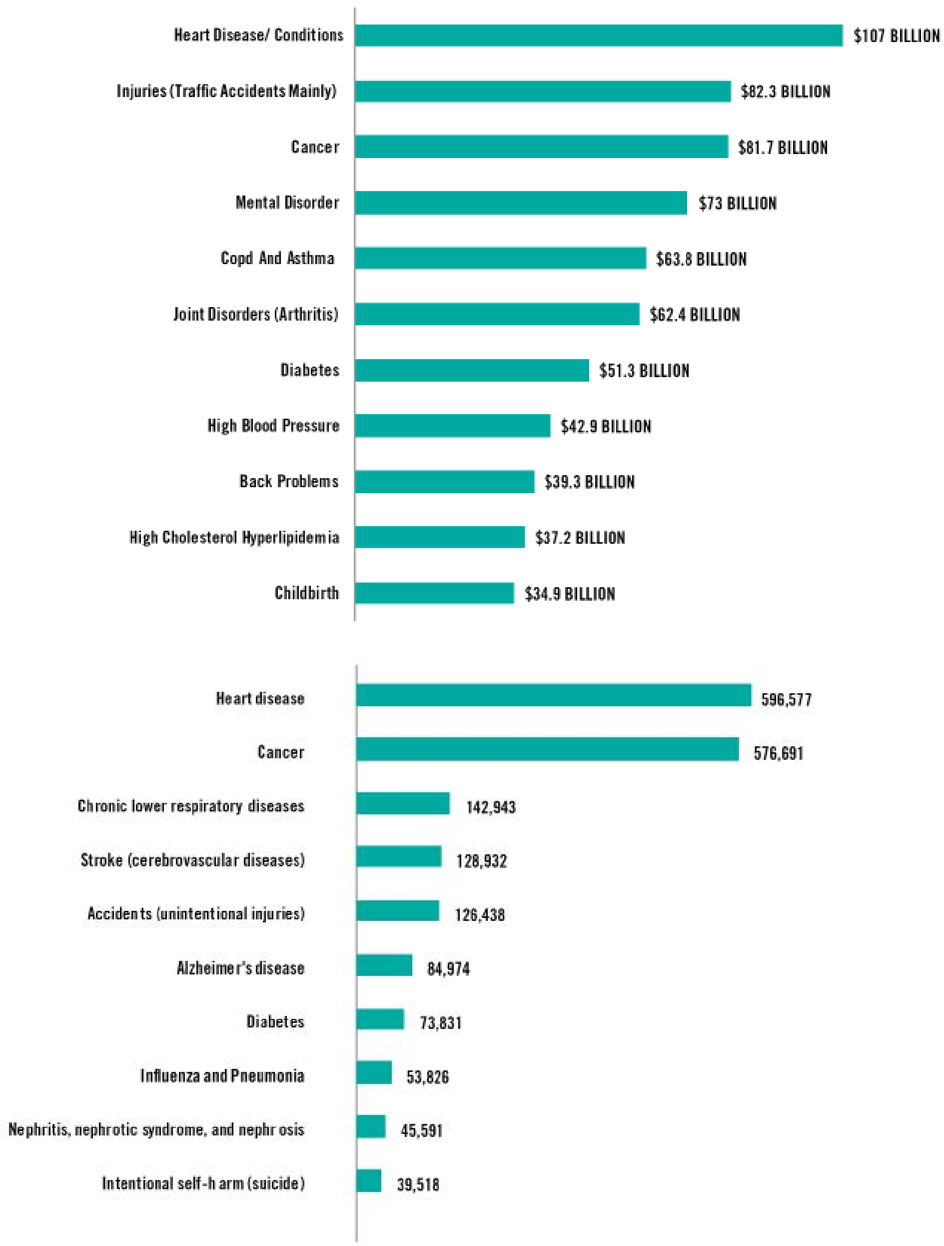

Figure 2: Top health care costs[4] and leading causes of death[5].

Through analysis of costs and high mortality rates, it was evident that many of the causes or aggravators of these categories are rooted in the built environment (Figure 3).

Chronic diseases, which comprise a large percentage of the most expensive and highest causes of mortality[5], are associated with the built environment. Figure 3 illustrates the relationships among conditions, such as separated uses, disconnected streets, air quality, toxic building materials, “food swamps” (an abundance of fast food restaurants and convenience stores), and “food deserts” (low access to a grocery store), and obesity. The metabolic syndromes associated with obesity include conditions such as diabetes, heart disease, as well as joint and back injuries.

The Robert Wood Johnson Foundation conducted extensive work in distilling the various indicators of population health down to the most prescient, with their County Health Rankings program[7]. The rankings were designed to give a holistic snapshot of population health at a county and state level. The researchers synthesized health information from a variety of national data sources to create the rankings[7].

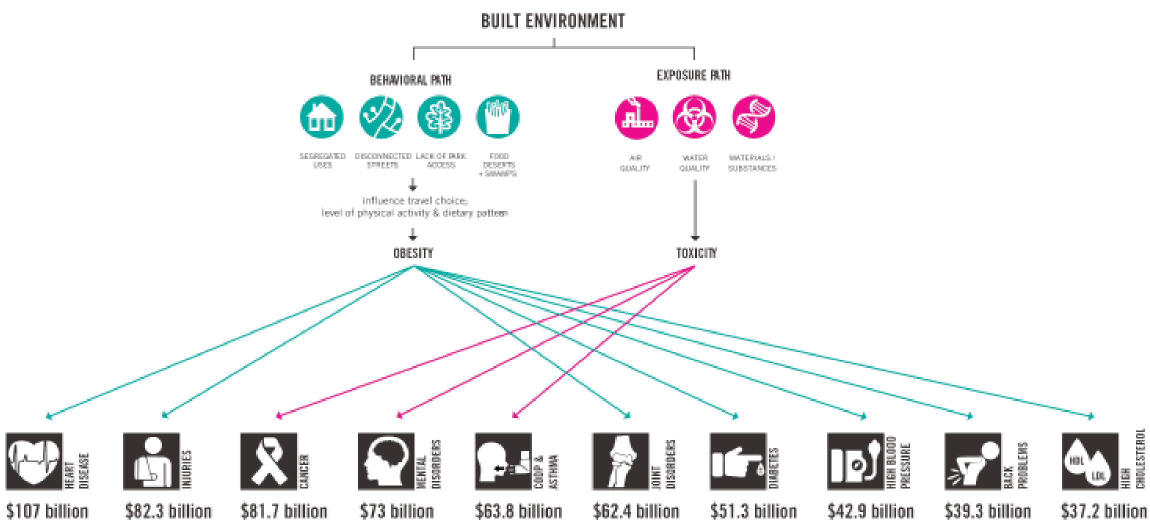

Figure 3: The built environment contributes to the highest-costing health conditions[6].

While there are conditions that architecture and urban design cannot readily affect, such as childbirth, we recognize that most of the highest-expense conditions are rooted in the built environment. These conditions also have high correlations to poverty, level of education, transportation access, and insurance status (Figure 4). The County Health Rankings model states that socio-economic factors contribute 40 percent to a person's overall heath and healthy behaviors contribute 30 percent; the purely physical environment, such as soil, climate, air and water supply, contributes 10 percent and clinical care contributes 20 percent. Funding and resources to address these problems are always scarce. Therefore, it is necessary to focus interventions to achieve the highest impact. Mapping can help define the most effective strategies for each community.

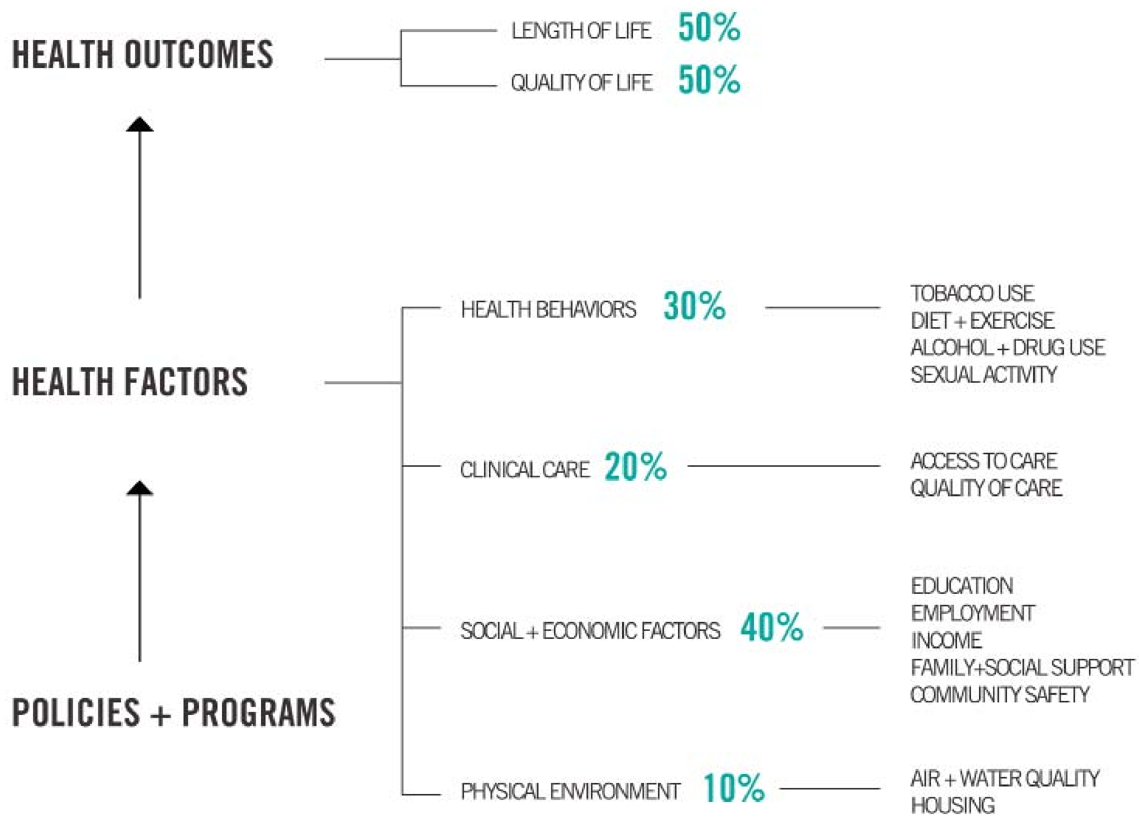

Figure 4: Factors that affect health[7].

3.0 MAPPING HEALTH

GIS is a system designed to visualize, store, manipulate and analyze data. The software stores data in different layers that can be turned on and off, merged, split, and overlaid to visualize data collected about a specific area in the world. The power in GIS comes from the ability to quickly see relationships, patterns and trends in physical space.

Mapping is a powerful tool in the effort to assist hospitals and health care providers to focus outreach programs or convene joint endeavors with city and county officials. With this intent in mind, this research illustrates a road-map for future projects to quickly generate a health mapping protocol.

In order for this process to be replicable, all data needed to be publicly accessible or data that the healthcare provider can supply (Figure 5). Much of the data represented here is open source and publicly available. Parks, transit, roadways and other types of data dealing with the built environment can be found through GIS resources.

The census bureau also collects fairly robust data and although it is not disaggregated data, it reaches down into small-scale units of information for particular locations. The American Community Survey (ACS) includes information such as car ownership, income level, age, education level, race, number of children living below the poverty line, health insurance status, and employment status.

The Centers for Disease Control and Prevention (CDC) hosts a dataset called the Modified Food Retail Environment Index (mRFEI)[8]. Using North American Industry Classification (NAICS) codes, mRFEI measures the number of healthy and unhealthy food retailers within census tracts across each state as defined by typical food offerings in specific types of said retail stores.

Information at the census level in many communities is still very broad and may not be scaled to detail specific issues in a particular community. But, there are many resources that allow one to find disaggregated data, such as addresses for grocery stores, businesses, doctors' offices, and many others types of uses. There is more work involved in cleaning the data so that this information can be geocoded in GIS, but it is worth the effort to be able to pinpoint, for example, exactly where all the convenience stores are in relation to grocery stores in a neighborhood. All of these data layers together create a tailored picture of the health environment in a community.

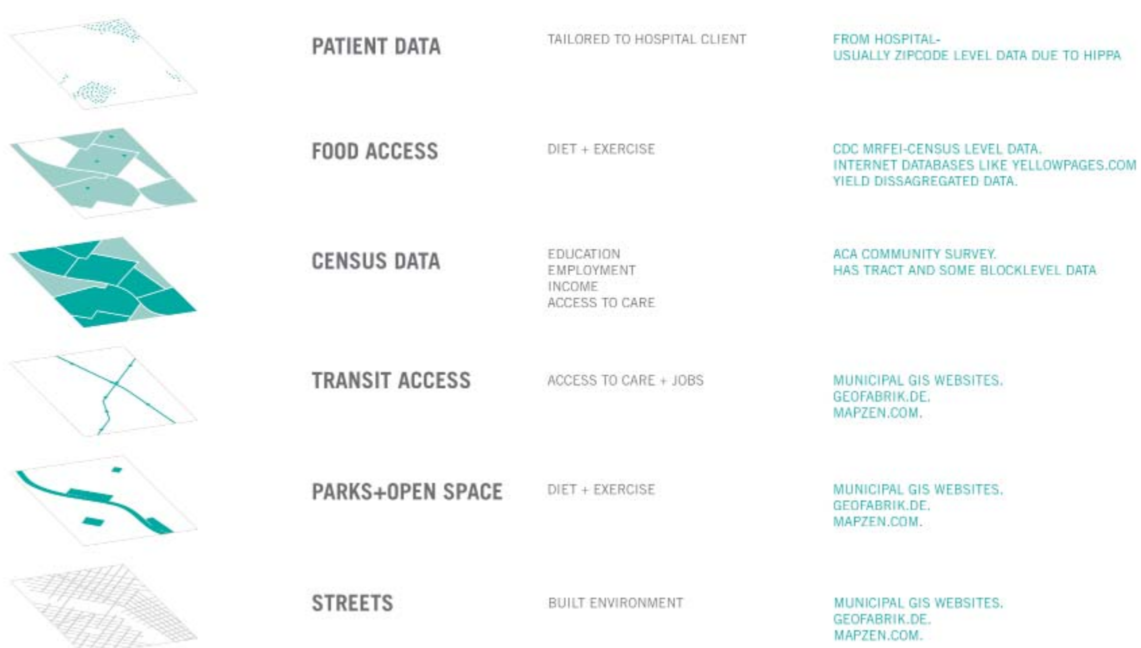

Figure 5: Health indicators and data location.

4.0 GRADY MEMORIAL HOSPITAL CASE STUDY

To put this process through a test run, we partnered with Grady Memorial Hospital, a public hospital in Atlanta, Georgia. The objective was to analyze these following three specific community health issues through mapping:

1) Care coordination for prostate cancer
- What kind of access do at-risk groups have to screening, health care and follow-ups?
- How can we better coordinate care between health partners?

2) Enabling Healthy Behaviors
- How can Grady Memorial Hospital support green space?
- How can new healthy food access be tied to new green space especially around the BeltLine[9]?

3) Pathways to Advantage
- How well is the BeltLine Workforce Partnership in Healthcare Program serving those who need it most?
- How can more potential applicants be targeted?

The maps focused on DeKalb County and Fulton County, which is the main catchment area for this hospital.

4.1 Care Coordination for Prostate Cancer

Officials at Grady Hospital noticed an increase in late-stage prostate cancer patients. They were interested in analyzing if there were any spatial relationships and if a map could help them focus their education and outreach efforts to reduce prostate cancer death rates, and increase early detection rates.

The data layers on the map shown in Figure 6 include the percentage of men without health insurance by census tract (from the ACS 2012 5-year survey), locations of hospitals (Perkins+Will dataset), locations of urologists' offices (from healthgrades.com), rail transit access (City of Atlanta GIS) and zip code level data of prostate cancer patients admitted to Grady Hospital (from Grady Hospital).

The majority of the urologists were located in the northern areas of the city, and only a handful of these offices were transit accessible. The late-stage prostate cancer patients originated from zip codes in which larger percentages of men without health insurance were located. These findings were in line with what Grady officials assumed, however they were still shocked to see the significant disparity.

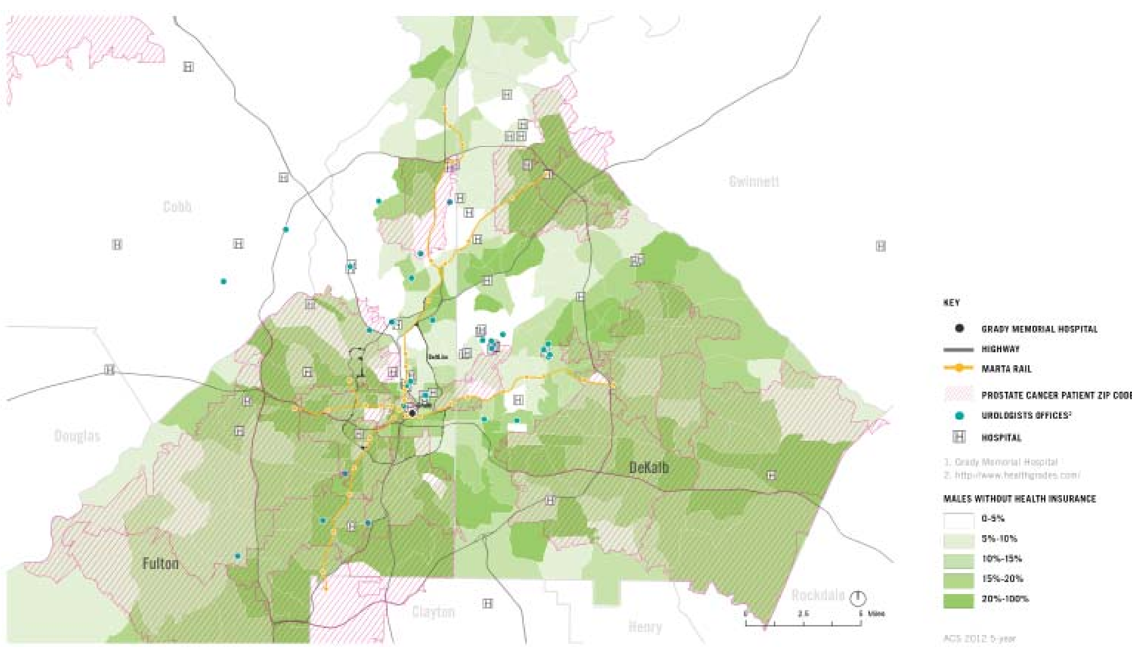

Figure 6: Care coordination for prostate cancer.

4.2 Enabling Healthy Behaviors

Child and adult obesity were also topics that officials at Grady Hospital were interested in seeing spatially represented on a map.

The data layers on the map shown in Figure 7 include parks and open space (Atlanta Regional Commission GIS), percentage of households with incomes below $25,000 per year by census tract (from the ACS 2012 5-year survey), locations of hospitals (Perkins+Will dataset), locations of convenience stores (from yellowpages.com), locations of grocery stores (from yellowpages.com), and rail transit access (City of Atlanta GIS). The map shows that the poorest areas are both food swamps, with a large number of convenience stores, and food deserts, with few, if any grocery stores. Park access was fairly well allocated in the census tracts.

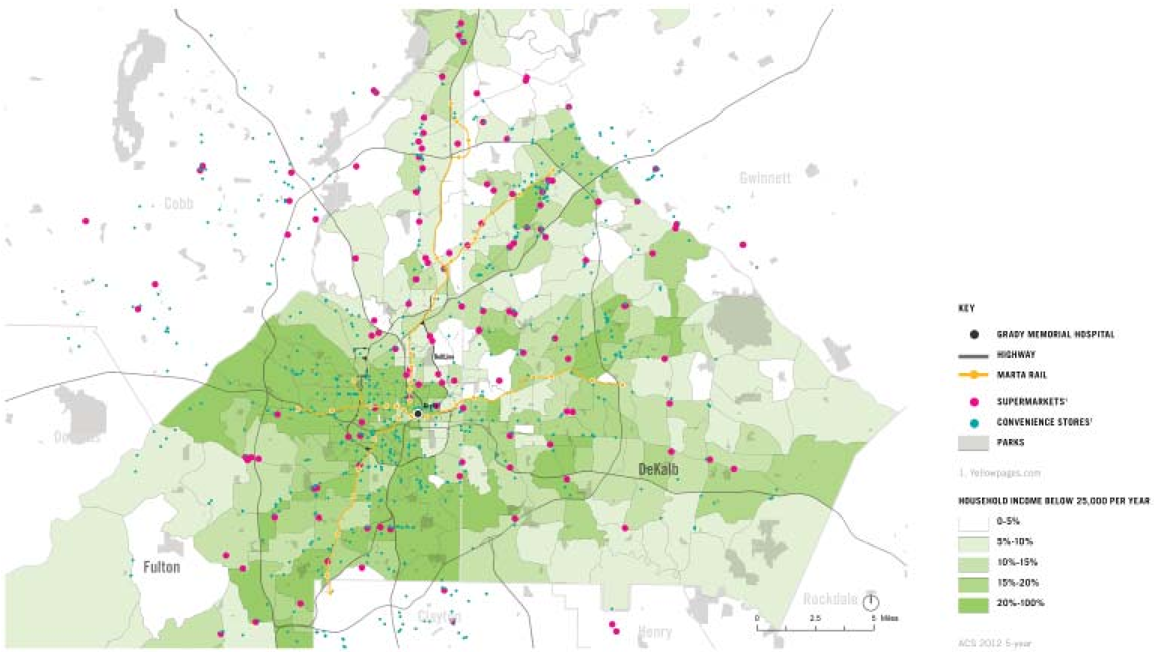

Figure 7: Enabling healthy behaviors.

4.3 Pathways to Advantage

The final map that was generated considered Grady's role as a member of the BeltLine[9] Pathways to Advantage program. The program links low-income Atlanta residents with jobs and job training for workers with lower-levels of education, such many healthcare jobs. The main demographic typically working in these types of low-skill healthcare jobs are women[10].

The data layers on the map shown in Figure 8 include the percentage of unemployed women by census tract (from the ACS 2012 5-year survey), locations of hospitals (Perkins+Will dataset), locations of nursing homes and assisted living facilities (from yellowpages.com), and rail transit access (City of Atlanta GIS). If the goal is to help unemployed women reach these low-skilled jobs, it is clear from the map that many of the locations of these jobs are not transit accessible, which will prove to be a barrier for many people.

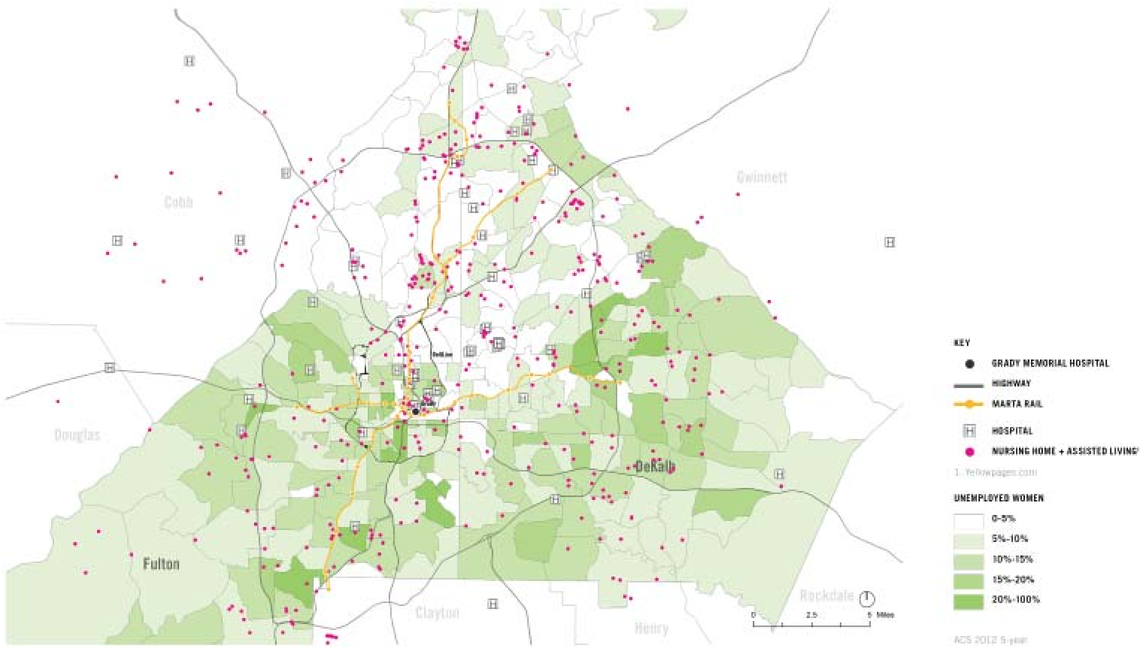

Figure 8: Pathways to advantage.

4.4 Interactive Maps

The final step was to create an interactive map, which users at Grady could implement as a tool to help illustrate problems in the community, and focus on specific areas for interventions.

Advantages of a digital online map include the ability to zoom in to specific areas, and the ability to click on a point or census tract to receive more detailed information.

At the time this article was written, Grady Memorial Hospital was in the process of getting grant funding to further explore health indicator mapping. Another health care institution, the Mercy Care Clinic, is also in the process of using this methodology and technology to create a detailed view of community health around their new clinic in Chamblee, Georgia.

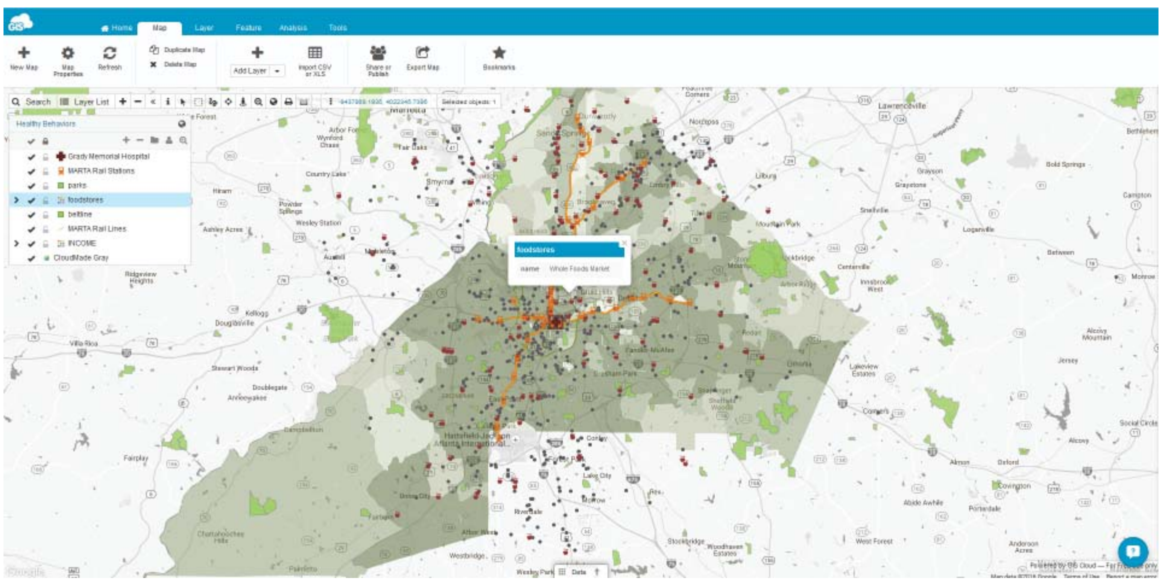

Figure 9: Screenshot of interactive online map.

5.0 CONCLUSION

With the U.S. healthcare industry in a state of flux, and both healthcare systems and communities seeking to enhance individual and population health, GIS and interactive mapping provide an important tool that can help healthcare clients visualize problem areas and focus resources to most effectively manage and improve community health.

By reviewing existing literature, this research determined that income level, level of education, employment status, health insurance status, transportation access, and food access are actionable and material indicators of community health. It also detailed a roadmap for future projects to quickly find and implement health mapping data, and used Grady Memorial Hospital in Atlanta, Georgia as a case study in for health indicator mapping.

This research project focused solely on creating a replicable and affordable methodology to gather reputable data sets and use the power of GIS to map the health of a community. Expanding the applicability of this work would enable a standardized methodology for analyzing data that could be applied to each project location. Data would address broader realms of access to various goods and services, as well as local statistical analysis most relevant to the unique conditions of each community health profile. Finally, after applying this research in several contexts, it would be beneficial to assess the research and visualization methods that are most effective in assisting design teams and healthcare providers to reach the best outcomes.

Acknowledgements

The author extends a heap of gratitude to Basak Alkan (Perkins+Will), Shannon Sale and Stephen Vault (Grady Memorial Hospital).

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02.
AUTOMATED ROBOTIC FABRICATION FOR TEMPORARY ARCHITECTURE:
Rethinking Plastics

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ABSTRACT
Driven by a bottom-up architectural approach to integrate phase changing materials and digital fabrication tools, such as industrial robotic arms, this article presents a novel materially generated fabrication process. The process 3D prints and stretches plastics, where the extruding and freezing temperatures, pulling speeds and angles are controlled through highly customized heads mounted on robots. The objective of the research was to investigate how the phase changing property of plastics can be exploited to its fullest potential using digital fabrication tools, specifically for temporary architecture. A fairly low working temperature bioplastic, polycaprolactone, was chosen as a material for its loose molecular structure, enabling the material to be reheated and reused as much as possible. Research methods included several material and digital experiments, conducted to control the height, temperature, and structural integrity of the pulled structures. As a result of surface tension, it was concluded that the triangle is the optimal shape to deposit the material and pull from. Thus, tetrahedron nodes are used to grow the structure as a continuous web. The research was used to investigate a specific case study, which resulted in a fabrication platform that addresses construction waste issue in London by presenting an autonomous robotic fabrication system and creates 100 percent reusable, biodegradable, self-binding and continuous temporary lattice structures, which can be welded on site. The fabrication process takes place in a mobile cell autonomously run by robots. Once the temporary structure is no longer in use, the unique property of the material fabrication system allows the built structure to be shredded down and refed into the fabrication system to build a new temporary architecture nearby or on another site.

KEYWORDS: material programming, bioplastics, robotics, 3D printing, digital fabrication

1.0 INTRODUCTION

1.1 Background and Motivation
Plastics have a wide range of usage in construction and architecture. Their adaptable technical properties allow for a wide range of form-making and finishes through thermal processes. This sets plastics apart from other materials in pursuing complex geometries with regards to digital fabrication procedures[1]. Yet, plastics are not used and exploited to their fullest potential. Its malleability has been mainly explored on an extrinsic level, such as form making and not on an intrinsic one, where the material behaviour is essential in informing the form and fabrication procedures. Thus, this research aims to highlight the intrinsic properties of plastic as a phase changing material and develop methods of fabrication that tease out its malleability to present a continuous mono material structure.

Industrial robotic arms have been used for many years in many fabrication processes in numerous industries, especially in the car industry since the 1970's. They are powerful machines that can execute repetitive actions accurately. However, in the traditional use of industrial robotic arms, a clear relation between the handled material and the robotic control has not been clearly addressed or investigated. Architects look at industrial robotic arms differently by utilizing their potentials[2]. Material significance has increased dramatically in the digital fabrication realm due to the shift from software-based experiments of virtual material to a more physical-driven fabrication, which necessitates real material constraints and behaviour analysis. Typically, generative design in architecture refers to computer algorithms that generate form. Materially-directed generative fabrication enables the material behaviour to generate form. In this research, they are combined. The dialogue between customized material geometries, along with parametric algorithms, designer's input and robotic parameters serve as a novel model of fabrication for material-based design and construction.

Addressing the construction waste issue in London, the fabrication system this research presents aids in reducing the waste generated by temporary architecture. Research shows that 1,418 temporary structures existed in London in 2015, and the numbers keep rising. Architecture and construction contribute to 70 percent of the overall waste production in London. Seventy percent of this waste ends up in landfills. By the year 2020, London's municipality is aiming to reduce landfill usage to twenty percent and to increase recycling by 14 percent. This demands a system that rethinks the problem with a holistic approach from material to fabrication. Thus, we are proposing a flexible automated robotic arm fabrication system that is based on programming a reusable and biodegradable material with the parameters of robotic automation, as a result, generating a 100 percent reusable and biodegradable temporary architecture.

1.2 Literature Review

A number of plastics have been used in architecture, developed since the 1940's, such as polyvinylchloride (PVC), polymethacrylate (PMMA), polystyrene (PS), polyethylene (PE), and polytetrafluoroethylene (PTFE). Although all plastics may look alike, they come in two major categories: thermosets and thermoplastics. Thermosets have a cross-linked molecular structure, making it harder to recycle compared to thermoplastics, which have an uncrossed-linked molecular structure, permitting the process of heat deformation to be repeatable. Although both types of plastics allow for the production of highly complicated forms accurately and in mass quantities, thermoplastics are easily converted to their initial state compared with thermosets due to their loose molecular structure, making them easily recyclable as well. Yet, the majority of thermoplastics are made of raw materials that originate from oil and natural gas, a nonrenewable resource. Bioplastics on the other hand, are a form of thermoplastic that are made from renewable raw materials, classifying them as environmentally friendly material that biodegrades eventually once the life of the plastic is over. Special additives can control the life span of bioplastics before they start to biodegrade[1].

"Materially-directed generative fabrication multiplies the possible uses of established technologies (plastic deposition, industrial robotic sensing, and generative coding) to explore the limits of machine-material-sensor interfaces. The ability to sense material behaviour in real-time radically expands the potentials of matter to inform fabrication and influence form."[3]

Recently, plastic in architecture and construction is being explored, exploiting the material diverse properties in search for new forms of construction methods appropriate for these types of materials. Andres Harris's research, "1.0 Biomimetics" and "2.0 Formfinding", serves as a good example[4]. The aim of this project was to develop a structure based on self-forming and self-optimizing morphologies. These morphologies are derived from the manipulation of viscous materials using both physical experimentation and parametric computation to simulate in a digital environment the physical processes, such as fluids and other malleable materials that have the ability to harden under certain pressures. The material that was explored was a bio-resin. The bio-resin material manipulation uses plates and pulling techniques to create the material structures, as shown in Figure 1[4].

Traditional digital fabrication methods tend to generate forms first digitally, without a direct connection to the fabrication method, whether it is an additive process, such as 3D printing, or a subtracting one, such as a CNC router machining. A new approach to digital fabrication is a materially driven approach, which is based on material properties. Therefore, the fabrication method becomes intrinsic to the design process rather than being an aftermath, without considering the material potential at hand[5]. A relevant example of a project that uses a phase changing plastic in a depositing manner by an industrial robotic arm is the "Sense It" workshop held at RobArch2014. It combined robotic plastic deposition (RBD) with temperature and distance sensing as a first case of materially directed generative fabrication. The customized end-effector melts the polypropylene granules into a viscous mass that is extruded through

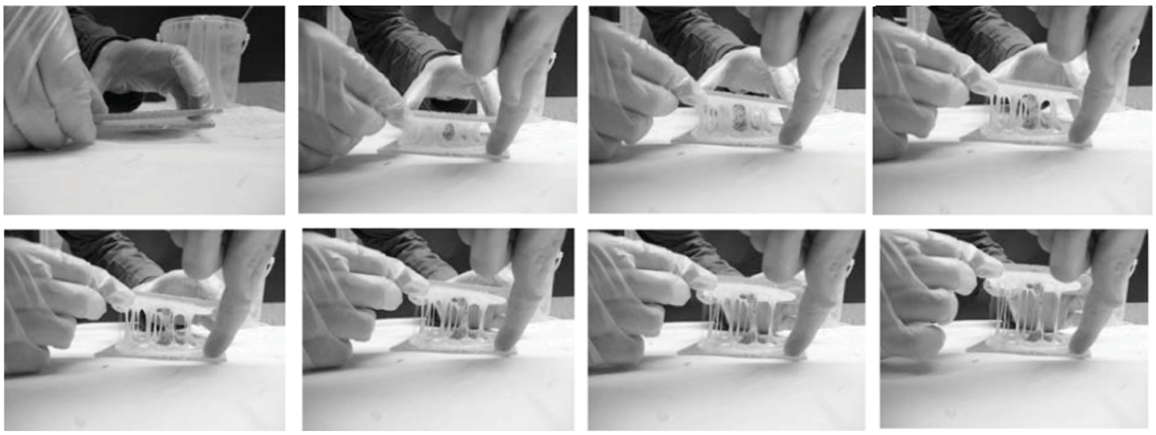

Figure 1: Using plates and pulling as a technique to create the material structure[4].

an aluminium nozzle. The shape and size of the nozzle affect the extrusion of the plastic deposition. By pausing the extrusion process in the code and moving the nozzle upwards exactly after each deposition, it prevents the plastic to harden on the nozzle itself, as shown in Figure 2. Due to the material intrinsic properties, the pouring mass hardens within seconds, right after its deposition, resulting in a lattice structure[3].

2.0 PROJECT OVERVIEW

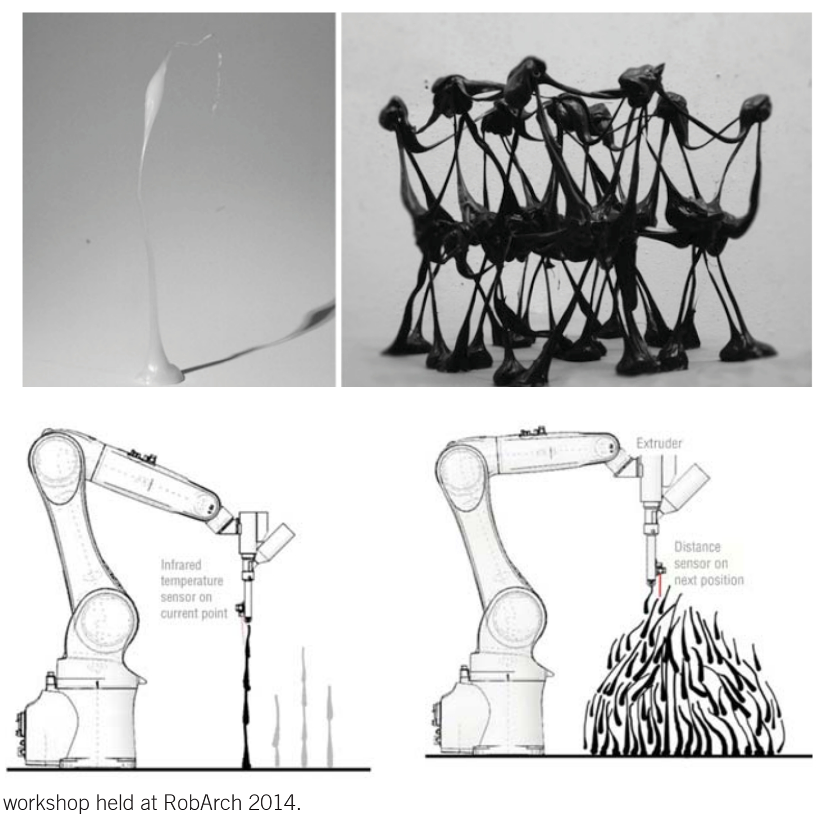

Figure 2: “Sense it” workshop held at RobArch 2014.

This study investigated the architectural and robotic fabrication potentials of 3D printing bioplastics, specifically focusing on the unique material properties of polycaprolactone. At just 60°C, polycaprolactone reaches a low melting point which breaks the material's structure into a soft, malleable consistency. This allows the polyester to be stretched into form and then hardened using a freezing spray. The stretched plastic grows as a lattice structure that can adapt locally to the expected loads within a single material system. The lattice consists of tetrahedron nodes and beams. To ensure all compression and tension forces reach equilibrium, the lattice is digitally "relaxed", redistributing all the nodes and beams lengths obeying the parameters obtained from the material experiments. Thus, depending on their structural capacity, heights of the extruded beams are maintained within a range of 15 to 60 cm long and an angle tolerance of 45 degrees from the normal of each face of the tetrahedron node. Due to the need of precise calculations in creating the complex geometric network, industrial robotic arms were used to control the pulling angles, extrusion lengths and nodes orientation in space. Moreover, the freedom in customizing the robot's end-effector along with its 6-axis movement match the need to freely pull the plastic in space at a controlled speed and temperatures. Therefore, customized pulling end-effectors were developed as the mediator between the material and the robotic arms to stretch the triangular deposition of the plastic between tetrahedral nodes. This dialogue between physical material properties input and digital fabrication creates a novel mode of fabrication. As one robotic arm stretches, another operates the freezing spray. To facilitate the ease of fabrication and eliminate the need to transfer the structure to site, the whole process is designed to fit in a standard truck, enabling the fabrication to take place on site. The fabricated units are assembled in place by welding meeting faces of the tetrahedron plastic nodes. Once cooled, the joined units work together as one structural system. Due to the phase changing property of polycaprolactone and the fact that the structure is all built from a singular material with zero joints, it can be easily shredded down into small pellets, which can be used again as an input material in the proposed fabrication system.

2.1 Project Objectives

The objective of this research was to investigate a robotically controlled and materially-tailored method for manufacturing biodegradable, reusable and lightweight structures with temporary functions. These structures address the temporary construction waste in London by challenging the conventional fabrication methods. The purpose was to investigate a fabrication system that is able to produce a reusable, biodegradable and temporary architecture. The fabrication process allows for flexibility in form, joinery, and reusability of the built structures due to the fact that is made of one material.

We addressed several questions during this research:

- Can we develop a fabrication method that utilizes industrial robotic arms and material intelligence?
- Can we rethink 3D printing by utilizing melting and hardening process?
- Can our method create reusable architecture?

3.0 RESEARCH METHODS

3.1 Material Research

A fairly malleable plastic was chosen, which can be easily reused and biodegrade. After many experiments in melting and stretching different kinds of plastics and researching their environmental properties, we identified a bioplastic called polycaprolactone, which is mainly used in medicine as a 3D printed implant and cast. Polycaprolactone falls under the bigger umbrella of thermoplastic polyurethanes (TPU). The technical name of the material is polycaprolactone (PCL) and its commercial names are many, among them are Polymorph, InstaMorph, CAPA, Shapelock, and Friendly Plastic. It is a biodegradable polyester with a low working temperature of 60°C due to its loose molecular structure, which permits the material to be thermally formed. It is considered easily recyclable due to its loose uncross-linked molecular assembly, which makes it ideal as a phase changing prototype material for our study. Initial physical state of polycaprolactone is solid granules that transform into a putty-like viscous mass when heated. The material can easily bind to itself or other plastics, as demonstrated in Figure 3. Polycaprolactone is classified as a low-temperature thermoplastic, with a density of 1.145 g/cm^3. It has an ultra-high molecular weight. It is a commonly used polymer, and was one of the first raw materials to be extruded through a RepRap extruder[6].

Although it is very malleable when heated, this material gets very rigid once set, becoming a fairly structural material in its solid state. Amongst its many advantages are its high abrasion resistance and elasticity across the entire hardness range, its excellent low temperature and impact strength in addition to its resiliency to oils, greases and numerous solvents. Moreover, it has good flexibility over a wide range of temperatures, robust weather and high-energy radiation resistance, pleasant tactile properties, suitable for bonding and welding, easy to colour and most importantly can be reused and it is 100 percent biodegradable[6]. This research chal-

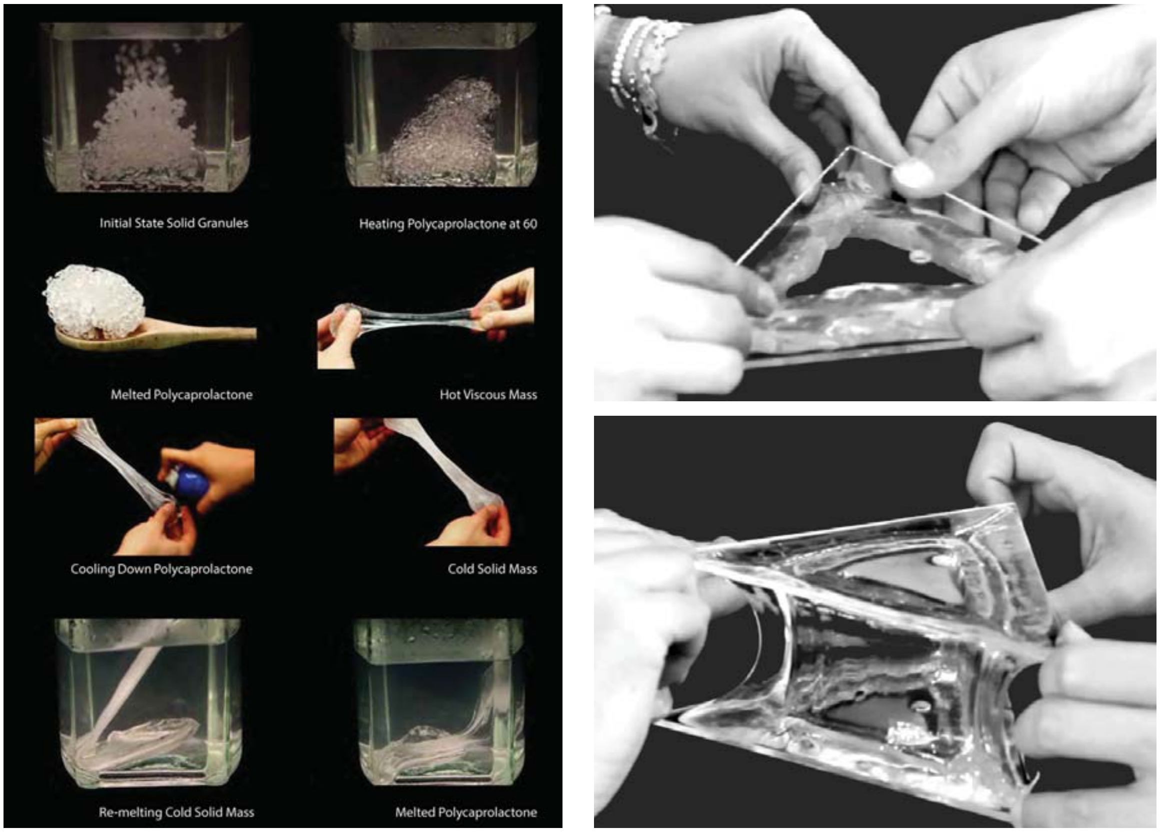

Figure 3: Demonstrating the phase changing cycle of polycaprolactone. *Courtesy of: Architectural Association Design Research Laboratory (AADRL).*

lenged the structural ability of plastics by pulling the material while hot to achieve structural beams.

Taking into consideration the material's potentials and constraints, several experiments were executed to understand its behaviour. We tested the material deposition pattern, temperature, quantity and height. After several experiments, shown in Figure 4, it was clear that our technique offered a unique fabrication method, where the shape of the bed that the material is being printed on has a direct effect on the stretched plastic structure and form. The experiments at this stage were conducted manually using triangular acrylic plates, where the plastic granules are heated through dropping them in 60-70°C hot water until they turn into elastic mass. The weight of the granules was monitored before each trial, as well as the height, pulling and freezing time of the stretched plastic. It took approximately three minutes for polycaprolactone plastic to reach the desired viscosity, stretch to the desired height and revert to a rigid state with the aid of a freezing spray.

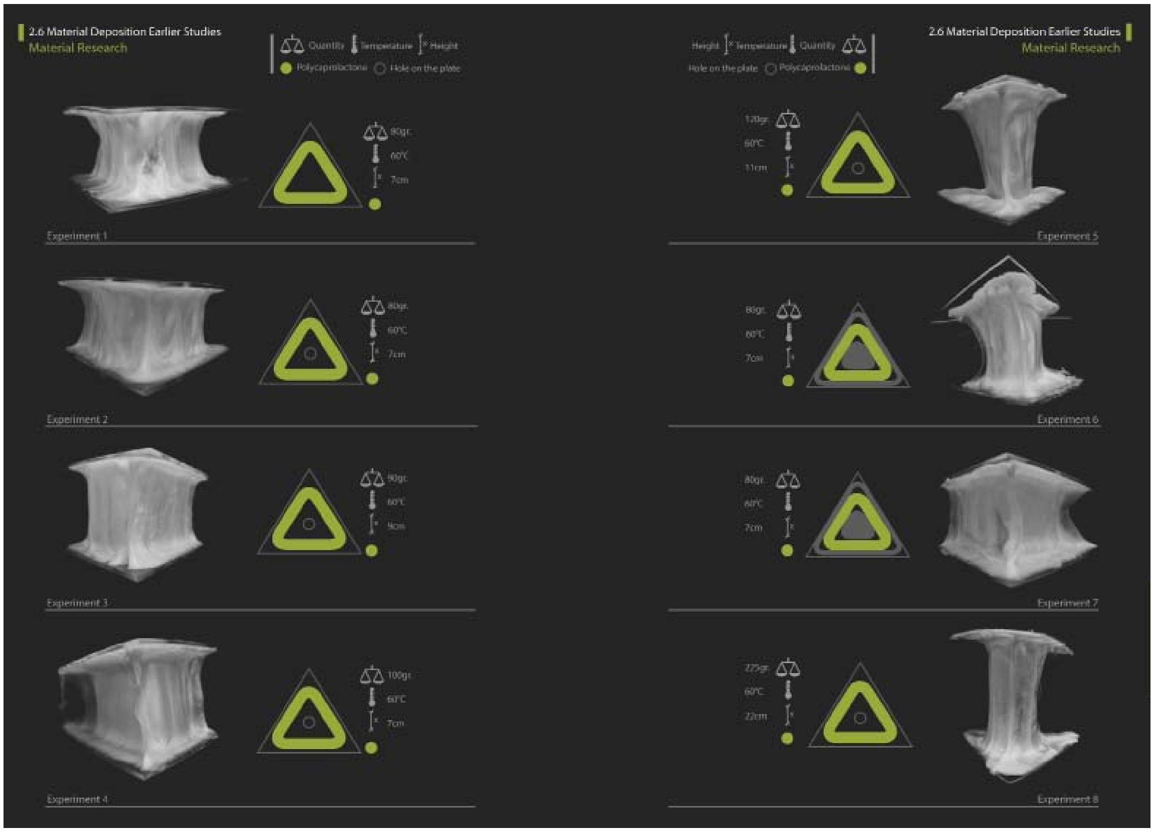

Figure 4: Material programming catalogue of some of the experiments with pulling different heights, weights and temperatures. *Courtesy of: AADRL.*

The optimal height ranged from 15 cm to 60 cm, with direct relationship between the weight of the amount being printed and the desired length, as shown in Figure 5. The weights for 15 cm, 20 cm and 60 cm high beams have been noted and used in this research as the optimal lengths for the fabricated lattice structure, which was tested in a 1:1 prototype discussed later in the article. Although surface tension of the triangular node controls the pulled beam's middle section, we concluded that other factors play a role in determining the plastic's structure integrity. These factors are:

- Deposition temperature
- Length of the plastic beam
- Pulling angle
- Pulling speed.

Special plates and nodes were made of tetrahedron nodes to permit material and structure continuity, resulting in homogeneous material elements, as shown in Figure 5. The nodes allows the pulled beams to grow in almost any direction. Tolerance angles are identified, as shown in Figure 6, before the material starts to shear. The angle range is wide and covers almost a 360 degrees sphere. At this stage it was necessary for the digital and fabrication work to become integrated. Thus, digital structural studies were conducted to simulate the physical behavior of the material and to study the growth logic of our material, in what direction and angle does the plastic gets pulled at and the position of the tetrahedrons in space. Because it was almost impossible to control the results every single time manually, the curtail parameters identified above needed to get controlled by robots and machines. Industrial robotic arms served as the best digital fabrication tool to use, due to their six-axis movement and the freedom to attach any custom head to them. It was concluded that there is an optimal temperature of the plastic that results in the best structural coherency of the material. Thus, an extruder machine was used to replace hot water to precisely control the temperature of the plastic while it is being printed and pulled.

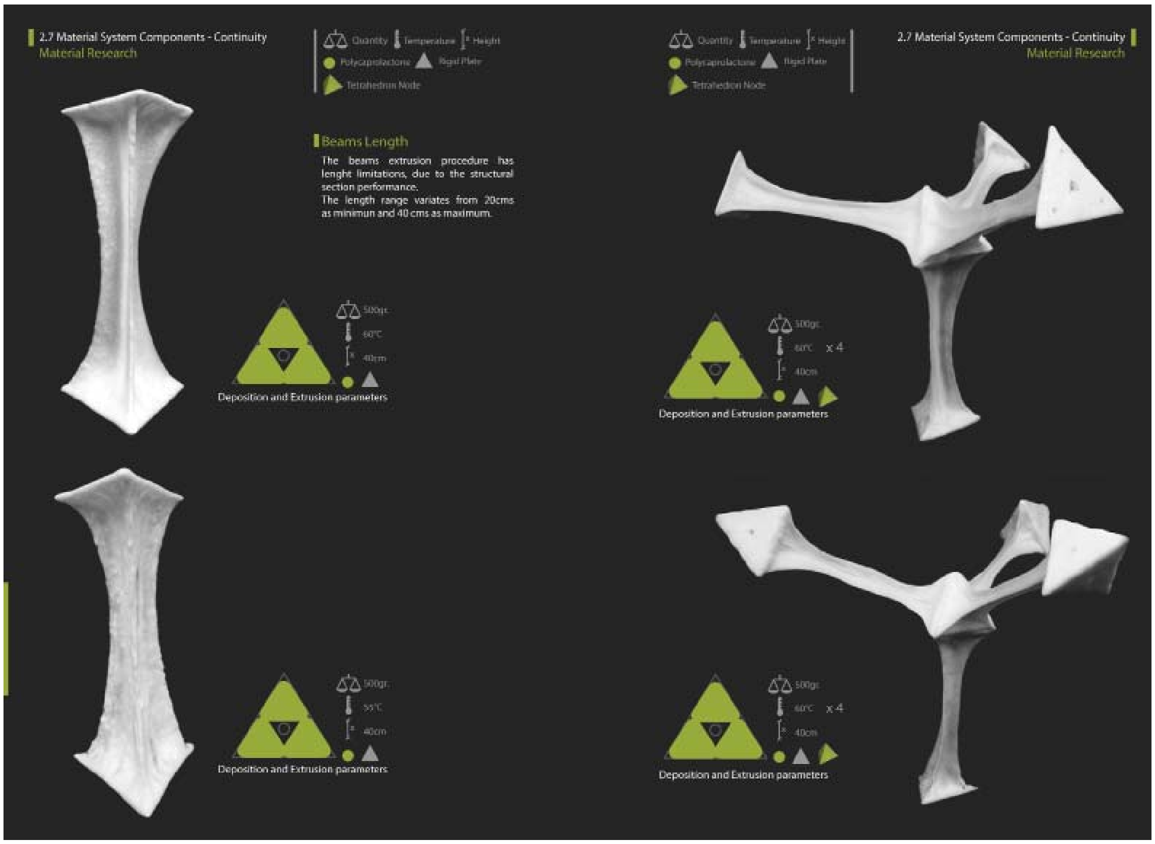

Figure 5: Material programming catalogue of some of the experiments with pulling different heights, weights and temperatures. *Courtesy of: AADRL.*

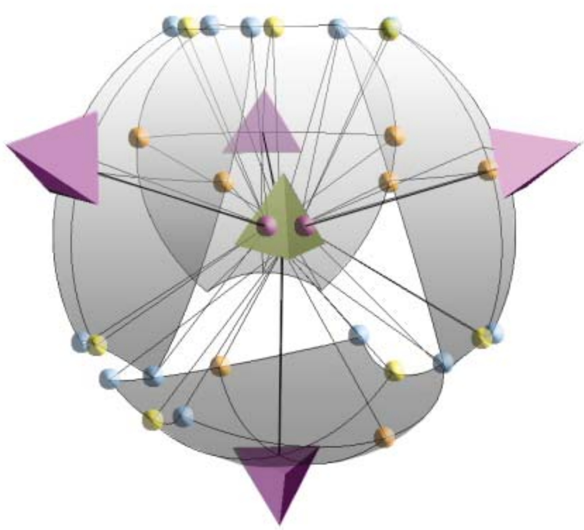

Figure 6: Pulling angles of polycaprolactone stretched beams. *Courtesy of: AADRL.*

3.2 Structural Studies

In line with the system constraints, different types of lattice structures were developed. These different lattices were evaluated according to their structural behavior, in order to define a configuration that best fits the material behavior and the structural requirements. Following the physical research, we simulated our physical experiments digitally to further understand the parameters controlling the behavior of polycaprolactone. It was concluded that the temperature, speed and angle of pulling affect the structural integrity of the material. As a result, varying those parameters digitally generated different thicknesses and holes in the simulated beams, affecting their structural behavior. The plastic network grows according to the nodes distribution in space, which are led by predefined support and load points. The material behavior generates beams that tend to have smaller section in the center of the beam; therefore these elements work better with pure axial forces when they are exposed to bending moments. Taking into consideration the material physical parameters, such as length range and angle requirement, tension and compression elements were defined in the structure digitally, which were then reconfigured to reach equilibrium by “relaxing” (tensioning) the lattice structure digitally. 3D Software Autodesk Maya and Grasshopper Karamba were used in this research to generate these structural studies, seen in Figure 7.

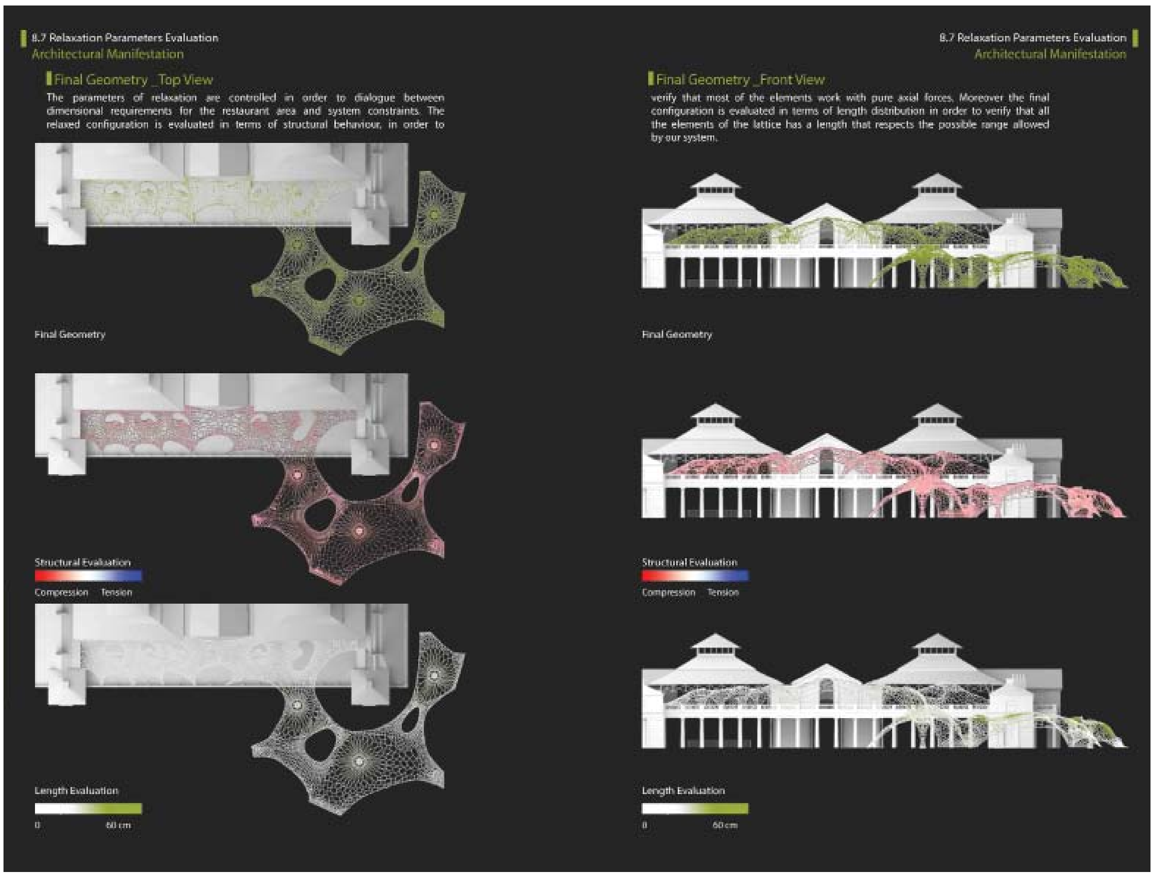

Figure 7: Mesh relaxation in order to redistribute the axial forces reaching equilibrium. *Courtesy of: AADRL.*

3.3 Industrial Robotic Arms Parameters

As mentioned previously, industrial robotic arms can be used in various fabrication processes. These processes mainly include fabrication of components, which are further assembled by humans. However, the execution time of these processes in terms of assembly, delay the efficient production of components by industrial robotic arms. Autonomous building robots as a system mimic the processes in nature, where self-organization concepts are applied intuitively. Hence, every component of the system, such as the robotic arm, end-effector and material, work together as a whole to create internal and external networks that go on to feed the system. Industrial robotic arms are excellent as free platforms to attach almost anything to their end-effector. It is a very flexible open platform for communication, where the software can be customized by artists, architects, and engineers to communicate to the robot from the same room or via the internet.

Taking into consideration physical and digital material studies, and respecting the accuracy and constraints of industrial robotic arms, structural beams were printed and stretched through simple repetitive actions. We used two six-axis Industrial robotic arms. Robotic arms have movement limitation and must move in a certain choreography to reach a certain point in space. This reachable space is called "working area". It has a bolted plate at the end of its arm, which can accept any customized hand or end-effector. The freedom in customizing the end-effector plays a crucial role in controlling the material. Several important industrial robotic fabrication parameters were investigated, including industrial robotic working area, start-up position, their arrangement in space, distance to the extruder machine and nodes. The setup of those parameters, which needs to be designed beforehand, is called the robot's "choreography". The choreography of the fabrication in this research was first determined digitally using 3D software Rhinoceros.

3.4 Fabrication Process

To proof our concept, we fabricated a 1:1 prototype at Robofold I.O in London, where a 1.5 m tall column was fabricated in two pieces and joined manually by welding. The whole fabrication process was automated, except for the freezing spray, as shown in Figure 8. Prefabricated nodes, consisting of tetrahedrons made from polycaprolactone, sit in a predefined location on a moving belt. The robot was autonomously programmed to pick through the tetrahedron-node pulling end-effector to the extruder machine. The extruder machine then prints the melted mass on the tetrahedron node surface in a controlled temperature to ensure that the right viscosity is met, in order to achieve the structural integrity of the material. The industrial robotic arm then picks the node with the freshly printed material while it is still hot and adheres it onto an assigned point of the beam growth, while pulling it at a predefined speed and angle. The integrity of the lattice structure is adhered, by maintaining the temperature of the material being extruded, and the accuracy with which the robotic arm is capable of controlling the speed and angle of the extrusion. This process is repeated as required by the design to complete the lattice units, and the corresponding meeting surfaces will be joined on site. The whole fabrication process is intended to happen in a standard size truck with the material supply on board, so that it can happen on site to minimize the transport of the fabricated units. Once the use of the structure is over, it can either be shredded and re-fed to produce another configuration, or just left to biodegrade.

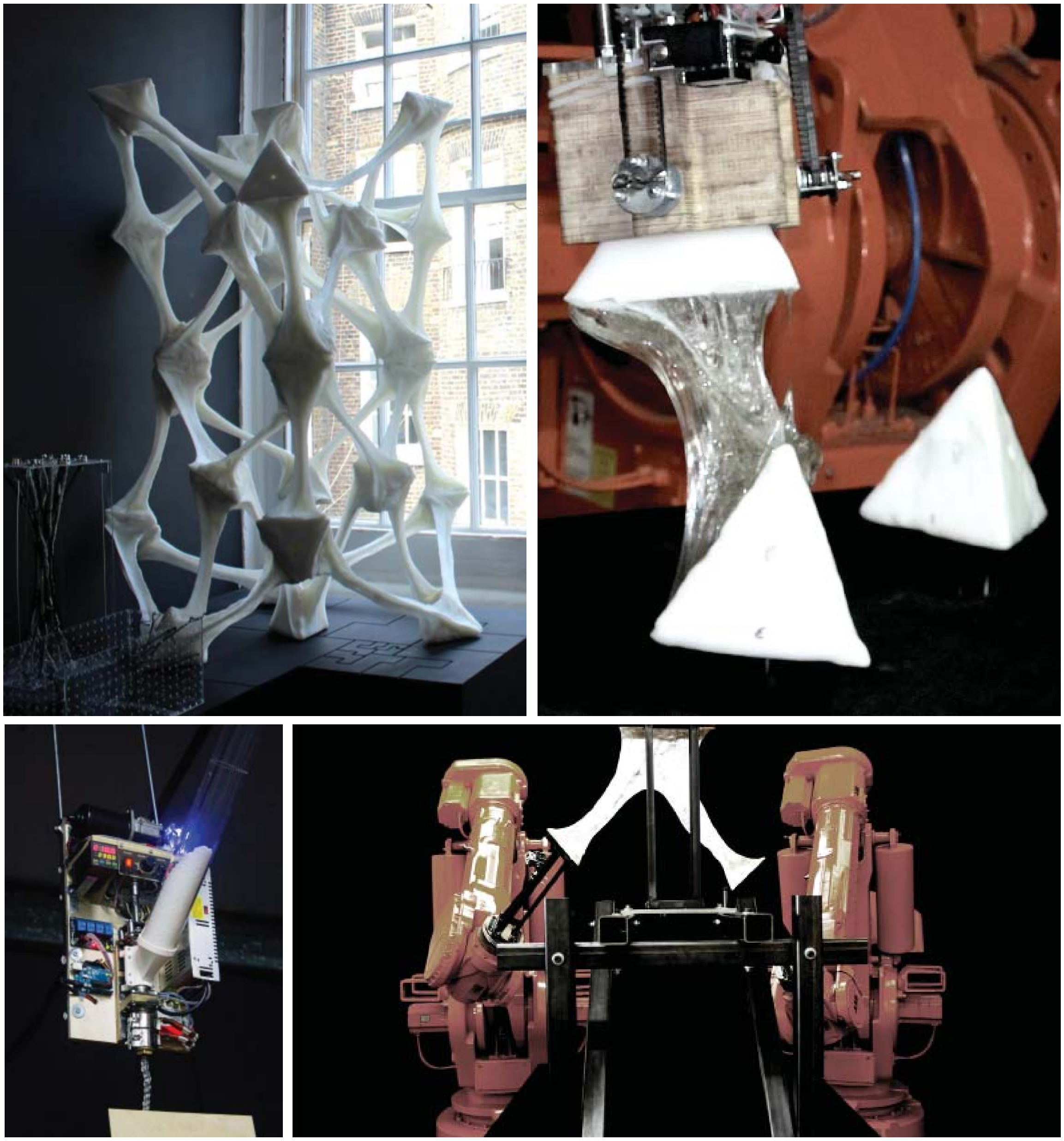

Figure 8: Prototype fabrication proof of concept at Robofold I.O. *Courtesy of: AADRL.*

4.0 RESULTS

4.1 Optimal Scenario

The materially driven fabrication system discussed in this research article presents a fabrication process that is fully automated in a controlled cell, where different parameters play a big role in the fabrication of the desired geometry. Our system uses prefabricated polycaprolactone nodes, currently in the shape of a tetrahedron. The results offer a fabrication process that builds upon material programming of a bioplastic, while being challenged to produce a 100 percent reused and biodegradable temporary structures using two industrial robotic arms that can be choreographed to control the pulling angles, speed and temperature. The proposed optimal fabrication scenario takes place in a standard mobile cell with two medium size industrial robotic arms facing each other 1.3 m wide, as shown in Figure 9. These two robots share a rotating table in the middle and two extruder machines on either side in the center. As one robot pulls the viscous 3D printed mass, the other freezes.

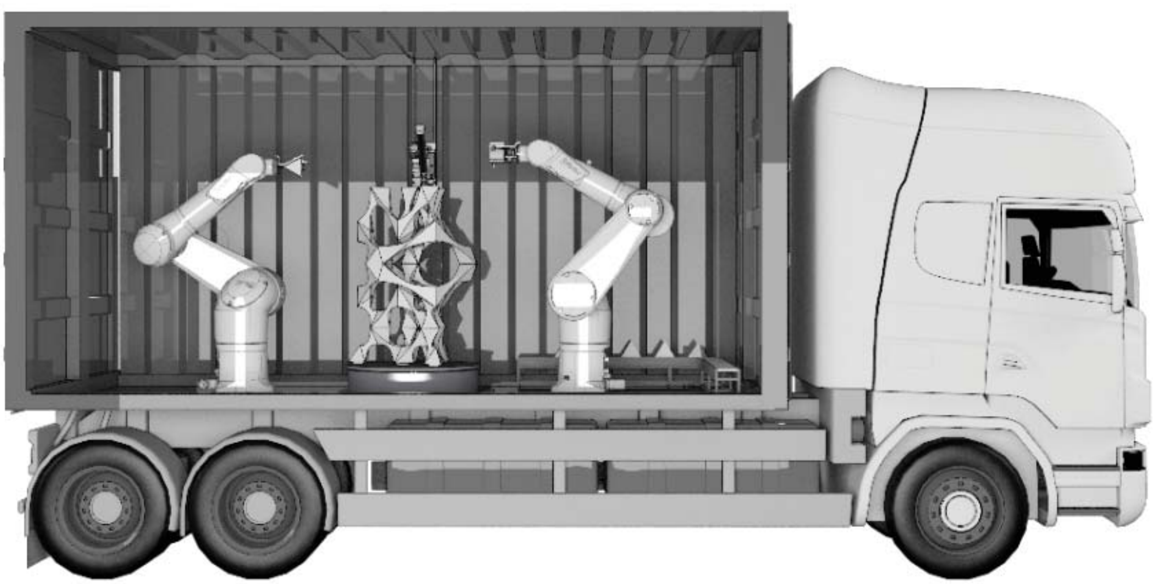

Figure 9: The proposed fabrication scenario. *Courtesy of: AADRL.*

We considered Covent Garden in London as a site to propose a temporary structure, which would act as a Market Pavilion. Circulation study diagrams were conducted, where a 2D tensioned mesh was populated with the pattern growth, then relaxed in 3D to redistribute all the forces to reach an equilibrium. To maximize the performance of the beams into different directions in space, it was necessary to study the maximum angles that the material can stretch before losing its structural integrity. Taking in consideration the normal of each face of the tetrahedron, which is the optimum extrusion, a 45 degree of tolerance was established in between each X, Y and XY axes from the normal. The result of this definition is a volume enclosed by tetrahedron structure, as seen in Figure 10.

Figure 10: Covent Garden as a case study. *Courtesy of: AADRL.*

5.0 CONCLUSION

We presented a materially-driven design process and a unique fabrication methods, which uses robotic manufacturing process for creating bioplastic structures. This approach offers an innovative, environmentally-friendly approach to temporary architecture. Due to the pulling technique of the bioplastic while still in its viscous state, the surface tension of the material causes the pulled structure form to be affected by its base. Therefore, it was concluded that the triangular base gave the best structural stretched beam resulting in a three star middle section. Triangular faces of the tetrahedron nodes were used to print the hot plastic and create a three dimensional lattice network. As a result, precision in melting and pulling the plastic in space is essential to achieve structural characteristics. Therefore, through designed choreography, industrial robotic arms were used to control the pulling speed and angles, along with two pulling end-effectors and a custom-built extrusion "3D printing" machine. Polycaprolactone is a biodegradable polyester used as a prototype material in this research, but any other plastic with similar characteristics can be used to achieve similar results. In addition to the material being biodegradable, the crucial properties of the material are its ability to have a fairly low working temperature and it being self-bondable which enable the creation of joint-less single material structures. By only varying the amounts of melted plastic and pulling lengths, different thicknesses and densities can be achieved to respond to various functions or structural requirements within a single unit. A 1:1 150 cm high column was fabricated using two robots as a proof of concept prototype, using two pulling end-effectors mounted on the industrial robotic arms and a fixed extruder in the middle reachable by the two robots. These structures can vary in usage from pavilions to temporary kiosks (pop-ups), or even scaffolding. Applications of the design can vary in scale and function, from lightweight dense panels to more porous large structures.

Acknowledgments

The authors would like to thank individuals who helped inform and guide this research, and for their collaboration and contribution to the research work presented in this article, as well as the Architectural Association Design Research Laboratory.

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03.
CRAFTING ARCHITECTURAL EXPERIENCES:
Exploring Memory Places

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ABSTRACT
This article discusses the importance of perception of spaces, and involvement with spaces during the design process. Over the last decade, mapping the relationship of architectural spaces to human experience has become popular as a successful design methodology. The beginning phase of the design process is characterized by perceptual integrity; unfortunately, this integrity often fades away or is even eliminated once the spaces become real and occupied.

The availability of advanced visual representation techniques has created a realistic clarity of visual experience in space. However, emphasis on the visual has resulted in the possibility that other sensory modalities will be ignored. The goal of the craft of architecture as a profession is to create experiential qualities. If well designed, an architectural space can effectively shape experiences and evoke feelings. This paper focuses on design processes and outlines a series of phenomenological arguments that arise in contemporary architecture. These arguments are presented through literature reviews, theoretical interpretation, and the building case studies that support findings. The purpose of this paper is to clarify the importance of imaginative perception in architecture, and to demonstrate how ideas are developed for the creation of impressive architectural spaces.

KEYWORDS: experience, memory, imagination, perception, design process, interstitial

1.0 INTRODUCTION:
The power of architecture as a practice lies in the impressiveness of the experiences that it shapes. Architects arrange spaces and create physical and cultural environments that we, as users, constantly interact with. We nurture our perceptions, memories, emotions, and feelings through our constant engagement with our environments. Our embodied experience of the world around us does not depend solely on the interpersonal relationship of our bodies to our minds; equally important are the atmospheres that we engage with. It is obvious that walking into the heavy and dim atmosphere of a cave temple gives a different effect than does being in the bright and airy interiors of a Gothic church. What we experience in these different environments is dependent on the moods that they evoke.

The intention of architectural design is to bring about complete satisfaction in users' experiences of spaces. In order to design with a specific effect in mind, architects should identify and perceive the experiential quality of spaces early in the design process. Quality and craftsmanship in a work of architecture must be thoroughly concerned with the quality of spatial experiences. We often admire a work of handicraft art for the practical skills involved in its creation. However, a piece of fine craftsmanship also involves the abstract quality of artistic talent. Similarly, the craft of architecture is not just about writing specifications to set up standards of quality for the construction of a project. Craftsmanship in architecture also involves creativity and the imagination of the architect. Architects imagine the experiential quality of spaces and articulate them by utilizing aspects of sound, light and color. To put this in another way: Architects craft spaces through perceiving the qualitative dimensions of experiences.

Perception of an object, and equally of an experience, only occurs once our mind assembles the related memories associated with these objects or experiences[1]. When architects seek to evoke experiences of space during the design process, they engage their memory to recollect spatial qualities that had previously been recognized and recorded. Theorists and scholars of philosophy see memory as a power of the human mind with two dimensions: natural and artificial. Frances Yates said that our artificial memory seeks to memorize through a method involving impressive places and images[2]. We comprehend architecture through our remembered spatial experiences. A memory of our interaction in space may "inspire" an idea or understanding of a complex concept that we had already experienced in the past.

This paper discusses the importance of the "inspirational mind" for architects during the design process as they attempt to create impressive architectural spaces. It includes a literature review that evaluates the qualitative dimension of architectural spaces. It also examines four selected case studies to demonstrate how the creative minds of architects have mediated the set of processes involved in design.

2.0 OBJECTIVES

Our knowledge about the overall quality of architecture is often restricted to functionality, planning principles and technical conditions of the buildings. When we praise an architectural design, we immediately admire all sorts of theoretical and practical values, but hardly ever recognize the emotional quality involved in the entire process of architectural design. The power of a good architectural design lies in both its technical values and in the elusive qualities of creativity and perception. This article highlights the importance of considering the emotional qualities of architectural spaces, and of doing this early in the design process. This aspect is critical because "emotion" is the multisensory medium through which we experience the world and equally the built environment[3]. This paper aims to highlight the importance of the sensory aspects of the design process, and how these aspects should be prioritized by architects in order to create architectural spaces with emotive experiential qualities.

Understanding the concept of "experience" and "experiential quality" involves a comprehension of human nature and its role in appreciating the quality of architectural spaces. The following section reviews the research methodology.

3.0 METHODOLOGY

This paper's research methodology involves a literature review, as well as an examination of building case studies. The collected works reviewed in this paper include theories related to memory, perception and imagination, and focus on the subject of phenomenological approach in architectural design processes. The arguments presented here derive from interpretation of findings from case studies, and use supporting literature to tie them to theory.

A literature review examines existing theories and gives insight into the potential role that re-imagining experiences can play in creating architectural spaces. This section is structured as follows: initially, it provides a brief chronological background study of the tension between the human body and mind, and architectural spaces. Subsequently, it reviews qualitative dimensions of human experiences and explains how they make architecture meaningful. The last part describes the importance of memory and of the perception of users' experiences during design processes in the creation of "memory places". For the purposes of this paper, the term "memory place" refers to an architectural space with memorable spatial qualities.

The case studies presented in the last section deal with two different concepts of "memory places": first, the concept of a memorable place as a highly stimulating environment that challenges users to come to terms with the intensity of their experience; and second, as a comfortable atmosphere that provides users with a sense of relaxation and sociability. The review of selected projects elucidate the argument that the purpose of the built environment is not merely to provide for the physical needs of users, but also to satisfy their psychological needs. The literature reviews presented in this article suggest that a profound architectural design provides more than merely accommodation and can help shape and represent our experiences of life and human existence. The act of representing spatial experiences before a building comes into existence involves approaching the design process with imaginative skills, as architects cannot evaluate experiential qualities without first being able to predict their effects and outcomes.

The four selected building case studies are presented to measure the potential benefits of involving the "imaginative mind" in the perception of spaces in architectural design processes. These case studies illuminate the importance of thinking about the living qualities of spaces very early in design explorations. What these four examples have in common is that, in the very early stages of design processes, the architects questioned the basic form and content of space from the perspective of users' experiences. In all examples, a series of imagined experiential qualities leads to the design of spaces that are more than just physical structures: they are places that affect the existential sense of users by engaging multisensory perception.

The case studies selected for the purposes of this paper consider users in the center of experiences and demonstrate how physical architectural spaces can be turned into lived spaces. The architects referred to in the examples take the experience of people as a starting point for the perception of quality of spaces. Quality indicators that are measured in case studies include spatial configuration, tension between interior and exterior, material compatibility and textural effects with respect to light, color, scale and proportion of the space.

All the buildings presented together constitute a special category in that they communicate with viewers, residents, and visitors. However, there is no common denominator for spatial qualities that can be applied to all the buildings. Each building presented in this paper has its own individuality and presents a unique experience.

4.0 ARCHITECTURAL EXPERIENCE AND HUMAN PERCEPTION

4.1 Body, Mind, and Architecture

The world is defined through the constant involvement of perception. Its subjective character derives from the projection of our body's image onto it. Throughout history, from the Renaissance to Post-Modernism, there was always a mysterious connection between the human body and architecture[4] (Figure 1). This section briefly reviews this relationship and explores the mental essence of architecture.

Until the Renaissance period, the main intellectual task of architecture was to mediate between the whole (macrocosm) and the part (microcosm). In the words of Rudolf Wittkower: "With the Renaissance revival of the Greek mathematical interpretation of God and the world, and invigorated by the Christian belief that man as the image of God embodied the harmonies of the Universe, the Vitruvian human figure inscribed in a square and a circle became a symbol of the mathematical sympathy between microcosm and macrocosm"[5]. During the Renaissance, the body became a direct projection onto a building; the body was perfection like the Vitruvian Man. Throughout the Renaissance, the celebration of the human body's relation to structure was continued and developed until it became a more involved process[6]. For instance, the projection of the body onto a building and the identification of the soul with the body's center of gravity were concepts found in the work of Francesco di Griorgo's Trattati di Architecttura[7]. Likewise, the 15th-century Italian architect Filarete explored voids, deep spaces and entrances by studying the body as regards its relationship to structure in order to create a more refined atmosphere[6].

Correspondingly, the architecture of the modern period was no longer a simple representation of bodily proportion and functions. During Modernism, the critical analysis of the formal qualities of Vitruvian man incorporated the presentation of sensation and movement in architecture. An example of this abstracted movement is found in Marcel Duchamp's Nude Descending a Staircase. The body in Marcel Duchamp's artwork communicates another language that is not static but dynamic[6]. In fact, the modern period realized a change in architectural theory and incorporated the concept of the body's sensations and movement into the design process.

During Modernism, the human body was understood as a combination of life and geometry, and human existence became a major inspiration in the expression of the quality of life and experience in architecture. Twentieth-century thinkers, such as Frank Lloyd Wright and John Dewey, explored the importance of "embodied experience" in architectural design and education. Wright believed that an experiential foundation was important in learning and practicing architecture. The idea of "to learn by doing", a driving principle for wright's Taliesin school of architecture, was an interpretation of Dewey's philosophy of "embodied experience"[3]. Furthermore, Richard Neutra, in his book *Survival Through Design*, talked about architecture that is more about people rather about buildings. He explains how architecture can bring man into harmony with nature and with himself. Neutra is known as an early proponent of the application of human biological and psychological needs to architectural practice[8].

Subsequently, during Post-Modernism the principles gleaned from human bodily experience projected a sense of aliveness onto architectural spaces. In Post-Modernism, the body is transformed: it is studied as fragmented and reformed; and designs are based on such bodily aspects as perception and consciousness. Likewise, a number of known contemporary architects like Tadao Ando have manifested corporeal experience in architecture. The importance of the empty cross in Tadao Ando's church of the light, built in 1989, involves the Shintai – a Japanese word for a living body. According to Japanese cultural tradition, Shintai surpasses the limits of sensation. The empty cross integrates natural light as an iconic representation of the standing body as an intangible reality[7]. Using the human body as analogy, Ando expresses a new meaning of light, gives it sense and makes it come alive.

Zumthor's Thermal Bath at Vals, in Switzerland, is a manifestation of architecture as a spatial art. Its spaces create a temporal feeling and produce a sense of freedom of movement for visitors. Zumthor imagines himself walking in space as if he is designing a stage setting and directing a play. His creative imagination follows the laws of sensual experiences: the Bath at Vals provides visitor with the opportunity to experience an exploration of known or unknown places just like as Zumthor himself did when he imagined himself strolling in space.

"Motility of the body in space" is an expression used by the contemporary American architect Steven Holl. He explains that space is defined through the body's movement within it. In his book *Parallax*[9], Holl explains that the spatial awareness of the body represents a fundamental quality for creation of architectural spaces. In his design of the Helsinki Museum of Contemporary Art, Holl has, by means of various design experiments, investigated different spatial perceptions for the moving body in an architectural space. For the museum design, Holl created perceptions of those spatial qualities that visitors in motion will experience.

The term "experience" is often used in contemporary architectural practice to express users' understanding of architectural spaces. Architects should question themselves early in the design process as to who the users will be and what they will want to experience in the created space. To achieve emotional quality in design, it is important for architects to keep questioning spatial qualities and imagining users' experience in space. This applies to all stages of the design process. Pallasma refers to Merleau Ponty's theoretical work and highlights architecture's ability to define spaces and to give them meaning:

"Lived space is both the object and context of the making of art as well as of architecture. The task of architecture is 'to make visible how the world touches us', as Maurice Merleau-Ponty wrote of the paintings of Paul Cezanne. In accordance with Merleau-Ponty, we live in the 'flesh of the world', and architecture structures and articulates this existential flesh, giving it specific meanings"[10].

To give "meaning" to an architectural space, we first must identify the qualitative dimensions of the embodied experiences of that space. Pallasma says: "Architectural quality cannot be derived from a formal or aesthetic game; it arises from experiences and an authentic sense of life"[10]. He suggests that the quality of architecture derives from the quality of the experiences that it shapes. In an effort to understand the qualitative dimensions of those atmospheres that our bodily nature interacts with, the next section identifies some fundamental recurring structures within our cognitive processes that form patterns of understanding relevant

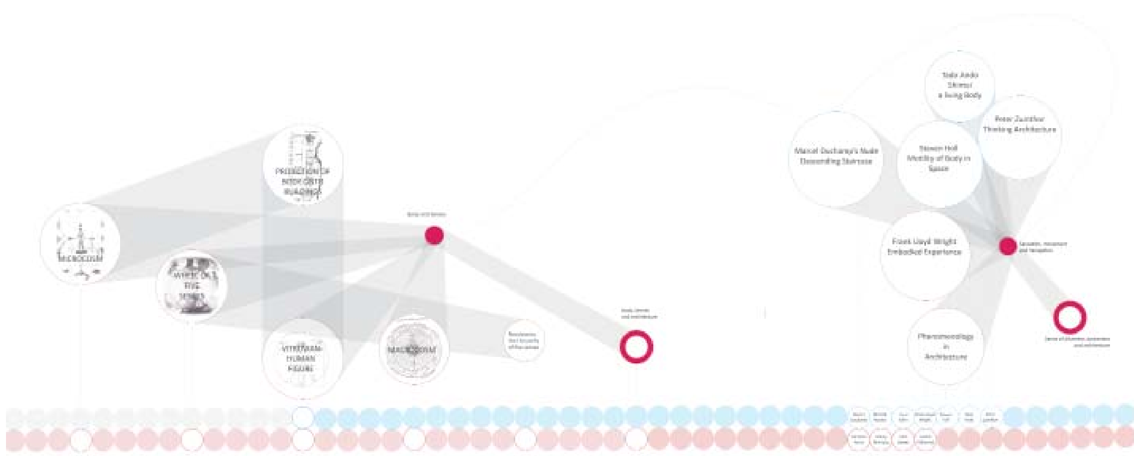

Figure 1: Body and architecture – 13th century to present.

to architectural spaces. The following accounts help us understand how and why architectural spaces can affect our human nature.

4.2 The Qualitative Dimensions of Architectural Experience

The act of "crafting" requires specific skills and knowledge on the part of its creator, as does architecture. Crafting architectural spaces requires architects to enhance their knowledge regarding the qualitative dimensions of the embodied experience. It also helps them hone their skills for the inclusion of the human dimension in their designs. The attempt to manifest architectural spaces as "lived" spaces arises from the fact that architectural spaces can act upon users by affecting their feelings and sensations. Pallasma refers to Louis Kahn's works and identifies them as buildings that are not "metaphysical symbols" but that are, rather, "a form of metaphysical meditation through the medium of architecture". The term "meditation" here refers to an inner exercise, which in words of Pallasma "leads us to recognize boundaries of our own existence and to deliberate on the essence of life"[10]. This concept of meditation suggests an inner experience of architectural spaces, one that cannot be achieved by the symbolic use of values, but rather by promoting a specific way of perceiving these values.

In order to develop a framework for understanding how humans perceive qualities of architectural spaces, we need to become familiar with the roles of our "emotions", our multisensory media, in understanding a situation or experience. In Renaissance times, five senses were introduced and formed in a hierarchical system. These senses were understood in relation to the universe. Vision was linked to light and fire, hearing to air, smell to vapor, taste to water and touch to earth[11]. However, giving a ranking to human sensory systems based on their importance or effectiveness does not fit into an interpretation of that perceptual quality by which we recognize the world around us. Pallasma suggests that "an atmospheric perception involves judgement beyond the five Aristotelian senses, and would include the sensations of orientation, gravity, balance, stability, motion, duration, continuity, scale and illumination"[12]. Pallasma refers to Merleau-Ponty's emphasis on unity and interaction of senses, and recommends that "the immediate judgment of the character of space and calls for our entire embodied and existential sense".

In fact, Pallasma's criticism regarding the isolation of senses notes that experiencing architecture involves an embodied and unified realization of sense and quality. Walking through the quaint streets of an old city, we may immediately feel a mystic atmosphere developed from a multi-modal reflection on our experience. We feel the rough patterns of paving stones, the warmth of the sun, the smells of aromatic herbs, the weightiness of ancient stone walls, the sounds of our footsteps, the chatter of the locals, and countless other factors that, when taken together, create an overall atmosphere.

It has been suggested that the human ability to experience, create and share meaning is not just an outcome of our bodies and minds, but rather is dependent on the quality of the environment that we interact with. It is through our bodily and cultural interactions with the physical and cultural environments that our experiences become meaningful and significant. The senses of orientation, balance and motion are initially formed from our bodily interaction with the environment around us. For instance, our sense of orientation is developed through our understanding of gravity. It is through this sense that we understand that the act of rising up involves power, strength, and balance. The motion of rising up itself makes us aware of our bodily movement. We feel our own rhythms in various movements, we feel the difference between gradual accelerations and deceleration and eventually we develop an understanding of "perceptual motion" in a physically static arrangement[3]. An example of the "perceptual motion" experience can be seen in Marcel Duchamp's Nude Descending the Stair Case, which conveys rhythm and an illusion of movement through demonstration of an abstract movement of the body parts.

In the same context of perceptual quality of an experience, empathy is one of our functional capacities that allows us to understand and share the feelings of others. It is empathy that enables us to recognize a work of art and to perceive the experiencing of architectural spaces. A sense of "empathy" can be fused throughout practice and experience[3]. All types of experience would involve the three components of attention: recognition, forming memories, and the ability to recall information[1]. It is through the senses of empathy and memory that we identify ourselves with a place and a moment[11]. In memorable experiences of architecture, the quality of space matters immensely. In order to achieve this quality, architects must imagine spaces during the design processes, and fuse them with felt experiences.

4.3 The Memorable Dimensions of Architectural Spaces: Exploring Intervals

If we question the quality of architectural experiences in regards to how they define the emotional characteristics of spaces, we must also consider what settings are required for the shaping of memorable conditions. As Rasmussen states, the architect is a kind of theatrical producer; at the beginning of design process, the scenario is usually incomplete. The architect plans the settings and articulates them during design processes to find the missing parts and to reveal the “transitions” between the parts[13].

The living quality of the built environment is lacking if it is designed based on external appearances. The practice of architecture should reveal interior voids and manifest their potential as *intervals*. Many interpretations throughout history have classified architecture along with sculpture and painting as one of the fine arts. However, architecture is not simply produced by manipulation of external appearances, such as form. It is a functional art that shapes the forms around our bodies. An architectural design creates “interstitial” spaces between the human body and the material body of structure. The art of architecture has the power to reveal interior voids and to manifest their potential as *intervals*.

We may need to ask what “interval” or “interstitial” means in terms of experiencing architectural spaces. The term “interstice” refers to an intervening space, or an interval between parts. Interstitial space can be recognized as a borderline between two contrasting aspects. It can represent various types of oppositions, such as multiple and zero, solid and hollow, sound and silence, positive and negative. An interstitial space can signify juxtaposition and it can be a midpoint between two opposing factors. Frances Yates in her book, *Art of Memory*, refers to *intervals* as one of the rules that helps us remember places[2].

The recent neuroscience engagement with phenomenology has resulted in the introduction of a software to measure the responses of the brain, mind and body while they are interacting with a full-scale virtual or physical model of a building. In relation to the discussion of intervals, it is useful to refer to a neuroscience experiment that tested the role of “cues” or “wayfinding strategies” in the memory-forming process. In this experiment, brain activity was documented while participants moved through a full-scale, immersive three-dimensional virtual environment. The methods included two different experiential conditions: one with “no prominent visual cues” and the other with “rich visual cues”. The results of the experiment suggested that brain dynamics are dissimilar under each of these differing conditions. As described by the researchers, “in the case where obvious cues were not presented the subject looked for any distinguishing features that might indicate location, including shadows around doors, or patterned finishes. This suggest a continuum of cue effectiveness dependent on the surrounding context and the opportunity to repeatedly search for cues”[15]. Human beings unconsciously notice changes and differences between things. It is humans’ ability to identify the transitions from one thing to another that enables us to understand the relationship between things. Architecture holds the power to make these transitional experiences so exceptional that they will never be forgotten.

In this context, and by means of recognizing the design intention that seeks to provide participants with a memorable spatial experience, a question to take into account is how much a static grid-based space can facilitate such objection. One of the traditional scientific accounts of spatial perception is Descartes’ Cartesian philosophy. According to Descartes’ hypothesis, spatial perception is achieved by presuming a given space, and it is understood by reconstituting measures of that given space. Descartes’ explanation, along with his analysis on Cartesian geometry and coordinate system, ties the two-and three-dimensional understandings of space together by using geometrical inferences. A Cartesian mind can comprehend a three-dimensional space from a range of recognized two-dimensional facts[16]. This geometrical-based strategy relies on flat images and on the mind’s presumption of the three-dimensional space. Does this approach deny the living experience of space? Does it disregard the living energy of the body - the “perceiver”? In a similar manner, do conventional architectural spaces designed based on Cartesian grid neglect the body and the tangible dynamics of lived space?

Traditional architectural spaces usually have a common concept of separation between floor plan, structure and skin of buildings. In conventional architectural designs, the structural grid often outlines a predetermined rule in defining exterior and interior spatial experiences. Does such an approach render built spaces flat, immaterial and unreal? The answer to this question depends on the approach taken during the design process. Taking a phenomenological approach in considering the experiential quality of spaces throughout the design process can help architecture to create emotions and to change the way we experience spaces. A phenomenological approach suggests that experience of spaces is naturally rooted in our bodies’ movement, and therefore perceiving a built space is a practice in living, not in a geometry or Cartesian Grid[16].

There are many contemporary architectural practices that intend to soften and emotionalize the architectural perception of spaces by challenging the conventional concepts of pre-determined architectural grids. Their level of success will depend on the approach taken during the design processes. There is a common design intention for all architectural projects that involve phenomenology, and that is to reflect the ideas and senses of life. Common in all case studies selected for the purpose of this article, is the creative approaches that the architects take in understanding the interplay between experiential phenomena and design intention. In the following sections, projects are presented not as wholes, but as a series of partial experiences. Discussions are organized thematically according to the concept of intervals and interstitials. The following project examples confirm that if human experience is the architect's initial design inspiration, the spaces can come alive for the visitors, much as they were initially envisioned in the imagination of the architect.

5.0 CASE STUDIES

5.1 Case Study 1

The Light Pavilion, Chengdu, China
Lebbeus Woods, 2012

Lebbeus Woods challenges conventional concepts of pre-determined architectural grids in order to create impressive spatial experiences. In the design of the Light Pavilion, in Chengdu, China, Lebbeus Woods brings an intervention or relief for the existing grid-based buildings. Like most of the Lebbeus Woods' proposals, the Light Pavilion is an experimental space. The installation's irregular form is set against regular rectilinear architectural geometries to create a moment of exception (an interval) in structure (Figure 2). The pavilion provides opportunities for users to experience new and unfamiliar spatial qualities.

The original renderings illustrate a dynamic quality; the illuminated supporting columns for the stairs and viewing platforms have a non-rectilinear grid, which frees the space from the conventional static stability of architectural settings. The irregular geometry of the columns, their change of scale, and altering orientation, in combination create an effect of motion in space. The drawings propose a sense of tension and edginess. Just as it was initially intended by the architect, the Light Pavilion is a presentation of something unknown. It is up to the visitor to explore the experiential potentials hidden in each moment of transitional spaces. As we climb up the space, the voids turn to solids and vice versa. Walking up the staircases, the columns open or enclose the views from one side to the other (Figure 3). Parallel to the architect's original design intention, the act of moving up the stairs to create a new orientation evokes our consciousness. Woods and Kumpusch describe the Light Pavilion as an example of experimental architecture, and by that they mean architecture that invites people in and encourages them to explore[17]. The Light Pavilion clarifies their preliminary design concept for creating architecture that is undecided, unrestricted, experimental and exploratory.

In the Light Pavilion, what visitors experiment is a series of progressively increasing or decreasing differences as they climb up or down the stairs. The unbalanced structure of the Pavilion invites visitors to participate in the space, engage and experience it. The spatial and temporal contrasts of the structure are so strong and sharp that they stir the visitors' minds, awake their memories, and evoke their emotions (Figure 3). The architect achieved striking moments through the use of irregular forms, in accordance with Quintilian's description of memorable places. He said that in order to shape a series of places in our memories, a building must be able to evoke various memories[2]. The preliminary sketches of the pavilion suggest a very distinct and experimental space, leading visitors to experience it with a strong awareness of contrast. The Light Pavilion creates a *memory place*. When we see ordinary things in our everyday lives, we usually fail to notice and remember them. To remember things, our minds must be inspired by something novel or marvelous[2]. The novel and marvelous experiences in the Light Pavilion are achieved by the use of irregular spatial qualities within the regular spatial quality of the Cartesian Grid.

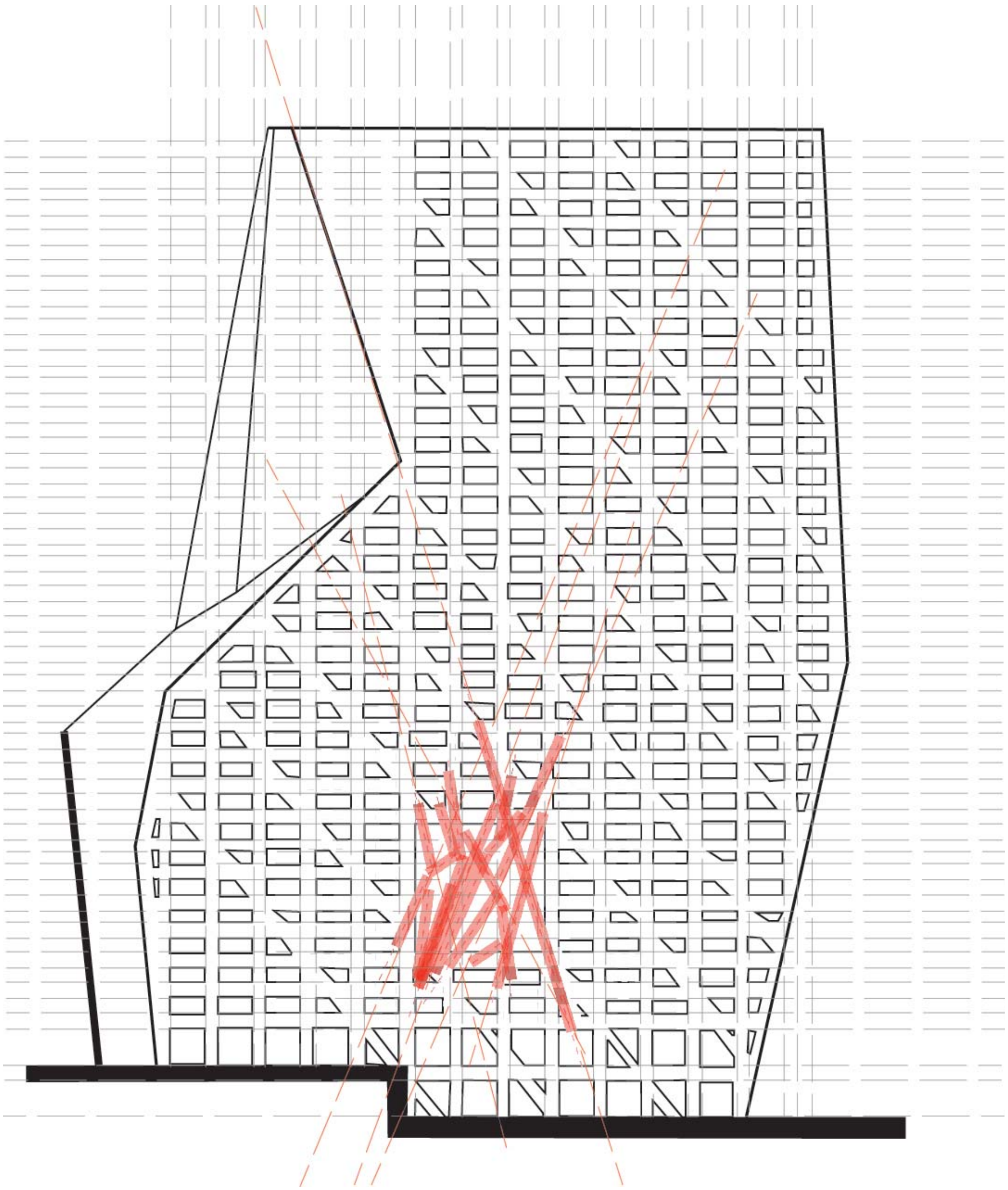

Figure 2: Elevation view, installation's irregular form set against regular rectilinear architectural geometries (derived from initial design process sketches).

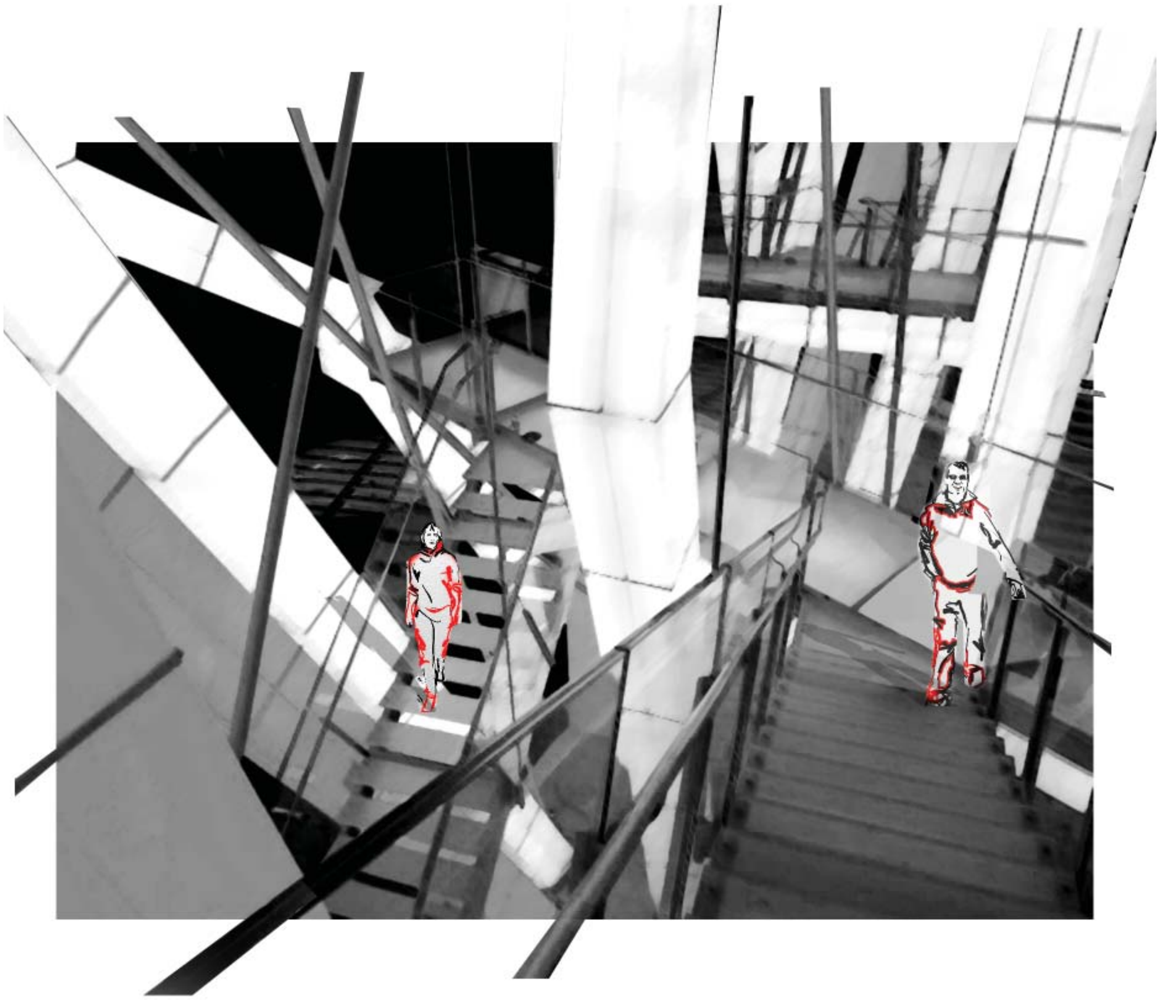

Figure 3: The Light Pavilion, an interior view.

5.2 Case Study 2
Thermal Bath at Vals, Graubunden
Peter Zumthor, 1990 – 1996

"The stone rooms should not compete with the body, they should flatter it and give it space."[18]

As opposed to Lebbeus Woods, Zumthor's creative imagination follows the laws of ideal geometry, but remains very complex with many layers of transitions (intervals). The design approach for Therme Vals expresses the notion of architecture as not being mainly visual. Throughout the whole design process journey, the architect takes a multisensory design approach in order to create a series of experiential intensities. With the focus on sensual experience, the Thermal Bath at Vals provides the opportunity for visitors to experience their own exploration of known or unknown places. In the previous case study, the Light Pavilion provided an *interval* through the inactive geometry of Cartesian grid in an attempt to enhance experiential qualities of the built spaces, whereas the Thermal Bath at Vals presents a different level in its representation of *intervals*. The experiential intensities are expressed through *transitions* between two opposing qualities; light to dark or sound to silence. The bath's mystical use of materials and its sensual architectural experiences contribute to making it a masterpiece.

In this design, Zumthor's methodology engaged a phenomenological approach in the very beginning of the design process. As Zumthor explains, the process of design for Therme Vals was a "playful but patient process of explorations."[19] The experiential qualities of spaces are a vibrant showcase for Zumthor's fantastic imagination during the design process. Right from the start, he conceived a scenario that gave particulars to the scenes, characters, situations, etc. The series of preliminary sketches show a mysterious journey of design explorations accompanied by the perception and visualization of physical events. The methods used in the entire design process of the bath are perfect examples for the Merleau-Ponty's definition of "perception", which includes the act of imagining and remembering[20]. The sensory animation of the *memory places*, developed throughout the design process, is an outcome of the imagining and remembering of the heritage of bathing complexes built by the ancient Romans.

A pure geometric pattern was initiated to define spaces. These spaces included the block spaces accommodating the baths, as well as the interconnected web of interstitial spaces between them. The initial sketches make clear that the bath should be conceived in terms of both blocks and interstitials (Figure 4). In a series of preliminary floor plan sketches, the voids between the blocks were recognized as moments of transitions: hot to cool, dark to light (Figure 5), sound to silent. While working on the design, the interstitials were conceived as potentials to create transitional moments in between contrasting experiential qualities[18]. Throughout the design exploration, the free configuration of the blocks continually became broken in pieces and arranged in a different way. Zumthor perceived each space in tight relation to its neighbor. Each programmed block expresses an extreme experiential quality, which is heightened through its proximity to a moment of pause or relief. The informal and tension-free quality of the voids between the programmed spaces prepares the bathers for the next experiment on their journey of explorations.

Frances Yates, in her book *Art of Memory*, refers to spaces between places and to five rules for remembering them. She explains the importance of these interstitial spaces as "pausing for reflection"[2]. The elaborate spatial design of Bath at Vals follows the same phenomenological rules, and provides a balance between tension and relaxation.

The building interprets the existing presence of the mountain and eventually becomes part of it. The totality of the building creates a powerful connection to the site, which mediates between the bodies of the bathers and the natural context of surrounding. One of the most impressive experiences happens at the connecting point between the inside pool and the outside pool. A visitor can swim through an opening in a large glass wall and suddenly encounter a mountainous climate and alpine conditions. Here the bather's body is put through a tension between interior and exterior. The interior experience that the bather got through--the humid and misty environment with "atmospheric illumination"--is now challenged by the bright, cool and crispy atmosphere of the mountain. The sudden change in temperature, light, sound and views, in conjunction with the close proximity of the bather's body to nature, creates an extreme experiential quality.

When one arrives at the bath, the entire journey from the entrance to the internal spaces is a continuum of sensual experiences. The consistency of the material between interior and exterior intensifies the continuality of the building as whole. As Zumthor explains, "the exterior of the building, the large stone block protruding from the mountainside, evolved and acquired its form from inside out"[18]. In the design of Thermal Bath,

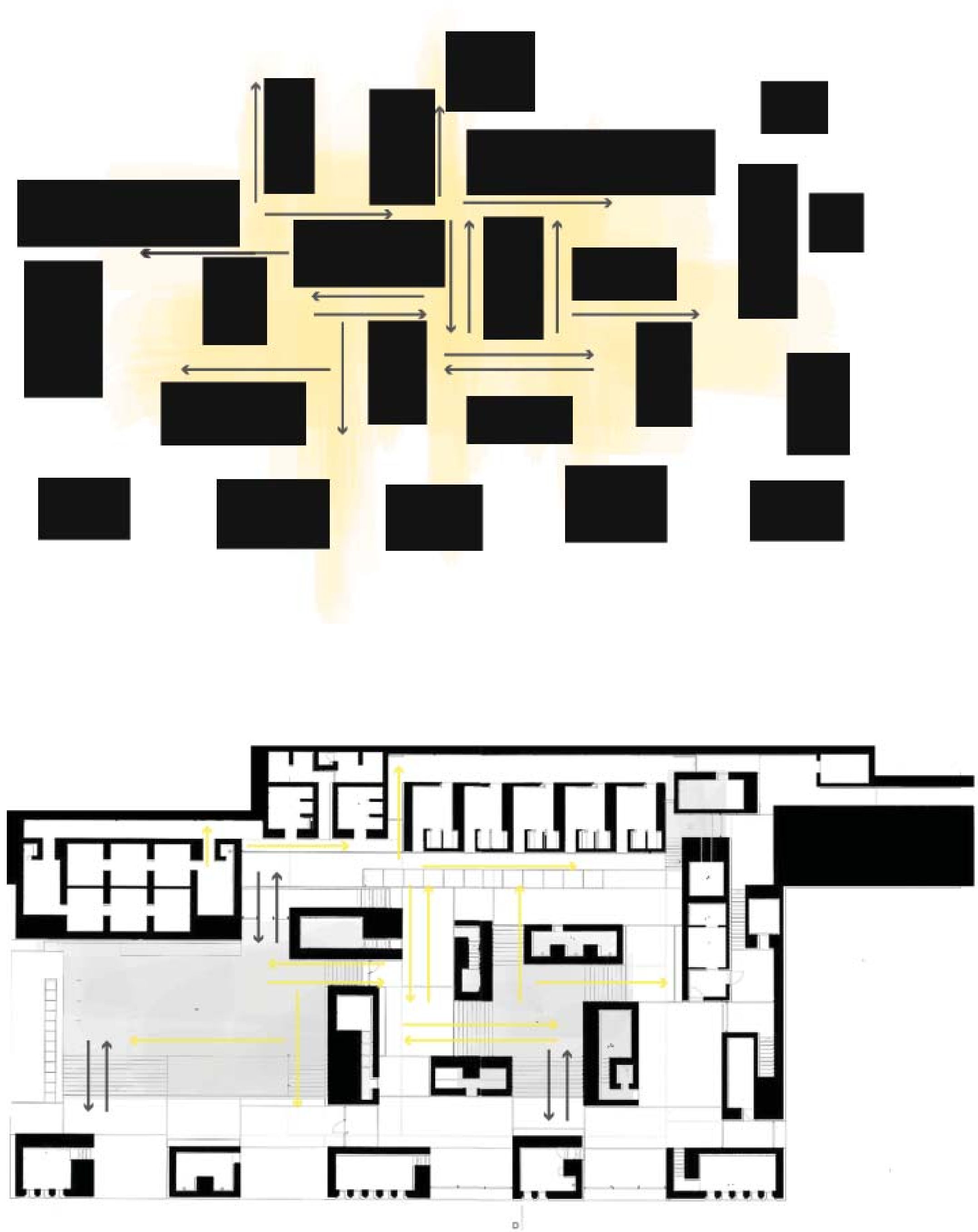

Figure 4: Preliminarily block studies, derived from early design sketches.

Figure 5: Thermal Bath at Vals, showing the void between the blocks.

the architect did not work on form to create spaces. Instead, the design process started with the understanding and perceiving of spaces in all their experiential qualities including sound, light and materials – all of which generated the building form. The power of design for the Thermal Bath derives from its manipulation of spatial qualities, through which it influences the bather's experiential qualities.

5.3 Case Study 3

Kiasma Museum of Contemporary Art, Helsinki, Finland

Steven Holl Architects, 1992-1998

The Kiasma Museum of Contemporary Art reveals Holl's distinctive approach in putting forward experimental designs within a phenomenological framework. The Museum represents an exclusive articulation of spaces, forms, and details an attempt to create particular experiential qualities in a continuum of linked spaces. The museum is located at the center of the city of Helsinki, a very important urban site. The design concept was developed through various levels of study and experiments. The very first step for the design process included in-depth research of the site, its context and its history. The accumulated information concerning the site was accompanied by an understanding of the purpose and perception of the experiential qualities of spaces. Similar to the previous case study, The Thermal Bath by Zumthor, the design process for Kiasma Museum was a long, experimental journey.

The initial idea concept was an outcome of interpreting the site-related inquiries, inspirations from phenomenological theories, and perceptions of interior spatial qualities. The building creates a metaphoric connection between the historic city center and the neighborhood. The mass of the building includes two intertwined volumes knotted with an atrium between them. The atrium or the void between the two volumes is an interpretation of an interval. The interstitial space between the two large volumes facilitates the sensual experiences of internal spaces. Placed at the lobby, between curved and the rectilinear volumes, a gently curved ramp creates a smooth connection to the next level and induces a sense of movement. The curvilinear shape of the building encompasses exhibiting galleries of various sizes, which heightens the dynamic atmosphere of the interstitial space.

The intertwining concept between the two volumes of the building is inspired by the idea of kiasma derived from Merleau-Ponty's concept of chiasm – a study of perception[14]. Holl's phenomenological approach in the design of the Helsinki museum imagines the building as a "knot" of combined perceptions; he perceives spaces through "sensation, intuition and comprehension"[14].

During the design process, Holl imagined the moving bodies of the visitors in space as a multi-sensorial experience. The spatial qualities of spaces were not perceived in a purely one-dimensional way. Rather, their perception involved a series of phenomenological components that included light and materials. While working on the design, understanding the visitors' expectations and needs had primary impacts on design decisions. Holl identifies with Merleau-Ponty's concept of chiasm, while creating intertwined relationship between the visitors' bodies and the built spaces. The phenomenological idea of the body and its movement in relation to a space is carried over into the whole process of design in an attempt to reveal the experiential potentials of spaces.

Design explorations included various spatial experiments that investigated perceptions of the moving bodies in space. The design concept emphasized the idea of "parallax", a term that defines a design exploration involving a series of surfaces created by the sequential movement of a body in space. The purpose of this exercise was to perceive the effects of material and light in spaces in an attempt to investigate the sensual qualities of visitors' experiences. A series of preliminary water color sketches represent the idea of "parallax" and reveal the design intention for the creation of fluid architectural spaces. The dynamic qualities of spaces are expressed through grades of light and shadow. The effect of natural light in regards to its creation of spatial qualities is dependent on the time of the day. Initiating the design on the concept of movement and body added a poetic dimension to the built spaces; the interstitial space between the two closely programmed volumes expresses an emotional style for the presentation of form, light and shadow (Figure 6).

In this architectural design, interpretation of phenomenological aspects played an important role throughout the entire design process journey. The design intension is mainly developed from perceiving a direct relation between the building and the visitors. The conceptual quality of initial drawings was carried over to the end of design process, with the result of an architectural creation with many layers of intervals. The strength of design intention arose from perceptions of spatial qualities through both reason and sensation.

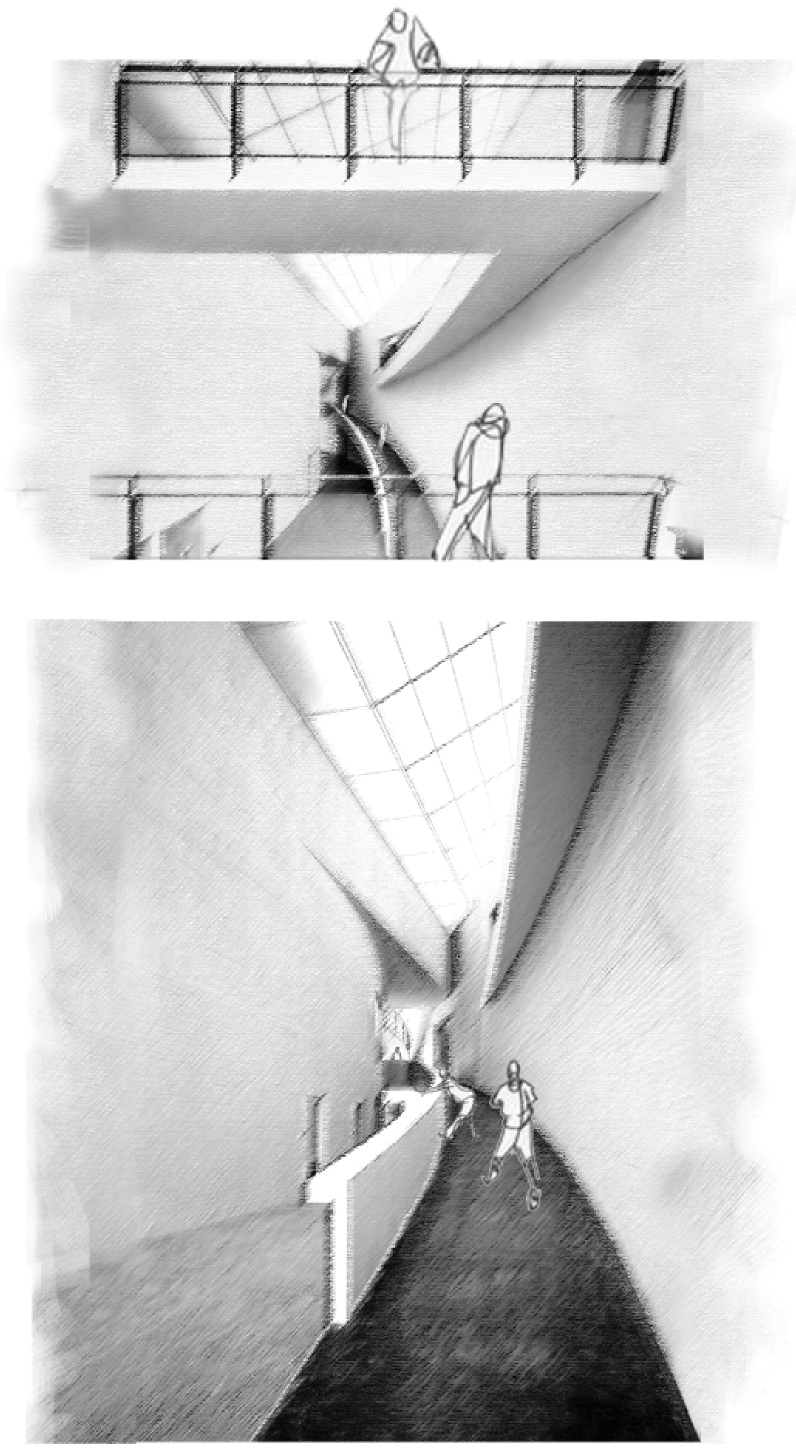

Figure 6: Kiasma Museum of Contemporary Art, interstitial space between two programmed volumes.

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5.4 Case Study 4

Instructional Centre, University of Toronto, Mississauga
Perkins+Will (2009 – 2011)

"Although the building is large and stands out, the well-executed design maintains a human scale that is friendly and generous.… The architect has chosen attractive building materials, which are further enhanced by their details, patterns and juxtaposition. The copper, wood and granite provide a harmonious palette that relates to the natural setting in a sophisticated and refined manner. This university building, along with the other newly built structures, demonstrates how an institute of higher learning can create high quality architecture that will be an inspiration and a symbol for future generations of students." (Noted jury members for the Urban Design Award of Excellence, 2012)

A multiple award-winning building, the Instructional Centre at the University of Toronto, Mississauga (IC UTM) expresses a poetic dimension of building and site relations. Like Holl's Kiasma Museum of Contemporary Art in Helsinki, the initial design study concentrated on the dynamics of the site and situation. From the very beginning, the design intention was identified as the creation of a strong sensory reaction to the surrounding natural context. The preliminary design concept emphasized on transitions, spaces in between and the experience of passing through. The spatial fabric of the interior is the result of making strong connections to the physical references of the site, its history, and the program. The design process demonstrates a clear dialogue between the initial perception of spatial qualities and the experiential qualities of the built form.

The study of the first drafts identifies that the most striking factors influencing primary design decisions were the present needs of the campus, possibilities of its future expansion, and the character of the surrounding landscape. The initial conception phase of the design started with block studies. One important rule in this exercise was to use the space between the blocks (intervals) as substantial design features that would affect the placement of the blocks. The overall physical form of the building, the distribution of the programs, and the building position in the site are clear outcomes of early explorations in block studies. The smaller and bigger blocks, and narrower or wider interstices, provided a balance in scale and proportion, which guided the formation of both interior and exterior spaces. The blocks represented the teaching spaces of various sizes that are stacked vertically and organized into three towers. The interstitial spaces between these densely programmed blocks represented intervals squeezed between the masses of the three towers (Figure 7).

Moving forward with explorations in design process, three major types of spaces were identified for the design of IC UTM building: *internal, interstitial,* and *peripheral*. The experiential qualities of these spaces take their cue from the initial spatial articulations and the understanding of relations to the site (Figure 8).

The *internal* space is calm, cool and symmetrical. The pure geometry of the internal space facilitates potentials to grade the effects of light and shadow.

The *interstitial* space includes a deep light-filled atrium located in-between architectural masses. The void reveals transitions between the two densely programmed areas even as it facilitates a passage of light. The mood of the patinated copper interior walls changes throughout the day, merging the poetic and pragmatic values of daylight. The uniformity of materials for interior walls induces a sense of transitional movement. The *interstitial* space makes a clear spatial flow to the forest and creates a strong sensory relation to the surrounding natural context.

The third type of space, identified in IC UTM building, is the *peripheral* at the outer edge of the building. A series of intimate student lounges and break-out spaces are positioned along the perimeter of each of the towers. The *peripheral* spaces challenge the visitors' perception for making sense of tension between interior and exterior. Placing the body in direct relation to the forest, the outer edges of the building create an abstract transition from a definite place to an infinite confusion of trees. Merleau-Ponty explored the role of the body as a sensory apparatus through which we understood the world around us; he proposed that there is always a give-and-take between our bodies and the world. His theory of perception suggests that any objective and subjective explanation of the world, in which we find ourselves, can challenge our understanding and experience of life. In a similar manner, the architect's use of phenomenology in *peripheral* spaces provides a new level of spatial quality that challenges the visitors' understanding and experiencing of architecture.

Very distinct from the interstitial lateral movement, there is a connecting gallery of student services and study lounges, which faces the campus green to the south. The gallery is positioned parallel to the landscape. The white, cool and luminous bridges cross over the intestinal space of the atrium and create a contrast between the depth of the forest and the depth of the interstitial copper cladding. Situated perpendicular to the lateral movement of the atria, the connective bridges induce the sense of movement – the experience of passing over to create a real, sensible and dynamic atmosphere. At the bridges, once again the visitors are positioned between the two contrasting voids: the intricate form of the nature and the pure geometry of the atrium.

Beside the pure geometric expressions and effects of light in the atrium, stairs have been placed in a manner that celebrates movement. The staircases put emphasis on a moving body's perception of architectural spaces, within which light and texture act as space-defining elements. The movement is measured against strong horizontal datums: the fine vertical grain of the copper panels and the organic texture of the material. The long, slow journey of walking up the stairs heightens the perceptions of surrounding spaces (Figure 9). The staircase arrives at the point of overlook into landscape, thereby projecting the visitors' attention deep into the forest. When we stand by the large window, the distant view, the light from the window, and the impressions of interior architectural materials start to merge perceptually. The outcome as a unified whole is the creation of a new dimension for experiential quality of the space.

Walking through the space, the haptic sensibility in geometry, space, and materials is clearly evident. The effects of natural and artificial lights provide a sensible spatial depth.

The IC UTM building as a whole provides a poetic and mythical meaning through its physical presence on the site (Figure 10). Derived from initial design explorations, the pure geometry of the building marks the spatial formation of intervals, which provides experiential intensities. The ongoing dialogue between the visitors and the forest constantly gives to the built spaces an experiential realm. Pallasma, in his essay "An Architecture of the Seven Senses", explains the memorable quality of architectural experiences. He states that "we identify ourselves with this space, this place, this moment and these dimensions as they become ingredients of our very existence. Architecture is the art of mediation and reconciliation"[11].

The same sources of inspiration are recognized in the design of IC UTM building. The experiential qualities of spaces add new values to the transient dimension of visitors and connecting spaces. The built spaces with their internal, interstitial, and peripheral aspects appeal to the senses and help us re-assess the ways in which we perceive and enjoy architecture.

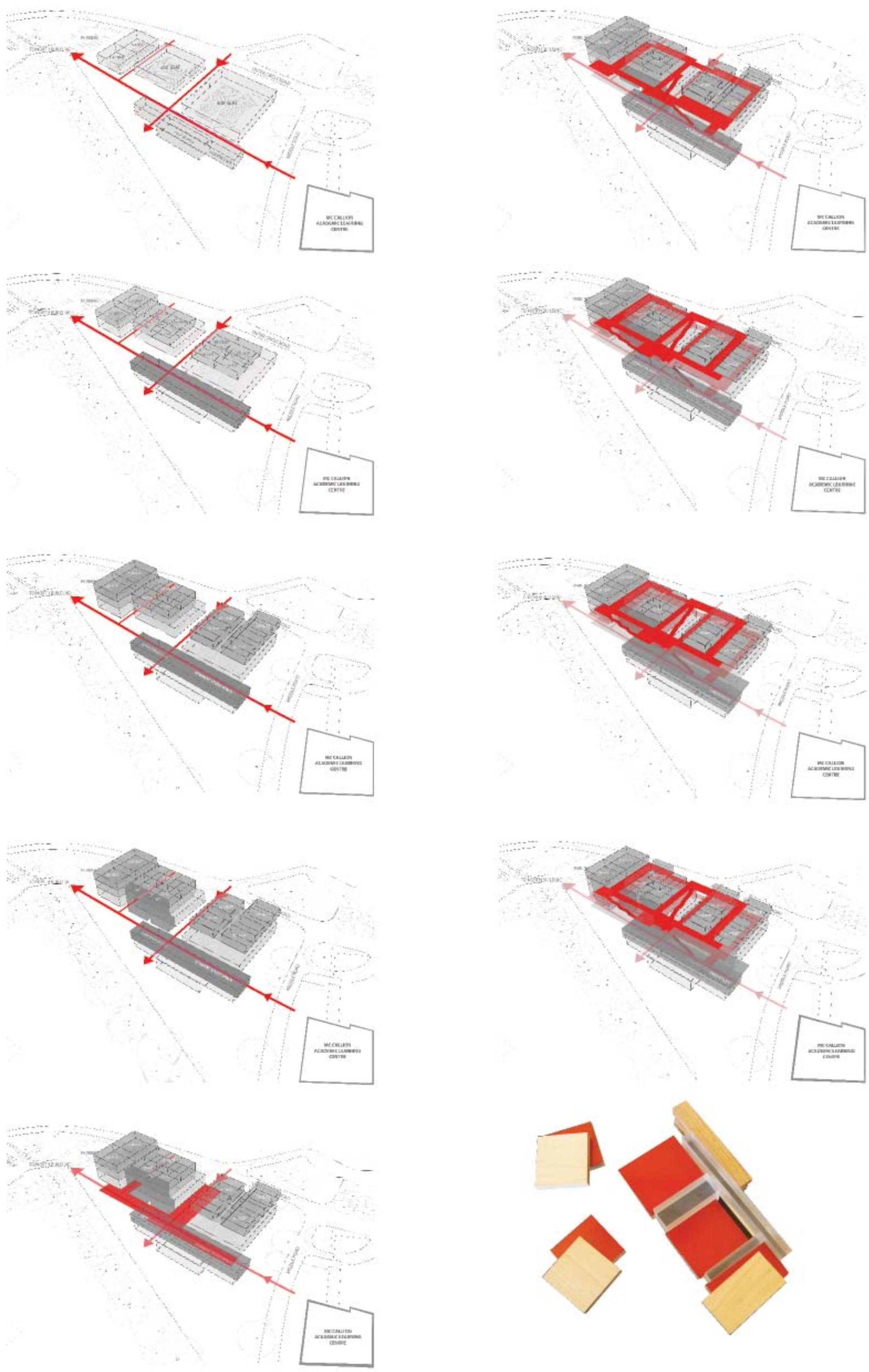

Figure 7: IC UTM, showing preliminarily block studies and exploring intervals.

Figure 8: IC UTM spatial configuration (internal, interstitial and peripheral spaces).

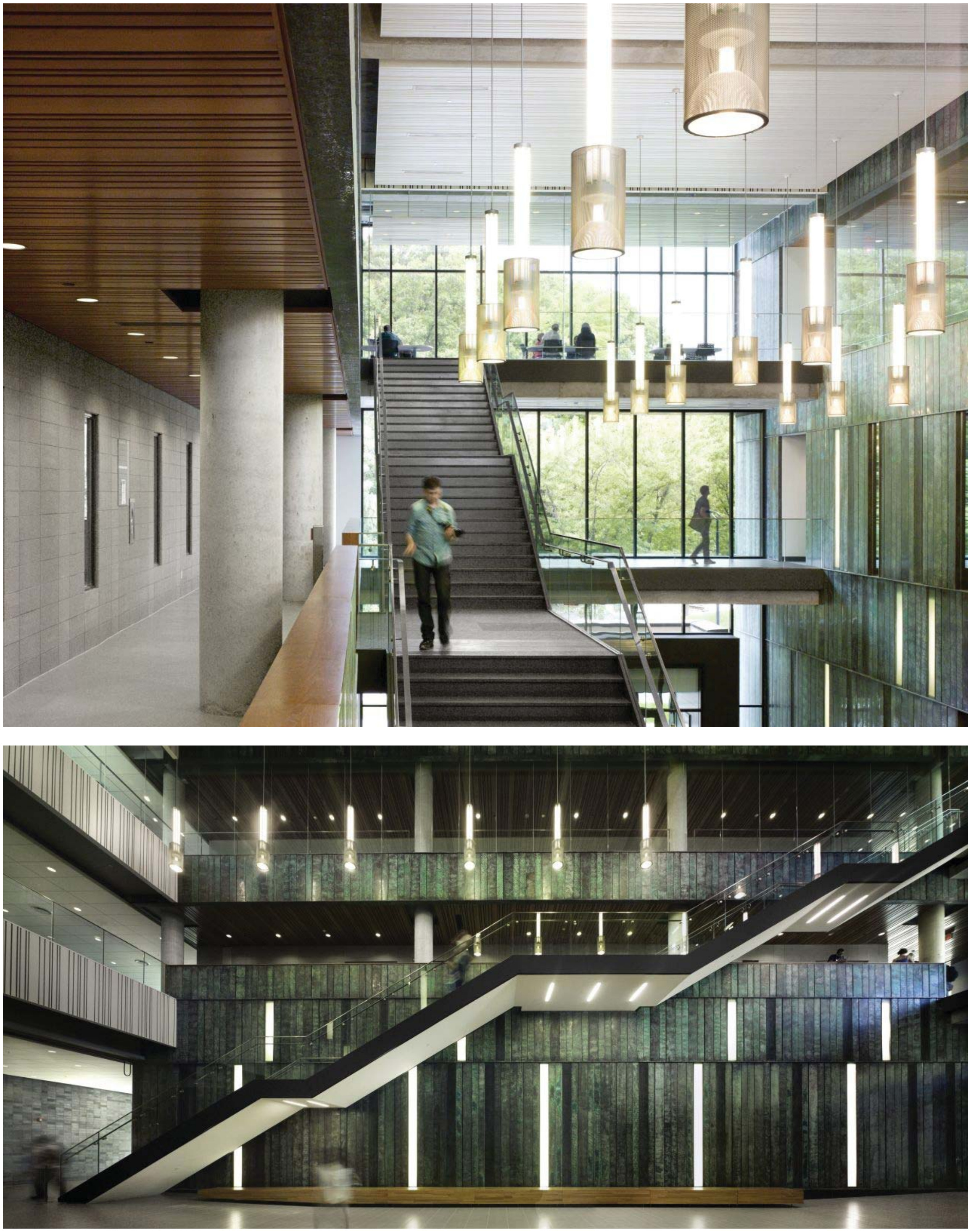

Figure 9: IC UTM, feature stairs.

Figure 10: IC UTM, exterior perspective.

6.0 CONCLUSION

The main objective of this article was to reveal the importance of the phenomenological approach in architectural planning and execution. The discussed case studies confirmed that a phenomenological approach in architectural design demands a continuous exploration of the experiential potential of spaces. All four projects demonstrate that the ways in which architects perceive spatial qualities lead them into experimental explorations, all of which aid in the creation of a meaningful articulation of spaces and forms.

While conducting the case studies, each project was distinctive, considering driving factors and constraints, such as site and program. Therefore, each case study had to be approached in a distinctive manner. The initial inspiration for architects in the development of a design concept may vary from one project to the other. However, what should be consistent and always present in the creation of built spaces is a phenomenological approach in their conception and creation.

Designing poetic architecture is not a process that can be defined by certain skills or techniques. It is dependent upon those inspirational moments when architects perceive the “sense of a place”. Architectural design processes can mirror delightful emotional memories and, in this way, are derived from our understanding of the world around us. The connections between our memories and our experience of architecture can become a foundation for designing and creating new architectural spaces. Architects can associate memories according to their clients’ needs, and their designs can represent architecturally the most touching moments experienced by them or by their clients. Although the notions of “empathy”, “perception”, and “memory” are old topics in the architectural field, many contemporary architectural scholars and architects have elaborated on them and have explored their potential to fulfil the needs of contemporary architectural design practice. Recent cognitive neuroscience studies, such as the way-finding experiment, also reveal the qualitative dimensions of human experience contribute to the evaluation of the importance of memory, and help to determine the memorable dimensions of architectural spaces. Expanding these theories with new knowledge can help architects to create functional buildings that also evoke emotional states.

This article introduced its topic by raising the question of whether or not architects are failing in craftsmanship skills by underestimating the notion of emotion in their designs. For architects, crafting does not merely mean that they must be physically involved in the act of construction by hand. Architects can craft inspirational spaces by using such phenomenological components as sound, light or color. An architectural design can be a phenomenological journey of exploration that takes us from the raising of an issue to the proposing of a solution to it. Each finding can be followed by an analysis that reveals the next step on the road. The act of designing in architecture is a multi-layered process within which major conceptual shifts should be responsive to human desires. If architects can engage the element of human perception throughout the entire design process, then they can continue to have a positive influence on the built environment that mediates between people and their surroundings.

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04.
CLIMATE CHANGE AND PERFORMANCE OF FACADE SYSTEMS:
Analysis of Thermal Behavior and Energy Consumption in Different Climate Types

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ABSTRACT
The facade is one of the most significant contributors to the energy budget and the comfort parameters of any building. Control of environmental factors must be considered during the design process. High-performance facades need to block adverse external environmental effects and maintain internal comfort conditions with minimum energy consumption. The purpose of this research was to analyze thermal behavior and energy performance of different facade types, as well as impacts of climate change on facade performance. The study was conducted by modelling conductive heat transfer in seven different exterior wall types, considering conventional and thermally improved opaque and glazed systems. Conventional facade systems included brick cavity wall, rainscreen facade with terracotta cladding, rainscreen facade with glass-fiber reinforced concrete cladding and a conventional curtain wall, while thermally improved systems included rainscreen facade with thermal spaces, rainscreen facade with thermal isolators and a curtain wall with thermally broken framing. Heat transfer and thermal gradients through these systems for four exterior environmental conditions were simulated, considering outside temperatures of 90°F, 60°F, 30°F and 0°F. Also, heat transfer coefficients (U-values) were calculated and compared to determine thermal performance. Impacts on energy use were also investigated, where energy usage was modeled for an office space enclosed with the analyzed facade types for all U.S. climate zones and 12 orientations, and for window-to-wall ratio of 20 and 40 percent, using historical weather data. The results show relative performance of analyzed exterior wall types, in terms of thermal performance and energy usage. Then, future climate conditions were considered, where the impacts of climate change on changing weather patterns were investigated. Specifically, predicated climate change weather files for the years 2050 and 2080 were used to model energy usage for the office space enclosed with analyzed exterior wall types. The results show the impacts of climate change on the energy performance, and show that the energy usage is increased for all investigated wall types and in almost all climates.

KEYWORDS: high-performance facades, simulations, heat transfer, energy modeling, energy efficiency, climate change

1.0 INTRODUCTION
Increases in average global temperatures are expected to be within the range of 0.5°F to 8.6°F by 2100, with a likely increase of at least 2.7°F due to climate change, with some regions projected to see larger temperature increases than the global average[1]. An increase in average global temperatures infers more numerous and extreme heat events. For most buildings, the facade affects the building's energy budget and the comfort of its occupants more than any other system, especially the glazed facade types[2]. Climate-specific guidelines must be considered during the design process of high-performing building enclosures[3,4]. Design strategies need to consider the temperature, humidity, wind, precipitation, solar radiation and other characteristics of the climate zone to minimize the impacts of external environmental conditions and reduce energy consumption[5].

There are essentially two types of facades, opaque and glazed. Opaque facades are primarily constructed of layers of solid materials, such as masonry, stone, precast concrete panels, metal cladding, insulation and framing, and may include windows. Glazed facades, such as curtain walls or storefront facades, primarily consist of transparent or translucent glazing materials and metal framing components. Physical behaviors of these two types of facade differ, since their components, materials, and construction methods are different. Opaque facades typically have more mass, greater insulation levels, and better heat retention than glazed facades. On the other hand, glazed facades usually allow more daylight to the interiors and provide better views for occupants. They also impose less dead load on the building structure than opaque facades.

The rate of conductive and convective heat transfer through the building skin depends on the difference between the interior and exterior temperatures, and the capacity of the facade to control heat flow[6]. Factors that influence heat flow within the facade include the overall thermal resistance, material properties and air leakage[7]. Design strategies for controlling heat flow include use of a continuous thermal barrier (insulation layer), filling air gaps between material layers to prevent conduction, providing a continuous air barrier to prevent heat loss through air leakage, and avoiding thermal bridging.

Improving thermal performance and minimizing thermal bridging are extremely important design strategies for high-performance facades. Thermal bridging within a wall occurs where a highly conductive material, such as a metal support, penetrates the facade's insulation layer. This can significantly affect the thermal performance of the wall, and decrease its effective thermal resistance[8]. Thermal bridging can occur in all types of facades, and significantly impacts thermal performance, energy consumption and thermal comfort of building occupants. Thermally improved facades limit thermal bridging, and can improve thermal performance by using materials that reduce heat transfer between different components.

The purpose of this research was to investigate heat transfer in several exterior wall types, methods for minimizing thermal bridging and improving thermal performance, and the effects of climate change on energy consumption. These following research questions were addressed:

- How do different types of opaque and glazed facades transfer heat under the same environmental conditions?
- What is the relative performance ranking of different facade systems in terms of their ability to resist heat transfer and U-value?
- How can thermal bridging be minimized?
- What is the effect of different facade configurations on energy consumption of commercial spaces in different climates?
- What is the effect of facade orientation and window-to-wall ratio on energy consumption of commercial spaces in different climates?
- What is the impact of climate change on energy consumption of commercial spaces for different facade configurations?

2.0 RESEARCH METHODS

The study consisted of two parts—thermal modeling and energy modeling. The analyzed facade systems included:

- Type 1: Brick cavity wall with metal framing
- Type 2: Rainscreen facade with terracotta cladding and metal framing
- Type 3: Rainscreen facade with glass-fiber reinforced concrete (GFRC) cladding and metal framing
- Type 4: Curtain wall with aluminum framing
- Type 5: Curtain wall with thermally broken aluminum framing
- Type 6: Rainscreen facade with terracotta cladding and thermal spacers
- Type 7: Rainscreen facade with terracotta cladding and thermal isolators.

Thermal modeling was performed using two-dimensional steady-state heat transfer simulation software THERM (version 6.3), developed by Lawrence Berkeley National Laboratory. Individual material layers and their properties were modeled in detail, as well as the boundary conditions for exterior and interior temperatures. Four exterior temperatures of 90°F, 60°F, 30°F and 0°F were used as boundary conditions to represent different climate types, while interior temperature was set at 72°F. U-values were also calculated for each facade system. The restrictions of the software is that it calculates heat transfer in two-dimensions and ignores the third dimension. There are existing studies that analyzed three-dimensional heat transfer in building envelopes[9]. However, THERM software is one of the few software programs approved by the National Fenestration Rating Council (NFRC) for calculating properties of glazed facades and framing, and thus was chosen for this study.

The energy performance of the seven facade types was studied using whole year energy simulations, which were performed using EnergyPlus (version 8.3) software for a typical office space. The total yearly energy values included heating, cooling, lighting and fans. Simulations were conducted for 15 cities in the U. S., representing different climate zones for three time periods: present day, the year 2050 and the year 2080. Weather files for 2050 and 2080 were created using a weather file generator that takes into account impacts of climate change on weather patterns[10].

2.1 Thermal Modeling and Heat Transfer Analysis

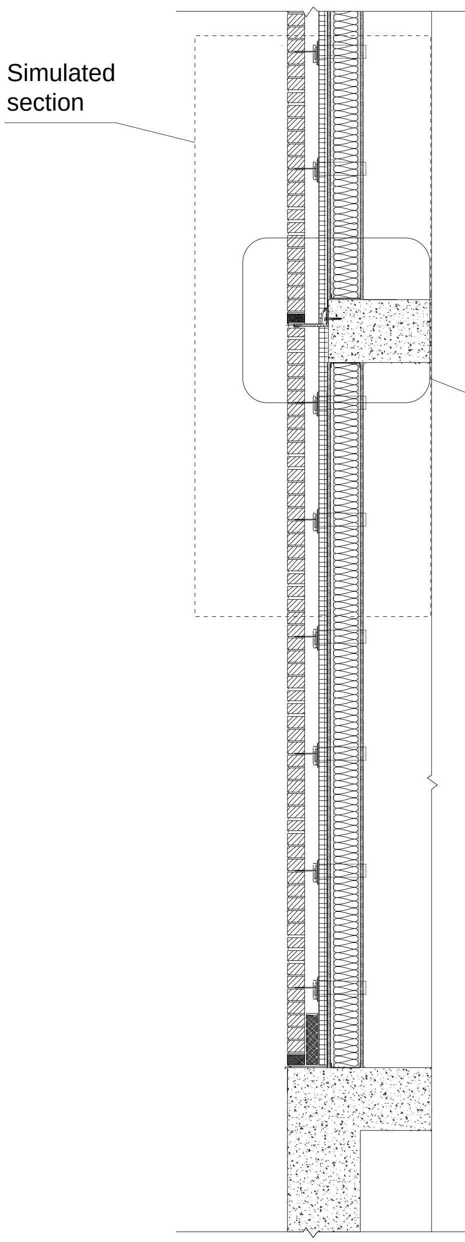
The properties of different facade materials are listed in Table 1. These values were used for the simulations and were constant throughout the study. The components of different facade types are discussed in more detail below.

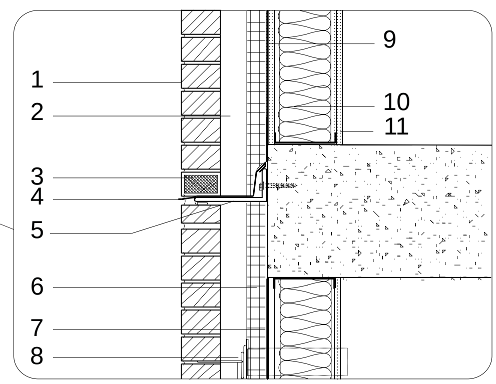
Table 1: Material properties.

Material/component	Conductivity (Btu/h-ft-°F)	U-value (Btu/h-ft^2-°F)	Solar Heat Gain Coefficient	Visual Transmittance
Air	0.01	-	-	-
Aluminum	137	-	-	-
Batt insulation in framing cavity	0.03	-	-	-
Brick	6.0	-	-	-
Exterior gypsum sheathing	1.8	-	-	-
Fiberglass spacer	0.17	-	-	-
GFRC	18.0	-	-	-
Glass	-	0.29	0.38	70%
Interior gypsum sheathing	1.8	-	-	-
Rigid insulation	0.03	-	-	-
Terracotta cladding	1.2	-	-	-
Thermal break for curtain wall framing	0.13	-	-	-
Thermal isolator	0.17	-	-	-

The first case (Type 1) considered brick cavity wall with steel framing, as seen in Figure 1. The components of the analyzed assembly are:

- Brick: 4 in
- Air cavity: 2 in
- Rigid insulation: 2 in
- Brick ties
- Air/vapor barrier
- Exterior gypsum sheathing: 5/8 in
- Framing cavity with batt insulation: 6 in
- Interior gypsum sheathing: 5/8 in.





1 Brick

2 Air cavity

3 Weep holes

4 Flashing

5 L-shaped brick support

6 Rigid insulation

7 Air/vapor barrier

8 Brick ties

9 Exterior gypsum sheathing

10 Batt insulation in framing cavity

11 Interior gypsum sheathing

Figure 1: Components of the brick cavity wall.

The second case (Type 2) considered rainscreen system with terracotta cladding and metal framing, shown in Figure 2. The components of the analyzed assembly are:

- Terracotta cladding: 1 3/16 in
- Aluminum clips
- Air cavity: 1 in
- Vertical aluminum support extrusions
- Rigid insulation: 3 in
- Horizontal L brackets
- Air/vapor barrier
- Exterior gypsum sheathing: 5/8 in
- Framing cavity with batt insulation: 6 in
- Interior gypsum sheathing: 5/8 in.

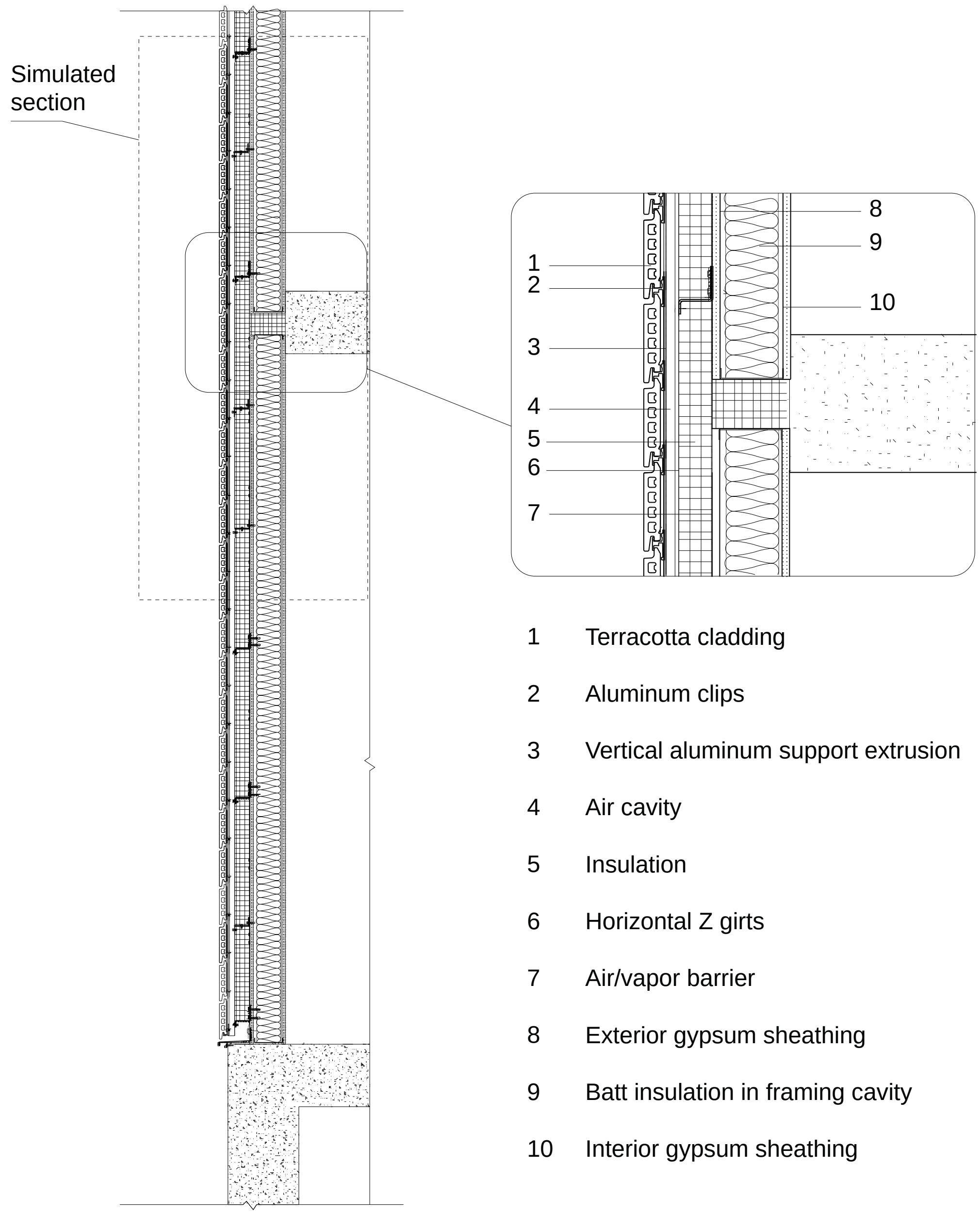
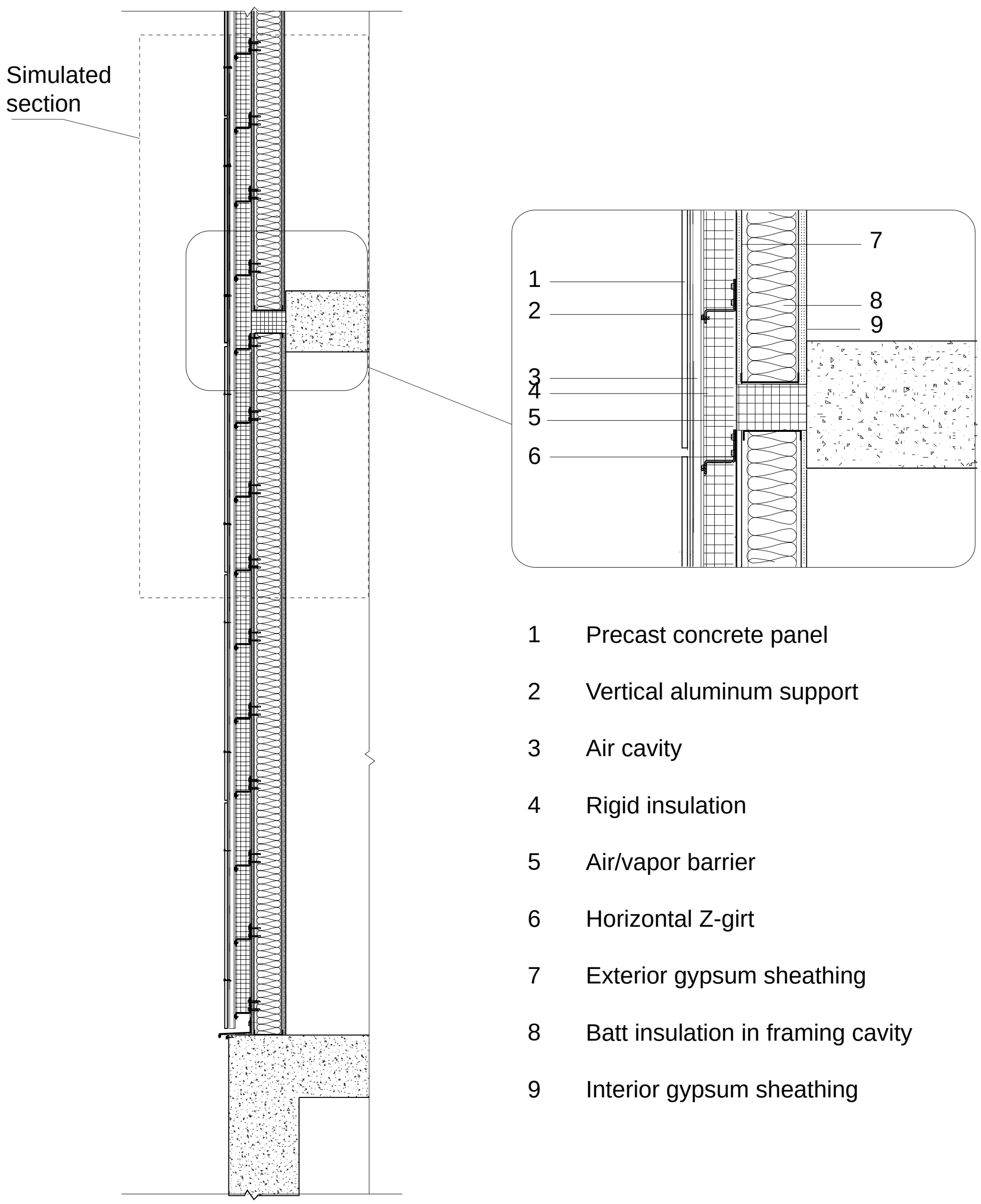


Figure 2: Components of the rainscreen facade with terracotta cladding.

The third case (Type 3) considered rainscreen system with GFRC cladding, as seen in Figure 3. The components of the analyzed assembly are:

- GFRC cladding: 3/4 in
- Air cavity: 1 in
- Vertical aluminum support extrusions
- Rigid insulation: 3 in
- Horizontal Z girts
- Air/vapor barrier
- Exterior gypsum sheathing: 5/8 in
- Framing cavity with batt insulation: 6 in
- Interior gypsum sheathing: 5/8 in.



1 Precast concrete panel

2 Vertical aluminum support

3 Air cavity

4 Rigid insulation

5 Air/vapor barrier

6 Horizontal Z-girt

7 Exterior gypsum sheathing

8 Batt insulation in framing cavity

9 Interior gypsum sheathing

Figure 3: Components of the rainscreen facade with GFRC cladding.

The fourth case (Type 4) considered a standard curtain wall, as shown in Figure 4. The analyzed curtain wall consisted of vision glazing 8 1/2 ft vertically, as well as spandrel area of 4 1/2 ft. The components of the analyzed curtain wall are:

- Vision glass: double, air-insulated low-e glazing unit
- Spandrel: spandrel glass, 3 in air cavity, 2 in insulation and aluminum back pan
- Aluminum framing members.

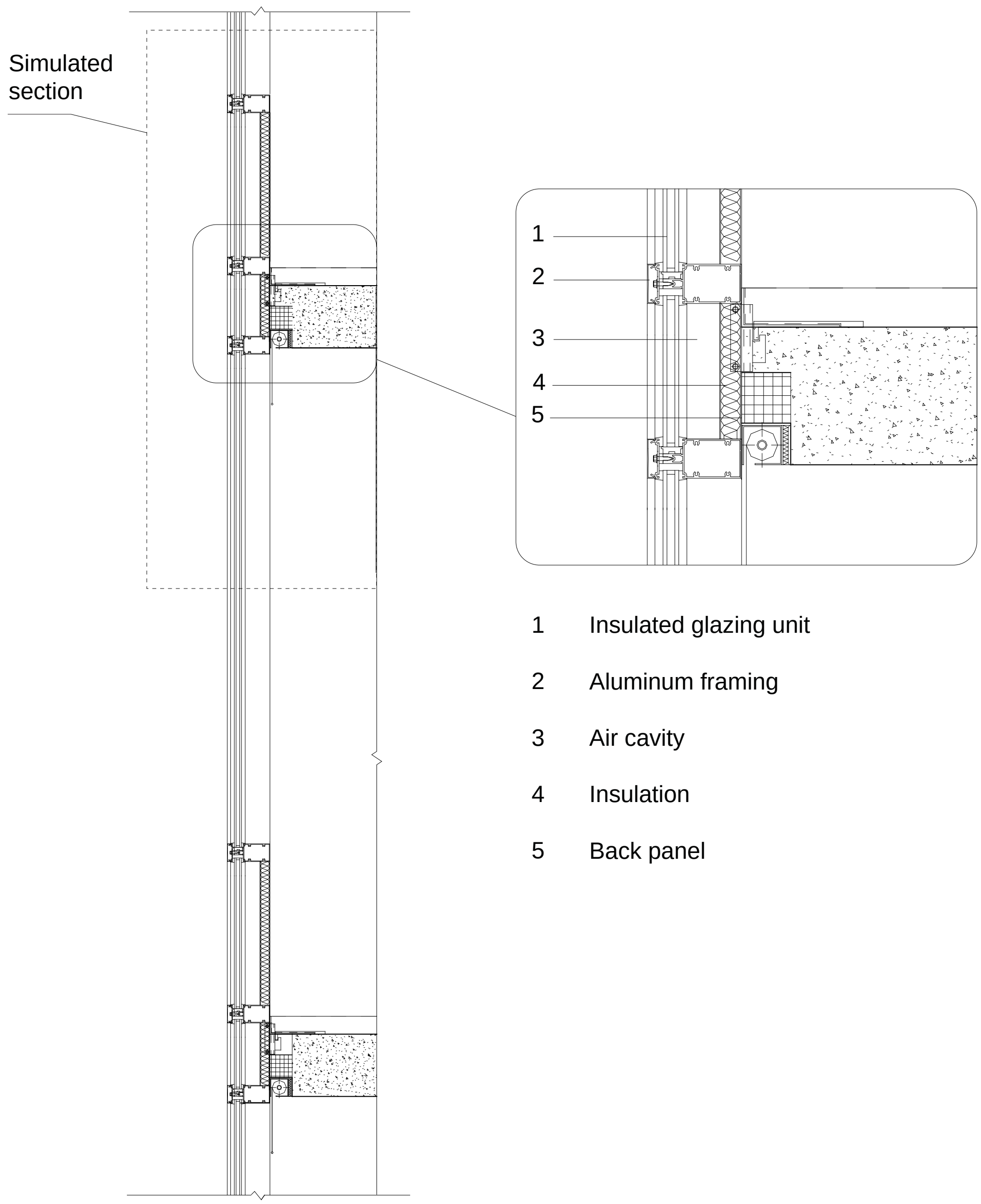


Figure 4: Components of the curtain wall.

The fifth case (Type 5) considered thermally improved curtain wall, shown in Figure 5. The analyzed curtain wall consisted of vision glazing 8 1/2 ft vertically, spandrel area of 4 1/2 ft, and thermal breaks within the framing members to minimize thermal bridging. The components of the analyzed curtain wall are:

- Vision glass: double, air-insulated low-e glazing unit
- Spandrel: spandrel glass, 3 in air cavity, 2 in insulation and aluminum back pan
- Aluminum framing members with thermal breaks.

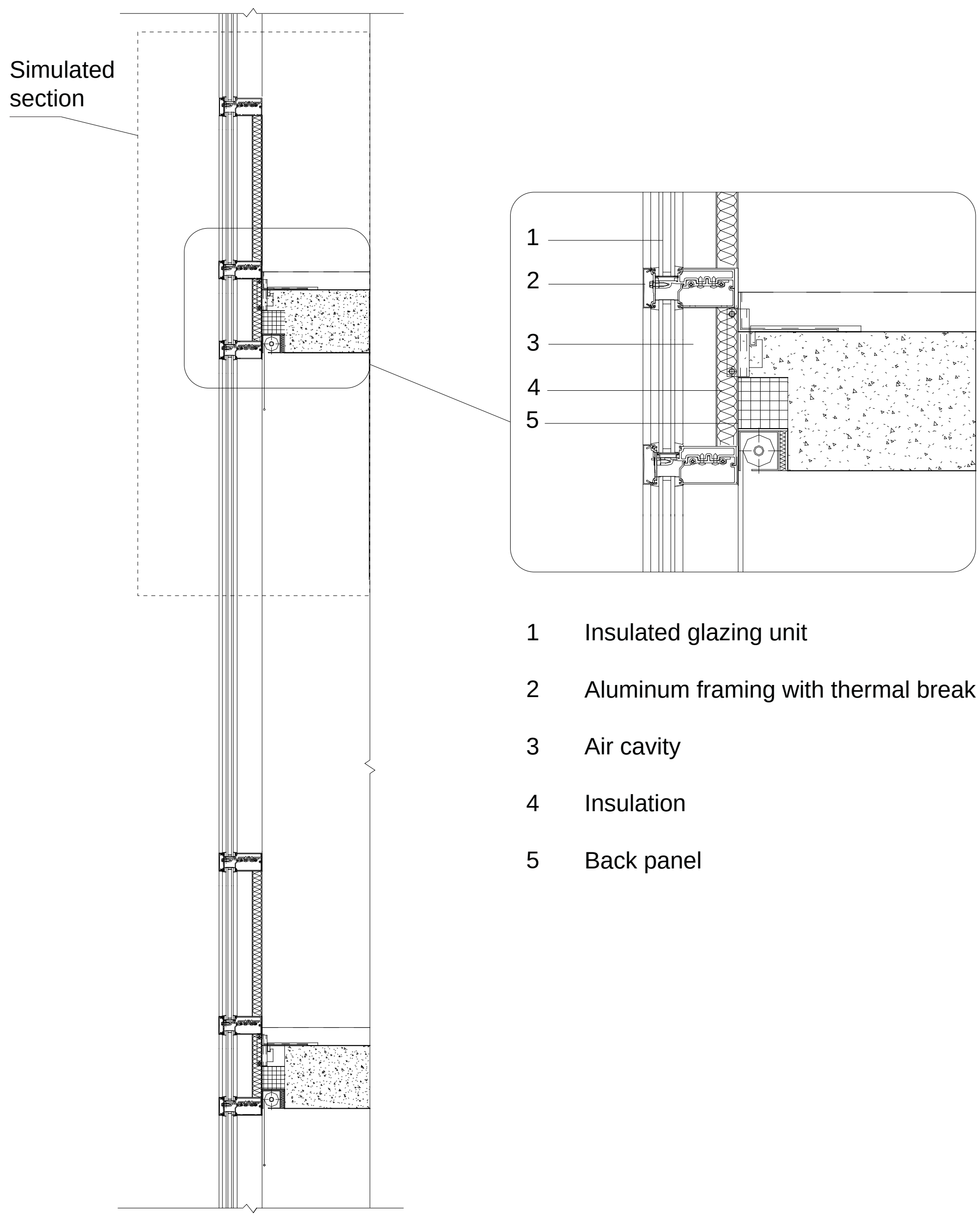


Figure 5: Components of the thermally broken curtain wall.

The sixth case (Type 6) considered rainscreen system with terracotta cladding, and fiberglass spacers that are used to minimize thermal bridging through the vertical cladding support system, as demonstrated in Figure 6. The components of the analyzed assembly are:

- Terracotta cladding: 1 3/16 in
- Aluminum clips
- Air cavity: 1 in
- Vertical aluminum support extrusions
- Fiberglass spacers
- Rigid insulation: 3 in
- Horizontal L brackets
- Air/vapor barrier
- Exterior gypsum sheathing: 5/8 in
- Framing cavity with batt insulation: 6 in
- Interior gypsum sheathing: 5/8 in.

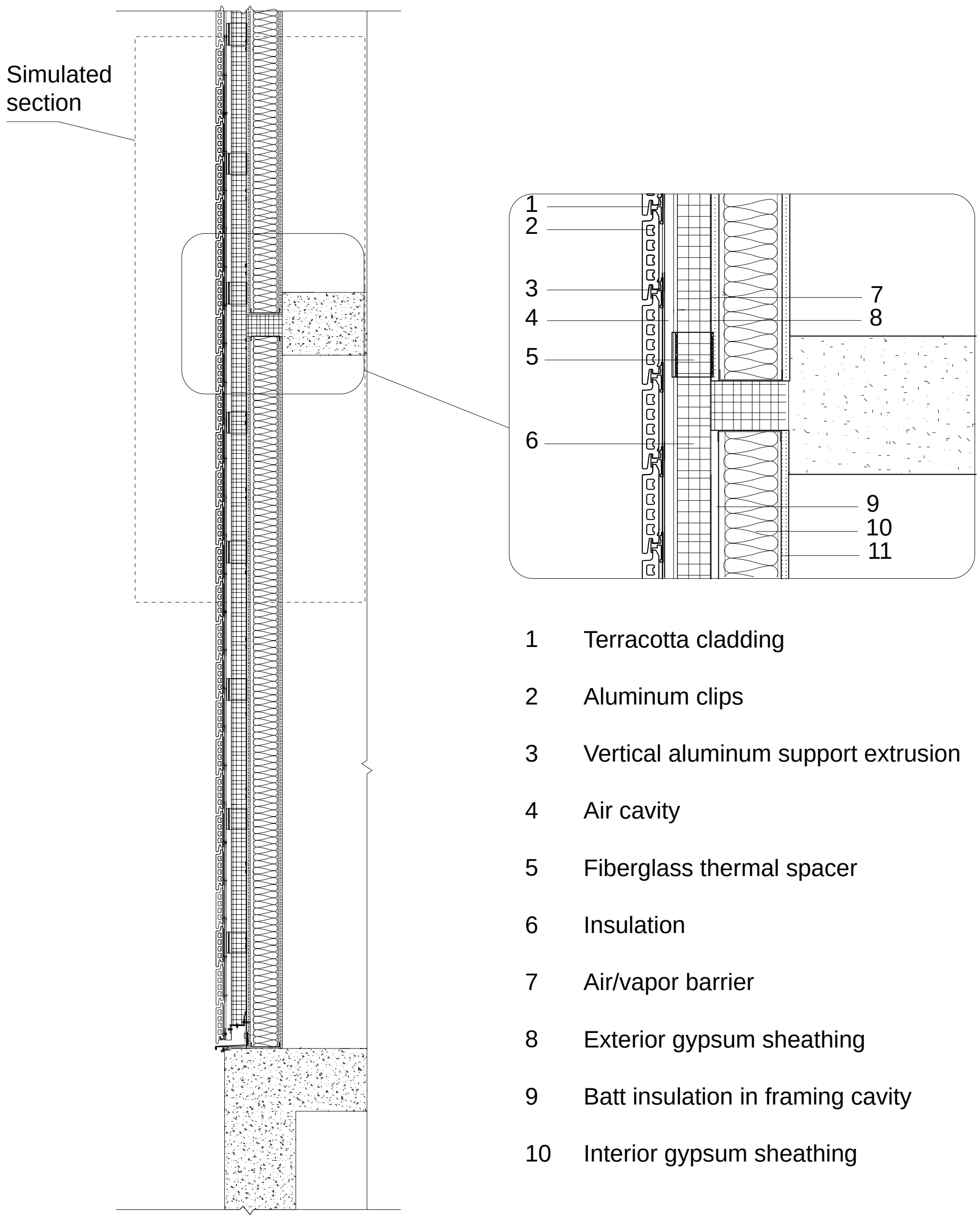
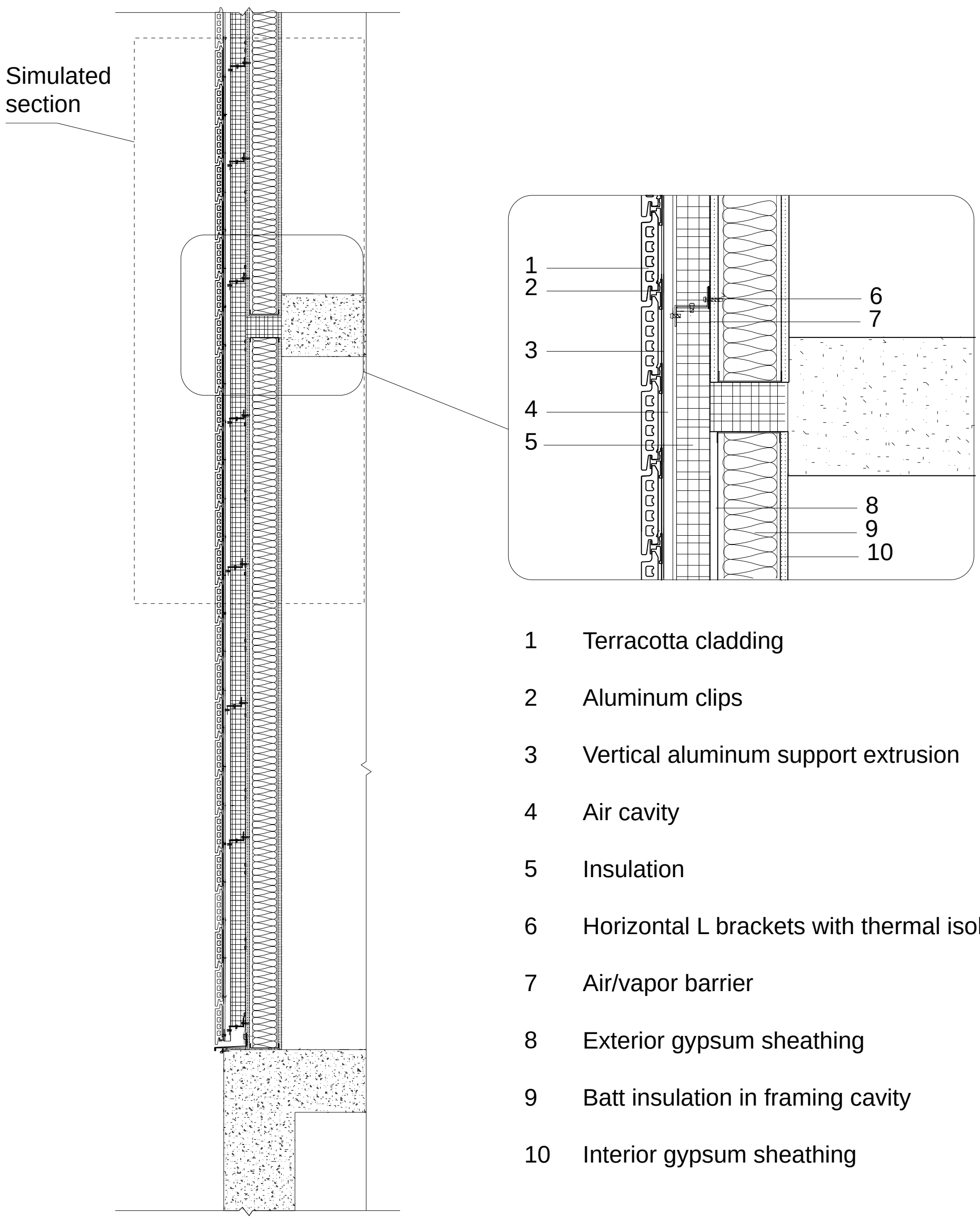


Figure 6: Components of the rainscreen facade with terracotta cladding and thermal spacers.

The seventh case (Type 7) considered rainscreen system with terracotta cladding, and thermal isolators placed on horizontal L brackets, shown in Figure 7. The components of the analyzed assembly are:

- Terracotta cladding: 1 3/16 in
- Aluminum clips
- Air cavity: 1 in
- Vertical aluminum support extrusions
- Rigid insulation: 3 in
- Horizontal L brackets with thermal isolators placed on the interior side of the brackets
- Air/vapor barrier
- Exterior gypsum sheathing: 5/8 in
- Framing cavity with batt insulation: 6 in
- Interior gypsum sheathing: 5/8 in.



1 Terracotta cladding

2 Aluminum clips

3 Vertical aluminum support extrusion

4 Air cavity

5 Insulation

6 Horizontal L brackets with thermal isolator

7 Air/vapor barrier

8 Exterior gypsum sheathing

9 Batt insulation in framing cavity

10 Interior gypsum sheathing

Figure 7: Components of the rainscreen facade with terracotta cladding and isolators.

2.2 Energy Modeling

The energy modeling was performed in EnergyPlus, simulating whole year total energy use for an office space, enclosed by the seven different exterior wall types. The five opaque walls were modeled with a window to wall ratio of both 20 and 40 percent for occupant views and daylighting, while glazed facades were modeled with 80 percent window to wall ratio.

A single zone office space was chosen in order to highlight the thermal properties of the different wall types at different orientations. The dimensions of the office space were modeled at 13 ft high by 12 ft wide and 16 ft deep, as seen in Figure 8. The facade was 13 ft high by 12 ft wide. The floor, ceiling and the three interior walls were modeled as adjacent to other interior spaces with the same thermal conditions without heat transfer occurring, but they will retain and release heat due to their thermal mass. The interior walls were modeled as gypsum board over steel studs, the floor was carpet over a concrete slab and the ceiling was a drop ceiling of standard acoustical tiles.

The office space was heated to 70°F with 60°F setback during unoccupied hours, and cooled to 75°F with 80°F setback using the Ideal Loads Air System component to maintain thermal comfort for the whole year. The Ideal Loads Air System component was used to study the performance of the office space without modeling a full HVAC system. Lighting was designed with a 0.5 W/ft^2 load density and continuous daylighting control[11]. Equipment load for the office was modeled at 0.7 W/ft^2, and the occupancy load was one person.

The single office space with each type of exterior wall was modeled and rotated in 12 different orientations at 30° increments, and using climate data for three time periods (present day, the year 2050 and the year 2080), for 15 different cities, representing all climate zones in the United States (Table 2). The zones are numbered from 1 (very hot) to 8 (subarctic). Some of the eight climate zones may also be subdivided into moist (A), dry (B), and marine (C) regions, giving a total of 15 different climate types in the U.S. Future predicted climate change weather files were created for the 15 climate zones for the years 2050 and 2080 using the climate change world weather file generator tool, developed by Sustainable Energy Research Group, University of Southampton (CCWorldWeather-Gen version 1.2). These files were used to simulate and compare present day energy use with future energy use for each of the facade types. A total of 3,780 simulations were run.

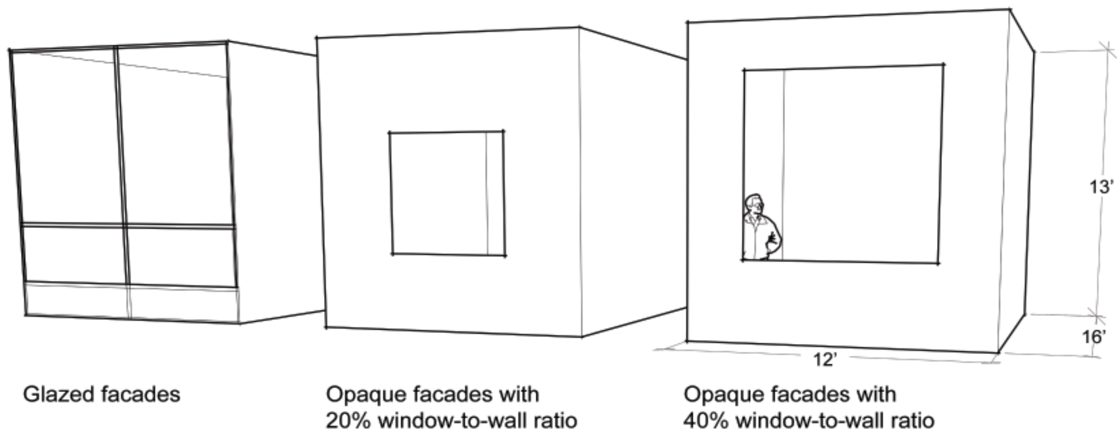


Figure 8: Diagram showing dimensions and components of the simulated office space.

Table 2: Climate zones and representative cities used for energy modeling.

	Climate Zone	City	Zone	Region
1	1A	Miami, FL	very hot	moist
2	2A	Houston, TX	hot	moist
3	2B	Phoenix, AZ	hot	dry
4	3A	Memphis, TN	warm	moist
5	3B	El Paso, TX	warm	dry
6	3C	San Francisco, CA	warm	marine
7	4A	Baltimore, MD	mixed	moist
8	4B	Albuquerque, NM	mixed	dry
9	4C	Salem, OR	mixed	marine
10	5A	Chicago, IL	cool	moist
11	5B	Boise, ID	cool	dry
12	6A	Burlington, VT	cold	moist
13	6B	Helena, MT	cold	dry
14	7	Duluth, MN	very cold	
15	8	Fairbanks, AK	subarctic	

3.0 RESULTS

3.1 Thermal Modeling Results

Four different thermal models were developed in THERM for each facade system, representing different exterior environmental conditions, where these conditions would be representative of different climate types and seasons. Interior conditions for all scenarios were kept constant at 72°F. The exterior temperatures of 90°F, 60°F, 30°F and 0°F were used to represent different climate types. This was conducted to understand behavior of these different exterior wall types under various conditions, and to determine thermal gradients since this information is useful for design decision-making process. Figures 9 to 12 show results for thermal gradients through all facade types.

Heat transfer coefficients (U-values) were also calculated for all of the analyzed facade systems using THERM software. Heat transfer through exterior walls depends on the following factors: 1) the difference between temperature between exterior and interior environment, 2) the materials of the wall and their thicknesses, and 3) the thermal conductivity of material layers. Total rate of heat transfer through an opaque wall assembly is calculated by area-weighted approach, where separate heat transfer contributions of different material layers are taken into account, based on the relative area that they occupy within the wall system. For glazed facades, area-weighted approach is also used to calculate heat transfer, where center-of-glass, edge-of-glass and frame U-values are taken into account. Standard exterior environmental conditions, prescribed by NFRC were used for the simulations, (outdoor temperature of 0°F and indoor temperature of 70°F)[12]. Therefore, a total of 35 thermal models were developed and simulated.

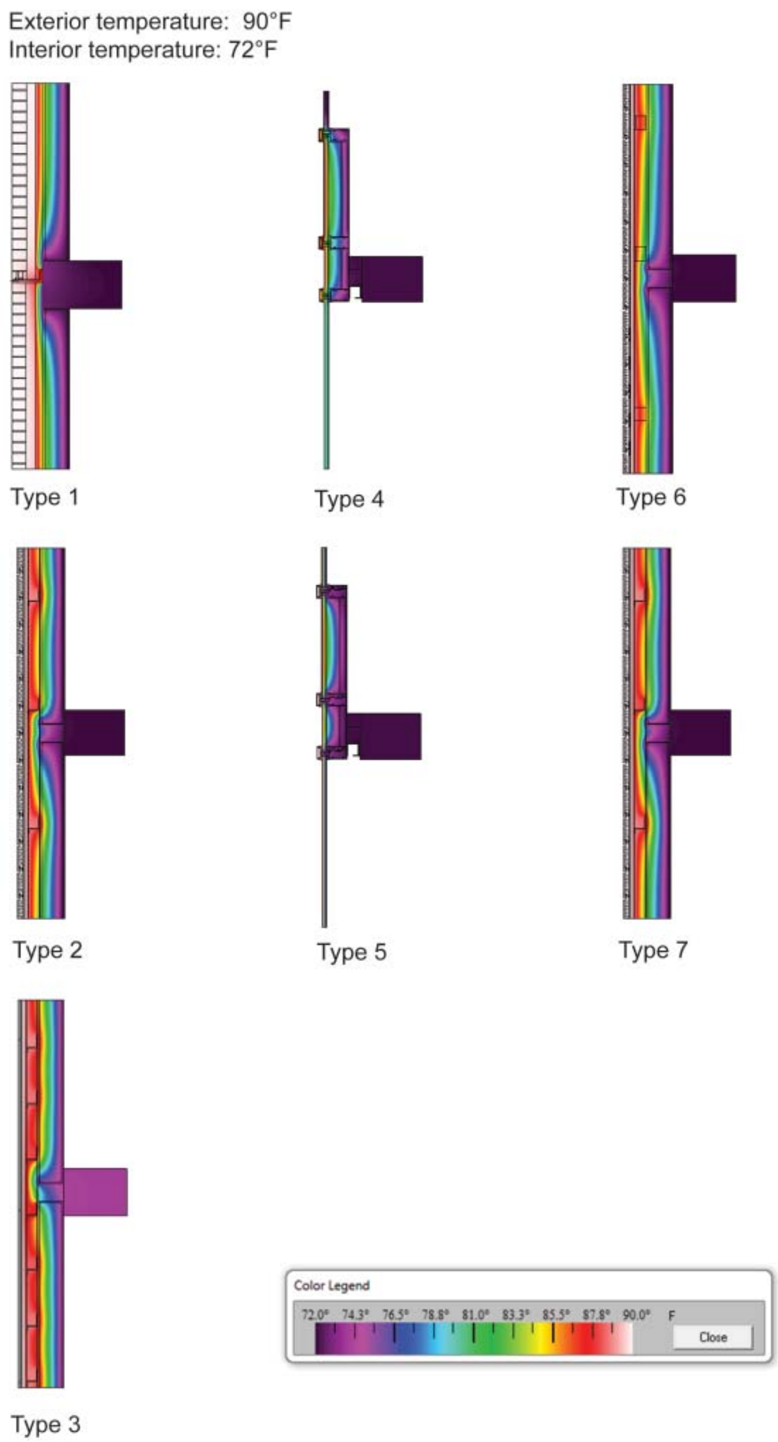


Figure 9: Results of thermal modeling, showing thermal gradient through the exterior wall assemblies, with exterior temperature of 90°F.

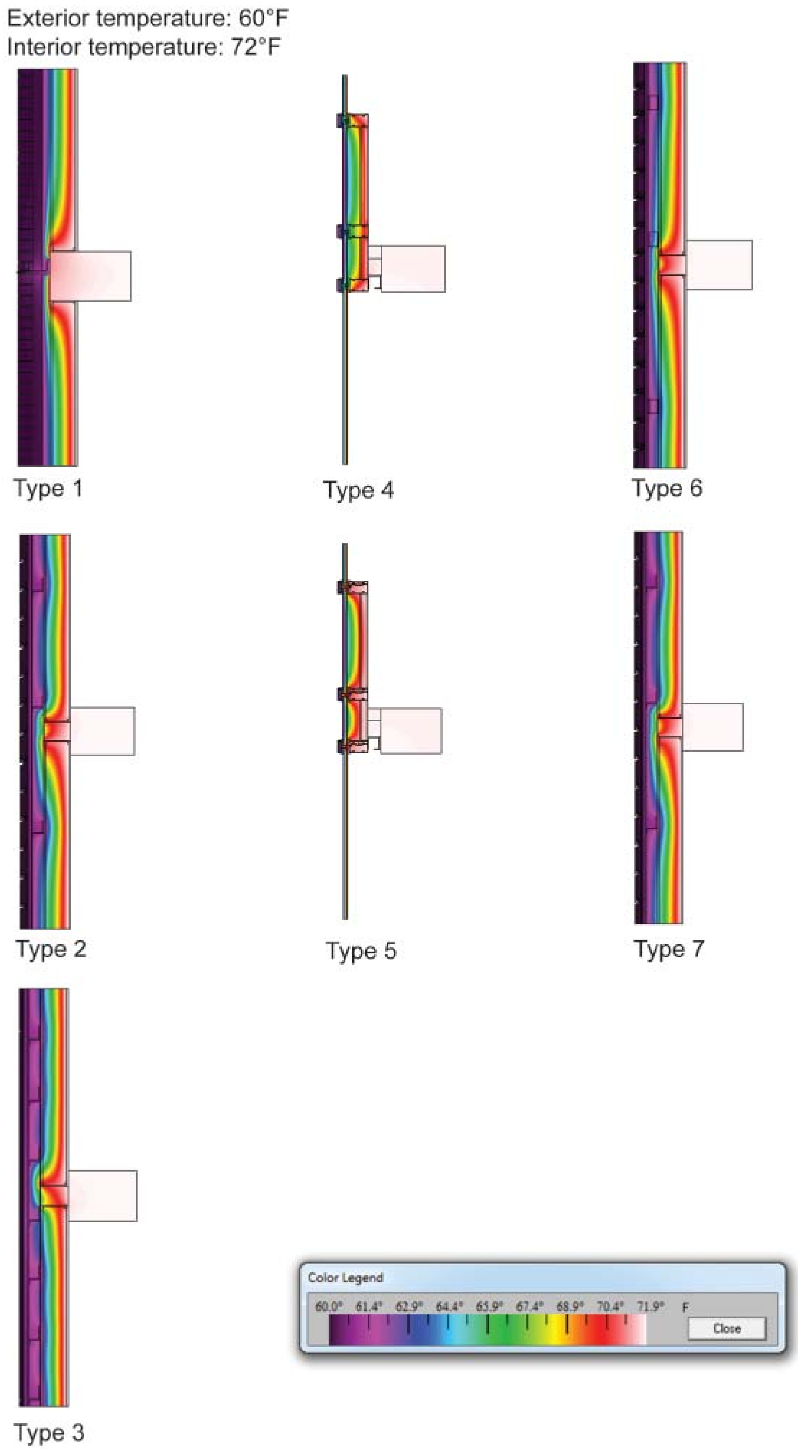


Figure 10: Results of thermal modeling, showing thermal gradient through the exterior wall assemblies, with exterior temperature of 60°F.

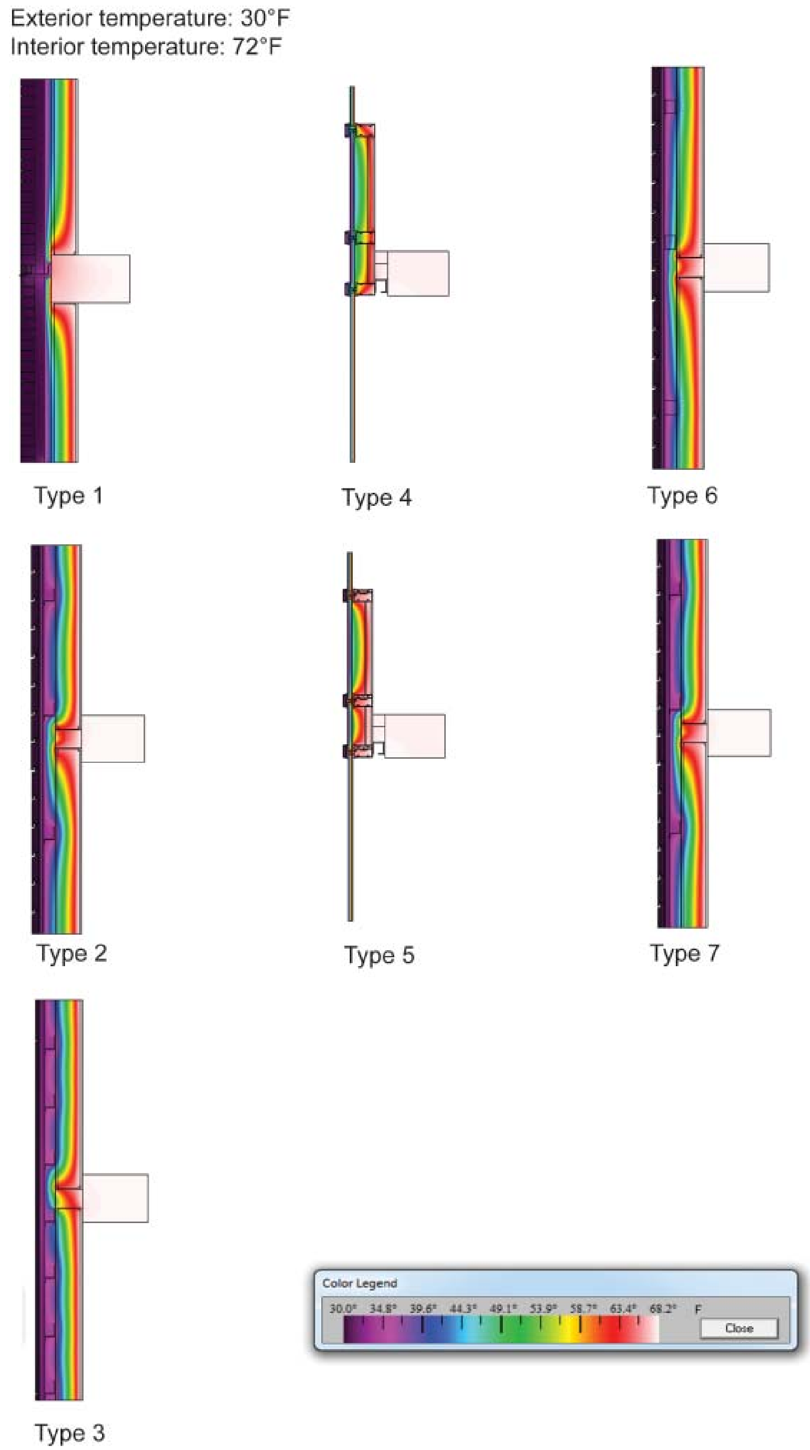


Figure 11: Results of thermal modeling, showing thermal gradient through the exterior wall assemblies, with exterior temperature of 30°F.

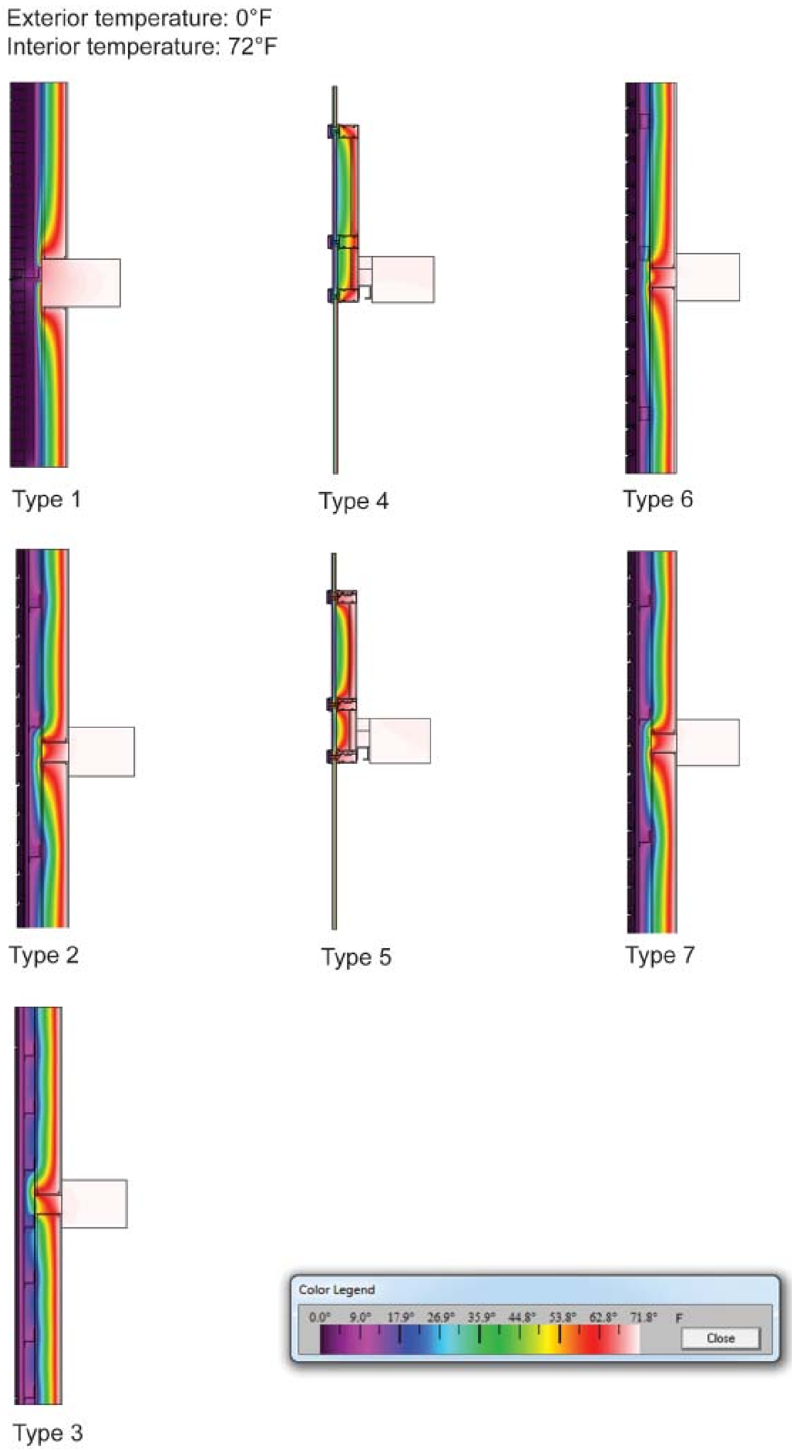


Figure 12: Results of thermal modeling, showing thermal gradient through the exterior wall assemblies, with exterior temperature of 0°F.

Results for U-values are shown in Figure 13. Thermal performance of analyzed facade systems was compared based on calculated U-values. Curtain wall is the worst performing assembly, followed by brick cavity wall. Curtain wall with thermally broken framing performs better than the analyzed brick cavity, but worse than all other types of opaque facades. Rainscreen facade with terracotta cladding has lower U-value coefficient than rainscreen facade with GFRC cladding, since it uses horizontal L brackets instead of Z girts to support exterior insulation layer and cladding, and spacing between them is larger. But, fiberglass spacers placed between the vertical cladding support system and framing improve U-value by 20 percent, since they minimize thermal bridging caused by metal components within the rainscreen assembly. Thermal isolators, placed on the interior side of L brackets, also reduce U-value by 20 percent, and are less expensive method for improving thermal performance.

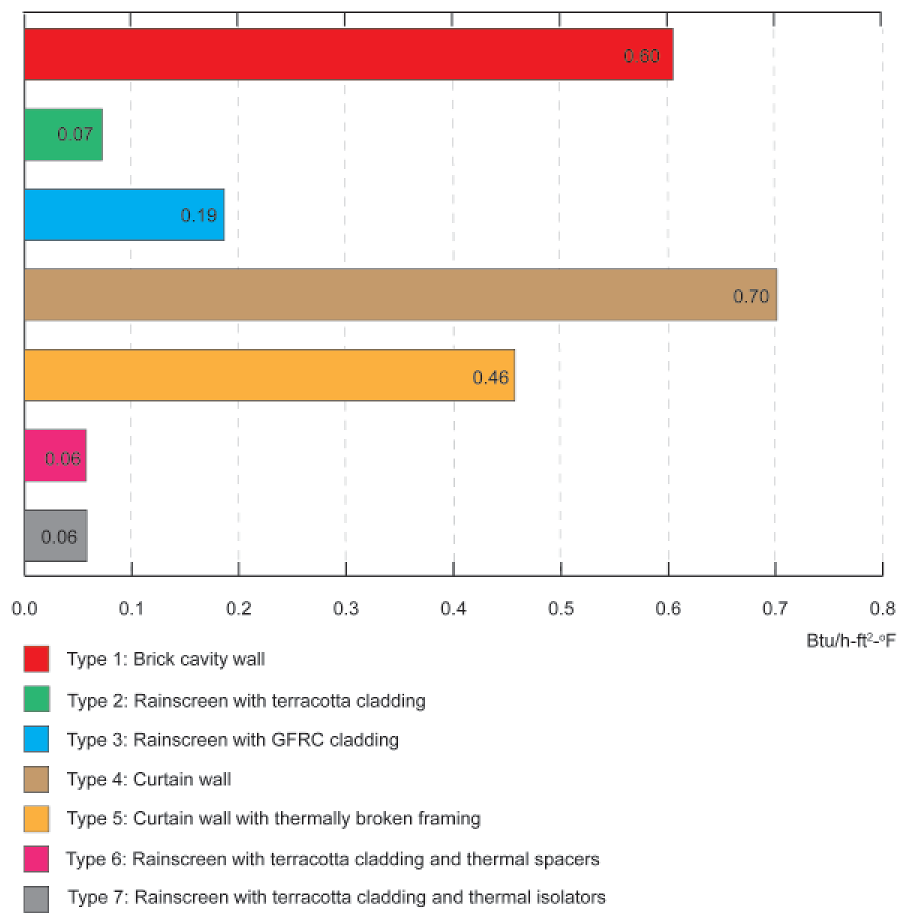


Figure 13: U-value comparison of all analyzed assemblies.

3.2 Energy Modeling Results

The plotted results, shown in Figure 14, indicate general patterns for each of the different wall types in the 15 climate zones, considering current climate data. Also, Tables 3 to 5 show detailed numeric results. The results of the simulations typically show that the facades with a lower U-value have better energy performance for the whole year in all climates and orientations. In general, the opaque facades all performed better than the transparent curtain walls, despite the energy reducing possibility of heat gain in winter and daylight harvesting. The opaque walls also performed similarly for all orientations, with slightly better performance towards the north in warm climates and towards the south in cold climates. Orientation had a greater effect for the glazed walls, with east and west performing the worst. The south orientation performed the best in the coldest climates, but north facing performed the best for most of the other climate zones. In climate zones 1A through 3C, the north facing glazed facades performed nearly as well as the opaque facades.

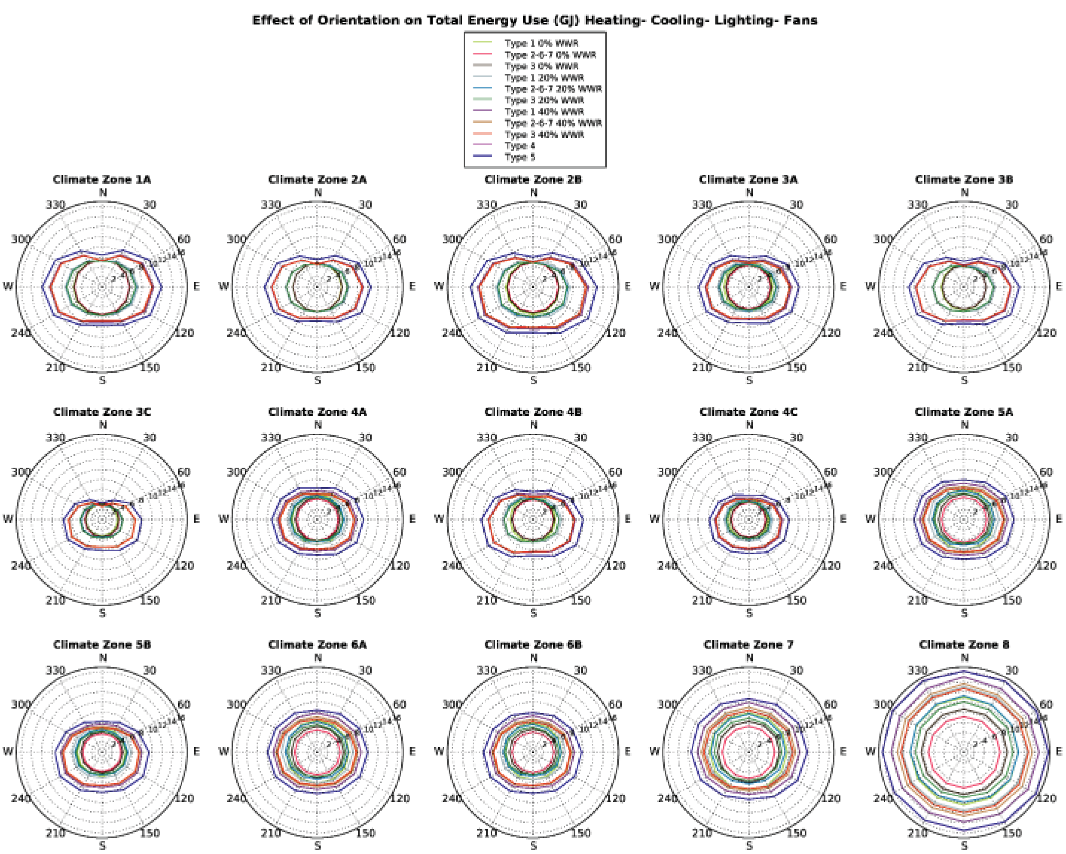


Figure 14: Total annual energy use for different wall types and orientations (current climate data).

Table 3: Total annual energy use for climate zones 1A-3C.

Effect of Orientation on Total Energy Use (GJ) Heating- Cooling- Lighting- Fans													
		Orientation											
Climate Zone	Wall Type	0	30	60	90	120	150	180	210	240	270	300	330
1A	Type 1, 0% WWR	5.46	5.52	5.61	5.67	5.69	5.66	5.63	5.64	5.64	5.56	5.50	5.49
1A	Type 2-6-7, 0% WWR	5.40	5.41	5.45	5.47	5.48	5.47	5.46	5.47	5.50	5.50	5.47	5.43
1A	Type 3, 0% WWR	5.45	5.47	5.53	5.56	5.58	5.57	5.56	5.59	5.61	5.61	5.56	5.51
1A	Type 1, 20% WWR	5.20	5.90	6.84	7.30	7.05	5.99	5.70	6.04	6.89	7.22	6.75	5.88
1A	Type 2-6-7, 20% WWR	5.20	5.85	6.63	7.06	6.83	5.97	5.63	5.84	6.56	6.87	6.43	5.64
1A	Type 3, 20% WWR	5.18	5.81	6.58	7.00	6.76	5.91	5.63	5.77	6.46	6.77	6.34	5.56
1A	Type 1, 40% WWR	5.26	7.36	9.45	10.48	9.98	8.02	7.04	8.00	9.81	10.32	9.34	7.45
1A	Type 2-6-7, 40% WWR	5.28	7.27	9.30	10.32	9.82	7.87	6.71	7.81	9.57	10.08	9.12	7.27
1A	Type 3, 40% WWR	5.26	7.26	9.26	10.27	9.77	7.83	6.69	7.75	9.50	10.00	9.05	7.22
1A	Type 4	6.40	8.33	10.70	11.91	11.12	8.76	7.62	8.80	11.11	11.89	10.81	8.49
1A	Type 5	6.40	8.33	10.70	11.91	11.12	8.76	7.62	8.80	11.11	11.89	10.81	8.49
2A	Type 1, 0% WWR	4.74	4.79	4.87	4.93	4.95	4.93	4.91	4.92	4.86	4.83	4.77	4.77
2A	Type 2-6-7, 0% WWR	4.82	4.83	4.87	4.89	4.90	4.90	4.89	4.91	4.93	4.93	4.89	4.85
2A	Type 3, 0% WWR	4.80	4.82	4.87	4.91	4.93	4.92	4.91	4.94	4.97	4.96	4.91	4.86
2A	Type 1, 20% WWR	4.45	5.08	5.89	6.34	6.17	5.34	4.93	5.32	6.06	6.30	5.84	5.00
2A	Type 2-6-7, 20% WWR	4.48	5.12	5.77	6.17	6.02	5.22	4.92	5.12	5.82	6.05	5.60	4.84
2A	Type 3, 20% WWR	4.50	5.13	5.77	6.17	6.01	5.22	4.90	5.10	5.77	6.00	5.57	4.69
2A	Type 1, 40% WWR	4.46	6.22	8.13	9.15	8.83	7.19	6.26	7.20	8.73	9.09	8.09	6.29
2A	Type 2-6-7, 40% WWR	4.46	6.19	8.04	9.05	8.72	7.09	6.13	7.06	8.55	8.90	7.91	6.17
2A	Type 3, 40% WWR	4.46	6.20	8.04	9.05	8.71	7.09	6.13	7.04	8.52	8.86	7.89	6.14
2A	Type 4	5.48	7.15	9.31	10.50	9.96	7.98	6.83	8.06	10.03	10.60	9.44	7.26
2A	Type 5	5.48	7.15	9.31	10.51	9.97	7.97	6.82	8.05	10.04	10.60	9.44	7.26
2B	Type 1, 0% WWR	5.04	5.11	5.25	5.37	5.44	5.44	5.44	5.44	5.33	5.25	5.13	5.07
2B	Type 2-6-7, 0% WWR	4.87	4.89	4.95	5.01	5.04	5.03	5.03	5.05	5.06	5.03	4.97	4.91
2B	Type 3, 0% WWR	4.95	4.99	5.08	5.15	5.20	5.20	5.19	5.23	5.25	5.21	5.12	5.03
2B	Type 1, 20% WWR	4.95	5.65	6.67	7.43	7.48	6.69	6.05	6.68	7.42	7.41	6.58	5.51
2B	Type 2-6-7, 20% WWR	4.79	5.58	6.44	7.13	7.16	6.36	5.94	6.18	6.98	6.98	6.21	5.09
2B	Type 3, 20% WWR	4.79	5.51	6.36	7.03	7.05	6.17	5.82	6.06	6.84	6.83	6.08	5.01
2B	Type 1, 40% WWR	5.04	6.88	9.30	10.97	11.13	9.50	8.40	9.58	11.11	11.02	9.30	6.90
2B	Type 2-6-7, 40% WWR	4.95	6.77	9.12	10.77	10.89	9.28	8.14	9.30	10.79	10.69	9.02	6.68
2B	Type 3, 40% WWR	4.88	6.72	9.07	10.69	10.80	9.20	8.06	9.18	10.67	10.58	8.91	6.60
2B	Type 4	5.99	7.80	10.52	12.46	12.45	10.48	9.11	10.66	12.66	12.73	10.71	7.85
2B	Type 5	5.99	7.80	10.52	12.46	12.45	10.48	9.11	10.66	12.66	12.73	10.71	7.84
3A	Type 1, 0% WWR	4.82	4.88	4.93	4.96	4.95	4.91	4.87	4.89	4.90	4.84	4.87	4.84
3A	Type 2-6-7, 0% WWR	4.31	4.32	4.36	4.38	4.39	4.39	4.39	4.40	4.41	4.41	4.38	4.35
3A	Type 3, 0% WWR	4.48	4.50	4.54	4.56	4.55	4.54	4.51	4.54	4.59	4.60	4.57	4.53
3A	Type 1, 20% WWR	4.91	5.41	5.87	6.14	6.01	5.38	4.88	5.36	5.94	6.08	5.75	5.17
3A	Type 2-6-7, 20% WWR	4.57	5.10	5.60	5.85	5.70	5.01	4.68	4.84	5.50	5.64	5.29	4.64
3A	Type 3, 20% WWR	4.37	4.94	5.47	5.74	5.59	4.91	4.58	4.73	5.37	5.48	5.10	4.47
3A	Type 1, 40% WWR	5.16	6.34	7.69	8.62	8.52	7.31	6.52	7.36	8.47	8.59	7.66	6.26
3A	Type 2-6-7, 40% WWR	4.89	6.13	7.47	8.42	8.33	7.11	6.28	7.11	8.20	8.29	7.35	5.94
3A	Type 3, 40% WWR	4.72	6.01	7.39	8.37	8.28	7.06	6.23	7.02	8.12	8.22	7.23	5.79
3A	Type 4	5.90	7.26	8.77	9.86	9.64	8.15	7.21	8.29	9.80	10.03	8.90	7.16
3A	Type 5	5.89	7.26	8.77	9.87	9.64	8.15	7.20	8.30	9.80	10.02	8.89	7.15
3B	Type 1, 0% WWR	4.36	4.43	4.52	4.59	4.60	4.58	4.53	4.53	4.46	4.44	4.37	4.37
3B	Type 2-6-7, 0% WWR	4.29	4.31	4.35	4.41	4.43	4.42	4.42	4.42	4.44	4.43	4.38	4.32
3B	Type 3, 0% WWR	4.29	4.32	4.37	4.42	4.46	4.44	4.43	4.46	4.47	4.46	4.41	4.33
3B	Type 1, 20% WWR	4.30	4.93	5.72	6.34	6.28	5.38	4.86	5.32	6.08	6.18	5.51	4.69
3B	Type 2-6-7, 20% WWR	4.09	4.82	5.59	6.19	6.11	5.27	4.83	5.05	5.77	5.86	5.20	4.37
3B	Type 3, 20% WWR	4.02	4.81	5.59	6.20	6.11	5.27	4.82	5.04	5.74	5.82	5.17	4.23
3B	Type 1, 40% WWR	4.41	5.96	8.14	9.65	9.60	7.85	6.68	7.77	9.37	9.44	7.97	5.90
3B	Type 2-6-7, 40% WWR	4.19	5.84	8.02	9.52	9.48	7.72	6.54	7.60	9.17	9.23	7.76	5.68
3B	Type 3, 40% WWR	4.17	5.83	8.04	9.54	9.49	7.73	6.53	7.59	9.14	9.22	7.74	5.64
3B	Type 4	5.14	6.85	9.29	11.01	10.79	8.69	7.27	8.70	10.81	11.05	9.32	6.81
3B	Type 5	5.14	6.84	9.29	11.01	10.80	8.69	7.27	8.69	10.80	11.05	9.32	6.80
3C	Type 1, 0% WWR	3.03	3.07	3.16	3.22	3.24	3.23	3.20	3.18	3.11	3.06	3.02	3.04
3C	Type 2-6-7, 0% WWR	3.35	3.36	3.39	3.43	3.45	3.46	3.46	3.47	3.46	3.45	3.41	3.39
3C	Type 3, 0% WWR	3.20	3.22	3.26	3.30	3.32	3.33	3.33	3.35	3.35	3.34	3.29	3.24
3C	Type 1, 20% WWR	2.73	3.24	3.75	4.19	4.25	3.82	3.50	3.86	4.28	4.21	3.67	3.00
3C	Type 2-6-7, 20% WWR	2.76	3.34	3.86	4.24	4.27	3.82	3.51	3.82	4.21	4.13	3.59	2.92
3C	Type 3, 20% WWR	2.82	3.45	3.98	4.37	4.39	3.93	3.62	3.92	4.29	4.22	3.68	3.01
3C	Type 1, 40% WWR	2.58	3.78	5.26	6.52	6.78	5.95	5.40	6.13	6.92	6.65	5.36	3.72
3C	Type 2-6-7, 40% WWR	2.59	3.86	5.31	6.55	6.80	5.98	5.39	6.10	6.88	6.61	5.32	3.69
3C	Type 3, 40% WWR	2.59	3.94	5.40	6.65	6.90	6.07	5.47	6.17	6.95	6.68	5.41	3.74
3C	Type 4	3.28	4.55	6.20	7.61	7.80	6.72	6.04	6.98	8.13	7.94	6.46	4.47
3C	Type 5	3.28	4.55	6.20	7.62	7.80	6.73	6.03	6.99	8.13	7.93	6.46	4.46

Table 4: Total annual energy use for climate zones 4A-5B.

Effect of Orientation on Total Energy Use (GJ) Heating- Cooling- Lighting- Fans													
		Orientation											
Climate Zone	Wall Type	0	30	60	90	120	150	180	210	240	270	300	330
4A	Type 1, 0% WWR	5.08	5.12	5.13	5.11	5.08	5.03	4.98	5.01	5.01	5.03	5.09	5.08
4A	Type 2-6-7, 0% WWR	4.13	4.14	4.16	4.17	4.17	4.16	4.16	4.17	4.19	4.20	4.18	4.15
4A	Type 3, 0% WWR	4.46	4.47	4.49	4.48	4.45	4.41	4.39	4.43	4.49	4.52	4.52	4.49
4A	Type 1, 20% WWR	5.40	5.66	5.88	5.94	5.75	5.21	4.85	5.19	5.67	5.88	5.77	5.44
4A	Type 2-6-7, 20% WWR	4.84	5.16	5.42	5.48	5.30	4.75	4.35	4.67	5.11	5.30	5.14	4.79
4A	Type 3, 20% WWR	4.53	4.87	5.18	5.30	5.11	4.57	4.18	4.49	4.90	5.06	4.86	4.50
4A	Type 1, 40% WWR	5.75	6.46	7.33	7.95	7.80	6.87	6.21	6.87	7.71	7.83	7.28	6.36
4A	Type 2-6-7, 40% WWR	5.35	6.10	6.99	7.66	7.55	6.60	5.93	6.56	7.37	7.45	6.86	5.91
4A	Type 3, 40% WWR	5.09	5.88	6.84	7.55	7.47	6.53	5.84	6.44	7.27	7.31	6.68	5.67
4A	Type 4	6.39	7.37	8.37	9.11	8.90	7.76	6.98	7.85	8.98	9.16	8.43	7.26
4A	Type 5	6.38	7.36	8.36	9.10	8.90	7.75	6.97	7.85	8.98	9.16	8.42	7.25
4B	Type 1, 0% WWR	4.54	4.60	4.62	4.62	4.58	4.51	4.45	4.46	4.44	4.47	4.48	4.54
4B	Type 2-6-7, 0% WWR	3.97	4.00	4.03	4.07	4.09	4.07	4.06	4.08	4.10	4.08	4.05	4.02
4B	Type 3, 0% WWR	4.13	4.16	4.20	4.20	4.17	4.12	4.08	4.12	4.18	4.22	4.22	4.17
4B	Type 1, 20% WWR	4.74	5.15	5.60	5.96	5.87	5.06	4.47	4.93	5.54	5.67	5.34	4.88
4B	Type 2-6-7, 20% WWR	4.30	4.80	5.32	5.71	5.64	4.84	4.40	4.54	5.17	5.24	4.84	4.31
4B	Type 3, 20% WWR	4.07	4.63	5.21	5.69	5.67	4.86	4.40	4.56	5.16	5.20	4.72	4.11
4B	Type 1, 40% WWR	5.02	6.04	7.62	8.98	9.09	7.59	6.44	7.33	8.56	8.50	7.33	5.93
4B	Type 2-6-7, 40% WWR	4.66	5.81	7.44	8.87	8.99	7.47	6.29	7.15	8.38	8.28	7.02	5.55
4B	Type 3, 40% WWR	4.46	5.69	7.41	8.90	9.02	7.51	6.30	7.17	8.39	8.28	6.95	5.40
4B	Type 4	5.60	6.93	8.74	10.31	10.31	8.49	7.11	8.33	9.99	10.05	8.60	6.79
4B	Type 5	5.59	6.93	8.73	10.33	10.32	8.50	7.13	8.34	9.99	10.05	8.59	6.77
4C	Type 1, 0% WWR	3.97	4.01	4.04	4.05	4.03	3.98	3.95	3.96	3.95	3.95	3.94	3.97
4C	Type 2-6-7, 0% WWR	3.39	3.40	3.43	3.45	3.46	3.47	3.47	3.49	3.49	3.48	3.45	3.42
4C	Type 3, 0% WWR	3.54	3.56	3.59	3.59	3.60	3.57	3.56	3.60	3.63	3.64	3.62	3.57
4C	Type 1, 20% WWR	4.13	4.38	4.68	4.86	4.82	4.49	4.25	4.53	4.86	4.86	4.56	4.16
4C	Type 2-6-7, 20% WWR	3.73	3.98	4.36	4.54	4.47	4.12	3.87	4.13	4.45	4.44	4.10	3.70
4C	Type 3, 20% WWR	3.50	3.81	4.23	4.43	4.38	4.03	3.76	4.02	4.32	4.29	3.94	3.50
4C	Type 1, 40% WWR	4.44	5.01	5.94	6.75	6.87	6.33	5.92	6.44	6.98	6.80	5.97	4.87
4C	Type 2-6-7, 40% WWR	4.10	4.75	5.71	6.56	6.69	6.13	5.69	6.21	6.72	6.53	5.68	4.53
4C	Type 3, 40% WWR	3.90	4.62	5.62	6.52	6.65	6.09	5.65	6.14	6.67	6.46	5.57	4.36
4C	Type 4	4.90	5.73	6.87	7.81	7.94	7.23	6.73	7.44	8.20	8.04	6.97	5.64
4C	Type 5	4.90	5.73	6.86	7.80	7.95	7.22	6.73	7.44	8.19	8.05	6.97	5.63
5A	Type 1, 0% WWR	6.11	6.15	6.15	6.13	6.07	6.00	5.95	5.99	6.03	6.04	6.11	6.11
5A	Type 2-6-7, 0% WWR	4.51	4.52	4.53	4.52	4.53	4.51	4.50	4.53	4.55	4.54	4.55	4.53
5A	Type 3, 0% WWR	5.12	5.12	5.14	5.12	5.08	5.02	4.99	5.03	5.09	5.13	5.16	5.14
5A	Type 1, 20% WWR	6.68	6.85	7.09	7.04	6.72	6.23	5.90	6.21	6.68	6.92	6.90	6.68
5A	Type 2-6-7, 20% WWR	5.88	6.07	6.33	6.32	6.00	5.49	5.05	5.42	5.85	6.05	6.01	5.76
5A	Type 3, 20% WWR	5.36	5.59	5.90	5.94	5.63	5.11	4.67	5.02	5.44	5.61	5.53	5.27
5A	Type 1, 40% WWR	7.31	7.80	8.47	8.85	8.55	7.64	7.05	7.68	8.48	8.69	8.36	7.65
5A	Type 2-6-7, 40% WWR	6.68	7.19	7.96	8.36	8.09	7.17	6.56	7.17	7.93	8.11	7.74	7.01
5A	Type 3, 40% WWR	6.29	6.83	7.67	8.12	7.86	6.96	6.34	6.92	7.67	7.83	7.41	6.64
5A	Type 4	7.93	8.74	9.59	10.03	9.68	8.59	7.91	8.71	9.74	10.01	9.52	8.61
5A	Type 5	7.92	8.73	9.57	10.01	9.66	8.58	7.90	8.70	9.73	9.99	9.51	8.59
5B	Type 1, 0% WWR	4.82	4.85	4.87	4.87	4.84	4.78	4.74	4.70	4.75	4.78	4.79	4.83
5B	Type 2-6-7, 0% WWR	3.78	3.79	3.82	3.84	3.85	3.83	3.83	3.84	3.86	3.86	3.83	3.80
5B	Type 3, 0% WWR	4.15	4.17	4.18	4.19	4.15	4.10	4.07	4.11	4.18	4.22	4.22	4.18
5B	Type 1, 20% WWR	5.23	5.37	5.69	5.94	5.86	5.41	5.03	5.33	5.74	5.85	5.61	5.23
5B	Type 2-6-7, 20% WWR	4.60	4.83	5.13	5.39	5.32	4.87	4.49	4.75	5.12	5.20	4.94	4.57
5B	Type 3, 20% WWR	4.24	4.52	4.85	5.14	5.11	4.69	4.31	4.56	4.91	4.93	4.62	4.23
5B	Type 1, 40% WWR	5.67	6.10	7.22	8.16	8.35	7.63	6.96	7.48	8.11	7.97	7.18	6.08
5B	Type 2-6-7, 40% WWR	5.16	5.68	6.84	7.81	8.02	7.31	6.63	7.12	7.74	7.55	6.72	5.60
5B	Type 3, 40% WWR	4.91	5.45	6.65	7.69	7.95	7.23	6.55	7.03	7.64	7.39	6.52	5.35
5B	Type 4	6.16	6.92	8.22	9.33	9.55	8.66	7.87	8.59	9.48	9.35	8.29	6.92
5B	Type 5	6.15	6.91	8.22	9.34	9.54	8.66	7.87	8.59	9.47	9.34	8.28	6.91

Table 5: Total annual energy use for climate zones 6A-8.

Effect of Orientation on Total Energy Use (GJ) Heating- Cooling- Lighting- Fans													
		Orientation											
Climate Zone	Wall Type	0	30	0	90	120	150	180	210	240	270	300	330
6A	Type 1, 0% WWR	6.40	6.41	6.39	6.34	6.27	6.19	6.15	6.19	6.22	6.28	6.36	6.38
6A	Type 2-6-7, 0% WWR	4.53	4.54	4.55	4.54	4.53	4.52	4.51	4.53	4.55	4.56	4.56	4.54
6A	Type 3, 0% WWR	5.21	5.22	5.22	5.20	5.16	5.11	5.08	5.12	5.18	5.23	5.25	5.24
6A	Type 1, 20% WWR	7.12	7.18	7.27	7.16	6.87	6.41	6.13	6.41	6.83	7.08	7.13	7.02
6A	Type 2-6-7, 20% WWR	6.16	6.26	6.41	6.37	6.07	5.62	5.29	5.54	5.94	6.14	6.15	6.00
6A	Type 3, 20% WWR	5.58	5.70	5.92	5.93	5.65	5.20	4.87	5.10	5.47	5.65	5.61	5.42
6A	Type 1, 40% WWR	7.86	8.06	8.53	8.80	8.55	7.79	7.29	7.80	8.49	8.68	8.46	7.95
6A	Type 2-6-7, 40% WWR	7.12	7.40	7.94	8.26	8.02	7.27	6.76	7.24	7.88	8.05	7.77	7.22
6A	Type 3, 40% WWR	6.66	6.99	7.59	7.96	7.76	7.02	6.50	6.97	7.60	7.73	7.40	6.79
6A	Type 4	8.42	9.04	9.60	9.92	9.64	8.75	8.16	8.81	9.69	9.95	9.58	8.92
6A	Type 5	8.40	9.03	9.58	9.91	9.62	8.74	8.14	8.81	9.68	9.95	9.57	8.90
6B	Type 1, 0% WWR	5.86	5.88	5.83	5.74	5.63	5.52	5.45	5.47	5.56	5.67	5.77	5.85
6B	Type 2-6-7, 0% WWR	4.08	4.09	4.11	4.11	4.10	4.07	4.05	4.06	4.10	4.12	4.11	4.10
6B	Type 3, 0% WWR	4.69	4.70	4.71	4.67	4.60	4.52	4.47	4.51	4.60	4.68	4.72	4.72
6B	Type 1, 20% WWR	6.61	6.66	6.72	6.67	6.41	5.87	5.44	5.71	6.17	6.46	6.55	6.46
6B	Type 2-6-7, 20% WWR	5.65	5.74	5.88	5.88	5.65	5.11	4.71	4.94	5.37	5.58	5.58	5.47
6B	Type 3, 20% WWR	5.06	5.22	5.44	5.50	5.31	4.79	4.41	4.63	5.02	5.17	5.08	4.91
6B	Type 1, 40% WWR	7.36	7.52	8.15	8.64	8.54	7.77	7.13	7.61	8.24	8.31	7.97	7.40
6B	Type 2-6-7, 40% WWR	6.63	6.86	7.56	8.13	8.08	7.33	6.69	7.13	7.74	7.75	7.31	6.68
6B	Type 3, 40% WWR	6.17	6.49	7.26	7.90	7.91	7.20	6.55	6.98	7.55	7.50	6.99	6.26
6B	Type 4	7.94	8.54	9.28	9.90	9.80	8.89	8.12	8.81	9.63	9.72	9.16	8.40
6B	Type 5	7.92	8.52	9.26	9.89	9.80	8.89	8.11	8.80	9.63	9.71	9.14	8.38
7	Type 1, 0% WWR	7.84	7.86	7.81	7.73	7.63	7.54	7.49	7.55	7.60	7.69	7.78	7.84
7	Type 2-6-7, 0% WWR	5.23	5.24	5.23	5.22	5.21	5.19	5.18	5.20	5.22	5.24	5.25	5.25
7	Type 3, 0% WWR	6.21	6.21	6.20	6.15	6.08	6.01	5.99	6.03	6.11	6.18	6.23	6.22
7	Type 1, 20% WWR	8.96	8.88	8.84	8.55	8.13	7.60	7.30	7.66	8.17	8.56	8.77	8.76
7	Type 2-6-7, 20% WWR	7.66	7.63	7.66	7.44	7.02	6.50	6.18	6.50	6.98	7.32	7.47	7.44
7	Type 3, 20% WWR	6.84	6.86	6.96	6.79	6.38	5.89	5.56	5.87	6.33	6.63	6.73	6.65
7	Type 1, 40% WWR	9.95	9.94	10.15	10.14	9.66	8.83	8.33	8.97	9.78	10.19	10.19	9.84
7	Type 2-6-7, 40% WWR	8.97	9.01	9.31	9.35	8.92	8.09	7.58	8.19	8.95	9.32	9.26	8.87
7	Type 3, 40% WWR	8.35	8.44	8.81	8.90	8.53	7.72	7.21	7.81	8.54	8.86	8.75	8.30
7	Type 4	10.68	11.11	11.42	11.43	10.95	9.97	9.38	10.20	11.19	11.65	11.50	11.03
7	Type 5	10.65	11.08	11.41	11.41	10.93	9.95	9.37	10.19	11.17	11.63	11.48	11.00
8	Type 1, 0% WWR	10.93	10.94	10.88	10.76	10.60	10.47	10.47	10.54	10.70	10.82	10.89	10.91
8	Type 2-6-7, 0% WWR	7.13	7.14	7.12	7.10	7.06	7.04	7.05	7.07	7.12	7.15	7.16	7.15
8	Type 3, 0% WWR	8.61	8.61	8.58	8.52	8.44	8.37	8.36	8.42	8.52	8.58	8.62	8.61
8	Type 1, 20% WWR	13.07	12.87	12.71	12.37	11.98	11.64	11.57	11.91	12.33	12.63	12.77	12.77
8	Type 2-6-7, 20% WWR	11.22	11.07	10.98	10.71	10.33	10.03	9.94	10.24	10.62	10.87	10.96	10.96
8	Type 3, 20% WWR	10.06	9.94	9.90	9.67	9.33	9.05	8.96	9.22	9.56	9.78	9.83	9.79
8	Type 1, 40% WWR	15.02	14.68	14.67	14.50	14.18	13.88	13.82	14.21	14.68	14.91	14.80	14.61
8	Type 2-6-7, 40% WWR	13.62	13.36	13.39	13.27	13.02	12.73	12.66	12.99	13.42	13.60	13.48	13.23
8	Type 3, 40% WWR	12.73	12.54	12.61	12.55	12.34	12.07	11.99	12.29	12.68	12.84	12.67	12.37
8	Type 4	16.23	16.42	16.48	16.31	15.99	15.64	15.57	16.02	16.55	16.80	16.63	16.32
8	Type 5	16.19	16.38	16.44	16.29	15.96	15.61	15.53	15.99	16.51	16.76	16.59	16.28

In terms of heating energy demand, curtain walls performed better than the brick cavity wall (Type 1) in climate zones 4A through climate zone 7 for southern orientations (90° to 270°). For all other cases, curtain walls are the worst performing types, with highest heating energy demand in all climate zones compared to other exterior wall types. Differences between the standard and thermally improved curtain walls were negligible, and north-facing curtain walls would significantly increase heating energy demand compared to other orientations. Thermally improved rainscreen facades would have the lowest heating energy demand, due to very high thermal resistance. In terms of cooling energy demand, curtain walls were the worst performing as well. However, east and west facing curtain walls typically have higher cooling energy demand than south orientated curtain walls for very hot (zone 1), hot (zone 2), warm (zone 3) and mixed climates (zone 4). In colder climates (zones 5 and 6), south oriented curtain wall would have higher cooling energy demand than other orientations. Opaque exterior wall types would have comparable effect on cooling energy demand, with only negligible differences for different wall types and orientations.

Figures 15 to 18 compare impacts of climate change on energy performance, considering current climate data, year 2050 and year 2080 for the best performing opaque and glazed exterior wall assemblies (Type 7 and Type 5).

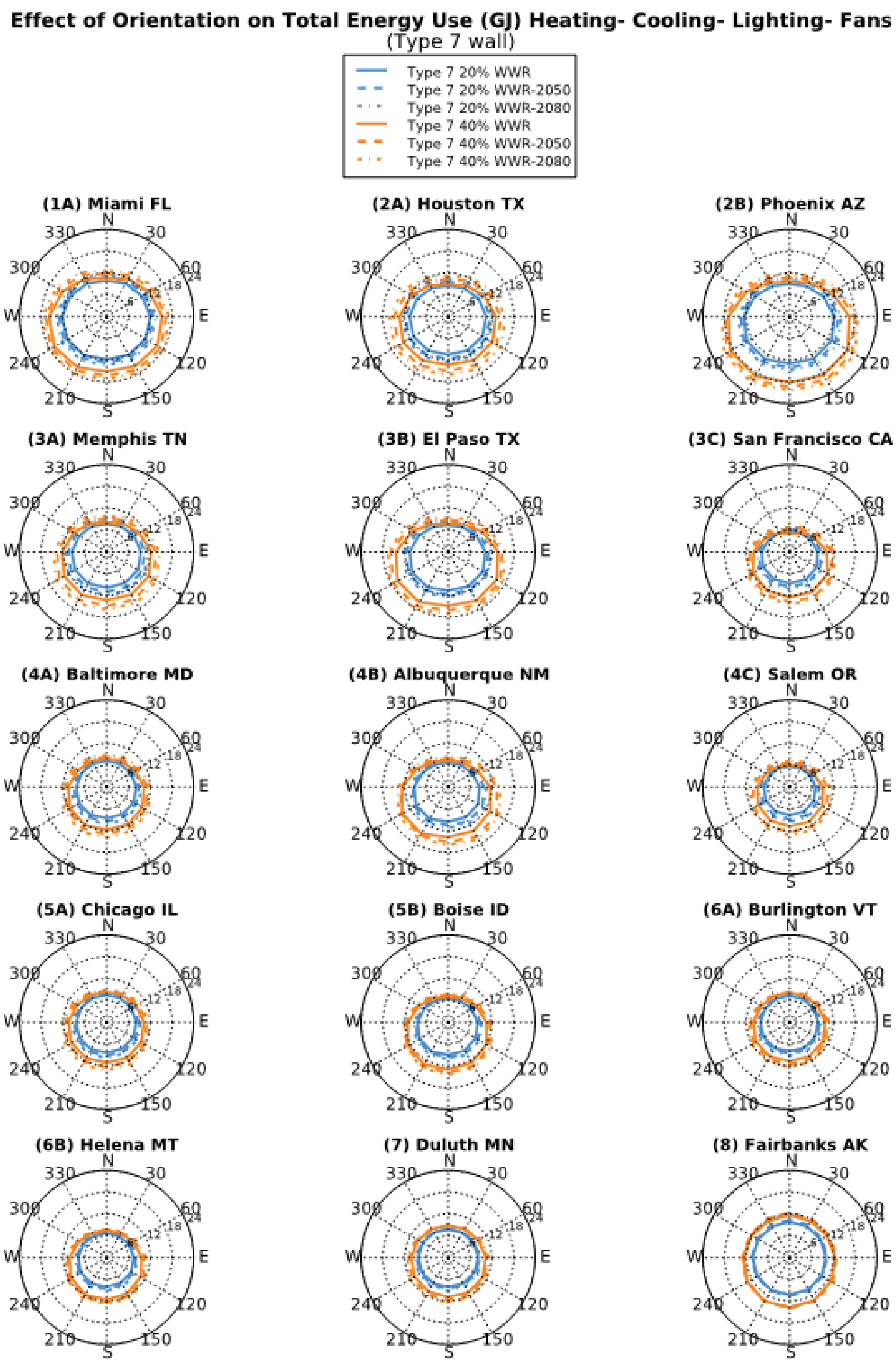


Figure 15: Total annual energy use for Type 7 exterior wall (current climate data).

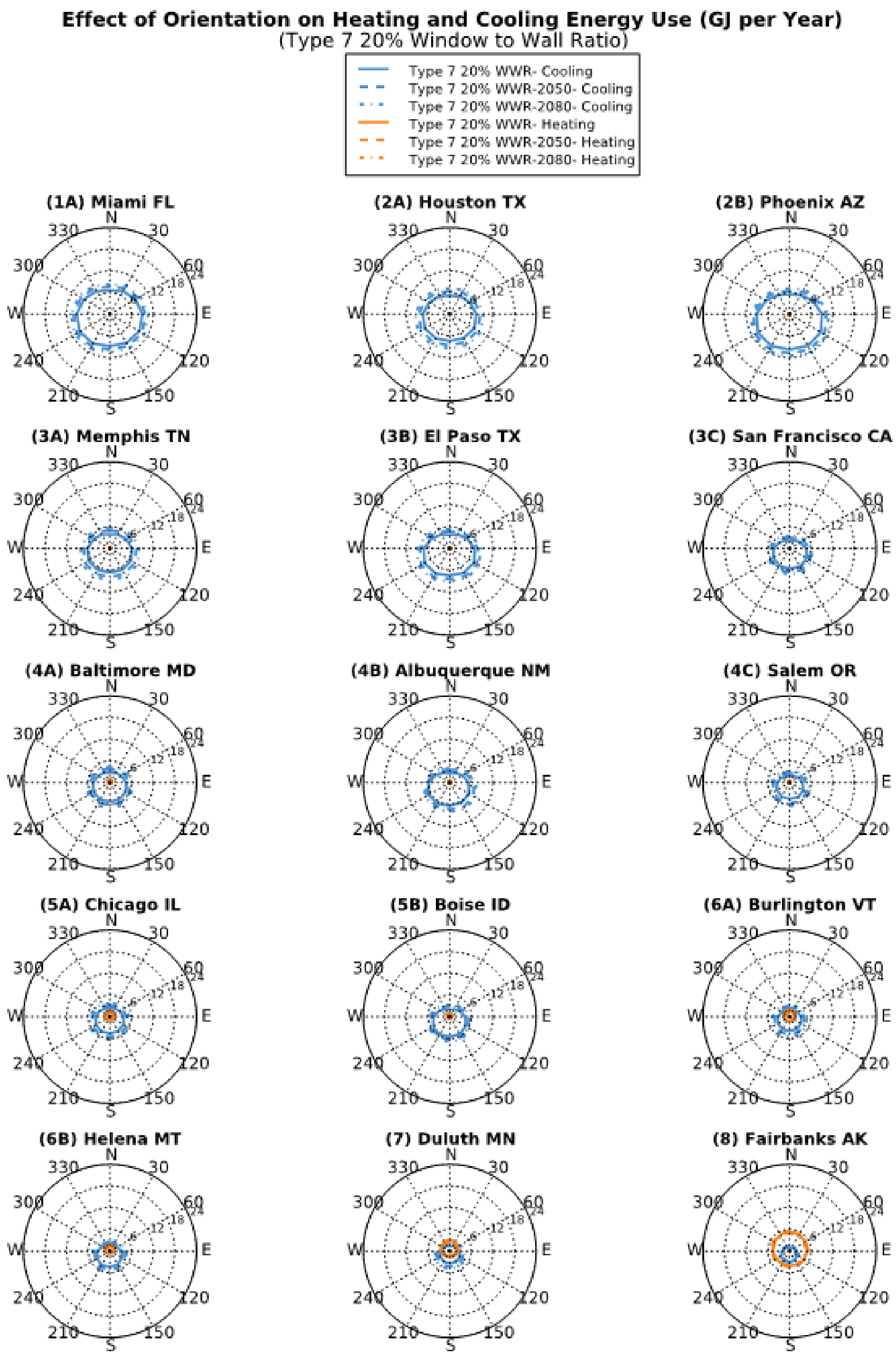


Figure 16: Comparison of heating and cooling energy use for Type 7 exterior wall (current climate data, year 2050 and year 2080).

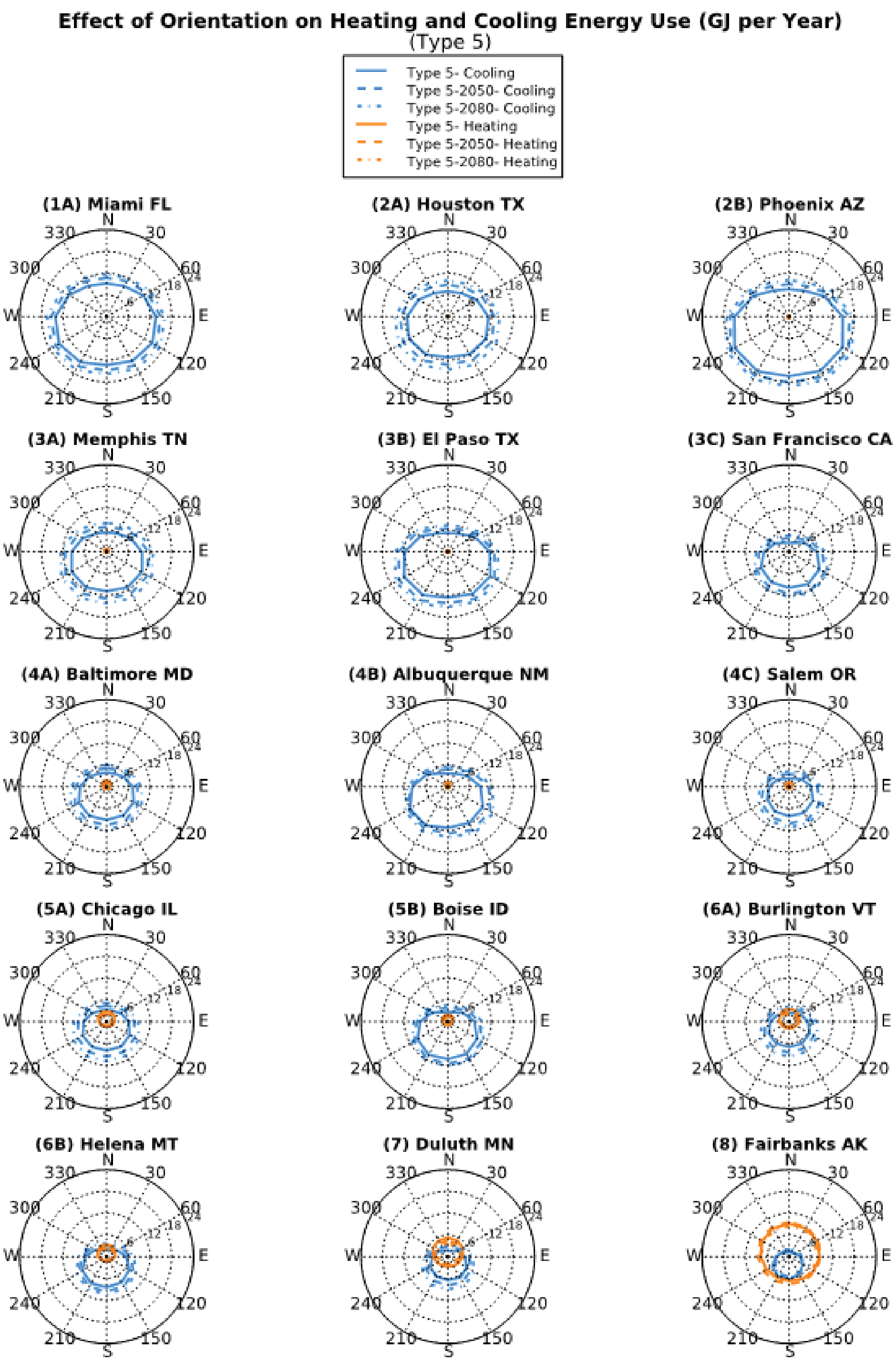


Figure 17: Comparison of heating and cooling energy use for Type 5 exterior wall (current climate data, year 2050 and year 2080).

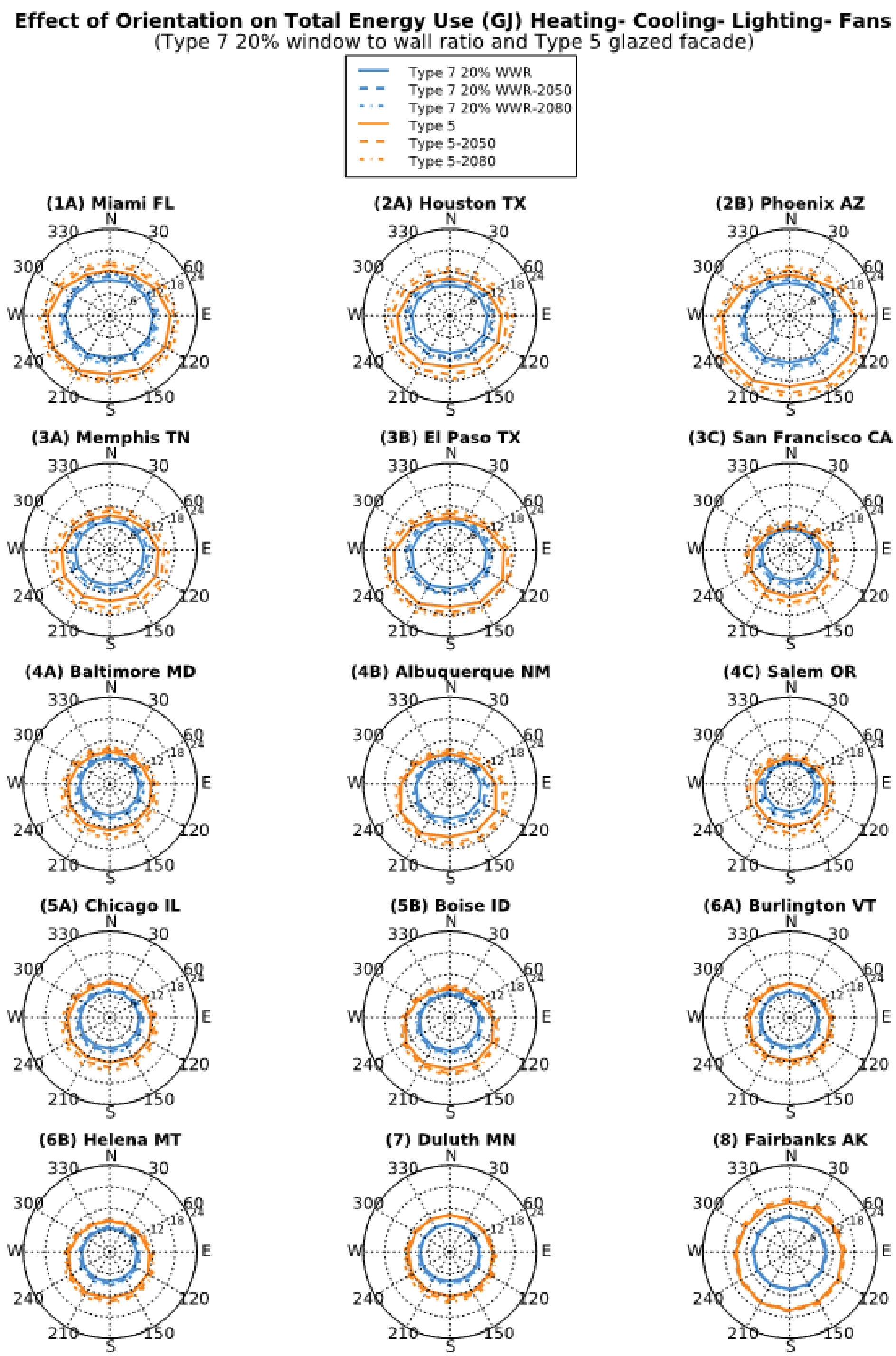


Figure 18: Comparison of total energy use for Type 7 (20% WTW) and Type 5 exterior walls (current climate data, year 2050 and year 2080).

The north facing facades performed the best for most of the climate zones due to lower cooling loads. All facade types showed the highest total energy use in the year 2080. The next highest was the year 2050, and the lowest total energy use was for present day weather files. The results for rainscreen facade with terracotta cladding and thermal isolators (Type 7) and curtain wall with thermally broken aluminum framing (Type 5) were plotted and compared to represent typical results of all of the wall types. Type 7 had the lowest conductance in this study for the opaque assembly, and Type 5 had the lowest conductance for a glazed facade. Type 7 with 20 percent window to wall ratio had lower total energy use than Type 7 with 40 percent window to wall ratio (Figure 15). Heating and cooling loads were compared for Type 7 with 20 percent window to wall ratio, which shows that cooling loads dominate the energy use for the office space, except in climate zones 7 and 8. Cooling loads increase by a greater amount than the decrease in heating loads, therefore net energy use is increased with climate change (Figure 16). Similar results are seen in Figure 17 for the curtain wall. A comparison of the total energy use between Type 7 with 20 percent window to wall ratio and curtain wall (Type 5) shows the curtain wall performing worse, and both wall types using greater amounts of energy in future simulated climate change weather files (Figure 18).

4.0 CONCLUSION

Exterior walls significantly influence energy consumption and occupants' comfort for any building. High-performing facades need to block exterior environmental conditions and maintain interior comfort conditions with minimum energy consumption. Climate-based design approaches are key elements in designing high-performance building facades, where specific climatic conditions need to be taken into account.

This research article discussed comparative study of seven different exterior wall types, where thermal performance, heat transfer and energy consumption were investigated, as well as their performance in different climate zones. Moreover, the impacts of climate change on energy consumption was investigated, where impacts of future predicted weather patterns for years 2050 and 2080 were studied. The research was conducted by initially modeling heat transfer in seven different exterior wall types, including conventional and thermally improved assemblies. Conventional systems included brick cavity wall with metal framing, rainscreen facade with terracotta cladding, rainscreen facade with glass-fiber reinforced concrete cladding, and a standard curtain wall. Thermally improved systems included a curtain wall with thermally broken framing, rainscreen facade with thermal spacers and a rainscreen facade with thermal isolators. Four different exterior environmental conditions were chosen, which would represent different climates. Thermal gradients through the exterior walls were modeled, and U-values were calculated for all seven exterior wall types. Results show that the curtain wall is the worst performing assembly, followed by a brick cavity wall. The best performing scenario is the rainscreen facade with terracotta cladding and thermal isolators, since the framing support for the insulation and cladding would exhibit lower thermal bridging compared to other analyzed opaque facades. Also, thermal bridging would be minimized by including thermal isolators, which would lower the effective U-value by 20 percent compared to conventional rainscreen facade.

Following the heat transfer analysis, energy modeling was conducted to analyze the effects of different exterior wall types on energy consumption of a commercial office space in various climate zones. The effects of orientation, as well as different window to wall ratio (20 and 40 percent) were investigated. A single office zone was simulated, enclosed with the analyzed exterior wall types, taking into account relative orientation of the facade, as well as specific climate data for three different time periods. Results show that the facades with a lower U-value have better energy performance. Orientation had a greater impact on the performance of glazed walls and curtain walls, where east and west oriented facades would have the highest energy use. Simulated climate change weather files for the year 2050 and the year 2080 increased the total energy use for all climates and facade types.

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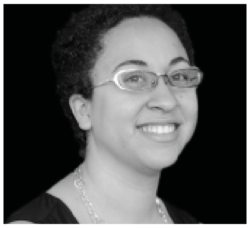
01. 

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