Divergence in Architectural Research

Proceeding Book of
ConCave Ph.D. Symposium
Georgia Institute of Technology
Atlanta, Georgia, USA
April 7-8, 2022

Edited by
Hayri Dortdivanlioglu
Eleanna Panagoulia
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CONCAVE Ph.D. Symposium
Proceedings 2022

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The second International ConCave Ph.D. Symposium “Divergence in Architectural Research” took place at Georgia Tech on April 7-8, 2022, after a year-long planning and preparations. Following the footprint of the successful first ever ConCave Ph.D. Symposium in 2020, our goal was to bring Ph.D. students from world-wide together to support and promote their research. We would like to thanks the members of the ConCave Ph.D. Student Group for their hard work in helping us achieve our goal.

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BECOMING AMIDST AMBIGUITY

Hayri Dortdivanlioglu
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This second volume of Divergence in Architectural Research brings together nineteen papers presented at the ConCave Ph.D. Symposium 2022, which took place at the Georgia Institute of Technology, Atlanta, Georgia on April 7-8, 2022. This international doctorate symposium was organized by the ConCave Ph.D. Student Group under the auspices of the School of Architecture and the College of Design at the Georgia Institute of Technology. The symposium sought to create a platform for sharing current research in architecture, with invited scholars and other doctoral students from architecture and allied fields. It was our desire to create an opportunity to gather, exchange formal, as well as spontaneous conversations in research, and explore possibilities of collaboration.

Right after the first ConCave Ph.D. Symposium in mid-March of 2020, like the entire world we found ourselves following planetary regulations and procedures dictated by the Covid-19 Pandemic. While the success of the first symposium raised the bar for the next event, besides our ambitions, we had to tackle with the daunting task of bringing Ph.D. scholars together during an on-going world health emergency. While in the last two years we learnt more about how to control and fight the disease, we were not certain about the possibility of an in-person symposium considering the emerging variants and the limited distribution of the vaccines only in some privileged regions of the world. The pandemic made the inequities and the issues of access to resources more visible in every aspect of human life, but more so in our Ph.D. community.

The isolation during the peak of the pandemic proved the necessity and importance of the ConCave Ph.D. Group and the Ph.D. Symposium. On the one hand, it showed us the value of belonging to a community and having a safe space to get together and interact with our peers and friends. On the other hand, the inequities emerging after Covid-19 compelled us to reimagine the structure of the symposium. In addition to physical gathering made possible by adoption of precautions, such as vaccination, mask wearing, and regular rapid Covid-19 testing, we offered a virtual space, in which the presenters and participants from all over the world followed the symposium and interacted with the other participants.

Amidst the ambiguity raised by the Covid-19 pandemic, in June 2021, we issued our call for the second ConCave Ph.D. Symposium. We are truly grateful that many responded to our call for Divergence in Architectural Research. Over fifty scholars submitted their abstracts, which were double-blind peer reviewed by the experts of their field. Among the scholars who passed the first peer review, twenty-four of them submitted their full paper for the second round of peer review. These papers engaged the divergent aspects of architectural research across epistemological frameworks, highlighting the emerging intersections in selected topics. The papers are presented in seven panels, each focusing on a different aspect of the broader architectural discourse. The panels including “Building Science and the Envelope,” “Architects and Documents,” “Weaving craft and Design,” “Hybrid Machines,” “Technocraft Explorations,” “Health and the Build Environment,” and “Post-colonial Narratives,” derive from a plethora of contexts, ranging from theory and information technology to materiality and craftmanship.

The event included presentations, remarkable talks and workshops that enriched the symposium. Keller Esterling gave the first keynote lecture entitles as her book “Medium Design”, in which she inverted an emphasis on object and figure to prompt innovative thought about both spatial and non-spatial problems. Cynthia Davison, director, and founder of Anyone Corporation, delivered the second keynote “Narrative Design” on gathering intelligence for architecture and design. Neil Leach introduced his most recent book *Architecture in the Age of Artificial Intelligence*, discussing the use of imagination for changing architectural practice through AI technology. Furthermore, four workshops conducted by Leslie Sharp, Karen Kelsky, Heather Ligler and Tarek Rakha provided guidance for Ph.D. students on their academic work and future careers.

We acknowledge that the term divergence holds an ambiguous meaning in disciplines, such as architecture, which are inherently open to different methodologies and approaches. We find value in the ambiguity of the term divergence, and celebrate the agency that it provides to question and blur the established boundaries of the disciplines. While we accept divergence in research, we do not adhere to the implication when it is understood as “unlikelihood of ultimate meeting or reconciliation.” Like the symposium, this edited book carries its title as it aims to converge various themes, topics, methodologies, strategies and perspectives that guide and influence architectural research. Together, they draw threads among the essays and map their movements. Our hope is that the reader will discover even more possibilities than those we set up within the existing structure of this book.

In order to emphasize the multifocal quality of the essays, we followed a different strategy to organize this book than the one adopted during the event, which favored a thematic organization. While the panels organized in specific themes allowed us to bring together the diverse methodologies and perspectives in related topics, we are aware of the limitations of such organization in encapsulating a wide range of research practices in a confined domain. Like the first volume of *Divergence in Architectural Research*, this volume is shaped as a “Choose Your Own Adventure” book. Rather than offering a linear reading pattern, this publication suggests different maps that the reader can choose to read the essays. We also invite the reader to draw their own reading maps and explore the divergent threads that wove the essays together in this edited volume.

The ConCave Ph.D. symposium became more inclusive and accessible amidst the ambiguity of Covid-19 Pandemic, we imagine that the domain of architectural research could continue to transform and mutate amidst the ambiguity of divergence.

Atlanta, 2023


ViewSonic


Georgia

ARCHI

Archi- is derived from Ancient Greek ἀρχι, *arkhi-*, meaning 'chief,' 'leading.'

ARCHIVES

GEOGRAPHIES

NARRATIVES

Tektōn in Ancient Greek τέκτων is a term for an artisan, craftsperson

TECTURE

DESIGN

CRAFT

TECHNIQUE

FABRICATION

MACHINES

MEDIA

CRAFT

TEXTILE

MATERIAL

SYSTEMS

BIOLOGY

DESIGN

NARRATIVES

THEORY

ARCHIVES

DATA

GEOGRAPHIES

HISTORY

TECHNOLOGY


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EXIT


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LANDSCAPE AND BUILDINGS CRAFTING NATIONAL HERITAGE

Barbara Cortizo de Aguiar
University of Texas at Austin

In this paper, I discuss the role of architecture and cultural landscape in our continent's national identity creation and nation-building processes. More specifically, I examine the creation of national heritage institutes in the United States and Brazil in the early 1900s to show how countries imagined their national identity through preservation endeavors and the built environment. As these processes might be understood through their territorial occupation, I argue that national heritage in the United States and Brazil were defined as landscapes and buildings, respectively. Looking at landscapes and buildings, I analyze how the National Park Service and the Serviço do Patrimônio Histórico Artístico Nacional were partially responsible for crafting the countries' national identities by preserving a mostly white aspect of their histories.

First, I explore the individual narrative of the National Park Service, seeking to understand how this agency defined the country's notion of national heritage. I present the first events of historic preservation in the United States and discuss the general image of place and identity derived from those endeavors. I discuss the establishment of the first national parks and how that led to creating a bureau to manage and preserve the United States' heritage. Second, I discuss the roles of historicism and architecture in shaping Brazilian national heritage from 1838 to 1938. I present the creation of the first memorialization offices in the nineteenth-century. Then, I show how this narrative changed in the twentieth century. Last, I argue that, by using architecture as a symbol of different historical periods in Brazil, it became a fundamental element in shaping the Brazilian heritage.

Governments and national institutions decide what aspects will be excluded from their narrative by acclaiming certain events and celebrating them as heritage. With this premise in mind, I seek to understand how two different countries created two different foundation myths that have since been used to define national identity and values. I look at national heritage studies by discussing celebration and erasure in national heritage narratives.

Keywords: National identity, national heritage, celebration, erasure.

INTRODUCTION

National heritage is related to the history of a nation and legacies from the past, considering patrimonial objects as both historicist and memorialization elements. Considering a nation is an imagined political community, national heritage would also be an abstraction, a curated selection of objects representing said community's identity. This abstraction allows for the continuity of the past, while simultaneously creating a rupture with it, and defining which memories could be erased from the official narrative. Within this construction and decision-making process on what to highlight and what to erase lies the self-proclaimed image of a country and how the country defines its national identity.

The notion of historic preservation in the Americas is still rooted in its colonial history and is deeply tied to European hegemonic influence. This influence has controlled which spaces and places are preserved, and how heritage designations validate specific histories. With time, what has started with the designation of monuments and the listing of historical objects and buildings has changed to encompass people, practices, and events. However, heritage-making and historic preservation in the Americas are still tied to a nineteenth-century discourse.

In this paper, I present memorialization processes in the Americas and study narratives of national heritage formation, aiming to explain how the concept of nation was imagined through the landscape and the built environment. I understand that by acclaiming certain events and celebrating them as national heritage, governments also decide what aspects to exclude from the national narrative.

Here, I highlight how different countries consider what events are part of their collective memory and which groups they celebrate and preserve. In sum, I debate whose memory these countries preserve, which groups are represented by this patrimony, and which groups were left out of the official narrative.

Heritage is the collection of one person or entity's assets that can be passed on to others. Collective heritage is an object or group of objects representing a community's identity and meant to remain for future generations. National heritage is a curated selection of objects representing a nation's identity. It is a subjective process of selecting, creating monuments, highlighting other elements, and silencing unwanted aspects of a country's past.

At the time both the National Park Service and Serviço do Patrimônio Histórico e Artístico Nacional[1] were created, the terminology used to talk about heritage was *historical monument*. Nowadays, the United States keeps relating the preservation field to *historical* heritage while Brazil understands it as working with *cultural* heritage. Note the difference between the two countries and compare them with the national narratives they created in the early twentieth century: on the one hand, nature and wilderness; on the other hand, architecture and artistic expression.

THE UNITED STATES

Mid-nineteenth century United States had a particular interest in everything related to the founding fathers, a feeling that grew significantly after the Union won the Civil War. The interest in the history of the country's formation made its way to the preservation of objects and buildings. The first building restoration actions were triggered by a conservative desire to restore a moment in the past and to help define the country's identity. At that time, however, there was not yet an established disciplinary field of architectural preservation in the United States. In the nineteenth-century, people sought for different ways of expressing their relationship with the land and environment. The first historic preservation initiatives, alongside regional artists', architects', and landscape designer's works, helped develop and define the country's national identity.

The first nationwide preservation society, the Mount Vernon Ladies' Association of the Union, a non-governmental organization founded by Ann Pamela Cunningham in 1853, advocated for and carried out the first preservation enterprise in the United States. Mount Vernon, George Washington's homestead in the Hudson River Valley, was abandoned and in disrepair when Cunningham decided to advocate for its preservation. The farmhouse was preserved for its historical significance. It was in that vernacular stone house that George Washington lived during the Revolutionary War. Cunningham and her companions raised funds to purchase Mount Vernon, making up the first grassroots effort to protect a historic site.

Mount Vernon Ladies and other similar associations preserved buildings and sites related to the history and life of famous white men. Later, those buildings became the image of the national architectural heritage.[2] A second landmark in the history of architectural preservation in the United States is the restoration of Colonial Williamsburg (started in 1926), considered the country's most iconic preservation initiative. A significant event that established what was possible in historic preservation in the United States, dictating the aesthetics and methodology of architectural restoration, and legitimizing corporate organization's role in the field.[3]

The centrality of the Thirteen Colonies was not limited to architecture and other cultural manifestations. Considered by many as the United States' initial territory, the region was defined initially by two frontiers: the European Atlantic frontier to the east and the wild lands to the west. Starting in the late eighteenth century, the United States slowly and steadily tried to push its boundaries and conquer the western frontier.[4]

WILDERNESS AND THE SUBLIME TERRITORY

The westward expansion became a necessity for U.S. Americans as part of its process of evolution, of developing a U.S. American environment by disseminating the European germ throughout the continent. From the Appalachian to the Rocky Mountains and then to the Pacific Ocean. The United States shaped its current political geography by battling the Indigenous peoples, enslaving Africans, fighting the Mexicans, purchasing land, expanding the territory, crossing the continent, and colonizing the natural environment they called the wilderness. The national discourse held the Indigenous groups as simple, primitive people in a dialectic relationship with the complex Europeans. Native Americans were considered savages, a threat, and a danger to the colonists.

In *The Significance of the Frontier in American History* (1893), Frederick Jackson Turner states that the conquest of the frontier—its expansion to the west—makes up the first period of American history. Advancing the frontier and moving westward to reach the Pacific Ocean also meant reducing dependence on England, representing an enormous act of nationalism.[5] By doing so, the United States became more American, and less European.

> The wilderness masters the colonist. It finds him a European in dress, industries, tools, modes of travel, and thought. It takes him from the railroad car and puts him in the birch canoe. It strips off the garments of civilization, and arrays him in the hunting shirt and the moccasin. It puts him in the log cabin of the Cherokee and the Iroquois, and runs an Indian palisade around him . . . In short, at the frontier the environment is at first too strong for the man.[6]

Dialectically, alongside wilderness and nature, there is always an idea of civilization, a tension between the country and the city. William Cronon (1996) highlights several interpretations of nature and wilderness: moving from a dangerous, threatening place to a sublime, pristine landscape.[7] The National Parks became the physical representation of the latter concept, the place one can encounter the wilderness at the cost of expropriating particular parts of the land, usually created on Native American reservations lands. The naming of natural elements, such as mountain ranges and valleys, also reflects this wilderness-civilization relationship.

> One could also argue that, given the status of more-or-less pristine landscapes and of national parks among much of the American public, the Arapaho names applied to the various mountains connote a kind of "sacral" status assigned to those areas, and that the "exotic" Indian names have even contributed to the evolution of such a status among some of the contemporary public. The mountains have thus become, for a second time, a site linked to the past, the exotic, and the "Other," as they were for the Arapaho as well.[8]

During the eighteenth and the nineteenth centuries, claiming the western frontier was considered a right of the U.S. Americans. Conquering the wilderness was understood as an act of modernization and social evolution. Facing and overcoming the frontier forced the complex society to confront the wild, sublime, and daunting nature. This process also shaped the idea of the United States as a nation of composite nationality.[9] The western frontier and the sublime landscape became powerful national symbols, and the wilderness became a sacred concept. Underwritten by the government, manifest destiny drove many people westward, following the myth of the frontier and expanding the country.

U.S. American expansionism was also triggered by a republican desire to augment the national territory and reach the Pacific coast, fulfilling old, colonial aspirations. Disguised as an Anglo-Saxon expansionist mission, manifest destiny was the perfect argument for bringing people and joining forces to expand the territory under a nationalist narrative, creating a new imperial power over a large tract of land. A strong and vast republic, with a growing population, bountiful and beautiful natural resources, and a strong emerging economy able to negotiate with Europe and Asia from ports located on its own territory.[10]

Once that western frontier disappeared, U.S. American leaders started engaging with wilderness conservation activities and creating the national parks. Over time, the notion of the wilderness changed from the original garden to the frontier, the bold landscape, and into the sacred sublime—all of those images becoming a part of the national identity construction in the United States. Initially, the wilderness was something to be conquered, colonized; then, it changed into a commodity, a place where one would escape, or the place of recreation for wealthy tourists.[11]

Reaching the western border and overcoming the old colonial frontier triggered the desire to protect the wild landscapes, protection, and permanence walking side by side. The initial landscape preservation endeavors in the United States focused on removing any trace of Indigenous communities from those areas, and creating an uninhabited wilderness. The National Parks became the physical representation of the sublime and pristine landscape in the United States; a place one can encounter the wilderness at the cost of enclosing land and dispossession, usually created on Native Americans' lands.[12]

PROTECTING THE UNITED STATES NATIONAL PARKS

The U.S. government, as a preservation agent, engaged in conserving the nation's natural features, especially in the western hinterlands. Known for its waterfalls, Yosemite became the nation's first State Park in 1864. A few years later, in 1872, the United States created what would be the world's first national park: Yellowstone National Park, comprised of lands in three different states. Moving west, conquering and grabbing land, and creating the national parks were essential parts of defining national identity in the United States, and strengthening the feeling of patriotism.

In 1906, the federal government passed the Antiquities Act, allowing the president to designate historic landmarks, structures, and objects in federal lands—thus, establishing the first national preservation legislation. Ten years later, the United States Department of Interior would create the National Park Service with the goal of establishing "an apparatus to handle sites too large for private protection or preservation."[13]

This move created a national parks system, still without a central management office. Given the rising interest in the national parks, the Department of Interior commended the creation of a dedicated bureau for them. The idea began taking shape in 1911 with an unsuccessful bill and regained strength after the "See America First" campaign beginning in 1914.[14] Establishing a National Park Service formalized a practice that had started forty years before. Little by little, every corner of the United States West had a national park, a constructed wilderness landscape to call their own. The federal government could publicize a national asset as a magnificent must-see natural site, reinforcing the mythology of the United States as nature's nation, and displaying the country's magnificence.[15]

As mentioned above, the Antiquities Act of 1906 gave the United States presidents the right to designate national monuments. When the National Park Service was created, there were eighteen national monuments and twelve national parks (Figure 1). Celebrating national parks and monuments in the western corner of the country was an apparent move to ratify those lands as part of the national territory. By doing so, the United States integrated the West into its national identity, calming the identity anxiety around the influx of Eastern and Southern Europeans at the turn of the century and creating a temporary solution to the North/South divide.

Figure 1: Location of National Parks (in black) and National Monuments (in gray) in the continental United States, established until 1916. At that time, there were other two national parks in Hawaii. Source: GoogleMaps 2022.

Established on August 25, 1916, by the Organic Act, the National Park Service was seen not only as the management bureau for parks and national monuments but was also a tool for educating the population on the values of those sites, as well as a tool for preserving them. The National Park Service is responsible for protecting one of the United States greatest assets. Along with the *See America First* campaign, the National Park Service forged the idea of the national parks as the quintessential American landscape and symbol of this country's character.[16] This sentiment of recognition and belonging is still a part of present-day U.S. Americans' identity.

A third architectural preservation milestone following the Mount Vernon Ladies Association led by amateur preservationists and the restoration of Colonial Williamsburg, backed by trained professionals, is the Historic American Building Survey (HABS, created in 1933). The survey was the first federal initiative aiming at the preservation of Indigenous cultures, along with the country's natural resources and architectural heritage. HABS was an attempt to expand the National Park Service's actions of "preserving naturalistic western landscapes to include the cultural heritage of the east."[17] The allure for a Colonial Revival architectural style grew with the independence centennial exhibitions. Sixty years after the celebrations, it seemed that the United States had finally overcome the manifest destiny call and decided to reclaim its colonial past.

BRAZIL

The arrival of the Portuguese court to Brazil in 1808 has traditionally been considered as the starting point for the former colony's modernization process. Modernization and development in the early nineteenth-century Brazil meant to civilize the land, transforming the country based on European standards. The presence of the Portuguese (1808-1822) and Imperial (1822-1889) courts in

Brazil allowed for the importation of cultural institutions, the creation of the first colleges,[18] and several museums,[19] institutes, and societies.

The nineteenth century also saw the emergence of historical and geographical institutes to build the past and systematize an official history. Emperor Pedro II and the Sociedade Auxiliadora da Indústria Nacional created the Instituto Histórico e Geográfico Brasileiro (IHGB, the Brazilian Historic and Geographic Institute) in 1838.[20] The mission of the Instituto Histórico e Geográfico Brasileiro is defined in the first article of its statute, which reads:

> To collect, systematize, publish or to archive the necessary documents for the Brazilian History and Geography, to promote the knowledge of these two branches of science [...] to consolidate itself in the provinces of the Empire, in order to facilitate the proposed objectives; and to publish the Revista do Instituto Histórico e Geográfico Brasileiro.[21]

The Sociedade Auxiliadora da Indústria Nacional intended to modernize the industry and develop the country under a capitalist, for-profit lens. It was tied to the imperial government and had a highly political agenda. IHGB focuses on producing symbolic representations and enjoying relative autonomy from the emperor. IHGB's project was to reconstruct Brazilian history based on a modern perspective. In her study of three scientific associations, Lilia Moritz Schwarcz (1989) states that Brazil's historical and geographical institutes selected moments in early Brazilian colonial history to establish a more substantial unifying project for the nation.[22]

By the very end of the nineteenth century, Brazil abolished slavery (in 1888), became a republic (in 1889), and started encouraging people from other nations to immigrate to work in the plantations. As a republic, the country needed to revisit its values and identity; it was a time to create a new myth of foundation, redefining its image for national and international audiences.

A STYLE FOR THE NATION

In the late 1800s, studies in biology and health-related sciences had a high impact on the humanities, giving rise to a wide range of utopian urbanism theories, and leading the way to urban reform proposals and city beautification plans. In its interest to modernize, Latin America continued to perpetuate a colonial dynamic—this time, under cultural and scientific lenses—becoming the place for experimentation of European sanitarian and eugenic theories.[23]

Brazil was no different. In the early 1900s, Oswaldo Cruz,[24] Brazil's most illustrious sanitary physician, and head of the Instituto Soroterápico Federal,[25] battled to vaccinate the poor and densified central region of Rio de Janeiro. In the first quarter of the twentieth-century, sanitation and city beautification plans dictated local and national politics in Brazil. Urban reformation plans served as the state's instrument for embellishing the cities—following a European idea of beauty, fighting physical and social diseases, eliminating viruses, expelling poverty, and whitening the population.[26]

The country was at a time of social, urban, and political change amidst an age of cultural effervescence. The newfound republican values and social patterns stimulated the search for a national identity. Compare the selectivity of republican values in each country: the celebration of the founding fathers' memory and private associations advocating for architectural preservation in the United States, and the search for modernization and progress fostered by the States in Brazil. In architecture, the critique of the vast number of eclectic and revivalist buildings resulted in a new style: the neocolonial. The demolition of Morro do Castelo in Rio de Janeiro—the original site of the sixteenth century colonial town—in1920 led the way for the 1922 Centennial Exhibition site with neocolonial buildings and, later, the Estado Novo's ministerial esplanade.[27] The neocolonial was also the style chosen for Brazilian pavilions at world fairs.

In the 1920s, intellectuals worried about the irreparable loss of colonial buildings and historical monuments, defending a preservation policy for urban areas. Parallel to that, José Mariano Filho—director of the Escola Nacional de Belas Artes—and Ricardo Severo, leaders of the neocolonial movement, defended Brazilian colonial art as the manifestation of the country's tradition.[28] Two groups fought to define architectural modernity in 1920s Brazil: the conservative modernists—represented by José Mariano Filho—and the vanguard ones led by Lucio Costa.[29] The latter group won this battle, defining the Brazilian modern style adopted by the front line of the government of President Getulio Vargas (in office from 1930-1945[30] and 1951-1954).

MEMORIALIZATION AND NATIONAL HERITAGE IN BRAZIL

The history of preservation in Brazil is usually constructed over a *rhetoric of loss* (loss due to decay or urban reform razing) and of legally protecting buildings, monuments, and collections.[31] In 1923, fearing the loss of old buildings and monuments, José Mariano Filho proposed the creation of the Inspetoria dos Monumentos Históricos dos Estados Unidos do Brasil (the National Historical Monuments Inspectorate).[32] Although not fully implemented, this project influenced the formation of regional offices of the Inspetoria Nacional de Monumentos Históricos in Minas Gerais (1926), in Bahia (1927), and in Pernambuco (1928).[33] It took a while for the Brazilian government to rethink Mariano Filho's proposition for an Inspetoria Nacional, which only became a reality during the Vargas regime in 1934.

The Inspetoria Nacional de Monumentos Históricos was closed down for political reasons and power disputes. Its works were limited to preservation actions in the city of Ouro Preto, which was nominated as a national monument in 1933. A second standing initiative was the creation of the Museu Histórico Nacional, directed by Gustavo Barroso. In 1937, the Inspetoria Nacional was replaced by the Serviço do Patrimônio Histórico e Artístico Nacional (SPHAN). The creation of the SPHAN resulted from preoccupations with the loss of several colonial buildings and monuments, the need to legally protect the monuments, and the urge to create a narrative for the country's national image and identity through its artistic manifestations and historical events. It was also the result of a decade of internal debate on what should be considered Brazilian heritage: even by its connection with the Brazilian history or by having an exceptional national value of archaeological, ethnographic, bibliographic, or artistic representations.

The Serviço do Patrimônio Histórico e Artístico Nacional was created through the Decreto-Lei nº 25/1937, which defined Brazilian historical and artistic heritage, established the national policy, and determined the way to protect it. The Decreto-Lei nº 25/1937 established guidelines for safeguarding the national heritage and defined the legal protection instrument. Once listed, a cultural asset is legally protected in Brazil. The majority of the first Brazilian landmarks, listed in 1938, were colonial buildings from the sixteenth, the seventeenth, and the eighteenth centuries, from Minas Gerais, Bahia, and Pernambuco—coinciding with the provinces that once housed an Inspetoria Nacional de Monumentos. Of the 329 listings (see Table 1), 102 objects are located in the State of Rio de Janeiro (of which 88 of them in the capital city of Rio de Janeiro), 63 in Minas Gerais, 58 in Bahia, and 45 in the State of Pernambuco. This movement sanctified Baroque religious architecture as the first genuinely Brazilian cultural manifestation.

Heritage classification – 1938	Total
Cultural object (movable and fixed)	8
Collections	13
Natural heritage	2
Architectural ensemble	15
Rural ensemble	3
Urban ensemble	7
Building	91
Building and [its] collections	167
Urban equipment or infrastructure	13
Historic garden	3
Ruin	7

Table 1: Breakdown of national listings in Brazil, in 1938, by classification category (the type of legal protection). Source: Brasil 2015.

In the initial years, the Serviço do Patrimônio Histórico e Artístico Nacional focused its action on cataloging Brazilian patrimony, with Lucio Costa as a fundamental stakeholder in this process. Costa dedicated most of his career to the SPHAN as the director of the *Divisão de Estudos e Tombamentos* from 1937 until his retirement in 1972. As part of his work as a consultant for the Serviço Nacional do Patrimônio Histórico e Artístico Nacional, Costa traveled the country on survey expeditions, wrote several listing proposals, and defined restoration projects.

Disciple of José Mariano Filho at the Escola Nacional de Belas Artes, Lucio Costa's career was initially shaped under the neocolonial style. It was Mariano Filho who introduced Costa to traditional Brazilian architecture. Over time, Costa developed a more critical approach to the idea of tradition in architecture, took upon colonial architecture as the traditional Brazilian architecture, and created the narrative that, in Brazil, tradition and modernity walked side by side. Costa, however, was not the only modern architect involved with Brazilian heritage; every person working at SPHAN in its earliest years was a modernist—either an architect, an artist, or a writer. As part of his work as a consultant for the Serviço Nacional do Patrimônio Histórico e Artístico Nacional, Costa and his team traveled the country extensively to build up the first national historic heritage survey catalog, wrote several listing proposals, and defined restoration projects. The modernist (re)shaped Brazil's past by defining what should be protected.

In Brazil, the government instated in 1930, deposing the first republican project, worked hard to recreate the country's image, and establish it on modern values. Architecture was in this battle's foreground and the means to tell a carefully curated version of the country's past. The country became a nation where modernity walked side-by-side with tradition, where the new republic celebrated its colonial past. The Federal State adopted modernist aesthetics for its new buildings, while some modernist architects nominated and listed national heritage objects and sites.

CONCLUSION

Two different narratives speak to the United States' identity: the Thirteen Colonies' past and the western hinterlands—constructed by private and public initiatives. We can translate these narratives as the landscape of New England and the wilderness. In the United States, the initial preservation endeavors were led by private associations intended to safekeep places connected with the men considered to have founded the country. The first federal preservation initiatives were the demarcation and enclosure of the lands in the west of the country, creating national parks open to the public. The preservation movement arrived at the federal institutions a few decades later and had much to do with national and state legislation over land use.

The National Parks Service consolidated a myth of wilderness, a pristine nature that has never existed—there was never an untouched nature in the terms shown in and by the parks. Tailored under the notion of the sublime, the places of monumental natural spectacles, these magnificent parcels of enclosed land followed the dispossession of numerous Indigenous groups. Over one-hundred years later, US Americans still consider the national parks as one of the United States' most remarkable assets, and a national character-defining feature.

In the history of U.S. American national parks, the Indigenous peoples were not the only ethnic group erased from the landscape or left out of the official narrative. Initially, African Americans were intentionally excluded from the targeted demography of visitors to the national parks. In addition to the costly train rides to their location, hotels and campsites within national parks would host only white individuals. In Jim Crow's United States, hotels for the Black population existed only outside the parks' limits. Aside from the erasure of the presence of Indigenous peoples in the national parks, those places were targeted only to a specific demographic of U.S. Americans: white, middle- and upper-class people—the only ones with the right to access the national sublime, sacred landscape and enjoy it.[34]

A similar process happened in Brazil. Eager to define and articulate its own identity, Brazil sought to deploy an art that would express its true characteristics, defining what were its national values and heritage during the early twentieth-century. The federal government created a national narrative of a modern country with deep roots in its past—as long as that past was Baroque and colonial. Backed by the government, modern architects managed to reach this goal by developing a local idiom influenced by artistic avant-gardes but rooted in traditional characteristics and local materials.[35]

Modern architecture in Brazil became a translation of the new-established Brazilian national identity: bold and monumental buildings with new materials, displaying a new image. On top of that, the modernists achieved another goal: reinventing the Brazilian past by advocating for what should be considered the Brazilian heritage. Architectonically, that meant not being a copy of older styles—and, with this, the modern architects managed to demote the neocolonial and eclectic architecture, leaving them out of the national heritage pantheon in the years that followed the creation of the national heritage agency. Nevertheless, the buildings and places listed as a national heritage in Brazil received said title due to artistic expression or being related to prominent, historic people only. There is no mention of the people involved with their construction, nor how and who went about those places.

Brazilian history has been told from the arrival of the Portuguese to the American territory. This historical landmark is also present in the creation of two narratives of the Brazilian past: the institutional memorialization of the empire defended and propagated by the Instituto Histórico e Geográfico Brasileiro and the celebration of the colonial past by the Serviço do Patrimônio Histórico e Artístico Nacional. The initial listings followed the old architectural tradition of some states that had already identified, cataloged, and protected a series of historical objects. It was a way of officially ignoring the architecture of the nineteenth-century monarchies and beginning to tell a new story. Both memorialization processes celebrated the deeds and cultural achievements of white European people, leaving

African and Indigenous populations outside the official heritage/history narrative for decades, becoming recognized as elements of the country's construction only in the year 2000.

Both Brazil and the United States found a way of translating their republican national identity into representations of the built environment. On the one hand: the transformation of a natural landscape into public parks and the creation of a stylistic idiom suited the landscape and matched a conservative audience. On the other: the celebration of historic buildings and old towns that represented the most genuine expression of the past, in contrast to the new modern architecture promoted by a popular yet authoritarian government.

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ENDNOTES

1 This is the original name of the Brazilian heritage institution. Currently, it is called Instituto do Patrimônio Histórico e Artístico Nacional (IPHAN, Institute for the National Artistic and Historic Heritage).
2 Mason and Page, 2004, p.113.
3 For a detailed chronological account on the history of preservation in the United States, see Hosmer, 1965; 1981.
4 Mason and Page, *op cit.*; Schuyler, 2012; Hietala, 1985; Joy, 2014.
5 Turner, 1993.
6 Turner, *op cit.*, p. 61.
7 Cronon, 1996.
8 Cowell, 2004, p. 31.
9 Turner's composite nationality is made of white people only, resulting from various European immigration, starting from the British in the early 1600s. The Indigenous peoples only appear as *Indians*, as the savages, as a danger. There is no reference to African descendants being part of this country—the only references to them are when Turner uses the terms *slaves* or *slavery*. (Turner op cit.)
10 Vevier, 1960; Merk, 1963; Hietala, 1985; Johannsen, Haynes, and Morris, 1997; Joy op cit.; Cardinal-Pett ,2016.
11 Cronon op cit.; Spence, 1999.
12 Runte, 1987; Shaffer *op cit.*; Dunbar-Ortiz, 2014.
13 Tyler, Ligibel, and Tyler, 2009, p. 32.
14 Shaffer, 2001, pp. 95-97. See America First was an initiative by the Department of Interior focused on domestic tourism and based on showing idyllic images—photographs and motion films—of the national parks. The successful campaign was one of the critical elements advocating for establishing a separate bureau to manage the parks.
15 Carr 1998; Murtagh 1997; Runte *op cit.*; Shaffer *op cit.*
16 Shaffer *ibid.*
17 Historic American Buildings Survey *et al.*, 2008, p. 1.
18 Namely, the School of Medicine in Rio de Janeiro and Salvador (both founded in 1808) and the Law School of São Paulo and Olinda (both from 1827).
19 Museological organization in Brazil was triggered by a project of modernity, which had its origins at the end of the eighteenth-century, with the first natural history collections and botanical gardens, such as the Casa dos Pássaros (Rio de Janeiro, 1784), and the Horto D'el Rei (Olinda, 1798). The transfer of the Portuguese royal court to Brazil in 1808 was a milestone for museum imagination in the country, articulating a narrative of historical and ethnographic collections in three-dimensional spaces. (Chagas 2009).
20 The Sociedade Auxiliadora da Indústria Nacional (1820-1904) was a society tied to the agricultural elites, the rise of industry (initially, textile and ceramic plants), and the strengthening of commerce. (Wehling, 1989)
21 Cited in Wehling *op cit.*, p. 88. Note the importance given by the Institute to archival documents. Translations are mine unless otherwise noted.
22 Schwarcz, 1989, p. 41.
23 López-Durán, 2018.
24 Brazilian physician Oswaldo Cruz studied bacteriology at the Pasteur Institute, Paris. As head of the Instituto Soroterápico Federal (established in 1900), he was responsible for eradicating yellow fever and bubonic plague from Rio de Janeiro. The Institute lost its autonomy after the *Revolução de 1930* (see note 30).

25 Founded in 1900 to study, develop, and produce vaccines and sera to treat smallpox, malaria, and the plague. The Instituto Soroterápico Federal (Federal Serotherapeutic Institute) soon had scientists exploring the Brazilian backlands, researching tropical diseases, their causes, and ways to cure them.

26 For an anthropological study of early twentieth-century urban reforms in Rio de Janeiro and their impact on the lives of people living in poor, central areas, see Leu, 2020.

27 López-Durán, 2018.

28 Cantarelli, 2016.

29 López-Durán *op cit.*

30 The *Revolução de 1930* inaugurated the New Republic in Brazil. As one of the leaders of this revolution. Getulio Vargas was nominated head of this provisional government until the 1934 Constitutional Assembly declared him President. In 1937, intending to perpetuate his rule, Vargas instituted the Estado Novo, a semi-totalitarian dictatorship that ended in 1945.

31 Gonçalves, 1996.

32 Based on the French legislation of 1887, the creation of the Inspetoria dos Monumentos Históricos dos Estados Unidos do Brasil, proposed in Congress by Luís Cedro, aimed for the protection of the national historical monuments (Malhano 2002, 81 apud Cantarelli *op. cit.,* 29).

33 Gonçalves, 2007, pp. 26-27.

34 Shaffer *op cit.*

35 Cotrim, Aguiar and Lara, 2018.

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PAKISTANI HOUSING SECTOR: EVOLUTION OF SPATIAL LAYOUT AND ENERGY CONSUMPTION

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Pakistan is facing the issue of energy shortage in the housing sector for the past two decades, with power outages throughout the country all year long. Increased rate of population growth and increased urbanization rate are the factors responsible for this issue, regarding the future of the energy supply in the urbanized regions of Pakistan. The urban housing sector has also emerged as one of the main sources of carbon emissions in the country and has become a serious concern from an environmental point of view. The housing sector is projected to become the biggest consumer of the two main energy sources (electricity and gas). The main objective of this paper is to carry out a review of literature focusing on the housing sector, in terms of energy consumption and coevolution of the spatial layout of the residential sector in Pakistan. As the paper is part of an ongoing Ph.D. research; therefore, the outcome of the paper was highlighting the issue of excessive use of energy in the single-family housing sector of Pakistani urban areas for building a foundation for further investigation of the reason behind excessive use of energy in this housing sector.

Keywords: Energy consumption, carbon emissions, single-family housing, Pakistan.

INTRODUCTION

Building energy use is one of the most crucial agents for climate change mitigation (Cabeza and Ürge-Vorsatz 2020) because it accounts for 39% of the total energy and process-related CO2 emissions and 36% of the final energy demand, globally (IEA 2019). However, efforts are being made the improvement of energy efficiency in buildings, and the demand for energy is increasing because of the growing need for thermal comfort and floor space (IEA 2019). Developing countries are expected to experience an unprecedented surge in the energy demand for buildings accompanied by a rapid expansion of the building stock due to growing incomes (Mastrucci et al. 2021). A report by IEA (2019) shows that the building stock is likely to double by 2050 globally; this presents a remarkable opportunity to mitigate the future demand for energy while improving indoor thermal comfort in developing countries by boosting energy and efficient building construction.

Solangi et al. (2019) indicated that Pakistan, a developing country, has been facing an energy crisis for the past two decades with daily power outages throughout the country. While the total electricity produced by all energy sources is 19,000 MW, the installed capacity is approximately 25,000

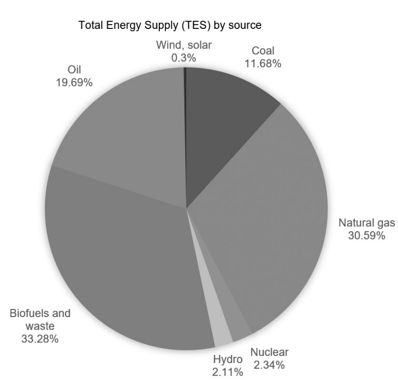


Figure 1: Sources of energy generation in Pakistan. Source: IEA 2019.

MW meaning energy is not being produced despite having the capacity to do so; this has resulted in a shortfall of 6,000 MW in the country (Owais et al. 2018). Proliferated growth of the population, natural disasters due to climatic changes, and a rise in CO2 emissions have led to serious concerns regarding the future of the energy supply in Pakistan (Solangi et al 2019). Electricity is used for indoor cooling, lighting, ventilation, and operating different equipment around the house, while liquid petroleum gas (LPG) and natural gas are used for heating and cooking in residential buildings in Pakistan (Rahut et al. 2020). With an annual urban population growth rate of 2.68% (United Nations 2018), an annual urban housing demand of 350,000 units, and a supply of only 150,000 units (Munir et al. 2021), energy shortfall will be expected to increase as the population and housing demand grows. Furthermore, residential buildings are the biggest consumers of energy in Pakistan and are responsible for producing half a million tons of carbon emissions per year (Azeem et al. 2017). Figure 1 shows the percent share of all sources of energy generation in Pakistan.

Efficient use of energy in the housing sector can help in decreasing the carbon footprint of this sector[1]. This paper seeks to understand the relationship between household practices and spatial layouts; and investigate the influence of these two factors on the consumption of energy in single-family housing in Pakistan, which is the most prevalent type of housing in Pakistan (Mahar, Anwar, and Attia 2018). This study aimed to answer the question: what is the impact of the evolution of spatial layout on the energy demand in single-family housing in Pakistan?

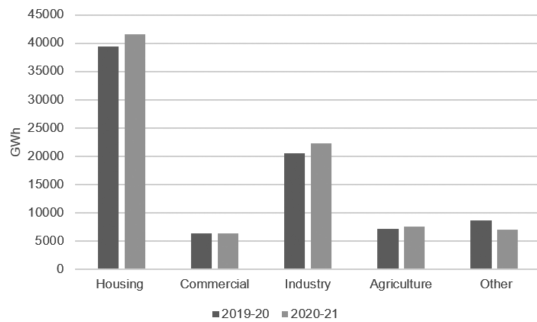
This paper is part of an ongoing Ph.D. research; therefore, the outcome of the paper was highlighting the issue of excessive use of energy in the single-family housing sector of Pakistani urban areas for building a foundation for further investigation of the reason behind the excessive use of energy in this housing sector which will eventually lead to proposing energy-efficient building design solutions for the future housing units.

With approximately 62% of the energy produced by fossil fuels (figure 1) and 45% of all the produced energy being consumed by the housing sector (figure 2), it can be deduced that the housing sector is contributing significantly to the overall CO2 emissions. Mahar, Anwar & Attia (2018) have highlighted the housing deficit with the growing population of the country. The rapid growth of urbanization has resulted in higher demand for new housing units in major urban centers of the country (Azeem et al. 2017). By 2050, the Pakistani urban population is projected to cross the 50% mark (United Nations 2018). The consumption of energy in the housing sector is only going to increase because most of the residences in the urban regions of the country use brick masonry or reinforced cement concrete (RCC) for the building envelope; and single pane glazing for windows (Mahar, Anwar and Attia 2018). The use of these construction materials requires mechanical means of heating and cooling, thus adding to the overall CO2 emissions (Azeem et al. 2017).

1. ENERGY CONSUMPTION IN PAKISTAN

Figure 3 shows the annual urban growth rate of Pakistan with the top five most populous countries in the world. Pakistan's overall annual population growth rate is 2.02% and the urban population is growing at an annual rate of 2.68% which is higher than the top five most populous countries of the world (World Bank 2019). The rapid growth of urbanization has resulted in higher demand for new housing units in major urban centers of the country. The demand for new housing units is an opportunity for constructing energy-efficient residential units/apartments in major urban centers like Karachi, Lahore, Islamabad, Peshawar, and Quetta.

The intensive use of energy in the housing sector can be reduced by focusing on the influence of climate on indoor thermal comfort, and the design



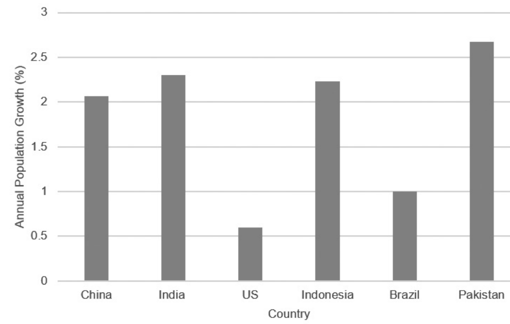


Figure 2 (left): Sector-wise annual energy consumption in Pakistan. Source: Pakistan Economic Survey, 2019.
Figure 3 (right): Population growth rate. Source: Pakistan | Data 2019.

parameters applied for the house. As Pakistan has a diverse climate, it is not possible to come up with a set of energy-efficient design principles that can be applied to every major city in the country. Geographically, Pakistan is divided into four states (provinces): Punjab, Sindh, Khyber Pakhtunkhwa (KP), Baluchistan; and two autonomous territories: Gilgit-Baltistan (GB) and Azad Jammu & Kashmir (AJK) as shown in figure 4.

The intensive use of energy in the housing sector can be reduced by focusing on the influence of climate on indoor thermal comfort, and the design parameters applied for the house. As Pakistan has a diverse climate, it is not possible to come up with a set of energy-efficient design principles that can be applied to every major city in the country. Geographically, Pakistan is divided into four states (provinces): Punjab, Sindh, Khyber Pakhtunkhwa (KP), Baluchistan; and two autonomous territories: Gilgit-Baltistan (GB) and Azad Jammu & Kashmir (AJK) as shown in figure 4.

Pakistan has hot summers in some regions like Karachi (Sindh), Larkana (Sindh), Multan (Punjab), and Peshawar (KP); and cold winters in other regions like Skardu (GB), Muzaffarabad (AJK), and Kalat (Baluchistan). There are some cities where, summers and winters, both seasons are extreme like Lahore (Punjab), Quetta (Baluchistan), and Islamabad (Federal Capital) (Javid et al. 2019).

Table 1 shows the annual growth rate of the five major cities of Pakistan. With an annual growth rate of the population as high as 4.9% in Islamabad and the lowest growth rate being 3.04% in Quetta, it can be deduced that these cities are going to have a higher demand for housing units in the near future. If the future demand for houses is met by constructing houses that are energy-efficient, it will help in keeping the carbon emissions for the residential sector lower. If the current trend of carbon emissions is not mitigated, the effects of future housing demand can be disastrous for Pakistan. A rise in temperatures due to climate change, the expected growth in population, and other socio-economic factors can influence the projected demand for energy for the future. Therefore, the practice of energy-intensive house designs needs to be changed significantly to cater to future needs and mitigate the rising carbon footprint of the country.

2. ENERGY CONSUMPTION BY THE HOUSING SECTOR OF PAKISTAN

Ghafoor et al. (2020) found through their study that apart from water and space heating/cooling, design of the building, shadowing due to neighboring buildings, household size, floor area; and number as well as the quality of the electric appliances also influence the energy demand of a housing unit. Ghafoor et al. (2020) carried out a survey of houses for quantifying the association between energy consumption and other variables and found that 11.84±0.33 Hm3 (1 Hm3

City	Annual urban population growth rate (%)
Islamabad	4.90
Lahore	3.80
Peshawar	3.72
Karachi	0.98 – 3.44
Quetta	3.04

Figure 4 (left): Map of Pakistan. Source: "Pakistan Map and Satellite Image" 2021.
Table 1 (right): Annual urban population growth rate in major cities of Pakistan. Source: Pakistan Bureau of Statistics 2018; Javid et al. 2019.

= 1000000 m3 = 35311 BTU) of natural gas and 2890±86.3 kWh of electricity was being consumed. The study also demonstrated that there is a significant relationship between energy consumption and the size of the plot because a plot size bigger than 404.7 m2 consumed more energy as compared to smaller plot sizes. Upper- and middle-income households were also found to be the main consumers of electricity but a relationship between consumption of natural gas with income/plot size in the houses was not found. Ghafoor et al. (2020) also found that detached houses were consuming 1.775 Hm3 /year and 564 kWh/year of gas and electricity respectively in excess as compared to attached houses (Ghafoor et al. 2020).

Yohanis et al. (2008) demonstrated through their study that in comparison with attached houses, an excess of 1.27 KWh/m2/month was being consumed by detached houses.

The detached houses are exposed to all kinds of weather extremes which is why these houses require more energy for indoor thermal comfort. Most of the houses in urban regions of Pakistan are concrete structures that do not have insulation installed in the building envelope. This is another reason for the high demand for energy for indoor thermal comfort during peak summers and winters (Yohanis et al. 2008). Figure 5 exhibits the projected consumption of electricity and gas in different sectors in Pakistan. The housing sector is projected to become the biggest consumer of the two main energy sources (electricity and gas) in Pakistan by 2030.

3. HOUSING DEMAND IN PAKISTANI URBAN AREAS

Figure 6 shows population growth and density per km2 in Pakistan. Mahar, Knapen, and Verbeeck (2017) showed in their study that sundried bricks are used for constructing houses in rural areas. Brick masonry, concrete blocks, and RCC frame structures with single-pane glass windows are dominant in the urban regions of Pakistan. There are three different plot sizes for single-family houses that are available in cities: 126.44 m2 (1,361 ft2), 252.88 m2 (2,722 ft2), and 505.85 m2 (5,445 ft2). With a building envelope that does not provide optimal insulation for summers (42 0C/107.6 0F) and winters (-18 0C/-0.4 0F), the consumption of natural gas is higher for heating, and consumption of electricity is higher for cooling indoors (Mahar et al., 2017).

The figure below shows the potential of conserving energy in the residential sector of Pakistan. By improving the building envelope only, 40% of the energy can be conserved, this is can result in significantly reducing the carbon footprint and energy consumption of the housing sector in the urban areas of Pakistan.

4. ACCESS TO ELECTRICITY IN URBAN REGIONS

The figure below shows that 100% of the urban population has access to electricity which is the primary source of energy for all building operations except for cooking and indoor space heating (Rahut et al. 2020). While accessibility to energy sources in urban areas has increased in the past decade, power outages last for 6-8 hours daily (Ghafoor and Munir 2015), and per capita consumption rose from 500 kWh to 960 kWh during the years 2012 to 2018 (NEPRA, 2017).

The power generation capacity increased by 2.7%, but there is still a gap between supply and demand (Raza et al., 2022) as seen in the figure below:

If the gap between the supply and demand of energy persists, the power outages in the housing sector will increase due to the increasing urban population and housing demand.

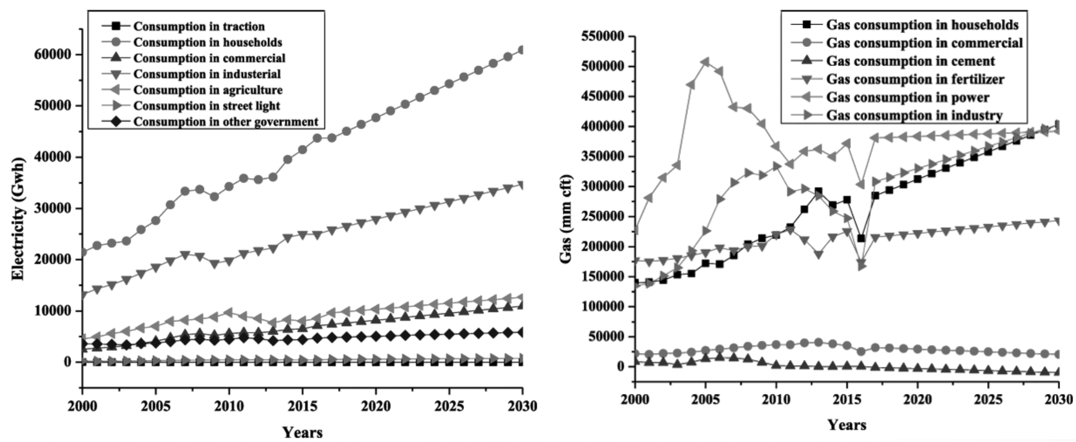


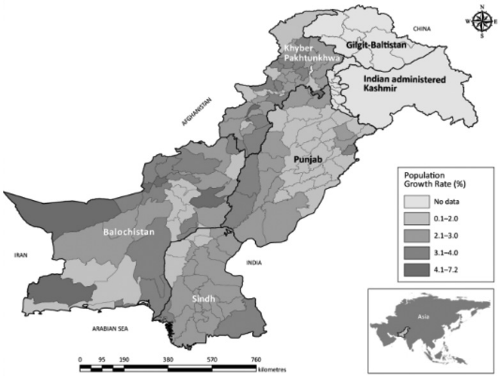
Figure 5: Electricity and gas consumption forecast in different sectors of Pakistan. Source: Rehman and Deyuan 2018.

5. EVOLUTION OF FLOOR PLANS IN PAKISTAN

A study carried out by Khalid and Sunikka-Blank (2017) showed that energy consumption and demand have a strong relationship with the user behavior in their daily lives and the cultural practices of the occupants of the housing unit. Khalid and Sunikka-Blank (2017) demonstrated the spatial layout of houses in Lahore (the second biggest city in Pakistan) has changed over time as seen in figure 10 below (Khalid and Sunikka-Blank 2017). In the study carried out by Khalid and Sunikka-Blank (2017), the occupants were asked about their daily practices in terms of housekeeping, communication devices, lighting, cooking, use of different appliances, and recreation activities such as watching television and so on.

The evolution of the spatial configuration of a typical house in Lahore is shown in figure 10. House 'A' demonstrates the introverted nature of the house which was later transformed into an outward bungalow-style structure (House 'B') during the British colonial times. House 'C' illustrates the further evolution of the dwelling into a modernistic structure that finally became the present-day spatial configuration with restricted open spaces (House 'F'). Even after the independence from British rule, 'modernistic' ideologies were adopted for form and material use. With the establishment of the city development authorities, building regulations were put in place that restricted the ownership of large plots. Adherence to building regulations has resulted in a typical style of spatial layout that has prevailed since the late 1980s (Khalid and Sunikka-Blank 2017).

After independence from the British colonizers in 1947, the colonial influences



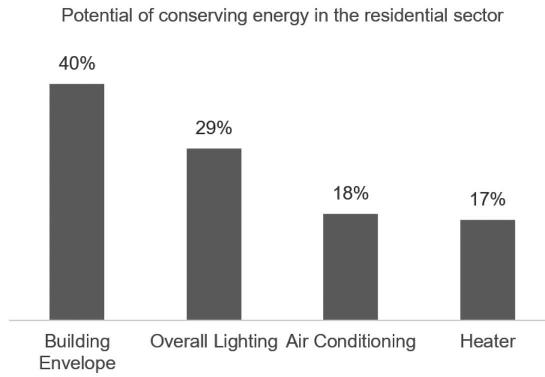


Figure 6 (left): Population density and growth rate in Pakistan. Source: Goujon, Wazir and Gailey 2020.
Figure 7 (right): Potential of conserving energy in the housing sector of Pakistan. Source: Mahar et al. 2017.

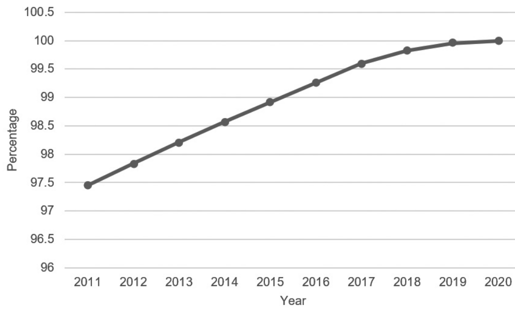
in the house layouts can be seen as the architectural style and were influenced by the modernistic Western ideologies. Towards the end of the 20th century, the inner courtyard disappeared completely (House ‘E’). Gated communities emerged in the country because of the commercialization and privatization of housing developments. Significant homogenization of houses can be seen nowadays due to rigid building regulations that usually adversely affect the key elements of the house like its micro-climate, access to sunlight, and fresh air. House ‘F’ illustrates the present-day house layouts that are maximizing the covered area with minimized outdoor spaces.

The main themes deduced from the analysis of these houses are as follows:

1. Reduced outdoor activities: the residents of the houses now spend most of their time indoors in the living room. Due to reduced plot size, verandahs have been replaced by indoor living rooms.
2. Increased dependency on active systems: introduction of air conditioning and television has encouraged the residents to spend more time indoors.
3. Spatial segregation: spaces for cooking and eating have now been separated. Open plans are now encouraged to give an illusion of bigger spaces in a small plot. An amalgamation of the kitchen, dining, and living room shows that these spaces are still interconnected but each function has a designated area now. This requires even more active systems for maintaining a comfortable temperature in these spaces (Khalid and Sunikka-Blank 2017).

The effects of colonial influence can be seen in these houses which have led to increased demand for energy due to the paradigm shift from outdoor activities to indoor activities. The modern-day spatial configurations of single-family houses in Pakistan need to be coupled with climatic considerations so that energy-efficient designs can be produced and constructed. Figure 10 also shows that a significant area is specified for a car porch in House ‘F’. This shows the residents’ dependency on cars. Figure 11 shows the arrangement of the spaces based on their level of functionality.

A typical Pakistani single-family house is divided into four zones: private, semi-private, public, and entry (Iftikhar, 2019). The public space is used for hosting guests and has a ‘formal’ feel to it while the semi-private section of the house is for general use by the residents for dining, cooking, and recreation. The segregation of the house into private and public spaces is closely related to the aspect of privacy in Pakistani culture. This indicates that although the spatial layouts of single-family houses in Pakistan are influenced by the western and colonial style of layouts there



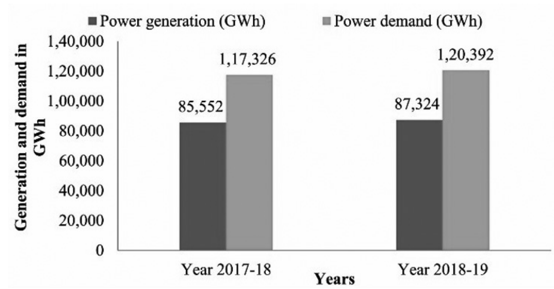


Figure 8 (left): Percentage of urban population's access to electricity. Source: World Bank 2021.
Figure 9 (right): Power generation and demand in Pakistan. Source: Raza et al. 2022.

is still the factor of privacy that is dominating the overall spatial configuration of the house. Due to the transformation from traditional to modern style of living, houses have become more restricted in terms of space utilization; this has given rise to the use of active means of heating and cooling in indoor spaces.

Mahar et al., (2018) have shown through their study that for achieving indoor thermal comfort, active means are used throughout the year in single-family houses in Quetta, which is an urban region of Pakistan. Heaters are used for 6-12h in winter, and air conditioners are used for 8-12h on average daily in these houses for achieving indoor thermal comfort (Mahar et al., 2018).

Amber et al. (2021) analyzed 523 houses in Pakistan and concluded that the energy consumed by a typical Pakistani house is 24 kWh/m2 /year. The study also demonstrated that since 2006, the consumption of energy in the residential sector of Pakistan has been increasing by more than 2.9% annually (Amber et al., 2021). While this study has given the researchers a benchmark of how much energy is being consumed by a typical house in Pakistan, the study has not been able to determine all the elements that are responsible for the higher demand for energy in these houses. Effective policies and building codes are the need of the hour for Pakistan because the rate of increase in the energy demand is very high and can increase even more with the rate of annual population growth in the country. After closely examining figure 10, it can be deduced that, apart from spatial configurations, the household practices being followed by the occupants of single-family houses in the cities of Pakistan are linked to the prolonged process of coevolution that was shaped by the material and social structures of urban housing and its consequent energy demands. Another major factor contributing to the excessive energy consumption in these housing units is the implementation of building regulations that support decreasing the area of the backyard which has diminished the role of open space as the center of activities in the house thus, encouraging more individualized spaces. The result of these building regulations is a floor plan that is culturally and climatically unsuitable and encourages intensive use of energy in the housing unit for thermal comfort and lighting.

CONCLUSION

The rapid growth of urbanization has resulted in higher demand of new housing units in major urban centers of the country. Construction material, building envelope, covered floor area, household size, quality and type of electric appliances used in the house, user behavior, and identification of other such factors can play a key role in reducing the energy consumption in the single-family houses of Pakistan. Although a comprehensive dataset is needed for figuring out the root cause of the problem, this study can be a starting point for identifying the reason for the excessive use of energy in a typical single-family house in Pakistan. The

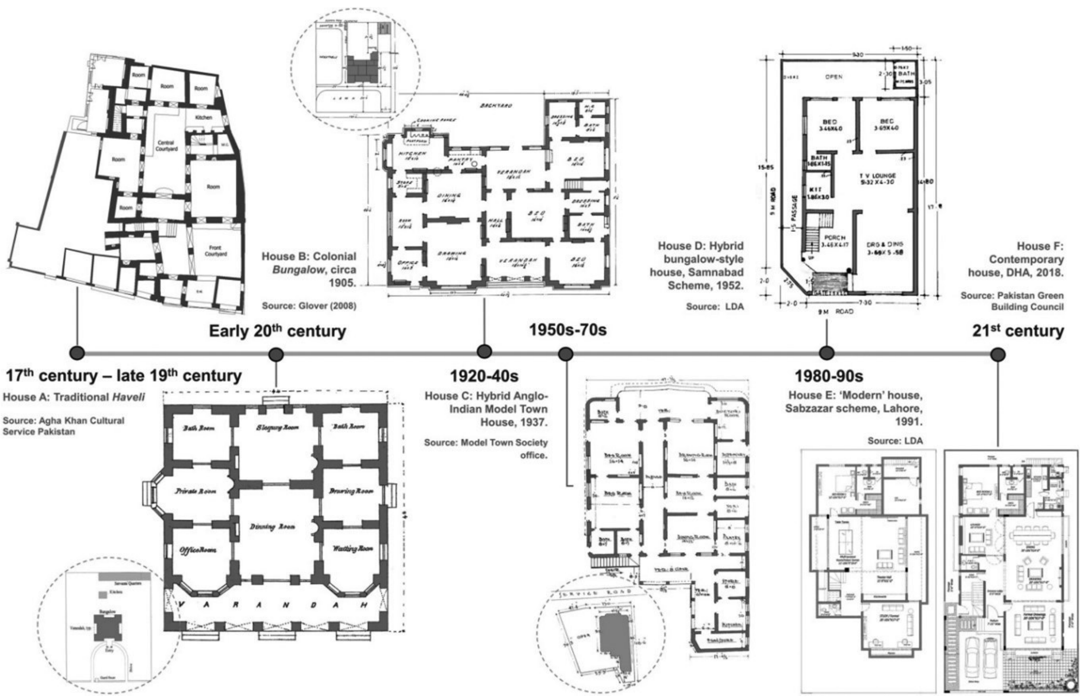


Figure 10: Evolution of spatial layout of houses in Lahore. Source: Khalid and Sunikka-Blank 2017.

housing sector consumes the highest share of the energy produced; therefore, it is essential for the housing sector to adopt practices that will use the country's natural resources efficiently and reduce the demand for energy.

Based on the discussed literature so far, it can be deduced that the housing sector in Pakistan needs to adopt energy-efficient building practices as this will play a significant role in the reduction of the carbon footprint of Pakistan and can result in optimal use of energy. The design principles incorporated by the housing sector will not only influence the patterns of energy consumption and its subsequent environmental impacts at present but will also positively influence the future generations to come.

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KONRAD WACHSMANN'S RESEARCH METHODOLOGY: DESIGNING A CONTEMPORARY CLIP SYSTEM

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As an architect and educator, Konrad Wachsmann's life's work demonstrates an architectural research methodology that uses prototyping and building as a means for testing ideas and theories in both his practice and teaching. In this paper, the author presents a methodological approach used to study the historical significance of Wachsmann's work from the 1940s-1950s and apply the results to contemporary architectural developments. To construct this dialogue with Wachsmann's work the author analyzed the Packaged House System and his theory of universality first in theoretical and historical context and then reconstructed the technical parameters that informed Wachsmann's' design process. Acting as the first part of a dialogue, this analysis of Wachsmann then informed the second part of the dialog where the author's developed a new building system that made use of contemporary tools and fabrication technologies. prefabrication problems addressed by Wachsmann in his work, and then re-examine their potentials through the application of contemporary tools and fabrication technologies. Through building—as an active research methodology of discovery, analysis, articulation, and re-application—lessons learned from Wachsmann's work create new scholarship, and can simultaneously be applied to prefabrication, building technologies, and systematic construction today. The essential dialog connecting historical search/analysis to informed making illustrates a methodology with the potential to further articulate and re-engage historical architectural works and practices through models/prototypes and simulations in ways that result in tactile and intellectual insight into contemporary architectural research projects.

Keywords: Kondrad Wachsmann, research methodology, architectural fabrication.

INTRODUCTION

In this paper, the author articulates an architectural research methodology that can be described as a dialog between a historical analysis of the work of Konrad Wachsmann, and the material development of a contemporary "universal building system." Konrad Wachsmann was a German architect, engineer, and educator who emigrated to the United States in 1941, following the escalation of hostilities during WWII. Trained as a carpenter, architecture for Wachsmann involved both making and theory in his practice from his earliest work with prefabricated wood construction as a lead architect at Christoph & Umack in Niesky (Wachsmann 1995), Germany to his latest built work at USC with the Location Orientation Manipulator in 1971. His ability to ground theoretical concepts, such as universality, through architectural prefabricated systems led to significant contributions in the design of systematic construction, prefabrication, industrial architecture, manufactured housing, architectural machines, and architectural methodologies during the 60+ years of his career. His methodological approach to architecture derived from both theory and practice is evident through his work with universal systems and building assembly such as the Packaged House System, his Mobilar space frame system, Grapevine Structure, and the Location Orientation Manipulator as well as through his academic appointments in Chicago and at USC.

The architectural methodology presented in this paper attempts to illustrate the benefits of creating an essential dialog between a historical analysis of architectural works and practices, and the iterative and explorative nature of architectural modeling/prototyping as a means to conduct architectural research. The methodology discussed could additionally be beneficial to students, practitioners, and designers from many disciplines who wish to actively engage in a physical artifact or theory. The example of this methodology applied within this paper focuses on a research dialog between Konrad Wachsmann and Walter

Gropius's Packaged House System and a contemporary Clip System. The author constructed this cyclical or looping dialog (see illustrations) through the analysis of Wachsmann's theoretical perspectives and built work as recorded in literature, photographs, drawings, models, and buildings (many of which are collected in Wachsmann's seminal writing of 1961, The Turning Point of Building: Structure and Design). This process, of informed making as an analytical tool—rather than as means to test scale and/or material performance as is common in fabrication-based research - led to a unique understanding of Wachsmann's Packaged House System and the serial development of his universal joint, the wedge connector. In this paper, the use of informed making as an analytical tool is employed to understand the design iterations of the wedge connector's evolution, extract, and articulate guiding principles of a Wachsmann-based universal building system, and finally to develop, fabricate, and test a contemporary take on the universal building system. This methodological approach to architecture—an essential dialog between traditional scholarship and traditional forms of architectural modeling/prototyping—forms the basis of a research methodology that engages practices specific to the field of architecture, practices commonly associated with a studio environment and the design of buildings.

PACKAGED HOUSE SYSTEM

Between 1939-1951, Konrad Wachsmann developed the universal joint or wedge connector with Walter Gropius as part of the General Panel Corporation's Packaged House System. The rise and fall of the General Panel Corporation's Packaged House System which ended in 1951 after producing roughly 200 houses are detailed in Herber Gilbert's "The Dream of the Factory-Made House". Though the General Panel Corporation failed, the Packaged House System—prefabricated wood panels jointed together by the specialized universal joint, the wedge connector—was a success for Wachsmann. In a blueprint for the T.D.U.-1/1943 version of the system, Wachsmann describes the system's highlights:

> All the panel units are tightly connected with each other by a 'wedge connector' without using any nails, screws, hooks or glue for the assembly. The erection can be done by unskilled laborers who simply have to hammer in the tightening wedges…the small number of component parts of this system can be applied for an infinite variety of building types and building designs.

Throughout this project, Wachsmann continually evolved the wedge connector as a singular product. Advancing building construction and prefabrication, he developed six joint iterations between 1939 and 1947, addressing the assembly in erecting prefabricated housing. The universal wedge connector and the Packaged House System became the starting point for the author, to analyze and reapply Wachsmann's principles to address contemporary housing.

WACHSMANN'S METHODOLOGY – DIALOG BETWEEN THEORY & BUILDING

In 1949, Wachsmann received his first teaching appointment at the Institute of Design in Chicago as part of the Department of Advanced Building Research. As an educator, Wachsmann involved students in design problems that required intensive physical testing and experimentation, engaging with "industry processes, production, assembly, materials, tools, machine and mass production, modules and standardization, joints and connections" (Ward 1972). Wachsmann also engaged in the theoretical origins/underpinnings of these projects; work that emerged from the "understanding of political, social, scientific and technological processes" (Ward 1972). This methodology of building research routinely employed the use of models and full-scale tests, in addition to writings and lectures that articulated theoretical principles and ideas (Ward 1972). After teaching internationally, Wachsmann returned to California in 1965 where he set up the Building Research Institute at USC which focused on an interdisciplinary approach to architectural research. His work there resulted in the invention of the LOM, (Location Orientation Manipulator), with students John Bollinger and Xavier Mendoza. As a product that combined the most cutting-edge technologies from the automotive and aerospace industries at the time, the LOM, a multi-axis mechanical manipulator specific to architecture, was developed to study the kinematics of building assembly (Bollinger and Mendoza 1971). This Institute and its activity are considered to be formative in the transformation of architectural research from a studio to a laboratory, one with modeling/prototyping/simulation and simulation at its core. The transformation is observed in The Natural Forces Laboratory: Ralph Knowles and the Instrumentalized Studio (Witt and Reznich 2018):

> The articulated and quasi-robotic armatures of Knowle's heliodon and Wachsmann's universal positioner are strikingly similar – both consist of a series of compound radial-arc tracks. Kinematically they are the same device. One is a tool for analyzing, and the other for assembling. Together, they point to the emergence of a mechanical but proto-computational method for design research in the late 1960s…. and with these… experimental machines, the architecture studio was transformed into a laboratory dense with instrumentation.

In the design and development of the LOM specifically, there is a suggestion that this studio-turned-laboratory was more than a space of building (noun) construction, analysis, or simulation; it was a space of experimental building (verb) process innovation through informed making.

In his body of work, Wachsmann actively practiced a research methodology founded on the relationship between architectural theory and the product produced through making and testing. In his book The Turning Point of Building, Wachsmann discusses the importance of fabrication, construction, and prototyping in architectural education:

> Models acquire a special importance when they are built to experiment on, rather than to simply look at… it provides a means of going beyond theoretical investigations and actually testing the standard of performance of any material, product or function…" (1961, 203).

At USC, Wachsmann diagramed the interrelationships between the various components of the Building Research Division, including the Information Center Library, Teacher Training, Research Testing, Faculty, Graduate Studies, and Educational Studies (Wachsmann 1965). A closer examination of the Graduate Studies depicts six different contributing clusters to making up graduate studies. Of particular interest is cluster e which is titled research. This cluster illustrates the relationship between associated methods, products, economics, analyses, coordination, and material (Wachsmann 1965). A closer examination of the Research Testing cluster f labeled development depicts a relationship between analyses, design, coordination, application, economic social, and product distribution (Wachsmann 1965). If we view these terms and diagrams as a culmination of his life's practices and methods, Wachsmann theorizes a design, develops the design considering production methods and materials, explores the economic and social impact of the design, and then analyzes its feasibility—looping backing into the process again.

When designing the Packaged House System, Wachsmann did not simply propose it through drawing, he iterated the system through different versions of the wedge connector across a twenty-year period. When there was to be a factory for producing General Panel Corporation panels, he did not relegate himself to theorizing about how the panels might be fabricated only, he designed the factory layout and its resource tendons himself. In his work with the Packaged House system, he actively participated in a total building process where everything was designed and considered—from material handling, fabrication methods, economic and social demands, to final product distribution and assembly of the architectural prefabricated system. Wachsmann announced his vision for the future of the architectural field in 1961 at the Aspen Conference, and later clarifies this vision in his unpublished autobiography entitled 1901-2001 Timebridge (1980, 380):

> When I said 'to build is everything', I meant to build includes and embraces everything… the common effort, the common evaluation, the collective work, the use of everything this time has to offer, this is building.

Translated into architectural research, his process and practice of physically manifesting theories through making or fabrication is evident in his search for the universal, articulated and developed through many physical and theoretical forms in his life's work.

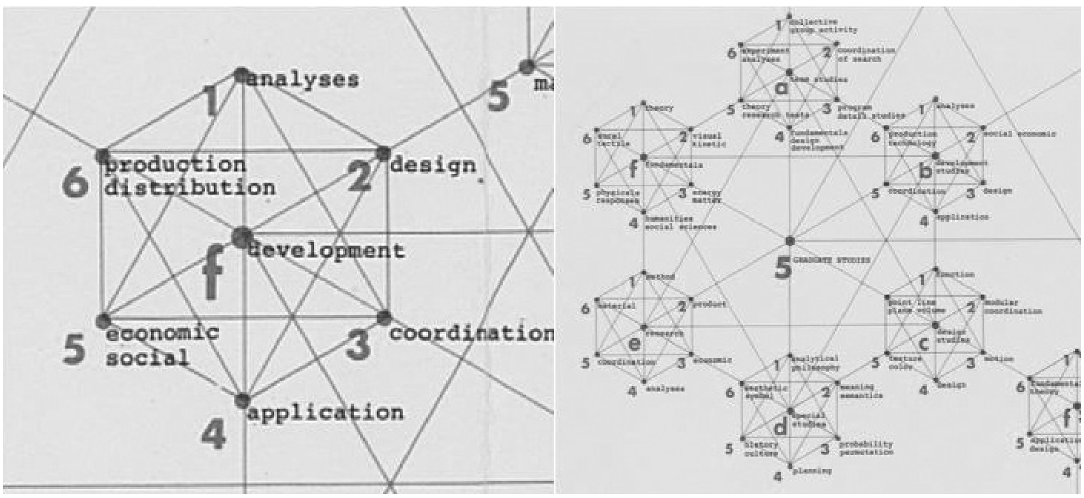


Figure 1: Wachsmann's development of the Packaged House System and wedge connector were influenced by the changing landscape of housing needs, and a continual evaluation of the design by theory and timely outside factors. Source: Konrad Wachsmann from ADK Archive, Berlin 1965

With the wedge connector, Wachsmann begins with problems inherent in the process of prefabricating housing. During and after WWII, the US government was in need of housing that could be erected efficiently, assembled by anyone, then dissembled, moved, and reused somewhere else. Each version of Wachsmann's wedge connector and subsequently the Packaged House System participated in a feedback loop of evaluation based on how it functioned and measured up to achieving true universality. Wachsmann defines a systems-based problem around the characteristics of universality, develops the system, and then evaluates the performance of the system for success at solving the defined problem, and then improves or changes the design based on more accurately defined goals for the system. This feedback loop as shown in figure 2, creates an essential dialog - as architectural research - between a physical output and its theoretical significance.

METHODOLOGY – DIALOG BETWEEN WACHSMANN & CLIP SYSTEM

From 2016-2018, a dialogue with the universal joint led to a rearticulated synthesis of universal principles for creating building systems. In Wachsmann's work, a universal building system is 1) efficient, 2) unskilled, 3) mobile, 4) scale-less, and 5) flexible/adaptable. These five principles articulated a basis for generating a contemporary universal building system. Overtime, the research uncovered a deeper understanding of Wachsmann's joint's open center, the

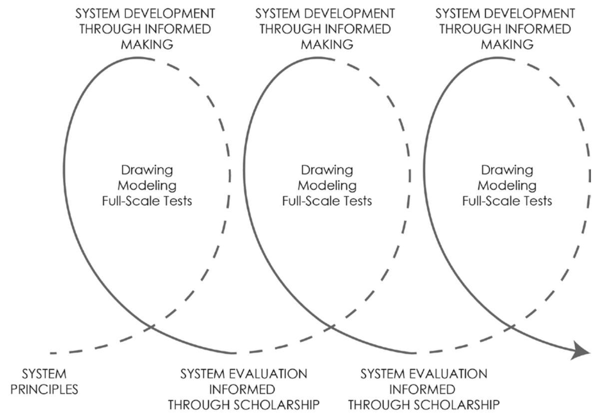
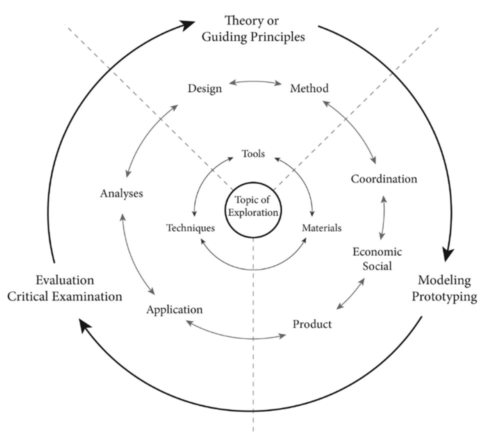


Figure 2: As Wachsmann develops his universal building systems, a dialog is created between the initial principles and the development of the system through drawings, models, and full-scale tests. With each iteration the System evolves. Source: Author 2020.

module, and systematic assembly. Though these system qualities are described in The Turning Point of Building: Structure and Design, actually working through the problem by constructing full scale tests and mock-ups revealed the real-life importance of Wachsmann's Universal. In an active extension of scholarship, the author uncovered Wachsmann's process through building. The resulting Clip System differed from Wachsmann's, placing more emphasis on panels created from available materials rather than relying on factory produced panels. The Clip System is made up of clips and nodes; clips attach to any available panel; nodes lock the panels together. Throughout co-development of clip, tool, and panel (guided by Wachsmann), 3D printing, plasma cutting, and forging were used to develop working prototypes of the system. Full-scale testing produced an 80”x85” unit, assembled by two people in 80 +/- minutes. While we are unable to have a conversation with Wachsmann about his motivations for the universal joint, this dialogue-through-building and testing allowed the author to learn from/re-engage his work by replicating his problems, parameters, and introducing new technologies and building methods to solve them.

Wachsmann's methods as visualized above in figure 4 could be applied to many areas of study. An example of a feedback loop that could be applied to various studies is pictured in figure 4, where the research topic of exploration is informed by theory or guiding principles, modeling, and prototyping, and evaluated through critical examination of the artifacts produced.

This same architectural methodology was applied to a research project, figure 4, which asked, “How can revisiting Wachsmann's ‘universal joint’ and the failed prefabrication systems of the past, inform the development of a new joint and panel-based open building system—one that accommodates low-skilled labor and allows for fast assembly, and flexible reuse of material and modification?” The research team applied this methodology which focused on understanding, informing, and furthering Wachsmann's work through the fabrication and analysis of reproductions tied to the historical development of his joints/connectors. While many students of architecture are simultaneously schooled in office practices and some degree of material knowledge, testing and analysis, this work focusing on Wachsmann's universal joint was led by an architecture graduate student with professional office experience and considerable experience in fabrication; skills/technologies including blacksmithing, welding, machining, and additive manufacturing. The working methodology shown in figure 6 eventually resulted in a contemporary Wachsmann-informed universal building system, one



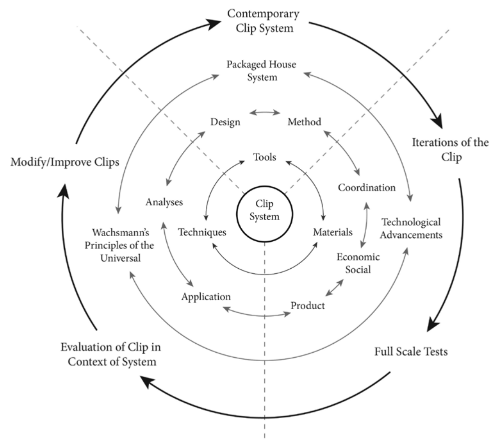


Figure 3 (left): Proposed methodology informed by theory or guiding principles, modeling, and prototyping, and evaluated through critical examination of the artifacts produced. Source: Author 2021.
Figure 4 (right): A contemporary universal system developed from a cyclical dialog considering Wachsmann's work with the Packaged House System and his theoretical universal principles. Through this process, Wachsmann's work influenced this Clip System and its development informed the research team's understanding of the Packaged House System and Wachsmann's theories of universal. Source: Author 2021.

generated from the co-development of clip connectors, panels, and associated tooling, designed through empirical testing, full-scale fabrication, and a close reading of Wachsmann's technological priorities as related to the "universal". The team's active engagement with a full range of fabrication technologies facilitated a deeper discovery of the difficulties and limitations of working with certain materials, construction systems-related issues/limitations, and a correlated focus on re-articulating principles of "universal" in the context of contemporary industrial housing.

APPLICATION OF METHODOLOGY – A CONTEMPORARY CLIP SYSTEM

The wedge connector, Wachsmann's universal joint, lies physically and metaphorically at the center of the Packaged House System. The team instinctually began by seeking to understand the Packaged House System through a deep analysis of the wedge connector as shown in figure 5. Initial studies focused on drawings and laser-cut cardboard models based on images of the 1947 version of the wedge connector as published in Wachsmann's book The Turning Point of Building (it was the final version and most idealized). Though this first study was slightly inaccurate, it demonstrated two things: first, the connector itself has a very specific assembly order which highlights the importance of assembly order in the system as a whole. Second, though the wedge connector is rarely depicted situated within the panels, they are an equally important component of the joint, allowing it to "wedge" together.

Next, the scale of the joint was studied further through a close reading of connector patent drawings of the connector dated 1945 as shown in figure 6. Though these documents did not yield the exact size of the wedge connector, its approximate size was determined based on the size of the panels which were denoted in these patents. Though there are discrepancies within the patents themselves, the small size of the connector was later verified at the Akademie der Künste archive and the viewing of an authentic Wachsmann wedge connector. Modeling and drawing each version of the wedge connector was what ultimately led to an understanding of its function and scale. In fact, it fits comfortably in the palm of a human hand.

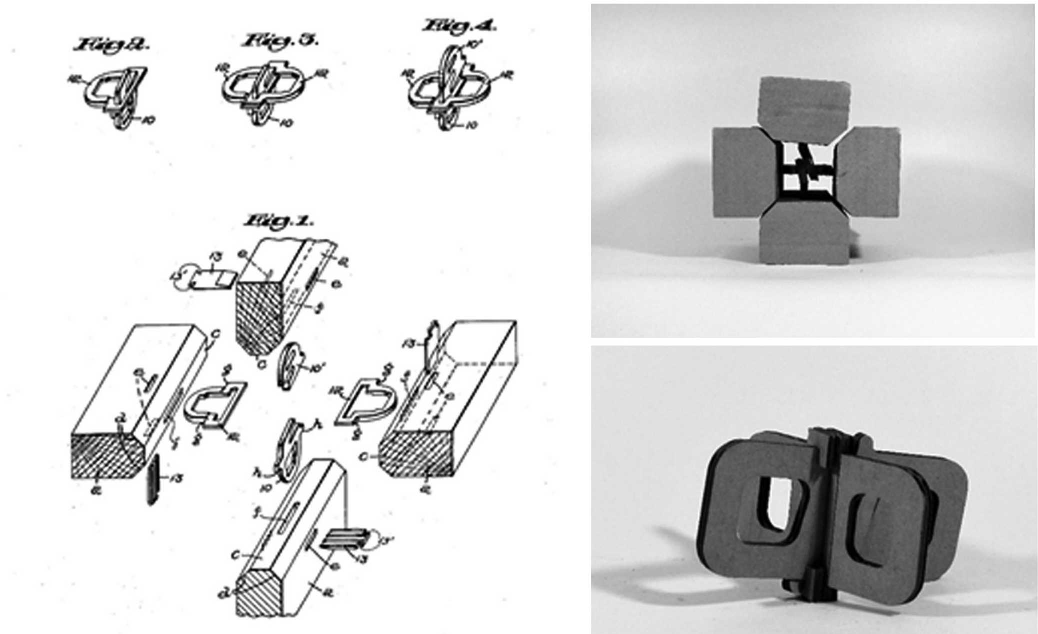


Figure 5: Studying patent drawings of the wedge connector as well as drawings and images from The Turning Point of Building, led to cardboard replications of the universal joint. These 3D models allowed the team to study the assembly order and understand a sense of scale. Source: US2421305, 1947 (left), Author 2021 (right).

With each study of the wedge connector, the team traced design changes to reasoning and logic that led to the physical evolution of its design, as recorded in historical documentation. During this process of discovery, there was a simultaneous dialog between the informed production of digital models, drawings, and 3D prints linked to a historical analysis of drawings and social/political factors that influenced and changed the objectives of the Packaged House System. The critical realization made using the dialog method was that relying solely on either reproductive models or historical analysis alone would have resulted in an incomplete understanding of Wachsmann's connector. The diagram pictured below, figure 7, illustrates the six distinct evolutions of Wachsmann's wedge connector, which can be understood as three phases of development from approximately 1939 to 1947 (Andrzejewski 2018, 21-30). Detailed findings of its evolution are recorded in a chapter that the team contributed to The Art of Joining: Designing the Universal Connector, which was published at the conclusion of the 2018 Bauhaus Lab. This was specifically informed by various patents, images, and blueprints of the Packaged House System. The dialog between the theoretical evolution of the wedge connector and its three-dimensional composition, figure 8, led to a deeper understanding of the system as a whole, and aided in articulating Wachsmann's underlying principles of a "Universal Building System".

A close study of Wachsmann's process of iterations through sequential versions of the wedge connectors reveals that the change in the design was not influenced solely by the functional requirements of the panel and associated system; they were products of the shifting world climate during and after WWII and developed in relation to fabrication methods available at the time. Figure 9, overlays our looping dialog cycle into Wachsmann's evolution of the wedge connector, and introduces some of the influencing factors which transformed the design development along the way. Sabatto details these historic economic

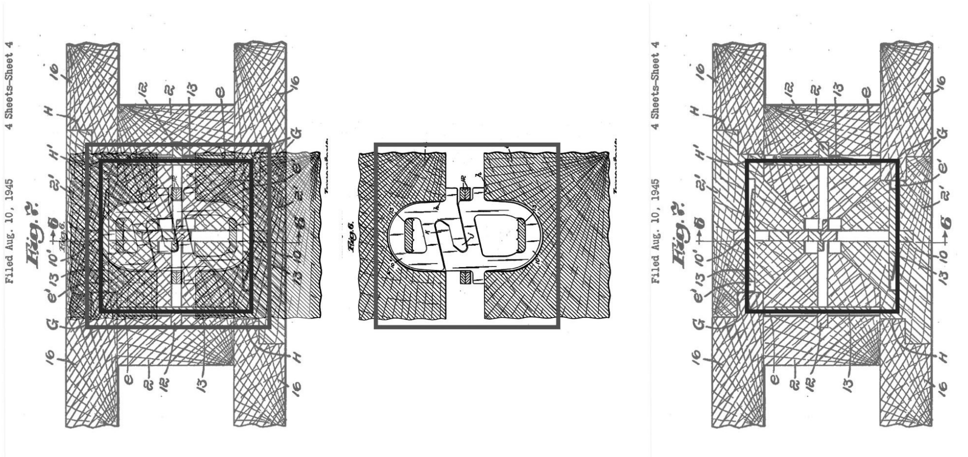


Figure 6: Study of wedge connector size from patent drawing reveals discrepancies in size between drawings. Source: Adapted from Patent US2421305, 1947.

and technological influences in "From Keying to Wedging: the Optimized Workability of Constructional Systems Designed by Konrad Wachsmann During the Cold War Under the Supervision of the North American Governmental Agencies" (Sabatto 2012).

After gaining a basic understanding of the wedge connector's development and scale, principles of Wachsmann's idealized universal building system began to emerge. Wachsmann' s obsession with themes of universality is evident in his approach to systems which did not stem from a need or desire to create a specific building, but rather create building systems composed of a series of universal parts without a predetermined outcome (endless/infinitely expansive architectures). After articulating the theoretical principles Wachsmann's universal by re-examining/replicating elements of his work, the author began to test them in the development of a contemporary universal building system. The goal was to produce a Wachsmann-informed architecture that could be used to construct an almost unlimited number of architectural possibilities, by anyone (that is unskilled workers), in a variety of environments. The author's close study of major works, publications, and patented systems—in dialog with routine informed making as depicted above in figure 6—revealed that, for Wachsmann, universal systems: 1) strive to be efficient in their assembly/disassembly process, 2) are accessible to the unskilled laborer, 3) are mobile, 4) are scale-less, and 5) are flexible/adaptable providing for material reuse. These five principles, efficient, unskilled, mobile, scale-less, and flexible/adaptable—not explicitly articulated in existing Wachsmann literature but derived from this research—became guiding design principles for the development, fabrication, and testing of a contemporary take on the universal building system.

The first step in designing the system was to reform Wachsmann's principles of the universal to accommodate material reuse and panels to be made from the system itself, rather than necessitating they be prefabricated in a factory. This substitution, of multi-use quality for scale-less, would allow the resulting system to engage today's DIY builder culture and allow for the possibility of panels made of repurposed materials such as discarded plywood, plastic, cardboard, etc. Subsequently, the five principles that guided the development of the contemporary building system—referred to as the "Clip System"—were that it was efficient, unskilled, mobile, flexible/adaptable, and provide for multi-use. Throughout the development of the Clip System, the updated theoretical principles

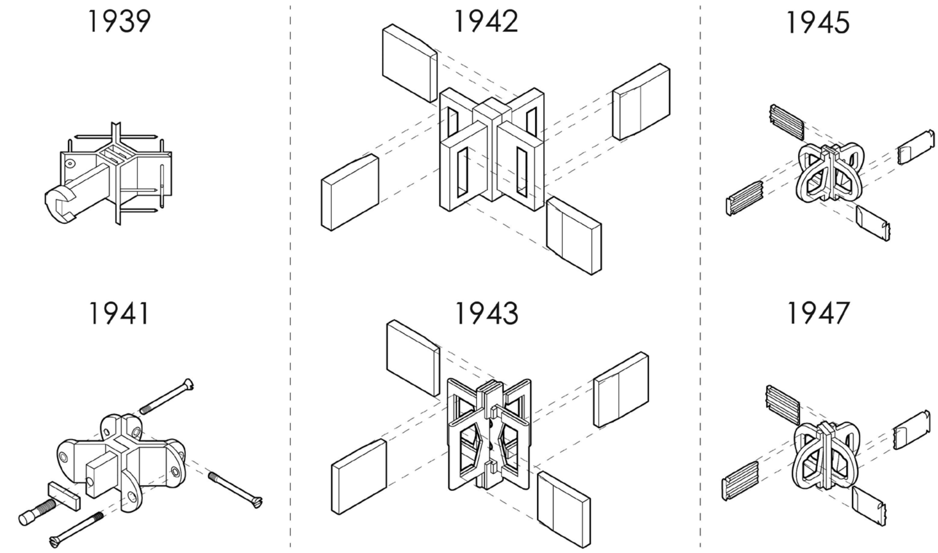


Figure 7: Evolution of the wedge connector over a period of 8 years – as explored through drawings. Source: Author 2018.

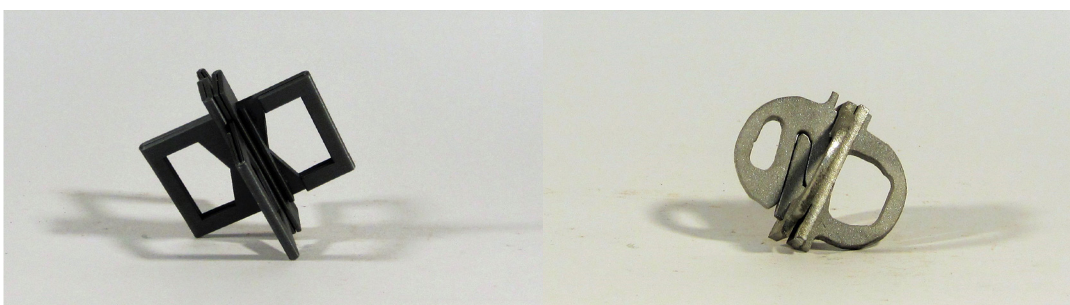


Figure 8: 3D printed and aluminum reproductions of the wedge connector through its evolution supplemented by a drawn analysis. The physicality of the 3D object led to an understanding of it as a precisely designed joint. Source: Author 2018.

of Wachsmann's universal were constantly used to test the development of joints, panels, and associated tooling. If the fabricated iterations, figure 10, of these systems, components were successful, they met all five of the principles derived from Wachsmann's work; conversely, if they were unsuccessful, they did not meet all requirements.

Over the course of two years, the Clip System, figure 11, developed through a dialog between empirical full-scale testing and models and determining their success or failure in dialog with the theoretical principles extracted from Wachsmann's universal. Similar to Wachsmann's methods, this research took a joint-first approach to designing a "Universal Building System". The principles of the universal became theoretical guiding rules for this process of clip evolution, grounding the work with a historical analysis of Wachsmann's work. As the Clip System developed, challenges inherent in designing a universal prefabricated system emerged. However, through the already established dialog between Wachsmann's work and the Clip System, "Wachsmann-ian" solutions were revealed and applied to the work. This resulted in a deeper understanding of Wachsmann's process, but also informed the evolution of a new Universal Building System design.

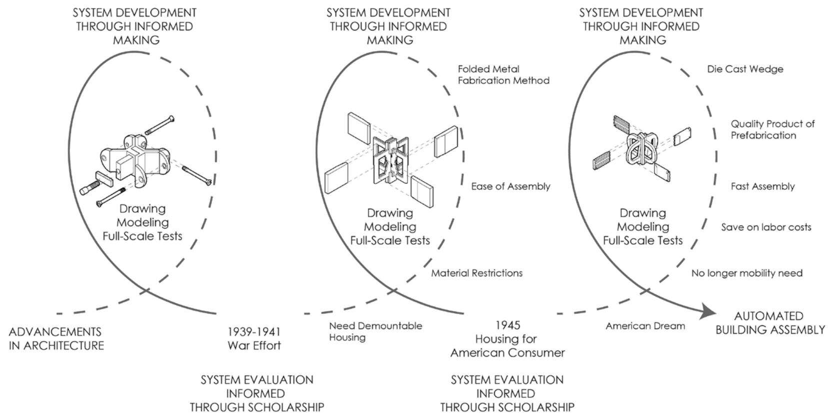


Figure 9: Development of the wedge connector by Wachsmann as a cyclical process of design, full-scale testing, and analysis. Source: Author 2020.

While the clip design informed the required tooling, the clip and node system evolved from Konrad Wachsmann's work, figure 12. Besides the principles of the universal, the assembly sequence and initial desire to produce a system capable of multi-directional assembly generated a unique challenge. Unlike the wedge connector, the Clip System is exposed, rather than embedded within the panel. Though this created new problems such as a gap between panels, it was a decision made to facilitate assembly and disassembly. Before arriving at a design that included an open center, the Clip System developed into a two-part system of clips and nodes. This allowed for panels to be assembled and arranged with one universal clip. The associated panels could be configured in a number of directional ways using one of four different nodes, as seen in figure 13. Initially, the node developed out of a desire to allow for multi-directional assembly; the panels could be set in place in any orientation or direction and then the nodes would simply be slid on top

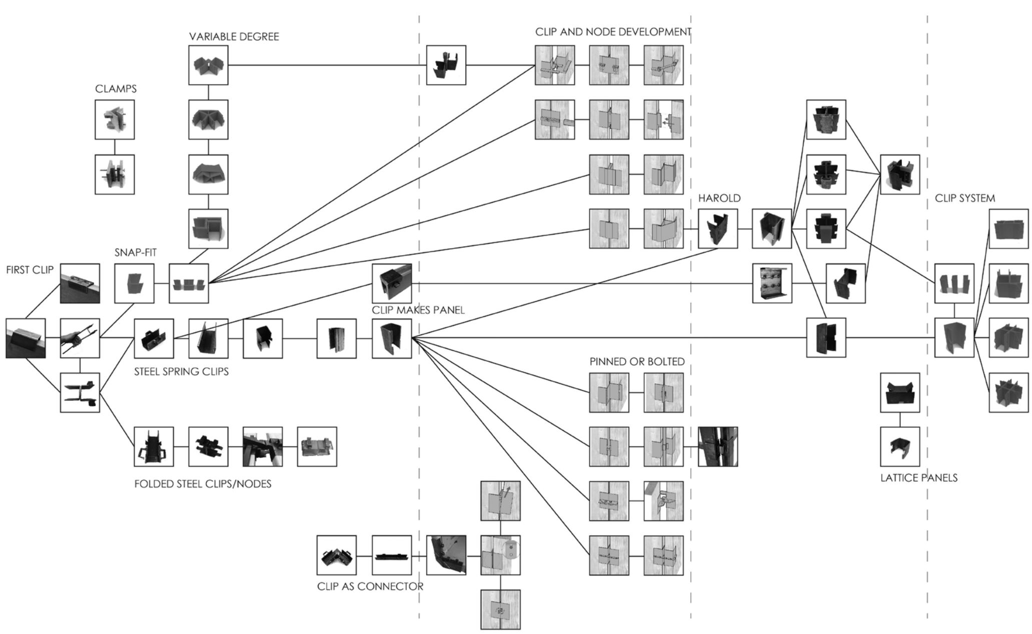


Figure 10: As the Clip System evolved over the course of two years, different lines of evolution worked toward a universal building system based on the principles laid out by Konrad Wachsmann. Source: Author 2018.

Figure 11: These three clip and node experiments explored the differences between the fabrication process for crafting the sliding node through welding, forging, and 3D printing. Source: Author 2018.

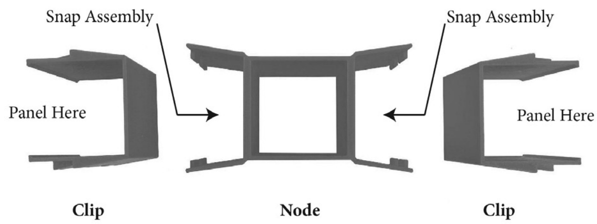


Figure 12: The Clip System is a snapfit system consisting of clips, nodes, and panels. Source: Author 2018.

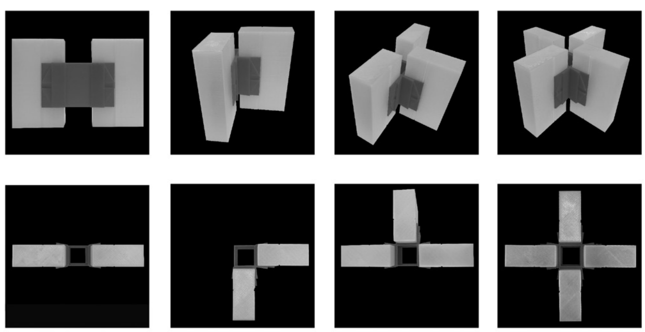


Figure 13: Final iteration of the Clip System includes parallel, perpendicular, three-way, and four-way connections. Source: Author 2018.

locking everything together. Eventually, the concept of a sliding node gave way to a snap-fit design with an open center, figure 14. Again, the solution was based on observations made through replicating and analyzing Wachsmann's work, wherein, ultimately everything has an assembly order, therefore multi-directional assembly is not necessary for the system to be universal.

A fixation on the joint and preliminary full-scale tests assembled from the joint and panel resulted in a small construction that could be assembled by two people in approximately 80 minutes and dissembled in about 40 minutes, figure 15. While this initial test was a successful proof of the concept of the clip, panel, and tool, it revealed the importance of assembly sequence and brought into focus a gap that formed between interconnected panels. When checked against Wachsmann's work, it became apparent that he also emphasized a very specific assembly sequence, one designed into the wedge connector itself. In addition, he detailed the importance of an "open center" in a joint and panel modular system as well as the module where "building elements and joint lines are always identical with the modular planning raster" (Wachsmann 1961, 78). Both of these properties of Wachsmann's universal building system "appeared" serendipitously in the system developed by the author.

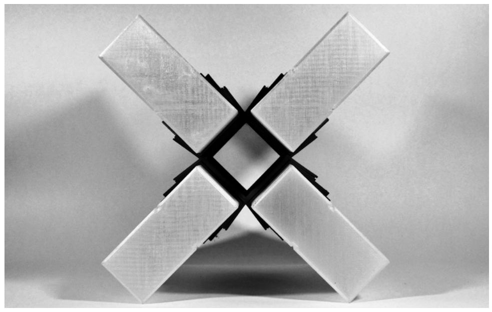


Figure 14: The open center of the clip system node is exemplified in this four-way connection. Source: Author 2018.

In the summer of 2018, a member of the research team participated in the Bauhaus Research Lab “The Art of Joining: Designing the Universal Connector” and contributed to an exhibition of findings resulting from the lab. The informed design and fabrication of the exhibition components acted as further proof of the importance of module, open center, and assembly sequencing in a universal system. In the spirit of Wachsmann, the exhibition structure used panels with a 1:3 proportion in a modular system, figure 17. Connectors were inserted into the edge of these panels to keep the center of each joint on the open center of the module. The module that included an expressed open center as a gap actually facilitated the success of the concept. This type of system made assembly quick and easy. The exhibition work proved that there are many types of systems that can be generated from a standard set of rules or templates for a universal building system as laid out by Wachsmann’s work. In this case, a kind of Universal Exhibition Structure facilitated the construction of spatial organizers with horizontal and vertical panels, while maintaining alignment to a grid turned 45 degrees in the gallery. Like Wachsmann’s system, this system contained only four types of connections: parallel, perpendicular, three-way, and four-way orthogonal connections.

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Figure 15: Full-scale assembly test of Wachsmann-based modular system. Source: Author 2018.

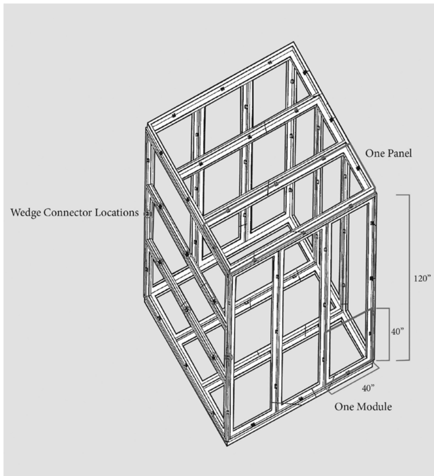

Figure 16 (left): This diagram shows Wachsmann's Packaged House System panel module and wedge connector locations. Source: Author 2018.
Figure 17 (right): Bauhaus Lab 2018 Exhibition of Findings "The Art of Joining: Designing the Universal Connector", demonstrates the success of Wachsmann's Modular System. Source: Author 2018.

exhibition work proved that there are many types of systems that can be generated from a standard set of rules or templates for a universal building system as laid out by Wachsmann's work. In this case, a kind of Universal Exhibition Structure facilitated the construction of spatial organizers with horizontal and vertical panels, while maintaining alignment to a grid turned 45 degrees in the gallery. Like Wachsmann's system, this system contained only four types of connections: parallel, perpendicular, three-way, and four-way orthogonal connections.

DISCUSSION & CONCLUSION

The dialog between Wachsmann's universal joint and the development of the Clip System supports an architectural methodology based on modeling, reproduction, and prototyping, in conversation with historical significance, scholarship, and theory as a means of pursuing when performing architectural research. This method can be utilized by students, researchers, and practitioners as a method for analyzing/re-engaging historical work and applying it to a contemporary context. The methodology discussed in this paper provides a useful method for leveraging the theory, successes, or failures of historical precedents against contemporary requirements of a specific problem. This paper describes an example of this methodology which utilized an iterative process of informed-making-based research to explore Konrad Wachsmann and the Packaged House System and led to a deep understanding of this historic precedent or prefabricated housing. If a research method of modeling, reproduction, and prototyping alone had been utilized, without critical observations about the theory of Wachsmann's work, the (uninformed) artifacts would not have had as much significance.

Making, the hand, a tactile connection to materials, parts, and building elements constitutes an intelligence that parallels one situated in the mind. Students of architecture and other design disciplines can employ prototyping/modeling as a research tool by using the process of informed-making to interact with, support, and enlighten historical analysis, and comparison, in a continuous dialog. In conclusion, an architectural methodology for research that creates a dialog between making and theory can lead to a deep understanding of architecture, building materials, and insight into the application of new discoveries to contemporary problems.

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AFRICAN ARCHITECTURE AND IDENTITY: THE NINETEENTH CENTURY ASANTE PALACE OF KUMASE, GHANA

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University of Florida

Architecture and ritual interconnect to define cultural identity. In the traditional procession ritual of the Asantehene, the Asante king, into the palace, the Golden Stool, Kente cloth, and Adinkra symbols are a part of the space and place narrative. These narratives encompass symbolic cultural habitation and the geographical landscape. This dissertation examines as a case study the nineteenth century Asante palace in the traditional city of Kumase, Ghana, Africa, to reveal the cultural and material connections to the identity of the Asante. In the nineteenth century, missionaries and European officials collected ethnographic surveys of the Asante palace before it was destroyed by the British during the colonial period. The existing ethnographic survey archives of Thomas Bowdich, a European official, explain the Asante Architecture and the palace from a European hegemonic perspective. Bowdich states that the construction of the ornamental architecture of "Coomassie" reminded him forcibly of Sir James Hall's essay, the Edinburgh Philosophical Transactions, that Asante Architecture was the tracing of the Gothic order to an architectural imitation of wickerwork. The records proclaim the architectural ornament on the Asante buildings was adopted from interior countries and did not originate with the Asante.[1] The findings in the survey do not address the phenomenological experience, ritual practice, holistic architectonic structure, and sociocultural expression of the Asante Palace according to the nation of the Asante.

This research aims to materialize and define the connection between the nineteenth century Asante palace of Kumase and the socio-cultural identity of the Asante to ameliorate the damaging effects of colonization on traditional structures. This research works between architecture and anthropology to reveal the ontological association of the Asante cultural elements, the Golden Stool, Kente cloth, and Adinkra symbols and their ritual significance to the Asante palace. From an anthropological point of view, collective memory, ritual praxis, and political and social organization explain the embodied meaning of Asante culture identity. The palace's architecture defines traditional construction methods, sustainable practices, structural phenomenological experience, and spatial narratives to interpret the social context. This research includes archival work of ethnographic records of the Asante palace, Asante culture, and the context of the city of Kumase. A close study of the Akan language of Twi reveals each cultural element's spiritual and social meaning that is an integral part of the Asante life. Analytical drawings of symbolic details and reconstructive drawings of the Asante palace are used to link material culture, phenomena, and the socio-cultural identity of the Asante based on the African point of view.

Expected results include the demonstration of the social and cultural expression of the Asante palace and the original embodied meaning based on the etymology of traditional structural references. Furthermore, this research will contribute to the history of African Architecture and vernacular palatial structures.

Keywords: Phenomenological, ritual, architectonic, identity, sociocultural, Asante.

INTRODUCTION

Since antiquity, the making of objects and symbols in many cultures in various regions has defined the purpose of existence. Making was the fundamental idea of communicating the intangible elements of the mind into tangible objects of meaning. The Asante used gold, the plentiful earth mineral of the region, to create artifacts of the culture's wealth, power, and spirituality. The most significant objects of the Asante are the Golden Stool, Kente Cloth, and Adinkra symbols. They relay a message to the people to create unity in the nation. These essential ritual elements were a part of the Asante king's procession into the Asante Palace (Figure 1). Historically, palace structures all over the world were edifices of power and authority. The monumental presence of the building or complex in the landscape was a symbolic representation of political hierarchy, religion,

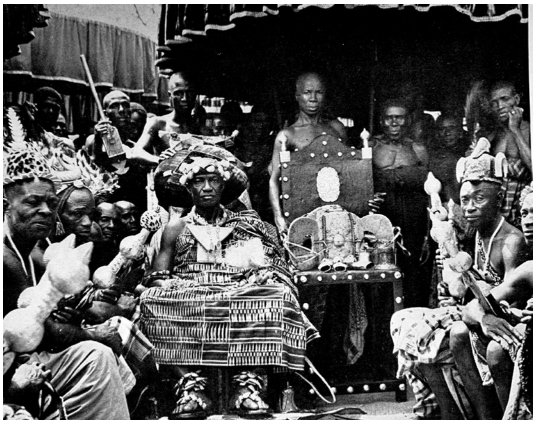

Figure 1 (left): The Golden Stool and the Asantehene Sir Osei Agyeman Prempeh II wearing a kente cloth robe. The Golden Stool, which takes precedence over the Asantehene, is lying on its side in its own chair of state with ceremonial bells of protection, the upper surface facing the spectators. Source: Ward, 1958.
Figure 2 (right): Palace of Asantehene in Kumase Ghana facing the center courtyard of the Halls of Justice. Source: Prussin, 1980.

and sociocultural identity. However, the Asante palace was destroyed during the Anglo-Asante war 1824-1901. Nevertheless, the archives of the palace and Asante's historical reference reveal the cultural significance of the structure to the identity of the Asante (Figure 2).

According to Akan oral history, the genesis of the Asante kingdom was of divine origin established by the royal ancestress of Okyoko, Ankyewa Nyame, daughter of the supreme sky god, Nyame. The ancestress descended from the sky to the ground, and out of holes in the earth emerged the Asante people; thus, the association with clay, which means *Asan*, that was recognized by all Akan states.[2]

Asante's historiography grounds the critical cultural criteria of being, belonging, and identity. The narrative of the Asante nation-state constituted the connection between the tangible and intangible to establish space and religious belief. The societies' traditional oral history rectifies their official and pragmatic past, constructing a historical synthesis layered with a series of phenomena interwoven with the cosmos, economic, political power, and nature.[3] Furthermore, the nineteenth century Asante palace was the symbolic structural thread of memory intertwined with material culture. Symbolic objects of Adinkra symbols, the Golden Stool, and the Kente cloth, based on oral history and meaning, disclose the purpose of the collective culture contextual system of the Asante nation displayed in the palace.

1. HERMENUTIC METHODLOGY

The research methodology for analyzing the archives of the palace as a case study draws from the theory of hermeneutics through interpreting the palace's cultural history and symbolic significance. The hermeneutic approach to observing the palace aims to understand the importance of the structure from the past and its memory in the present. This research discloses the significance of the Asante Palace in the past, the relevance of its memory for the present, and its implications for future research and scholarship. The vanishing point of cultural explication in the Asante society gives a range of vision that includes everything that can be seen as significant to the Asante identity. The Asante palace's ontological importance is based on the structure's function as a sacred dwelling for the authority of the Asante king and as a ritual space for the Asante. Specifically, the interpretation of the ontological meaning and essence of Adinkra symbols, the Golden Stool, and the Kente cloth based on oral history reveals the purpose of the collective cultural identity of the Asante displayed in the palace. The methodological, ethical, and moral criticism of colonial perspectives of African history and architecture of the Asante were based on the insights and human vision available in the built environment at the time.[4] For this research, the methodology of interpreting the temporal space, material culture, and context is from an African point of view. This vanishing point in the Asante society gives a range of vision that includes everything that can be seen as significant to the Asante identity. The interpretation of the ontological meaning and essence of Adinkra symbols, the Golden Stool, and the Kente cloth based on oral history will disclose the purpose of the collective cultural contextual system of the nation of the Asante displayed in the palace. The intention is to understand the relevance of the shared system of ideas, values, and ethics within the Asante society that influences the palace representing a symbolic structure of authority.

2. MAKING AND MEANING

Language and meaning are interconnected to understand authentic cultural identity. The term for the West African historian is *doma* or *doma dieli*. The *doma*, the "knowers" or "makers of knowledge," were traditionalists and kept secrets of cosmic genesis and the sciences of life. The traditional doma is an archivist of past events transmitted over generations, and it is customarily understood that the *doma* is gifted with a prodigious memory.[5] John Ki-Zerbo explains that the traditionalist *domas* were proceeded against by the colonial power, which sought to uproot local traditions to implant its ideas in large towns called "*tubabu-dugus*" or "town of whites"—meaning colonizers. The historic hegemonic transition explains the misinterpretation of the meaning of the African historian being derived from the French term *griot* instead of the African term *doma*.[6] In 2008 John Adjaye built upon the African historiography works of Ki-Zerbo by identifying, the *doma,* oral historian, based on the local context of Ghana. He reveals that the keeper of memories of the Asante is the *okyeame* in the Akan Twi language. The *okyeame* is a metalinguistic and court historian to the king.[7]

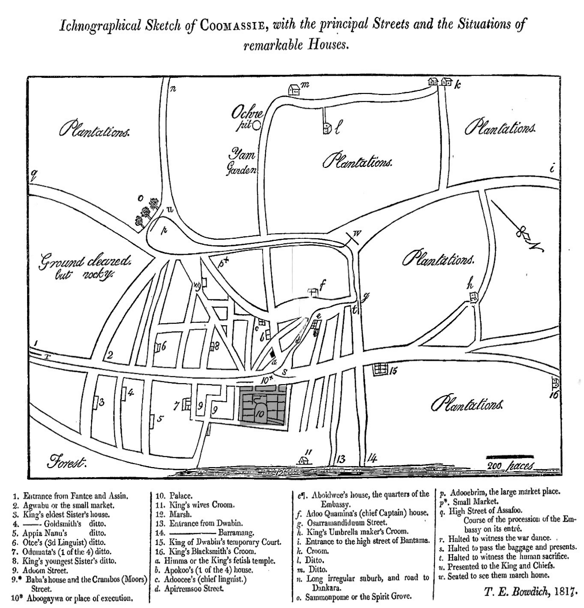

Figure 3: Drawing of Kumase city map with Asantehene's Palace complex (10. indicated in gray) and the King's fetish temple (a. indicated in black) showing the close alignment between the political and religious structures. Source: Bodwich ,1819, Buah 1996.

Based on oral history, the establishment of the imperial city of Kumase, which means "under the *kumnini* tree," was ascertained through a process conducted by the priest Okomfo Anokye (Figure 3). He planted three trees at different locations. Two of the trees died, and the surviving tree was in Kumase.[8] Additionally, Okomfo Anokye in 1695, during the *Odwira* festival, which means purification, caused the Golden Stool "*Sika Dwa Kofi,*" which means Golden Stool born on Friday, to descend from the sky before the Asantehene, king, Osei Tutu before the Akan nation (Figure 4). The people received the supernatural display by the priest. The act enshrined the soul of the kingdom in the religious, political, and economic power of the Asantehene Osei Tutu, also regarded as *Nyame Kese*, the great god.[9]

Figure 4: Ethnographic drawing of the First day of the Yam Custom by colonial surveyor Thomas Bodwich. The illustration depicts the annual *Odwira* festival, also known as the Yam festival in Kumase. It was an enforced attendance for the provincial chiefs. The point of these festivals in their rituals, drama, and pageant was to reenact, reinterpret and transmit Asante history, renew communion between the dead and the living and emphasize the unity of the Asante nation. Everyone in attendance of the festivals was theoretically united in their allegiance to the occupant of the Golden Stool, the center of the festival (under the large red umbrella with an elephant finial). Source: Bodwich, 1819, Arhin, 1967.

2.1. GOLDEN STOOL

The union of the Asante nation began in the seventeenth century in the city of Kumase under the leadership of Prempeh Osei Tutu. The aura of the magical powers of Okomfo Anokye, a priest, aided Osei Tutu in sealing the union of the Asante nation with the "Golden Stool," *Sika Dwa Kofi*. The Asante's kingship is a constituted political institution of the Asante nation in two parts. The Golden Stool, the sacred element of the Asante and the Asantehene Oaths, makes the king 'the hub of the Asante political system. The Asante king's position is of divine symbolic significance linked to the Golden Stool, which represents the seat of power to the Asante nation. The ceremonial oaths and structural institutions reinforce the social implications, values, and norms to invoke the continued fortune of the kingdom. The two themes are related: while it is the Golden Stool that prescribes ritual, it is through oaths that ultimate validation facilitates the authority of the Asante king.[10] In the ritual procession of the Asantehene to the palace, the Golden Stool is never allowed to touch the ground and is carried on the shoulders of the ceremonial official (Figure 5). The stool is considered so sacred that no one is allowed to sit on it. Each new Asante king is lowered and raised over the Golden Stool without touching it. The enstoolment ceremony interconnects with the Asante palace as the structural symbol of authority that house both the Golden Stool and the Asantehene.

2.2. KENTE CLOTH

In the ritual procession of the Asantehene into the palace, special Kente cloth was woven for the ceremony. The cultural object of the Kente cloth, as explained by

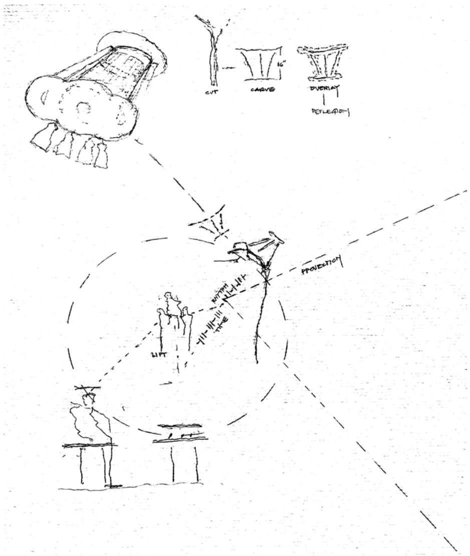

Figure 5 (left): Analytic drawing of the Asantehene and Golden Stool ritual procession. Source: Drawing by the author.
Figure 6 (right): Kente cloth Right, Weaver in loom making Kente cloth in Accra, Ghana. Source: Author 2019.

Abraham Ekow Asmah, a scholar of African art history, states that the Kente fabric is a historical royal cloth. Kente (*kenten* which means basket) cloth is an "African traditional textile that is a visual representation of history, philosophy, ethics, social conduct, religious beliefs, political thought, and aesthetic principles."[11] The narratives of Kente cloth and Kente weaving vary in measure and degree. Kente weaving is an indigenous technique dating back to the 16th century in Ghana. The Asante pioneered Kente weaving, having a traditional story told over generations about two brothers, Nana Kuragu and Nana Ameyaw, who learned the noble art by observing a spider spin its web on a farm they visited. Each geometric shape has a symbolic meaning, collectively revealing a hidden message.[12] Weavers were considered to have supernatural powers and significance because their work was considered a gift from God, *Nyame,* the supreme God of the Asante. Kente weaving is also strictly done by men. The parts of the weaver's loom also have symbolic meaning.

Kente weaving designs evolve on the Nsadua Kofi, a traditional loom according to the weaver's philosophy, creativity, and intention for weaving the cloth (Figure 6).[13] There are eight parts of the frame; four represent elements of nature; earth, air, fire, and water, and the other four parts symbolize the cardinal directions; north, south, east, and west. The weaver was also counted as a part of the divine essence of the loom. Before the weaver began to work, a ritual of invocation and touching every part of the loom was performed.[14] The Asante Kente cloth design comprises dots, lines, shapes, textures, and colors carefully crafted to form geometric shapes and intricate patterns that exhibit balance, rhythm, variety, proportion, and repetition. Ghana's indigenous Asante Kente fabric is woven in long, narrow strips on traditional looms using brightly colored silk or cotton yarns that are then stitched lengthways to form different sizes of cloth for men and women.[15]

Historically in Ghana, the technical arts of Kente cloth weavers and artisans attached religious practices to their profession. Rituals were performed to invoke the blessing of God and the deities associated with the particular craft. Workshops and tools had to be consecrated by the pouring of libations and offerings of the blood of an animal before work started.[16] The

Figure 7: Woven wattle and daub system in the entablature of the Asante palace Source: Prussin 1980.

practical construction of the Kente cloth, philosophical creation of the weaver, and sacred spiritual ceremony were a unit of symbolism that represented a deeper meaning of truths and values of the life of the Asante. The pattern designs, both symmetrical and asymmetrical, colors and motifs were instruments of secret communication that strengthened the Asante culture.[17] African architecture and arts had a sacred quality that exceeded the technical construction and physical beauty. There was an intangible body, soul, and cosmological communication with buildings and cultural objects.

In Thomas Bodwich's ethnographic survey of Kumase, the Asante palace and houses were constructed of local materials such as bamboo, laterite clay, stones, cottonwood, cane, grasses, and palm leaves.[18] The natural materials used to weave Kente fabric and the palace were symbolic representations of the Earth, which was considered sacred. Enclosed spaces with walls constructed of textiles or woven bamboo and earth were the expanse of existence. The supernatural belief and tangible craft merged to validate life and belonging.

2.3. ADINKRA SYMBOLS

The cultural element of Adinkra is an Akan Twi word that means farewell or good-bye. It is a group of symbols created by the Asante as a writing system. Each sign can be associated with an aphorism that offers insight into the Akan way of life. The Adinkra and their accompanying proverb were and still is a form of a communication system that preserves and transmits the cultural and spiritual values of the Asante. These symbols were also used on the facade of buildings designed by the Asante.[19] Adinkra symbols on the Asante palace's facade were carved into the structure to display a message of meaning (Figure 8). The reliefs of Adinkra symbol Dwenini Aben "ram and horn," which means "humility and strength," are displayed on the plinth of the building and base of the column, and the passive cooling brise soleil system has the symbol of Tabon, a paddle which means "courage and hard work."[20] The building speaks through the Adinkra symbols inscribed on the facade of the Asante palace. The weaving technique was also displayed in the palace's wall construction of wattle and daub and the thatch roof system. Wattle, and daub is a typical wall assembly used to create buildings by the Asante using local materials. It consists of a wood framework that builders craft as a woven lattice of horizontal and vertical branches or wood posts; upon this system, wet laterite balls are pressed onto the lattice surface at a thickness ranging from six to nine inches.[21] Traditionally, African masons or builders were not esteemed for their technical expertise but respected for the magical powers

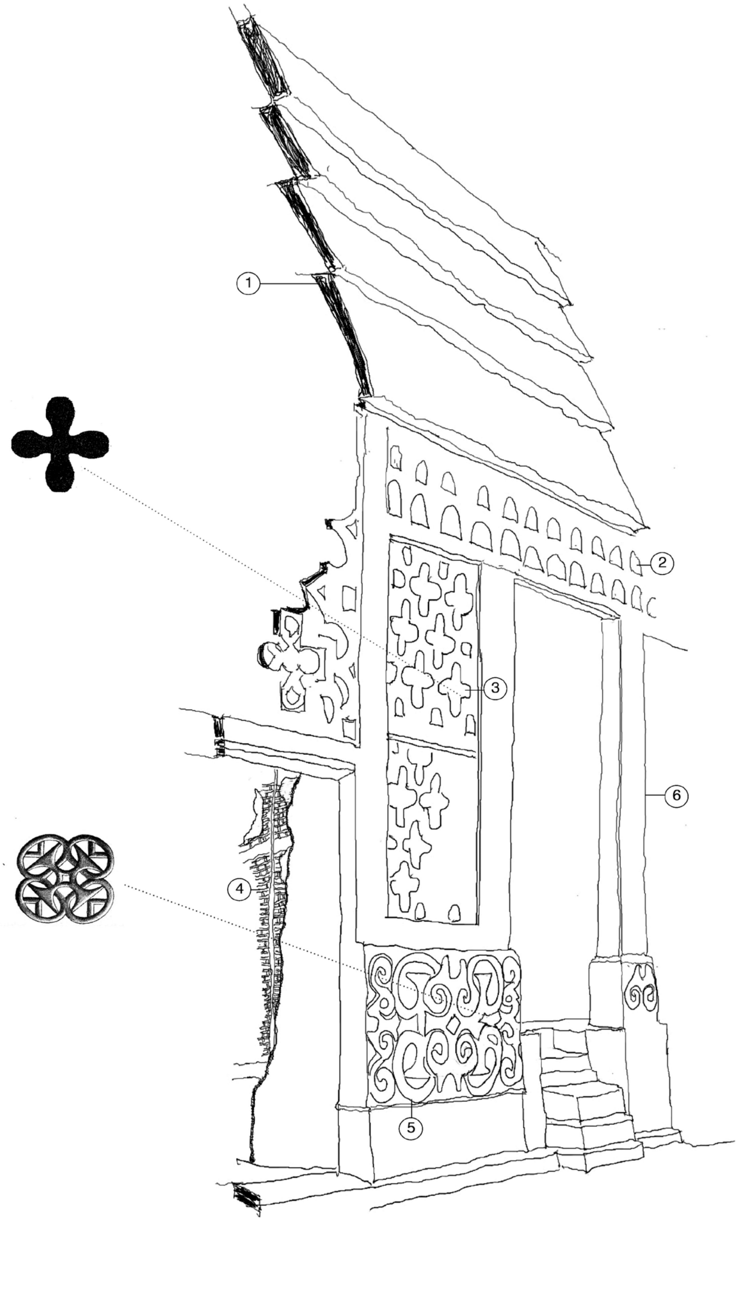

Figure 8: Right, Detail drawing analysis of the Asante palace façade 1. Thatch roof 2. Ornament brise soleil system 3. Brise soleil system with Tabon Adinkra symbol 4. Wattle and daub wall construction 5. Plinth with Dewenini Aben "ram and horn" Adinkra symbol 6. Column with base "ram and horn" Adinkra symbol. Source: Drawing by author. Tabon symbol Source: Glover, 1992 Dewenini Aben. Source: Ramseyer and Steiner, 1901.

Figure 9: Exterior of Asante Palace, National Archives, UK, CO 1069-34-132-2-001, Source: Unknown 1874.

granted to them by the deities of the Earth and their ancestors. The skill of erecting an earthen wall was interpreted as a gift from supernatural forces. Several propitiatory rites must be addressed to the builder to ensure the success of the building process. The structure built by the mason becomes a sacred place.[22] The earthen wall's technical woven lattice system and thatch roof transform into a symbolic enclosure of divine existence (Figure 9).

3. RITUAL SIGNIFICANCE

The implicit meaning of a space is revealed through the interaction and movement of society with buildings. Rituals and architecture are interconnected to shaping the experience with structures. The intentional coded message in the aesthetics, the meanings established during ceremonies, and the relationships people enact with a building penetrate beyond traditional utility assumptions. Architecture reflects society as an element of time and memory.[23] The cosmical symbolism in temples and palaces is a reduplication of structures made not with hands. The divine or heavenly association is interlinked with sacred ceremony and the building.[24] In traditional Asante architecture, architectonic components of a built environment and the natural landscape merge into a conscious spatial frame through rituals to establish space. The establishment of place through the medium of ancestral attachment validates human existence. The Asante palace was a spiritual place for the Asante people.[25] The destruction of the Asante palace royal compound in 1896 was a displacement of ceremonial grounds and the ritual space of the Asante. The British transformed the area into a colonial commercial district, and the materials from the palace were used to build a fort. After World War I, as a form of repatriation, the British erected a new palace, the Manhyia Palace, as the new seat of the Asante nation, which became a museum in 1995.[26] Hess reveals that the Manhyia Palace is forcibly serving as a cultural ritual significant structure for the Asante. During the museum's opening, a replication of the Asantehene (King) ceremonial procession was conducted from the king's residence to the palace grounds, representing the authority of the Asante nation.

From a phenomenological point of view, the ritual culture explains the lived spatial experiences between the body, the building, and the phenomena associated with the Asante palace. In understanding phenomena, the symbolic cultural representation in the palatial architecture of the Asante reveals the philosophical meaning of "being" and existence in the Asante society. From an ontological perspective, ritual and spiritual connections of the Asante material culture are linked to the palace. The concept of "being" references that the structure of experience was connected to the cultural objects of meaning: the Kente cloth, Golden Stool, and Adinkra symbols that were inscribed into the construction of the palace. The temporality of the cultural elements is the implication of the phenomena.[27] The building, cultural objects, and ceremony create an intangible spatial experience. The Asante palace's ontological significance is based on the structure functioning as a sacred dwelling to the authority of the Asante king and ritual space for the Asante. Additionally, the presence of the building was emblematic of belonging, safety, and stability in the society.[28] The aspects of symbolization in the nineteenth century Asante palace are critical cultural criteria to the concept of being, belonging, and identity.

CONCLUSION

This research contributes to the African Architecture body of knowledge. Furthermore, the palace study elucidates the Asante hierarchy in the material culture and its symbolic significance. The current literature on the 19th century Asante palace of Kumase consists mainly of colonial historiography. Research after Ghana's independence in 1957 has yielded sparse cultural and architectural knowledge of the contextual dialogue of the country. The preliminary findings of the palace based on archival analysis of images reveals a holistic architectonic structure of memory. Asante's traditional building methods and cultural elements of making and meaning are displayed in the façade of the palace. The meaning of the motifs reveals philosophies, religious beliefs, and social norms based on the Akan Twi language of the Asante. This research will define the connection between the nineteenth century Asante palace of Kumase sociocultural identity of the Asante from an African historiographic perspective to ameliorate the damaging effects of colonization on traditional structures and contribute to the gap of knowledge on the palace.

Furthermore, this research contributes to understanding indigenous technologies and materials conducive to climatic conditions, topography, and geographical location that can be implemented in modern built environments. The information on the nineteenth century Asante palace can be used as a reference for architectural study relating to language and meaning. The knowledge attained from this study will be used for future digital reconstruction of the nineteenth century Asante Palace. The research will also serve as a didactic pedagogy model for African Architecture History, transitioning from colonial to African historiography. Furthermore, the research knowledge and the 3D digital model will provide a virtual spatial experience of the palace and give insight into the Asante vernacular architecture and culture.

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DISSEMINATION THROUGH ARCHITECTURE PERIODICALS: JOURNEYS OF ARCHITECTS FROM TURKEY

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In the twentieth century, architects' mobility and tendency to document and publish their travels played an important role in disseminating an architectural culture. While architectural ideas were disseminated through institutions and a variety of representations, traveling provided a practice through which new encounters could occur. In Turkey, beginning with the 1930s, architects and academics were sent abroad on study trips funded by architecture magazines, educational institutions, and the government, mostly to inspect the architectural production of western countries. Some architects published reviews and articles on their trips, in Turkish architecture magazines, especially in Mimarlık and Arkitekt. Through these magazines, architects and academics mobilized and translated ideas extracted from their 'on-site' experiences to 'off-site' materials. In that way, the architecture magazines in Turkey became agents through which ideas were disseminated, and presented to Turkish-speaking architects. Architects' observations clustered around urbanism, modernism, modern dwelling, and occasional exhibitions. The articles emphasized the importance of seeing new implementations in construction technologies, architectural styles and urban planning through traveling. This research aims to analyze the relationship between architects' journeys and the tendency to publishing and disseminating in architectural culture.

Keywords: Architecture culture, architectural publishing, journey, mobility, traveling.

INTRODUCTION

Working in a discipline related to creative production, society and culture, an architect is an intellectual person who develops a professional architectural identity and approach through an accumulation of personal experiences, education and knowledge. Although a formal education has not always been a prerequisite for an architecture profession, architects' initial years are signified by the mobility of ideas and encounters through which an architecture culture forms and disseminates. Traveling and new encounters can positively impact an architect's professional career, yet there are few studies that explore and focus on traveling as a fundamental part of an architect's professional identity and its contribution to architecture culture. The white male architect conquering and rationalizing their surrounding has been a recurring and common image throughout history. In fact, Esra Akcan (2009) shows through Le Corbusier's Voyage d'Orient diary notes that the perceptions of such architects are usually full of factual mistakes.

The Grand Tour, perhaps the European predecessor of the concept of traveling as a rite of passage, was followed by prizes and modes of teaching that adopted a similar way of operating. For instance, Grand Prix de Rome was a scholarship offered to French fine arts students to study in Rome in the seventeenth century as well as to architecture students by the eighteenth century. The following example could be the American Academy in Rome (founded in 1894 and followed by other 'academies' in different cities in Europe for American students to gain insight and knowledge of history through visiting Europe), which has been one of the institutions that have promoted a combination of study and travel for its architecture students. For architects such as Robert Venturi, the experience in the Academy in 1954-1956 was so influential that the study tour itself became a reference for the architect's own design approach and view of architectural history (Stierli 2010). Michael Graves was another fellow in 1960-1962 who described his experience as the basis of his understanding of architecture as a language and the continuation of history (Ambroziak 2005, ix).

Nevertheless, along with travel culture's celebrated aspects such as inner discovery, production of knowledge, first-hand experience, and development of new ways of forming relationships, the colonizing aspect of traveling should not be missed. Historically, traveling has maintained a position of home, destination, traveler, and 'the other' and established a hierarchy between them (Kaplan 1996). As a matter of fact, one of the major bodies of research that deals with traveling, i.e. travel literature, largely looks at material, such as travelogues, drawings and maps that western male travelers produced. There are many accounts that associate travel writing with colonialist expansion and a continuation of imperial power (Ivison 2003, 200). As Jilly Traganou (2009) suggests, for architecture, traveling does not have the same critical position as it does for anthropology or cultural studies. Yet it also has the potential to transform architects through the mobility of representations, encounters, and dissemination of knowledge.

1. BACKGROUND AND METHOD

In modern society, the creation of knowledge is not static and directly transferable. However, the knowledge of the precedent has often been debated in the architecture discipline. The architect's educated gaze is often positioned superior to the indifferent sight of the local or the tourist (Deriu, Piccoli, & Turan Özkaya, 2016, s. 4). In fact, according to Alcolea and Tarrago (2011), historically, architects traveled and exhibited their work and converted their journeys and mediatization they gained with each encounter into parts of their existence.

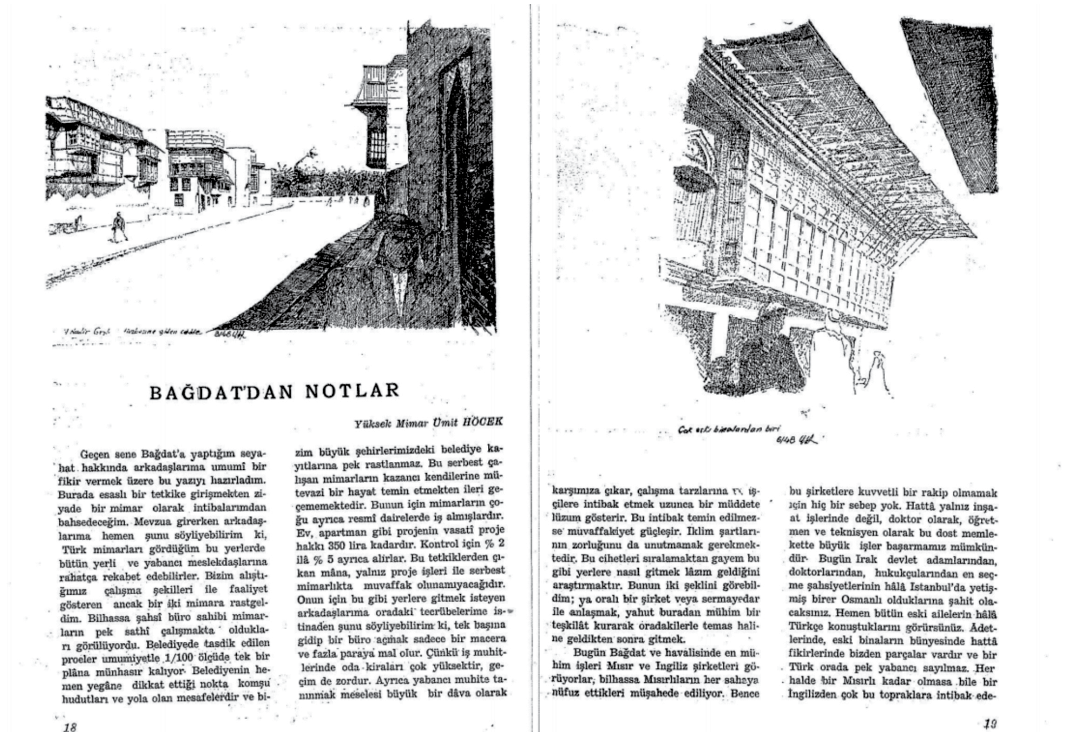
In the twentieth century, the mobility of architects and ideas played an important role in disseminating an architectural culture characterized by modernity and change. This study identifies the components shared by the fields of architecture as encounter, representation and dissemination. Architectural ideas disseminate through institutions, visual representations, verbal or textual representations, as well as encounters between these materials, and humans. An idea often needs to be represented before disseminating, and an encounter often triggers that idea to be represented in the first place. Traveling, with its ability to trigger the production of visual, verbal, and textual representations, appears to be a generative practice through which components of architecture culture can be understood.

In the initial decades after the establishment of the republic in Turkey, traveling abroad to study and/or to inspect the architectural production of western countries to experience such encounters was valued so profoundly that the government awarded successful architecture students with scholarships to study in western countries.[1] The architectural institutions and magazines played a major role in how architects chose their destinations to travel. Throughout the 1930s and 40s, architects in Turkey exchanged information and experience through a small number of publications, architecture schools and architectural actors. Traveling and productions related to it—especially architects' articles in architectural magazines- provided a ground for disseminating knowledge and experiences architects gained abroad, particularly in the west. The published articles show how encounters and "translations" through them, was mobilized by traveling academics and architects.

Either hosted by the government or autonomously produced by architects, the main platform where travel material met an architectural audience was the architectural magazines available in Turkey. In fact, since their foundation in post-republic, architectural magazines in Turkey have become more institutional and professional while still having an effect in a digitized world (Akay 2018). There were few architecture magazines available in Turkey in the 1930s, and they were valuable sources through which architectural ideas were disseminated. *Arkitekt* (1931-1980) (initially named *Mimar*) was established by Zeki Sayar, Abidin

Figure 1: The cover of CHP (Republican People's Party) Architecture Trip exhibition catalogue, displaying a drawing of The Double Minaret Madrasa—an example of Seljuk architecture, 1944. Source: SALT Archive, https://archives.saltresearch.org/handle/123456789/69172

Mortaş, and Aptullah Ziya Kozanoğlu, and was the single architectural design and culture magazine of the early Republic until 1941. It was followed by a few others, such as *Yapı* (1941-1943), *Mimarlık* (1944-1953) published by Turkish Architects Association (TAA)[2], *Eser* (1947-1948)—an art, architecture and culture magazine, *Mimarlık ve Sanat* (1961-1963), *Mimarlık* (1963-present) published by the Chamber of Architects in Turkey (TMMOB) and Akademi (1964-1975) published by the oldest architecture school—Mimar Sinan Fine Arts Faculty of Architecture—in Turkey (Tuluk 2009). Many of the early-period magazines had published less than ten issues; therefore, out of the given examples, *Arkitekt*, *Mimarlık* published by TAA, and *Mimarlık* published by TMMOB were reviewed for this research. The majority of architects' travels were funded by the government or academic institutions, and articles were commissioned by these magazines. The commissioned trips and articles had recurring research themes such as exhibitions and architectural typologies (for instance, stadiums or social housing). As a matter of fact, these topics were global in architects' main interest in the pre- and post-war period.



BAĞDAT'DAN NOTLAR

Yüksek Mimar Ümit HÖCEK

Geçen sene Bağdat'a yaptığım seyahat hakkında arkadaşlarıma umumî bir fikir vermek üzere bu yazıyı hazırladım. Burada esaslı bir tetkike girişmekten ziyade bir mimar olarak intibalarımdan bahsedeceğim. Mevzua girerken arkadaşlarıma hemen şunu söyliyebilirim ki, Türk mimarları gördüğüm bu yerlerde bütün yerli ve yabancı meslekdaşlarına rahatça rekabet edebilirler. Bizim alıştığımız çalışma şekilleri ile faaliyet gösteren ancak bir iki mimara rastgeldim. Bilhassa şahsî büro sahibi mimarların pek sathî çalışmakta oldukları görülüyordu. Belediyede tasdik edilen proeler umumiyetle 1/100 ölçüde tek bir plâna münhasır kalıyor. Belediyenin hemen yegâne dikkat ettiği nokta komşu hudutları ve yola olan mesafelerdir ve bizim büyük şehirlerimizdeki belediye kayıtlarına pek rastlanmaz. Bu serbest çalışan mimarların kazancı kendilerine mütevazi bir hayat temin etmekten ileri geçememektedir. Bunun için mimarların çoğu ayrıca resmî dairelerde iş almışlardır. Ev, apartman gibi projenin vasatî proje hakkı 350 lira kadardır. Kontrol için % 2 ilâ % 5 ayrıca alirlar. Bu tetkiklerden çıkan mâna, yalnız proje işleri ile serbest mimarlıkta muvaffak olunamıyacağıdır. Onun için bu gibi yerlere gitmek isteyen arkadaşlarıma oradaki tecrübelerime istinaden şunu söyliyebilirim ki, tek başına gidip bir büro açmak sadece bir macera ve fazla paraya mal olur. Çünkü iş muhitlerinde oda kiraları çok yüksektir, geçim de zordur. Ayrıca yabancı muhite tanınmak meselesi büyük bir dâva olarak

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Çok eski binalardan biri

karşımıza çıkar, çalışma tarzlarına ve işçilere intibak etmek uzunca bir müddete lüzum gösterir. Bu intibak temin edilmezse muvaffakiyet güçleşir. Iklim şartlarının zorluğunu da unutmamak gerekmektedir. Bu cihetleri sıralamaktan gayem bu gibi yerlere nasıl gitmek lâzım geldiğini araştırmaktır. Bunun iki şeklini görebildim; ya oralı bir şirket veya sermayedar ile anlaşmak, yahut buradan mühim bir teşkilât kurarak oradakilerle temas haline geldikten sonra gitmek.

Bugün Bağdat ve havalisinde en mühim işleri Mısır ve Ingiliz şirketleri görüyorlar, bilhassa Mısırlıların her sahaya nüfuz ettikleri müşahede ediliyor. Bence bu şirketlere kuvvetli bir rakip olmamak için hiç bir sebep yok. Hattâ yalnız inşaat işlerinde değil, doktor olarak, öğretmen ve teknisyen olarak bu dost memlekette büyük işler başarmamız mümkündür. Bugün Irak devlet adamlarından, doktorlarından, hukukçularından en seçme şahsiyetlerinin hâlâ Istanbul'da yetişmiş birer Osmanlı olduklarına şahit olacaksınız. Hemen bütün eski ailelerin hâlâ Türkçe konuştuklarını görürsünüz. Âdetlerinde, eski binaların bünyesinde hattâ fikirlerinde bizden parçalar vardır ve bir Türk orada pek yabancı sayılmaz. Her halde bir Mısırlı kadar olmasa bile bir İngilizden çok bu topraklara intibak ede-

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Figure 2: Ümit Höcek's article entitled "Notes from Baghdad". Source: *Mimarlık* 3-4 1949.

2. CASE STUDIES

Although it stands out as a singular example, the Republican People's Party (CHP)[3] had organized an architectural research trip to Erzurum—a city in eastern Turkey—in 1944. The trip displays how the government evaluated traveling and research as an ideological tool and a way of "returning to oneself," as expressed in the trip's announcement published in *Mimarlık* magazine's fourth issue in 1944. The event was an extended version of 'country trips' that had already been taking place since 1938 but were mainly addressed to artists. Through these trips, artists were expected to see the beauty of Anatolia and produce artworks based on their experiences. Although the scope was extended to include architects as well, the 1944 trip would be the first and last one. An exhibition was organized after, displaying attending architects Ali Saim Ülgen, Harika and Kemali Söylemezoğlu, Dündar Beyce, and archaeologist Mahmut Alok's survey drawings (Figure 1). According to the exhibition catalog, Erzurum was chosen as a destination because it consisted of the oldest examples of Anatolian Turkic architecture, and the main objective of the trip was to produce survey drawings to be exhibited.[4]

While on the one hand, there were many trips made to Anatolia to learn one's 'own roots,' local geography and history through first-hand experience, there were many more to countries abroad. Especially Germany was a popular destination throughout the 1930s and until the 1960s (Kayım 2010). The architecture culture of the first few decades of the Republic (first and second national architecture movements in Turkey) was in a close relationship with German-speaking countries as many architects migrated or traveled back and forth between Germany and Turkey (Akcan 2012). In addition to the existing architecture faculty at Mimar Sinan University, the establishment of architecture faculties at Istanbul Technical University in 1940 and at Middle East Technical University in 1956 changed the course of the "translations" that were taking place through these travels—at least, the USA, Italy and Scandinavian countries became frequent destinations for young architects as well.

Exhibitions were a particularly recurring motivation for architects to travel abroad because they were an elaborate way of seeing new implementations and methods in construction technologies, architectural style and urban planning in a post-industrial world. For instance, Şevki Balmumcu was delegated to study exhibition design in Europe and write an article in 1934. In his article, Balmumcu (1934) expresses particular fondness for the Fascist Exhibition in Rome and gives detailed descriptions of the structures. Given that the previous year Balmumcu had won the competition for the design of Ankara Exhibition Hall with an iconic modernist design, his interest in the ultra-modern qualities of the structures in Rome seems to be embedded in the fascination with modernist details. Unfortunately, the same details had been adopted as the architectural language of interwar totalitarianism.

Similar to exhibitions, international congresses or academic traveling was another major event to commission architects to travel abroad. In such travels, the city and urbanity were usually in focus. Urbanist Burhan Arif Ongun (Ongun 1935, 306) thoroughly reports each bullet point from the 13th Architecture Congress in Rome: he starts with a brief history of the conference, its main objectives, and outcomes and continues with discussed topics such as new construction materials and the importance of the urbanist's role in organizing a modern city, without using any photographs.

Modernity and its physical and social attributions are usually the subthemes of the published articles in Turkish architectural magazines of the period. In many of these articles, architects often try to convey their experiences in a technical and "objective" manner; they usually report back what they see with all of its details but not necessarily analyze and prioritize specific concepts. The audience rarely gets a glimpse of anything outside the commissioned topic or traveling experience.

However, architect Orhan Alsaç and engineer Salahattin Onat's article series entitled "Travel Notes: Urbanism in France and England," published in the issues 2, 3, 4, and 5 of *Mimarlık* are different. Immediately, one can see the change in focus of the subject from nationalist expressionism to the housing crisis and rebuilding of cities. Alsaç, and Onat were invited by the France government to visit the 'Urbanism and Dwelling' exhibition in Grand Palais, the 'Documentation' congress in Paris, as well as the 'International Union of Cities' congress in London and their trip was funded by Turkey Ministry of Foreign Affairs in 1947[5]. Their trip takes around one and a half months, from July 16th, 1947, to September 1st, 1947, and the duo gives details about the difficulties in transportation as well as vehicles used. The accompany of the mayors of Aydın, Konya and Reyhanlı[6] shows how the government of Turkey took the matter as a formal inspection. Apart from descriptions of the contents of the exhibition, which focus on technology, modern materials in dwelling design, standardization, the garden city (Welwyn specifically), and accessibility to post-war social housing, Alsaç, and Onat (1948) emphasize the importance of rapid holistic planning and the role of law makers in implementing planning decisions, after seeing the aspiration in rebuilding postwar cities in Europe. At several points in the article, they offer their own comments on the issues they encountered, such as prefabrication, low-cost housing, and whether they would be feasible in Turkey. They even comment on the benefits of traveling, when it is done for pleasure, experience and increasing knowledge, and how their travels have made them well aware of the serenity of living in Turkey (Onat and Alsaç 1948).

Exhibitions and fairs were a common motivation for traveling abroad in Turkey. In his essay on Milano Fair published in 1950 in Mimarlık, Şevki Vanlı (1950, 32) draws a clear relationship between fairs and cities: "fairs bear the trails

Çok kıymetli Üyelerimiz,

Geçici bir resmî görev dolayısiyle şimdilik sizlerden uzaktayım. Buralar esasen aşağı yukarı hepinizin yabancısı olmadığınız yerler. Birçoklarınızın gördüğü, geri kalanların da mecmualardan mimarî havasını bildiği memleketler. Ama ne de olsa insanın bildiğini tekrar hatırlaması kötü bir şey değil. Bu sebeple buralardan sizlere ufak bazı hâtıralar göndermeyi uygun gördüm. Konular üzerine ancak kısa ve hızlı bir bakış mahiyetinde olmaktan ileri gidemiyecek ve bu sebeple bir seyahatname tarzında hazırlanması uygun olacak bu yazıların şimdilik üç tanesini hazırladım. Zürich konulu ilkini aşağıhda sunuyorum. Hoşgörürlüğünüzü rica eder, hepinize selâm ve hürmetler gönderirim

İ. Hulûsi GÜNGÖR

Zürich şehrinin gölden genel görünüşü.

Figure 3: Hulusi Güngör's sketch of a lakeview from Zurich. Source: *Mimarlık* 5 1965.

of years, they are in a way the catalog of a time period." He quickly dismisses the pavilions from the nineteenth century, stating that they are neither interesting nor of value, but finds modernist and industrial examples such as the Italian Radio and main building designed by Angelo Bianchetti "simple and pretty." All in all, it is clear that Vanlı has opinions and he is eager to present them as part of his article. In 1960, Baran Çağa (1960) also reports from Milan—this time the article is about the Triennale which was mainly focused on the theme of "dwelling and school". Çağa informed the Turkish-speaking architectural crowd about the British standards of school furniture as well as photographs of the furniture to create a better learning environment. Similarly, Hulusi Güngör reports on the physical qualities of the 1965 Hannover Fair itself, and its buildings.

Very different from the previous examples' distanced and technical writing manner, Ümit Höcek's (1949) "Notes from Baghdad," published in 1949, adopts a much looser tone that correlates with the idleness of traveling. Höcek gave Turkish architects advice on starting an architecture business in Baghdad, explained about construction materials used there, and his interest in traditional architects. What is fascinating about his article, though, is his intricate drawings of buildings and streets (Figure 2). This example stands out as the sole representative of a journey to an Eastern country, yet his subtle indication of the East being underdeveloped is perceivable (Zelef 2014, 95).

İ. Hulusi Güngör's (1965a) "Travel Notes: Zurich," which is part of a three-piece travel series, is another example that self-identified as a travel production. The author starts his article with a sketch of the view of the city from the lake (Figure 3) and includes a short introduction that is pertinent to the architecture culture and traveling relationship: "[…] Hereabouts is more or less places that we all know. Most of us have seen these countries, and the rest knows the architectural aura from magazines. But it is not bad for one to recall what one already knows" (Güngör 1965a, 18). He then continues with the descriptions of buildings he saw: Le Corbusier's Technische Hochschule, Professor Salvisberg's[7] office building, Professor Hoffman's Aluminum Company Building, Haefeli, Steiger & Mozer's Zur Palme, all modernist examples of architecture. He is clearly impressed by examples of modernism: in his article about Ulm, he seems to be fascinated with the new architecture education in the Hochschule für Gestaltung—paying particular emphasis on the renewed version of the basic design course and Bauhaus education, that Ulm School of Design was renowned for (Güngör 1965c).

The school would be closed three years after Güngör's visit, however his interest in the subject seems to have continued since he published a book called Basic Design for Visual Arts and Architecture in 2000.

The architect's travel notes about Vienna are a little scattered: the text begins with a nationalistic and patriarchal remark, "The pretty Vienna which our ancestors lusted after but could not wed"[8] (Güngör 1965b, 13); he continues with nostalgic notes on how 'old Vienna' was more magnificent than the 'new Vienna' which was filled with "cheap social housing units" after WWI. He blames the sterility of architecture in Vienna on the Austrian education system yet seems impressed with the country's implementation of a five-year practice period and mandatory exam to become a qualified architect; he provides descriptions of a few buildings yet names only Prof. Karl Schwanser as one of the architects. In almost all of the given examples, there is a constant urge for comparison in the writers' tone. Modern Turkey's contentious history of dealing with modernization -through radical top-down implementations in the first decades after the establishment of the Republic (1923) and later through rapid adoption of liberal economy—had permeated every area of life from bureaucracy to how citizens viewed their own identities. Moreover, the implementations were always in comparison with the West. These dichotomic descriptions of Turkey vis-à-vis foreign countries, built environment, and modernization give an idea about the dominance of modernity, as well as efforts in trying to re-invent representations of Turkey through travel accounts published between the 1930s and 1960s in Turkish architectural periodicals.

CONCLUSION

In prewar Turkey, during a period when modernization was attempted to be systematized, architects' productions during and after their travels, such as drawings, photographs, articles, class notes, and memoirs, helped to disseminate the architecture culture they 'brought back' with each experience. In a time period when writing was not the major asset and fundamental tool for an architect to disseminate their ideas, architectural periodicals made it possible to make this habit more prevalent and contributed to the culture of architectural writing.

Despite architects started practicing combining text and images, the articles published between 1931 and 1965 almost never used theory, they were often technical reports that included the details of the exhibitions, events, or buildings visited. However, there were usually comparisons between the country visited and Turkey. There is hardly ever information on the journey itself and the personal experiences of the architects, with few exceptions. Ways of representation also varied. Apart from Güngör's and Höcek's sketches, there were no drawings produced by architects. Interestingly these two authors also adopted a looser structure and included varied examples in their writing. The main representation medium was photographs; not only did their numbers increase over the years but architects also started including their own photographs after the 1950s. The latter is probably parallel to the accessibility of cameras.

Most importantly, the articles, travel notes, and publications in architectural magazines were a part of the architects' journeys as they moved within the profession: with each experience or inspection, architects learned about and formed their views of western cities, building typologies, ways of construction, as well as of their own countries. In that sense, architectural magazines were agents through which architectural culture was encountered and disseminated.

ACKNOWLEDGEMENTS

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ENDNOTES

1 The 1416 legislation of sending students to foreign countries, which came into force in 1929, demonstrates the first attempt in regulating traveling abroad for education and returning to Turkey to take on jobs as civil servants.
2 The first architects' association founded in modern Turkey in 1927. The association changed names over the course of time and today is called Mimarlar Derneği 1927 (Architects Association 1927).
3 CHP, the first political party of Turkey founded by Mustafa Kemal Atatürk, was the ruling party until 1950, and currently is the main opposition party in Turkey.
4 CHP government's emphasis on eastern Anatolia and pre-Ottoman Turkic settlements can be read as part of their concern to realign Turkey's past closer to pre-Islamic Turkic groups, and the growing interest in the pre-Ottoman past in history writing.
5 Given the difficulties in transportation, it is not a surprise that most of the architects were funded by an institution. Especially architecture students almost entirely depended on institutional funding if they wished to study abroad.
6 Cities located in the western, central and southeastern parts of Turkey, respectively.
7 Güngör mentions Professor Salvisberg's building among the most important buildings in Zurich. Emin Onat, who studied in Zurich, was a student of Salvisberg, and Metin Hepgüler worked with Salvisberg for a while, that is most probably how Güngör got interested in his work.
8 "Ecdadımızın göz koyup bir türlü nikahlayamadığı güzel Viyana" (Gungor 1965b, 13). Translated by Ceren Hamiloğlu.

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PARAMETRIC ALGORITHMS TO EXTRACT ROOT TRAITS FOR BIOLOGY AND BIOMIMICRY

Thibaut Houette[1], Elena Stachew[1]
Claudia Naményi[1],
Jason W. Miesbauer[2], & Petra Gruber[1,3]

The study of tree root systems has been introduced in a biomimicry framework for engineering design because of current problems with soil instability due to urbanization, climate change, and the subsequent increase of extreme weather events affecting the built environment. Current civil and coastal infrastructures are static, limited by insertion techniques, monofunctional, and unable to adapt. In nature, root systems grow through various media as a dynamic, adaptive, multifunctional, and self-healing structure. Root systems' morphology can inform the design of multifunctional infrastructure.

The biomimicry transfer from root biology to technology is currently limited to generic morphological principles and strategies. Manual methods to measure and analyze root system architecture are labor-intensive and time-consuming, resulting in a lack of available data and difficulties when comparing results between studies. Recently, digital imaging techniques, including photogrammetry, are deployed to generate virtual 3D models of root systems.

Characterization of root system traits allows the abstraction and biomimicry transfer of specific root traits of interest (e.g., topology, surface-area-to-volume ratio, departure angle, tapering, porosity, curvature) to inform the design of architectural applications. Such characterization requires a standard method to measure root traits automatically, and reliably.

A parametric algorithm was developed with computational architectural tools, Rhinoceros and the plugin Grasshopper, to extract biological root traits of interest from virtual 3D models and find emerging patterns for biomimicry transfer. A skeletonization algorithm, developed in Grasshopper, extracts root system topology and associated architecture traits from 3D models of root systems. A manual step is needed to remove irregularities. Due to the large amount of root data exported, a brief statistical analysis follows to find emerging root morphology patterns. Finally, abstracted patterns will be applied to technical parametric designs toward multifunctional civil and coastal infrastructure.

This semi-automated process, extracting system architecture of biological tree roots from 3D models, not only serves the transfer of biological knowledge to technical applications, but allows for improved studies of root morphological traits in a systematic way, and potentially further investigations such as the adaptation of different species to various environments. Furthermore, it also showcases the potential of architectural tools for research on the morphologies of biological systems.

Keywords: Bioinspired design, parametric design, root research, civil engineering, coastal engineering.

1. INTRODUCTION

1.1. TOWARDS BIOMIMETIC CIVIL INFRASTRUCTURE INSPIRED BY ROOT SYSTEM ARCHITECTURE

With the continuous expansion of urban environments, ecosystem services once provided by natural environments are lost (Duraiappah et al. 2005; Grimm et al. 2008; McHale et al. 2015; McPhearson et al. 2016). The built environment should aim to provide the ecosystem services of the natural environment it replaces. For instance, cities produce impervious surfaces, and their stability relies on soil compaction. Soil compaction and impermeability compromise water storage and infiltration and so contribute to increased risks of flooding and erosion (Brown, Keath, and Wong 2009; Yang and Zhang 2011; Burns et al. 2012; Alaoui et al. 2018). Civil infrastructure is currently limited to monofunctional systems with simple morphologies, surface textures, and material choices, by the lack of accessibility, maintenance, and adaptation (Das 2007; Frost et al. 2017; Stachew, Houette, and Gruber 2021).

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As a potential response to these limits, natural systems can serve as inspiration for the design of sustainable civil infrastructure. A variety of terms have been employed to describe the process of transferring biological knowledge to the fields of engineering, design, and architecture (i.e., bioinspiration, biomimetics, biomimicry, bionics, nature-based design) (ISO/TC 266 2015; Fayemi et al. 2017). In this paper, the term biomimicry serves to describe the method by which natural strategies and principles are analyzed, abstracted and applied to the sustainable designs of biomimetic foundation and coastal infrastructure. Well-known examples of biomimicry include the invention of VELCRO® (De Mestral 1961) from the morphology of burdock seeds and, for architecture, the passive ventilation of the Eastgate Center in Zimbabwe designed by Mick Pearce inspired by termite mounds (Turner and Soar 2008). Since biological and engineering contexts are very different in terms of scale, materials, manufacturing process, durability, and environment, the abstraction of principles is required for biomimicry transfer. Based on the understanding of the biological strategy, this abstraction can be performed at various levels, from form/organism to process/function to the ecosystem (Benyus 1997; Pawlyn 2011; Pedersen Zari 2012). In the research about tree root systems, the goal is to transfer morphological properties and processes towards the design of civil infrastructure to partially restore natural ecosystem services and functions.

In contrast to traditional civil infrastructure, root systems are multifunctional. They support the tree mechanically, explore soil media, uptake, store, and transport nutrients, prevent erosion, and create habitats. Root strategies of particular interest for the design of biomimetic civil infrastructure include self-penetrating tips, branched system increasing bearing area, enhanced friction through surface texture, integration of multifunctionality into individual components, self-healing processes, programmable decay, and dynamic adaptation to internal and external stimuli, especially in the wake of increasing urbanization and storm events. A comprehensive overview of root strategies of interest and analogies for civil infrastructure is presented in (Stachew, Houette, and Gruber 2021).

1.2. ROOT ANALYSIS TECHNIQUES

A deep understanding of root system principles and strategies is required for the abstraction and application of the design of civil infrastructure. Morphological tree root knowledge is limited due to the difficulty to visualize underground morphology, analyze complex architecture, and the high variation between species and environment (Waisel, Eshel, and Kafkafi 2002; Gyssels and Poesen 2003; Tamasi et al. 2005; Nicoll 2006; Danjon and Reubens 2008). Root traits have been analyzed through manual measurements in the field upon excavation entered in a program such as ArchiRoot (Dupuy 2007; www.archiroot.org.uk); or semi-automated processes manually entering root system data measured with an expensive field imaging tool (e.g. 3D digitizer) into a root analyzing software (e.g., AMAPmod (Godin, Caragilo, and Costes 1997)) using Multi-Tree Graph data as input (Danjon et al. 1999; Danjon and Reubens 2008) or CAD software such as Solidworks (Liang et al. 2017). These processes are tedious, time-consuming, and prone to user error, so it only allows researchers to gather a limited amount of root traits across an entire root system, which serves to answer a specific research question (Danjon and Reubens 2008). No standard procedure (e.g., similar to ASTM standards in material testing) has been developed to extract traits from root systems in a systematic way. The comparison of root system architectures across sites, species, and environments is therefore difficult since traits can be missing and extracting procedures are not standardized.

In response to these limitations, there is a push to apply advanced imaging systems for the analysis of 3D models. Various imaging devices are used to generate models of root systems including Computed Tomography (CT)-scanners, terrestrial laser scanners, and ground-penetrating radars. The appropriate 3D imaging technique for a specific research project should be selected based on trade-offs between the following properties: accuracy, cost, ability to be performed in the field, accessibility, limitation from occlusion, and object size (Danjon and Reubens 2008). The complex morphology of root systems and occlusion caused by the roots, along with the soil, in visual imaging limit the application of those imaging techniques. Laser scanning and radar technologies can be used in the field but cannot detect occluded parts (Bucksch 2014) and require expensive equipment. X-ray, Magnetic Resonance Imaging, confocal microscopy, and Computed Tomography have the advantage of imaging elements through material such as soil or plant anatomy, but the specimen size is limited to small volumes imaged in a laboratory setting with expensive equipment (Fiorani et al. 2012; Kumi et al. 2015; van Dusschoten et al. 2016; Bucksch et al. 2017). In comparison, photogrammetry, also known as SFM-MVS (Structure from Motion and Multiple-View Stereophotogrammetry) has already been used to model coarse roots in the field at a low cost while preserving root system architecture (Morgenroth and Gomez 2014; Koeser et al. 2016; Miesbauer and Koeser 2019). While this technique does not require expensive equipment, it is still challenging to collect accurate morphological data from complex dense structures due to occluded parts. On the other hand, its accessibility facilitates standardized deployment across the globe to gather 3D models of diverse species adapted to various environments, which is the reasoning for choosing this technique for this project.

1.3. PARAMETRIC ALGORITHM FOR ROOT TRAIT EXTRACTION FROM 3D MODELS

This paper focuses on algorithmic abstraction and not on the photogrammetry process to obtain the 3D models nor the design of biomimetic infrastructure from the data extracted, which are topics of future publications. Similar to the imaging techniques, the analysis of root traits is currently performed manually or in a semi-automated manner which results in a time-consuming repetitive process, limiting the amount of collected data. In addition, most techniques cannot automatically gather both system topology and morphological traits, since they refer to different types of data and representations. The topology relates to the branching hierarchy of the root system. Morphological traits are characteristics of its form. In architecture and design, parametric plug-ins are often added to architectural software to perform actions more efficiently to a wide dataset (e.g., Grasshopper in Rhinoceros, Dynamo in Autodesk Revit). Such tools allow for repetitive analytic processes. The possibility to code in these parametric plug-ins allows users to go beyond the initial scope of the software and produce algorithms for various purposes.

Most morphological traits (i.e., length, diameter/radius, cross-section, orientation, departure angle, curvature) are based on root medial axes (i.e., centerlines), so the skeleton (i.e., collection of centerlines) of the root system needs to be generated (Danjon and Reubens 2008). 3D skeletonization processes have been of great interest to plant sciences, including the study of tree crowns, and root systems (Côté et al. 2009; Bucksch 2014). Main 3D skeletonization methods include: 3D Euclidean distance map (Nyström and Smedby 2001; Maddah, Hamid, and Afzali-Kusha 2003); Voronoi diagram (Näf et al. 1997); 3D thinning (Ma 1994; Ma and Sonka 1996; Palagyi 2008; She et al. 2009; Lohou 2010); and Reeb graph (Reeb 1946; Basiotti et al. 2008; Bucksch et al. 2010). The Reeb graph is of great interest for its robustness and potential for plant sciences most often utilized in plant sciences (Bucksch 2014). This concept generates the centerline of an object by: cutting slices of that object following a given path (e.g., height of object); and connecting the centroids (i.e., geometric center point of a 2D shape) of each slice along that path. For simple objects (e.g., a cylinder), the slicing path can be defined following the linearity of the object. However, for complex 3D objects, the slicing path is not aligned with the centerline. For instance, when root branches or curves out, its centerline axis is at a different angle or blends in a curvature. As a result, slices following a single linear path over the entire geometry can no longer be perpendicular to the axes of all root components. One solution to this problem is to define slicing paths locally (Biasotti et al. 2008; Bucksch et al. 2010). However, these algorithms are developed in Python (developed by Guido van Rossum) or other coding languages without instantaneous feedback on a visual 3D representation, which makes them difficult to comprehend for non-experts and subsequently to adapt to specific case studies. Since the goal is to apply the abstracted knowledge to technical applications, the algorithm needs to be as comprehensive as possible for a wide range of users (i.e., both biologists and designers). Visual programming allows users to automatically visualize the outcome of each coding component in the 3D interface, which facilitates the comprehension and modification of algorithms by a wider audience while reducing user error through interactive visual assessment. The expertise on our team in visual programming was therefore leveraged to develop a 3D skeletonization algorithm in the visual programming language and interface, Grasshopper (by David Rutten at Robert McNeel & Associates) in the 3D modeling software, Rhinoceros (Robert McNeel & Associates, Seattle, WA, USA). Finally, the data extracted will be applied to technical systems through parametric design in Rhinoceros/Grasshopper. The development of the algorithms in the same software reduces the number of problems due to converting and transferring files between software and file types. In conclusion, a succession of parametric algorithms based on the Reeb graph was developed in Rhinoceros/Grasshopper to extract system topology and morphological traits of the root system architecture of 3D models generated from real root systems in the field through photogrammetry.

2. MATERIALS AND METHODS

2.1. DESCRIPTION OF MATERIALS

The root system model is from a 10-year-old Patmore green ash (Fraxinus pennsylvanica 'Patmore') tree which was processed as described in Koeser et al. (2016). The root system was excavated using a 244-cm (96-in.) hydraulic tree spade. Once harvested, the soil inside the root ball was removed using an air excavating tool (Airspade2000, Guardair Corporation, Chicopee, MA, USA), along with all roots less than 1-cm in diameter to reduce occlusion. The root system was then inverted and placed on a surface with paper-coded targets. A series of approximately 120 digital images was taken at distances of 1-2 meters all around the root system along three planes (i.e., slightly above, parallel to, and slightly below the root system), using a digital single-lens reflex camera (on a Nikon D7000 with an AF-S DX NIKKOR 12–24 mm f/4G lens, Nikon Corporation, Tokyo, Japan). A photogrammetry software (PhotoScan, Agisoft, LLC, St. Petersburg, Russia) was used to generate a 3D model of the root system from these images.

2.2. PARAMETRIC ALGORITHMS

The algorithm designed to extract morphological root traits is described in the following steps (Figure 1). First, traits pertaining to the overall root system morphology (i.e., volume, surface area, overall dimensions, porosity, 2D projections) are directly extracted from the 3D model and exported to a .csv file.

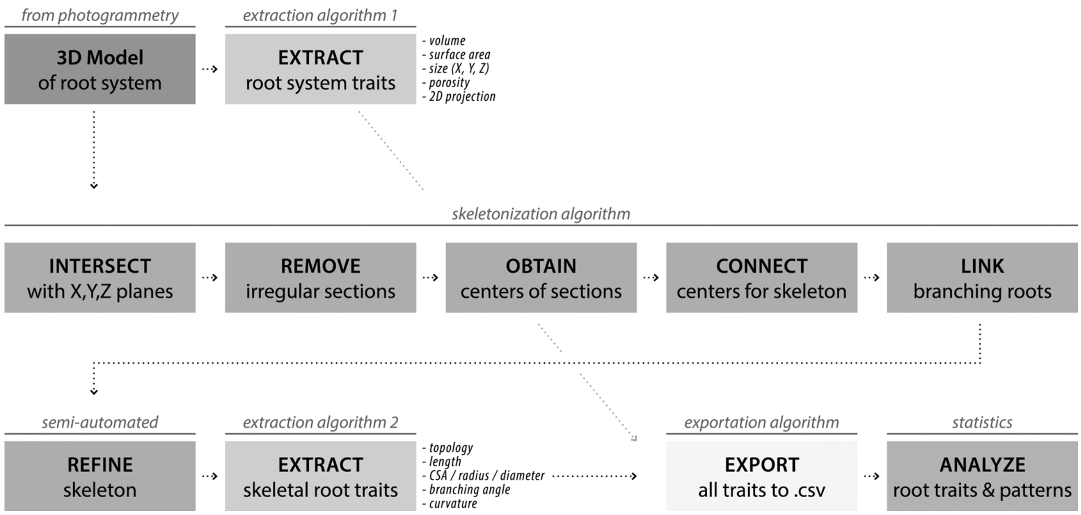

Figure 1: Workflow of the root trait extraction process performed in Rhinoceros with the Grasshopper plugin. CSA refers to cross-sectional area. Source: Author 2022.

Second, root centerlines (i.e., axes) are generated to extract system topology and morphological traits (i.e., length, diameter/radius, cross-section, orientation, departure angle, curvature). In this regard, the 3D model is skeletonized starting with intersecting the model with a number (e.g., 100) of equally spaced X, Y, Z planes to obtain random sections of the root systems along these planes (Figure 2-A). Depending on the roots' orientation in the 3D environment, those planes are not perpendicular to the root axes, resulting in incorrect centroids in cases where the deviation angle is too large. Therefore, the eccentricity of each intersection is computed and those with a major axis twice as long as the minor axis are automatically removed from the next steps of the algorithm (Figure 2-B). In this way, only the intersections in a plane closely aligned to the cross-section of the root are kept. In addition, some planes intersect a root at a branching location, resulting in sections with concave parts. To avoid highly incorrect centroid emergence, intersections containing concave parts are also automatically excluded. The centroids of the remaining sections (Figure 2-C) are connected through a looping algorithm generated with the plugin Octopus (by Robert Vierlinger), in Grasshopper. Starting from the trunk, the process connects each centroid (e.g., Point A) to its closest neighboring centroid (e.g., Point B). Once a centroid (i.e., Point B) is used, it becomes the next starting centroid (i.e., Point A) and is removed from the list of available neighbors (i.e., Points B). The loop stops when all points are connected. To avoid the reconnection of root tips with each other, line elements (i.e., connections between centroids) that are longer than a specified value, relating to the model's scale, are removed. The resulting collection of lines is then smoothed into curves (Figure 2-D).

Since the centerline curve stops at the last centroid identified (root tip in Figure 2-D), these curves' ends are elongated at their tip until they intersect the model's 3D surface. For the centerlines' base, the algorithm then connects branches together, which consists of several steps that extend each centerline at its base to find the intersection with their neighboring centerline (demonstrated in Figure 3).

The set of curves generated from this process represents the total 3D skeleton of the coarse root model. However, the process still results in inaccuracies in some centroids and resulting curves. Therefore, a manual step is required to adjust or delete some curves. In the manual refining process, the

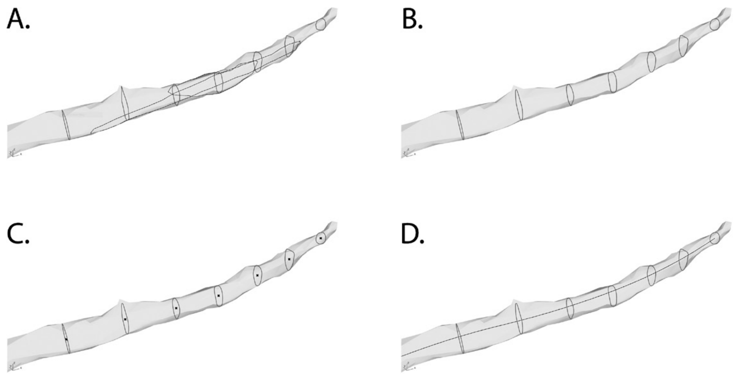

Figure 2: Screenshots of a root tip to show the main steps of the skeletonization algorithm in Rhinoceros with the Grasshopper plugin. First, the 3D model is intersected with 100 X, Y, and Z planes. Since the planes are not perpendicular to the root axes, the concavity and eccentricity of all sections is computed to find those with high eccentricity and concave elements (A), which are then automatically removed (B). Then, the centroids of each section are gathered (C) and connected through a looping algorithm to generate the centerline of the root (D). Source: Author 2022.

3D model is displayed together with the skeleton and serves as a reference for adjustments (Figure 4-B and C). These adjustments consist of deleting curves that still connect root tips (i.e., those with a length under the threshold given in the automated step), recentering curves along the centerline axis of the roots through manipulation of control points, and rectifying incorrect branching connections (i.e., moving the centerlines' intersection where they should be based on an understanding of biological branching connections). The 3D model and its current skeleton are saved as a separate file after each step to keep track of the process and manual edits (Figure 4). Despite the need to generate the entire skeleton of the root system to extract all morphological traits in relation to the system topology, this is not possible for the stump (i.e., region at the center of the root system immediately below the trunk). In its center, roots merge with their neighbors through secondary growth, so that the axes of individual roots are no longer identifiable. For a mature root system, roots' centerlines cannot be generated from a 3D model alone (Figure 4-D). To avoid the generation of an incorrect skeleton and mistakes in the resulting topology, the root centerlines stop at this stump region, when individual root axes can no longer be determined.

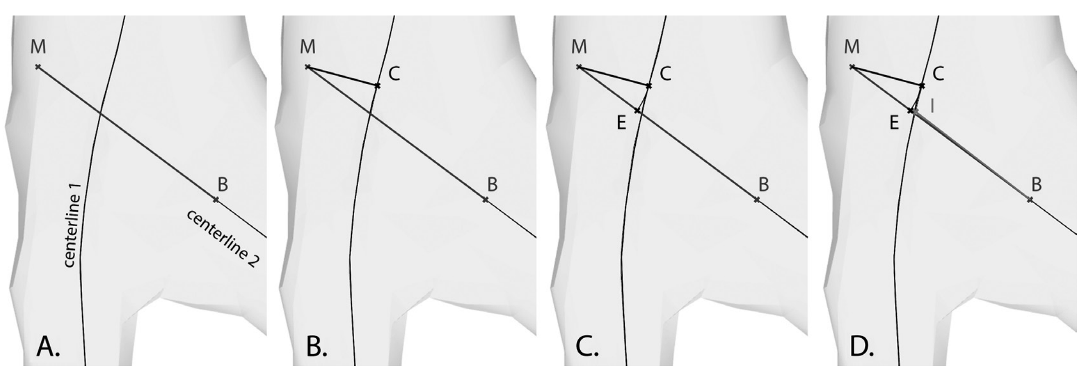

Figure 3: Diagram showing how the branches are connected to each other. Centerline 2, which needs to be connected to centerline 1, is extended at its base (Point B) until it intersects with the 3D surface of the mesh in point M (A). While this extension seems to intersect centerline 1 in a 2D view, both curves do not intersect in 3D. Therefore, the closest point to this intersection on the neighboring root centerline (Point C) is identified with a perpendicular projection (B). The distance from M to C is measured and removed from the previous curve extension to get Point E (C). Finally, the closest point to Point E on centerline 1 (Point I) is defined as the axes' intersection and is connected to the initial base of centerline 2 (Point B in D). Source: Author 2022.

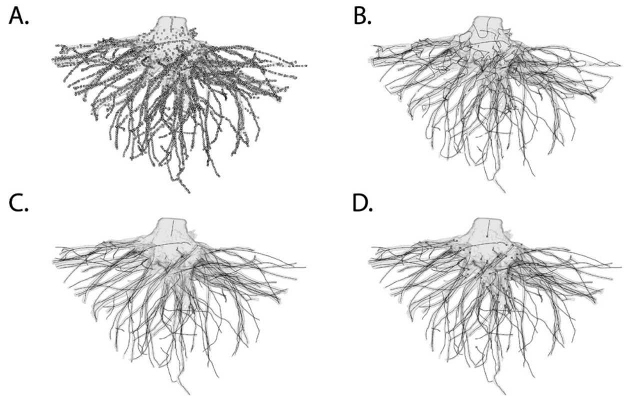

Figure 4: Screenshots of the 3D model of the root system throughout the skeletonization process: centroids generated (A), skeleton before manual revision (B), skeleton after manual revision (C), bases of roots which cannot be further connected in the stump area (D). Source: Author 2022.

After the skeletonization process, the skeleton, and more specifically each axis (i.e., centerline) serves as the basis to extract the second part of root traits (i.e., topology, length, diameter/radius, cross-section, orientation, departure angle, curvature). However, the root system's topology needs to be known to extract comparable morphological root trait data pertaining to specific roots within the system hierarchy. Four main types of topological ordering systems are used depending on the direction (i.e., centrifugal from base to root tips or centripetal from tips to base) and unit of ordering (i.e., segment or link): centrifugal link, centrifugal segment, centripetal link, centripetal segment (Berntson 1997). The centrifugal direction relates to the developmental growth of the roots, while centripetal corresponds to their functional aspect and physiology (Berntson 1997). The unit of ordering "segment" considers each root, from base to tip, as one topological order (e.g., the entire taproot being 0 in the centrifugal direction). This unit of ordering requires a clear understanding of which offspring is the continuation of the parent root, after a branching location. This can only be determined through judgment calls by researchers or growth analysis (Cannon 1949; Berntson 1997). When using "links" as the unit of ordering, the topological order changes at each branching location, resulting in a greater number of orders and subsequent higher resolution (Crawford and Young 1990). The centrifugal link system was selected for this algorithm for the following reasons. Links allow for comparison at branching locations. The centrifugal direction puts more emphasis on the structural roots and does not depend on finer roots. This topology is collected by identifying branching points, creating a hierarchy of topological orders, and assigning each root link to its corresponding order starting from the first parent root (Figure 5-B and C). The connectivity between root link centerlines is partly computed with the Sandbox Topology plugin (by tobesch)[1] in Grasshopper. Since the root system's center cannot be skeletonized accurately, the topological order of each root link emerging from the stump bulb was set to 0. To answer some biological questions, such as the relationship between the diameters of root links before and after branching, parent/offspring relationships are also required. Therefore, an additional part of the algorithm uses branching connections to assign a number to each root link based on its location within the root hierarchy. The name of each root link consists of the name of its parent root with an additional number, which makes each root link identifiable within the topological ordering system (Figure 5-D). At the end of the algorithm, root trait data is automatically exported to .csv files into a database from which statistical analysis is carried out to answer research questions.

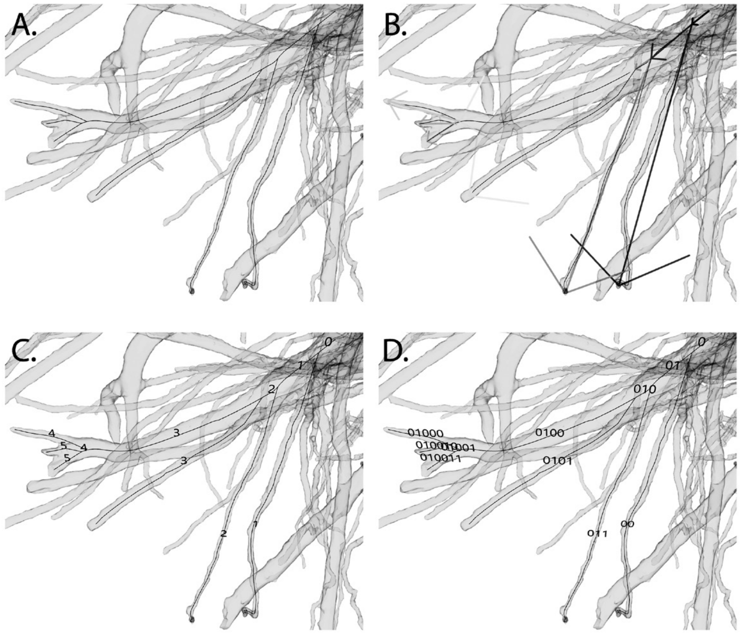

Figure 5: Screenshots of the topology and hierarchy of a selected root family (A). Topological orders shown through vectors (B) and numbering following the centrifugal link topological ordering system (C). To perform analyses of traits from parents to offspring, a name is given to each root link based on its location in the hierarchy (D). For example, root link "0" branches out into root link "00" and link "01" which then branches out into root links "010" and "011" (D). Source: Author 2022.

2.3. QUESTIONS TO BE ADDRESSED WITH EXTRACTED DATA

Once the algorithm exports root trait data to .csv files, it is statistically analyzed to answer specific research questions. With this type of morphological data, a wide range of research questions can be addressed for biomimicry transfer, as well as basic biological research, such as: How much tapering happens along a root link? How does the cross-section of a root vary along its length? How does the porosity of a root system differ between species and environments, such as along riverbanks?

Depending on the questions addressed, different types of statistical analysis are performed (Danjon and Reubens 2008). Examples include comparing specific traits between topological orders, quadrants (i.e., North, East, South, West), soil depths, distances from root center, or species and environment. To showcase the potential of this process, three main questions (one relating to biology, and two to biomimicry) are shown below. While root system trait abstraction for biomimicry transfer in the applications of architecture and engineering is the primary aim of this endeavor, the developed algorithm may also assist in answering questions related to furthering the understanding of the biology of root systems.

1. What is the ratio between the radius of a parent root and the sum of the radii of its offspring roots? This question comes from an interest in transport mechanisms and relates to the pipe model theory (Shinozaki et al. 1964; Lehnebach et al. 2018) and Murray's law (Murray 1926; McCulloh, Sperry, and Adler 2003).
2. What is the porosity of the root system and how does it vary per depth layer and distance from the trunk? This question provides insight regarding the formation of a soil-root plate, erosion prevention, and wave attenuation potential along coastlines for the design of

multifunctional civil and coastal infrastructure (Stachew, Houette, and Gruber 2021). Porosity is a significant geometrical parameter of aquatic vegetation ecosystems (e.g., seagrass beds, coral reefs, and mangrove forests) that influences bulk drag coefficient, subsequent flow attenuation, steady wake length development, and downstream velocity and turbulence responses (Nepf 1999; Lowe et al. 2007; Kazemi, Van de Riet, and Curet 2017).

3. What is the distribution of departure angles at branching locations? This question gives valuable insight for the bioinspired design of multifunctional hollow foundations, which can spread through larger volumes of soil, support structures, and transport resources through their centers.

2.4. EXTRACTION OF SPECIFIC ROOT TRAITS TO ADDRESS THE QUESTIONS SELECTED

To answer the first question about the ratio between the parent root's radius and the sum of the offspring's radii about the pipe model theory and Murray's law, the following data is exported from the algorithm to .csv files for each root link: topological order (e.g., 0, 1, 2), topological name (e.g., "0", "01", "010"), radius and cubed radius of the parent, radii and cubed radii of both offspring, and final ratios between parent and offspring radii or their cubed radii. The algorithm assesses the root system's hierarchy to compare the radius of each parent root to its two respective offspring roots. This ratio is calculated locally around each branching location and does not take the other root parts into consideration. Each virtual root link is cut by a perpendicular plane at its midpoint to collect the root's cross-section. The middle of each root link was chosen for the cutting plane since branching connections increase the thickness of each root link at its base and tip (Bucksch 2014). The average radius at this cross-section is then extracted and serves to compare each root. Twenty distinct root families (i.e., collection of roots descending from the same parent at topological order 0) with branching connections were selected throughout the entire root system to answer this question. Some cross sections are cutting through merged roots, due to local secondary growth or inaccuracy of the technique used to generate the virtual 3D model of the root system. These root links were removed from the analysis to only compare accurate data and extract reliable patterns.

To answer the second question, the root system's porosity was analyzed in 3 different ways: (1) volumetric porosity of the overall root system, (2) projection porosities in the X, Y, and Z directions, and (3) changes in sectional porosity across depth and distance from the trunk. Porosity is defined as the ratio of void space (i.e., soil particles and air between them) divided by the total space, which includes both void and solid space occupied by roots. This value is reported as a percentage. The porosity is calculated from the model's convex hull (i.e., the smallest convex shape that contains the entire 3D model) to follow its shape based on the excavation procedure (i.e., tree spade). The overall volumetric porosity of the root system is calculated by dividing the soil volume by the convex hull volume. The volume of soil equals the convex hull's volume minus the root system's volume. The projection porosities of the root system are also obtained from the surface area of the model projections in the X, Y, Z directions (i.e., 2D projection of 3D model on a plane following a specific direction) due to the researchers' interest in testing prototypes in these axial directions. For the sectional porosities throughout the soil depth, the 3D model is cut by horizontal planes every 10 cm. For the sectional porosities away from the trunk, the model is cut by concentric vertical cylinders of increasing radii, every 10 cm. In both cases, the surface area of these sections is then compared to the section of the convex hull at the same locations.

For the third question, the departure angles at each branching location are extracted from the same twenty root families used to answer the first question. The departure angle represents the branching angle between the two offspring centerlines of a parent root, measured 3 cm away from their branching location (or the entire offspring's length for links shorter than 3 cm long). This value was set because a longer distance would include root curvature while a smaller distance would integrate inaccuracies from root thickening at branching locations. The topological name of the parent root link serves as a reference for the location of each departure angle in the hierarchy.

3. RESULTS

3.1. ANALYSIS OF TRAITS TO ADDRESS THE BIOLOGICAL QUESTION

The distribution of ratios between the radius of each parent root link to the sum of the radii of its offspring (n = 21) follows a normal distribution with a mean of 93.00 ± 17.41% (Figure 6-A). It means that, on average, the radius of the parent root link is slightly smaller than the sum of the offspring root links. This ratio is not correlated with respect to topological orders (p-value = 0.0525, $F_{1,19}$ = 4.2788) nor radius of parent (p-value = 0.8213, $F_{1,19}$ = 0.0525). As expected, the parent radius is correlated with the sum of the offspring radii (p-value < 0.0001, $F_{1,19}$ = 43.1651) (Figure 6-B). Concerning Murray's law, the ratio between the cubed radius of each parent to the sum of the cubed radii of its offspring shows a mean of 279.55 ± 190.21%. Murray's law predicts this ratio to be 100% for vascular systems (e.g., xylem in plants). Since our study considers the entire root cross-section, it seems logical that the ratio observed here does not equal 100%.

3.2. ANALYSIS OF TRAITS TO INFORM BIOMIMETIC DESIGN OF CIVIL INFRASTRUCTURE

For the transfer of root data toward biomimetic design, abstracted traits can be used. The shape and size of the root system that can be researched are contingent on the excavation technique (i.e., hydraulic tree spade in this case). The root system analyzed has a diameter of 2.02m and a height of 1.33m. The overall porosity of the root system equals 95.76% of the total volume (i.e., from the convex hull of the 3D model). The porosity along the X, Y, and Z projections respectively equals 47.80%, 43.33%, and 64.58% (Figure 7-A). The surface-to-volume ratio of this root system equals 79:1. The porosity throughout the root system's depth and distance from the trunk increases rapidly with increasing distance from the stump (Figure 7-B & C).

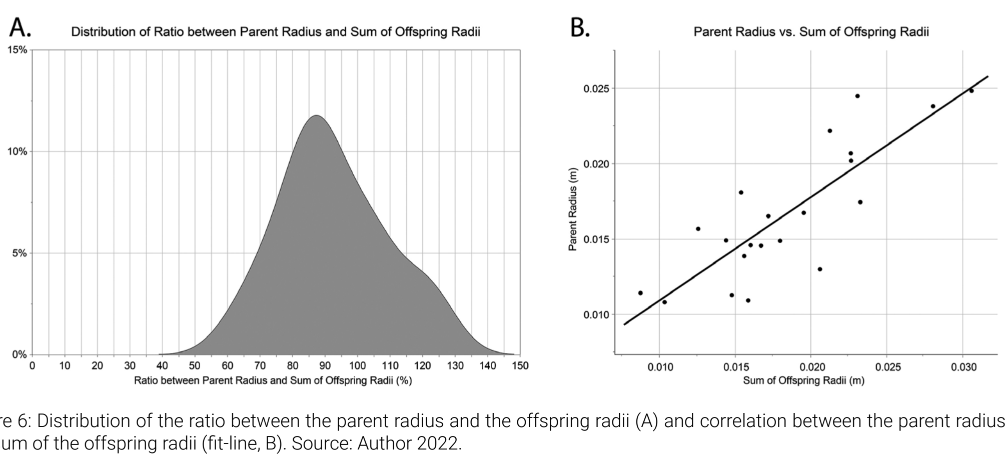

Figure 6: Distribution of the ratio between the parent radius and the offspring radii (A) and correlation between the parent radius and the sum of the offspring radii (fit-line, B). Source: Author 2022.

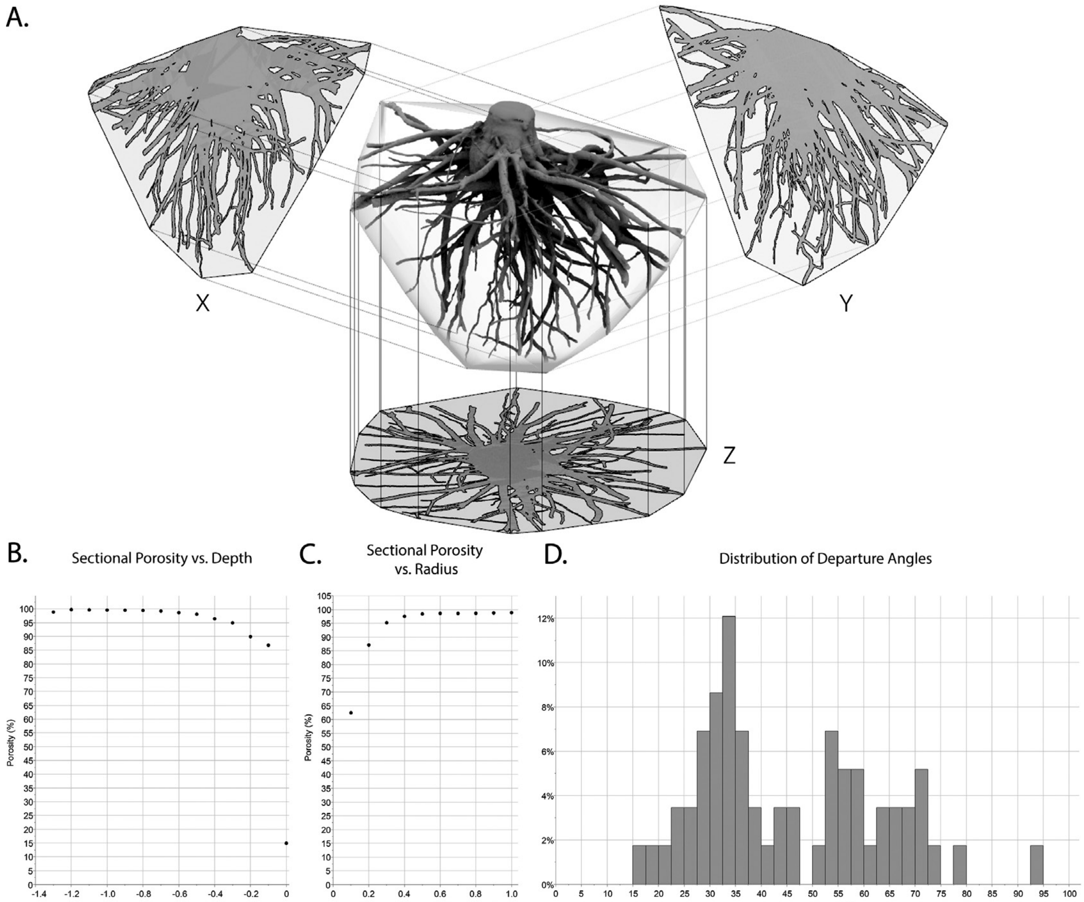

Figure 7: Shows the 3D model of the root system and its 2D projections in the X, Y and Z directions along with the 3D and 2D convex hulls used to calculate the different types of porosities (A), sectional porosity of the root system throughout its depth (B) and distance from the trunk center shown as the radius of each cylindrical cut (C), and the distribution of the departure angles throughout the root system (D). Source: Author 2022.

The distribution of departure angles (n = 56) throughout the root system showed peaks at approximately 33 degrees and 54 degrees, with an overall mean of 45.87 ± 17.38 degrees (Figure 7-D). The data shows no correlation between the departure angles and the topological order (p-value = 0.1968, $F_{1,54}$ = 1.7082) nor the radius of parent root (p-value = 0.8453, $F_{1,54}$ = 0.0384).

4. DISCUSSION AND CONCLUSION

4.1 ASSESSMENT OF ROOT TRAIT EXTRACTION ALGORITHMS

As described by Bucksch 2014, the extracted skeleton does not perfectly represent the actual plant network due to the limitation of the imaging technology. First, since the coarse roots in the root system's center (i.e., stump) merge together through secondary growth, it is not possible to reconstruct the complete plant network from the 3D model of the root system without making topological assumptions, tracking the root centerlines throughout time in 3D, or dissecting the roots to find growth patterns (Danjon and Reubens 2008). The lack of traceable morphology for this region of the root system means that the topological information cannot be derived. This impacts the entire root system's topology and limits the comparison of root traits per topological order. In our analysis, the topological order of each root link emerging from the stump bulb was set to 0, but it is important to note that this apparent topological order does not correspond to the topological order of the actual growth process. This could be one reason for the absence of correlation between the root traits analyzed and the topological orders for this root system. Future research could focus on extracting the stump's topology and extracting the same data from other root systems to increase the number of data points and potentially identify emerging patterns.

Second, the extracted data's accuracy depends on the accuracy of the 3D model to be skeletonized and the limitations of the technique used to generate it. In the current case, photogrammetry is limited by occlusion, resulting in thicker roots, especially in the zone of rapid taper and at branching locations. Fine roots (i.e., under 1 cm in diameter) were lost and intentionally removed during the root excavation and preparation so that the data extracted from the 3D model only accounts for the coarse roots. For example, considering fine roots and root hairs would highly increase the surface area-to-volume ratio and decrease porosity. Fine roots amplify connectivity to soil particles and subsequently enhance erosion prevention (Reubens et al. 2007; Xiong et al. 2007; De Baets et al. 2020). Different excavation processes modify the root system's morphology in different ways. For instance, since roots are flexible and bend under mechanical loads (i.e., loads applied during excavation, soil/root removal, and gravity once the soil has been removed), traits related to the original orientation of the roots may need to be extracted from 3D models of roots imaged in their soil medium.

Five main requirements serve to assess skeletonization processes: (1) centerline location, (2) connected skeleton, (3) topology preservation, (4) thinnest skeleton possible and (5) independence from scaling, displacement, and rotation (Jiang et al. 2007; She et al. 2009). When considering the entire skeletonization process (i.e., including the manual refining step), all requirements are mostly satisfied. The current approach requires manual input to verify and adjust the centerline location (1). To improve the algorithm and reduce manual input, the centerlines generated with the current skeletonization algorithm could be used as local paths for orienting the cutting planes, similar to how contour lines of a mapping function can divide the complex model into local regions (Khromov and Mestetskiy 2012). Another iteration of the skeletonization algorithm would then use these paths to skeletonize each root in the system and connect their centerlines. However, similar problems will still occur, such as non-centeredness at branching locations. The connectivity (2) and topology (3) of the root system are preserved since the algorithm connects branches together at their branching location. The only exception to the connectivity and topology preservation is the stump, where topology cannot be determined. Therefore, parts of the skeleton are not connected. However, this limitation emerges from the characteristics of the root system and 3D model, not the skeletonization process. While traditional skeletonization methods are based on voxels and aim at the thinnest algorithm possible (i.e., 1-voxel thin) (She et al. 2009), our algorithm generates a vectorial centerline from a 3D mesh and is not constrained by the limitations of voxels (4). Finally, our process does not rely on scaling, displacement, and rotation (5) since the cutting planes and the rest of the algorithm use the boundary box of the root system model as a reference.

Once the skeleton has been generated and refined, morphological root traits and their place in the system topology are extracted for analysis. Therefore, research questions can be answered by comparing both data types and their effects on each other, such as the decrease in diameter from one topological order to the next. The results section shows how topology serves to answer specific biological or biomimicry questions.

4.2. COLLECTION OF ROOT TRAITS TO STUDY ADAPTATION ACROSS SPECIES AND ENVIRONMENTS

This algorithm extracts system topology and morphological root traits from 3D models in a systematic process. Extracting traits from accurate 3D models of root systems allows for research questions to be answered long after the 3D model has been generated. In addition, a standard root analysis process facilitates the data comparison between studies and the subsequent emergence of trends. The large amount of root trait data extracted from each root model can feed a database, such as the Fine-Root Ecology Database (FRED) (Iversen et al. 2017) or the Digital Imaging of Root Traits (DIRT) (Das et al. 2015). Similar to the 3D models, the database can act as a storage of root knowledge for future research questions. Root models from around the globe could be analyzed with this standard process to produce a wide set of comparable data. Broader questions, such as the adaptation of different tree species to different environments, could therefore be addressed.

4.3. TRANSFER OF ROOT KNOWLEDGE TO BIOMIMETIC DESIGN

For the design of biomimetic civil infrastructure, specific root traits are relevant for different related functions. Therefore, the functions of interest dictate the type of root trait to be extracted from the root model. For instance, the distribution of departure angles in root systems can inform the morphology of branched building foundations to optimize their spread throughout the soil media for structural support and erosion prevention. For example, a vertical pile branching into multiple offspring following a small departure angle allows it to reach deeper soil layers, as the offspring's orientation remains similar to the parent. A pile branching with a larger departure angle would greatly modify the offspring's orientation and could, for instance, serve to increase the bearing area. Furthermore, the surface-to-volume ratio of the root system analyzed equals 79:1. In comparison, a traditional pipe foundation with a 50-cm diameter and 10-m depth has a surface area-to-volume ratio of 8:1. In both cases, only the surface area in contact with the soil is taken into account (i.e., not the cross-sectional area of the trunk or pile at the soil surface). A higher surface-to-volume ratio means that for an equal volume of foundation material, a wider volume of soil is recruited to transfer structural loads (i.e., larger bearing and frictional area), or exchange resources. This high surface-to-volume ratio is also reflected in the porosity results which can provide valuable insight for structural support, erosion prevention, and natural habitat creation. Volumetric porosity, in addition to other root traits such as diameter, tapering, and departure angle that influence the size, structure, and distribution of open areas along the dimensions of the root system, can be tested to understand their singular and interactive effects on downstream flow and turbulence responses, affecting wave attenuation and erosion performance. For example, porosities of traditional coastal protection revetment structures such as concrete block, porous concrete block, and ecological concrete vary from 15-40% (Chen, Xu, and Ying 2016), while the overall volumetric porosity of the root system analyzed is 96%. In lab studies where vegetation is often modeled as an array of rigid, vertical cylinders of the same diameter and spacing (Chen et al. 2012; Zong and Nepf 2012), the geometric parameters are assumed to be equivalent throughout the length, width, and depth of the vegetative region. However, spacing between individual elements along the dimensions of a coastal structure can be varied to create habitat by targeting the preferred flow and energy regimes of native fish species (Hockley et al. 2014; Kerr et al. 2021). Variations in sectional and projection porosities in the root system analyzed (Figure 7) provide additional geometrical parameters and possibilities for localized habitat creation, wave attenuation, and coastal erosion reduction performance.

In addition to extracting root traits to inform a desired function, transferring and integrating abstracted root strategies and principles can also lead to concepts and designs of multifunctional adaptive root-inspired infrastructure, which have been explored in Stachew, Houette, and Gruber (2021). Since root systems and civil infrastructure do not exist in the same context (in terms of scale, materials, environment, and requirements), the efficiency of the transferred traits and resulting designs will be evaluated through extensive prototyping testing. These tests could then, in a process called reverse biomimetics (VDI 6220 2012), also serve to learn more about the biological role model itself.

CONCLUSION

In response to the current limitations of civil infrastructure, especially with the need for sustainability and to address the increasing stress of climate change, the biomimicry transfer of root strategies, principles, and traits offers an avenue for the design of multifunctional adaptive civil infrastructure. In the analysis of root system architecture, root traits need to be extracted in a systematic way to be comparable between studies. The focus of this paper is to present a semi-automated algorithm to extract traits from 3D models of root systems, in a visual programming language and 3D interface to facilitate its comprehension and usability by researchers and practitioners. The algorithm is skeletonizing root systems' 3D models based on the Reeb graph. A manual step is required to adjust skeleton inaccuracies. The skeleton is the basis to extract morphological root traits and system topology, which serves to answer both biological questions and inform the design of root-inspired infrastructure. This root analysis process allows for answering emerging research questions long after the 3D model has been generated. Future research could aim at improving the algorithm with machine learning, feeding the extracted root traits into databases, and continuing to evaluate and integrate these abstracted traits for the design of civil infrastructure.

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ENDNOTES

1 Plugin available on food4Rhino which hosts grasshopper plugins: https://www.food4rhino.com/en/app/sandbox-topology

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SYMPOIETIC PLEKSIS: THEORETICAL AND PRACTICAL APPROACHES FROM TEXTILES TO ARCHITECTURE

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In the past decades, due to advancements in digital technologies, digital fabrication, and material sciences, there has been a theoretical and design shift. Prior to this, architectural discourse tended to prioritize and segregate form over its materiality, as matter followed the design, creating a clear distinction between design and making. In comparison, craft lies upon the idea of the applied skill and mastery of the material. In craft, matter and its properties are the progenitors of the form alongside the methods of fabrication and forces applied to it. Neri Oxman uses the term material ecology to describe the shift towards new material-based design processes and looks at how craft processes can inform current manufacturing methods. The proposed practice-based research sets out to develop and examine forms of architectural craft alongside fabricating prototypes. It uses textiles as a medium to explore how craft techniques can be re-interpreted to inform our current design and material processes. Textile making is a craft known from prehistoric times. It is a performative action of construction and deconstruction that could be considered the first architecture. Thus, the first known architects can be identified as weavers with the skills to produce structurally complex enclosures. Also, textiles can be seen as a medium to express stories transferred from one generation to another and can indicate aesthetic values, technological advancements, and sociocultural characteristics. The key scope of this paper is to establish the theoretical background that contributes to the conceptual framework of my research. Firstly, it examines the dynamic relations between the maker, materials, and tools. This is followed by an exploration of how such interconnected relationships can be translated to creating design principles and methodologies. Additionally, it includes an overview of textiles in architecture and how they can be used as a fabrication method and as a theoretical metaphor. The process can be seen as 're-coding' the textiles through material choices, pattern creation, computation, and fabrication methods. The paper aims to provide an overview of the ideas leading to creating a dynamic methodological framework, exploring how textile craft can be applied and re-interpreted in an architectural context by emphasizing material programmability and computation.

Keywords: Craftmanship, sympoietic, textiles, making-with, bio-yarns.

INTRODUCTION

There is a long history in architecture between design and production and the association of matter and form. The term architecton is derived from Greek αρχιτέκτων (*architéktōn*) αρχι (*archi*: the lead, the first who commands) and τέκτων (*tecton*: master builder) and traditionally the role of the architect was associated with the work of a master builder (Online Etymology Dictionary n.d.). The physical construction and making were very closely related to the design ideas. At least up to the Renaissance, the master architects had a close relationship with making—craft as most of them were also painters and sculptors (Brothers 2008). With the introduction of architectural drawings and advancements in technology, the role and responsibilities have changed throughout the years. From a highly skilled master in charge of conceptualising, managing the project and the construction; to a contractor in charge of designing and being partially involved in the implementation.

The Industrial Revolution was a key point for this transition with the invention of the printing press, mechanised processes, mass production and standardisation (Carpo 2011). This shift has led to a decline in traditional building craft due to the need for standardised design processes. Architects started to design in an isolated manner, excluding the traditional building craft driven by technological advancements and craftwork was identified as ornamental (Djabarouti & O'Flaherty 2020).

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The next key shift is the "digital turn", a term coined by Mario Carpo to signify the use and effect of computers and digital technology on architectural design (Carpo 2011). The use of such digital tools is leading to design outcomes that are highly formalistic and are further disconnected from the material choices. There is an imposition of material to form (Picon 2011). Yet, in the past decades with the developments in computation, material science, technology and fabrication there is an attempt to reinterpret craft techniques and create innovative methodologies (Oxman 2014). The paper aims to provide a brief overview of the theoretical background related to craft processes, particularly looking at textiles and how they can be used to expand and explore new architectural methodologies.

1. THEORETICAL BACKGROUND

Craftmanship may be reinterpreted as a set of instructions combining knowledge and application, matter and tools. An operational framework for processing and re-organising material constructs. Thus, a craft of any kind may potentially serve as a guiding instruction—set, a formalism witch merges knowledge of application with instrumentality of material organization (Oxman 2014 2).

1.1. DEFINING CRAFT INTERDEPENDENCIES

The term craft comes from Old English cræft (West Saxon, Northumbria) "power, physical strength" and from Proto-Germanic *krab-/kraf-* "strength-skill" (Doyle 2016) (Online Etymology Dictionary n.d.). In his book The Craftsman, Richard Sennett gives examples of craft practices from cooking, potting, weaving, music, and medicine (Sennet 2008). He emphasizes the importance of creating tactile experiences through engagement to form tacit knowledge and relational understanding. Such an approach highlights a constant synergy between thinking, tools, making, development of skill and production. The dialogue between thinking and making leads to habitual rhythms and establishes a close relationship between problem-solving, problem-finding, and the creations of the craftsman's ethical stand (Sennet 2008).

For Pallasma, craftmanship denotes a close collaboration with the material capabilities to inform the process instead of imposing a pre-convinced idea. He mentions that the craftsman needs to listen to the material and establish associations of concept and execution, thinking and making, learning and performance, action, and matter (Pallasmaa 2009). Furthermore, in The Nature and Art of Craftmanship, David Pye defines craft as the result of a process where the outcome depends on the dexterity and care of the maker, and there is no predetermined output (Pye 1978). Core to his definition is the notion of risk during the making process. The risk is managed through the craftsman's skill and knowledge, providing a relationship between certainty and risk (Pye 1978).

If the craft is defined by skill and our active engagement with the material and building processes architects have long been disconnected from the process. This part was instead given to builders and constructors. Digital fabrication, simulations and material science have given the opportunity to reconnect with these processes of making and are key in re-establishing and enhancing craftsmanship methodologies to be applied in architecture, toward a digital craft.

1.2. DEFINING DIGITAL CRAFT

Malcolm McCullough is one of the critical figures discussing the idea of digital craft in 1996. He explores the idea of computer as the medium between hand and maker, claiming that to substantiate the work there is always a need for a medium. The medium facilitates the actions of hands, tools, materials to create a habitual practice. Thus, it can have multiple meanings, it can be raw material, immaterial, an agency, a person, a tool, and a complex process. It can become challenging to indicate when the tool ends, and the medium begins (McCullough 1996). Going back to the notion of risk posed by Pye and its relationship to craftsmanship, there is a need to consider how that affects the definition of digital craft. Within traditional craft, there is no option of going back whereas within a digital environment the notion of risk-taking can be minimal. McCullough, through his work, establishes the basic ideas to define the intellectual understanding of craft through a continually working medium. One of his key points is the notion and importance of density “increased notational density supports quasi–continuous operations formerly only available from physical materials” (McCullough 1996). Based on an increase in computational power thus high precision numerical representations, the data structures allow for continuity and an increased engagement with structural manipulations. Through this process skill and intellect begins to reunite (McCullough 1996). Computational principles are often associated with domestic crafts such as weaving, ceramics and embroidery. Based on this, S. Doyle and L. Forehand urge for cultivating and expanding new cultures of digital craft through CNC and fabrication methods by recalling the historical links to crafts and feminine labor (Doyle & Forehand 2017).

1.3. AUTOPOIETIC AND SYMPOIETIC SYSTEMS

In formulating a new framework based on craft processes, it is key to understand and create the new interdependencies between maker, tools, material technology, and makers ethos. In doing so, autopoietic and sympoietic systems are explored, seeking to comprehend their organizational differences and the effects each could have on a design process.

The principles of autopoietic systems are that they are organizationally closed and can produce their own boundaries, resulting in autonomous units in terms of self-governing (Maturana & Varela 1980). They are structurally linked to their environment; they can adapt according to their local condition and maintain their internal organization. There can be a constant interaction—transmittal—continuous feedback at multiple levels (Boyer 2015). Applications of this theoretical framework can be seen in multiple domains. For instance, Paul Loh argues that craft can be considered autopoietic as it is both self–referential and self-making simultaneously as continuously designing (Loh et al. 2016). This is based on the continuous relationship between material, tool, skill, and technique. Biocomputational scientists are creating agent-based and evolutionary models. In architecture, autopoietic systems are often preferred due to their predictability, automation, and ability to simulate dynamic controlled systems.

Yet there are downsides to this model. Donna Harraway claims that such models could be at risk and can stop us from the capacity to imagine other possibilities, other worlds. She characterizes the use of such systems as the “unthinkable” theory of relations that feeds a utilitarian individualistic model (Haraway 2016). Instead, she proposes a sympoietic model, an idea of tentacular thinking based on co-production, making with (Haraway 2016). Sympoiesis comes from the Greek σύν (syn, together) and ποίησις (poíēsis, creation) for collectively producing. Key characteristics of the systems are the lack of self-defined spatial and temporal boundaries. They are characterized by complex interactions among components that enable them to be organizationally ajar and allow for integrating new information and dynamic organization of evolving, interdependent complexity (Dempster 1998). Sympoietic systems can be complex, dynamic, situated, and historical. A key example, where she describes sympoietic relations, is through the Navajo Weaving–Churro Sheep alliances. She looks at the weavers around Black Mesa, which is closely related to the exitance of Churro—rough sheep brought to America in the sixteenth century.

Over time, Navaho herders have co-developed it as a distinct sheep that relates to the people—to the place and making (Haraway 2016). The sheep ties people to making through patterns of care response-ability. It is an excellent example of the interconnectedness of making—thinking—weaving—locality—situated knowledge and local habitats.

The interrelations described above through Navajo Weaving would act as a starting point to create the new framework. The key principles favouring adopting an overarching sympoietic framework, which can lead to new possibilities and have an emphasis on situated knowledge and locality. The sympoietic system would be used to explore the dynamic relationships between maker, locality, material, tools, and fabrication. The architect becomes the 'architect weaver' who can re-code textiles and create analogies between fibres, materials, patterns, technology, fabrication, body, and environment. The overarching framework will be a sympoietic approach and use textiles—"pleksis" (from Greek πλέκω–for fabricating using fibres) as a means of explorations to create new architectures of digital craft. Textile and technology are derived from the Latin "texere" meaning to weave, construct, fabricate. Furthermore, the key reasons for choosing textiles as a medium are their close relationship with craft, dexterity, technology, and theoretical signification. Thus, they can be explored both as a theoretical metaphor and a construction method.

2. TEXTILES AS A MEDIUM

Weaving is a useful practice, to be sure, and an economic one; but fundamentally weaving is also cosmological performance, knotting proper relationality and connectedness into the wrap and weft of the fabric. Weaving is neither secular, nor religious; it is sensible. It performs and manifests the meaningful lived connections for sustaining kinship, behavior, relational action for—honhzo—humans and non-human. Situated worlding in ongoing, neither traditional nor modern (Haraway 2016).

2.1. TEXTILES AND STORYTELLING

Textiles have always been a key source of telling—narrating stories from one generation to another. The weaver figure in mythology is ubiquitous in a plethora of ancient civilizations, such as India, Native Americans, Central Asia, and Ancient Greece. In Greek mythology, Penelope, Philomena, Arachne, Calypso, Goddess Athena were all weavers who, through their textiles, create storylines. Penelope weaved and repeatedly unraveled whilst waiting for the return of Odysseus Odysseus, an action that binds her with time and denotes her oath to society. On the contrary, Arachne's textile seeks to express her dissatisfaction towards power by challenging the institution of Olympian Gods, which results in her punishment by Goddess Athena to a spider (αράχνη in Greek), so that she can weave meaninglessly for the rest of her life (Kruger 1998). Furthermore, the materiality of the cloths was also a signification of the socio-cultural status and locality of the material. For instance, wealthy women in Athens were working with fine wool and linen, whereas slaves with coarse wool. Weaver, fibers pattern, and loom all become entangled, negotiating their relationship to narrate a story through the material, cloth, and process. An important part of the exploration would be to identify how such relations can be re-interpreted and used in today's context. To further unravel these relationships, I would also look to explore: entanglements (Haraway 2016) lines—weaving—storytelling, (Ingold 2017), relational architectural ecologies (Rawes 2013), relationality (Barad 2007) reciprocal, relationships (Stiegler, 1998) and vibrant matter (Bennett 2010).

2.2. HISTORIC OVERVIEW OF TEXTILES IN ARCHITECTURE

Architecture and textiles trace date to the first human dwellings, where branches and plant fibers were woven together to provide shelter. The earliest finding of tent structures made from branches, leaves, barks, animal fur and kin is estimated to be from 30,000 years old camps of Paleolithic hunters in the tundra. (Krüger & Hill 2009). The branches were later replaced by animal cloth and spun woven fibers to create textiles, baskets and tents. Greek, Asian, Egyptian, and South American civilizations used textiles as decorative, functional (baskets, mats, carpets, blankets) and construction materials. According to Semper, threading, twisting, and knotting were among the most ancient human arts derived from everything else, including buildings and textiles. He proposes that the origins of architecture are found in four separate elements, which originate in the arts (clay, wood, textiles, stone), each element being inextricable of material, technique and form. According to his "theory of Dressing", fences for animal pens, woven branches were the early man-made partition wall, thus the first space definers (Semper & Mallgrave 2007). Following Semper's logic, Adolf Loos in his essay "the Principle of Dressing" encouraged architects to first engage with textiles to grasp meaning and aesthetics and then apply—employ that to architecture (Loos 1989).

In the 20th century, Anni Alberts emphasized the importance of material and structure in weaving and explored their similarities to architecture. For her, it is key to work with the material's properties and not by imposing a design (Albers, 1965). Architecture and textile have been instruments to express theory, aesthetics, and fabrications of an era. "Architextiles" is a hybrid term looking into uniting the worlds of architecture and textiles. These relationships are also investigated in the literature through books, journals and exhibitions: *Architextiles AD* (Garcia, 2006), *Extreme Textiles designing for high performance* (McQuaid, Becker, & Beesley 2005), *Textile Architecture* (Krüger & Hill 2009), *Skin + Bones: Parallel Practices in Fashion and Architecture* (Hodge 2007), and *Textile Tectonics* (Spuybroek 2011). The theoretical shift during the late 90's and the advancement of technology made fabrication and material sciences working with textiles a promising research field. To this end, textiles as an interface can be an excellent platform to explore and challenge the relationships of making, craft, tools, technology, and digital fabrication.

2.3. RECENT OVERVIEW OF TEXTILES IN ARCHITECTURE

In the field of textile design during the 1980s, there have been great advancements in high-performance fibers, primarily in geotextiles, aerospace and military industry performance (McQuaid, Becker, & Beesley 2005). Textiles can offer a high level of customization by varying the fibers, composite fiber combination and use of various weave techniques performance (McQuaid, Becker, & Beesley 2005) . Knitting, weaving, braiding, and embroidery have a long history of craft and techniques as they have been evolving through centuries. The inherited knowledge accompanied by high-performance fibers and the ability to locally control the structure could lead to promising levels of built performance (Oxman et al. 2010). Thus, textiles can become an excellent platform to explore how material programmability can inform the design of a continuous heterogeneous form with varying properties. Knitting can allow for various performances within a continuous single-form system (Scott n.d.). Such systems with hierarchical relations are useful for multi-performative hybrid structures (Menges & Reichert 2012).

Thomsen has pushed the boundaries and explored textile processes and the idea of highly specified materials in response to design criteria. The knitting pattern becomes a material code that details the structural logic of the form (Thomse & Bech 2012). Through the projects Listener and Strange Metabolism the logic of knitting is exploited and used to create material designs in response to the structural and programmatic requirements of the environment. Slow Furl and Lace Wall investigate how the textile can become an integral part of the structural support (Thomsen 2008).

Furthermore, Jane Scott explores heterogeneity and hierarchy in knitted forms through moisture actuation on fabrics using natural materials. This is achieved by controlling the knitting pattern, fibers with different properties and wood veneer placed within the fabric. The knitted pieces exploit the material properties and actuate once exposed to moisture. Additionally, there are key examples of textiles as part of hybrid systems. Knitflatable combines both pneumatic and knitting systems (Baranovskaya 2016). "Semi-Toroidal Textile Hybrid Installation" introduces elastically bent beams that allow the pre-programmed textile to pre-stress internally and resolve its equilibrium. Similar work achieved a uniform piece of textile that integrates both tensile and bending active elements (Ahlquist & Menges 2013). Finally, Philip Beesley designs and fabricates highly complex self-organized scaffolds based on knitting and folding techniques using various materials (soft, hard, mechanical, living, non-living). All components are interweaved together to produce a fabric that responds to the environment (Beesley 2010).

Despite the wide scope of the projects, it is evident that the process of knitting as a fabrication method and material science has not been explored to its full extent; as a tool for creating highly complex designed structures. Most projects examine a part of the material programmability without a cross-scalar and interdisciplinary approach. It is essential to look at engineered textiles across disciplines such as space design, medicine, bio-design, filtration systems, sailing and landscape engineering and feed that into the design process. Furthermore, most projects concentrate on one key advancement, which could be seen as a more autonomous—autopoietic approach. Part of the scope of the research would be to explore how textiles can enable us to establish and create sympoietic processes.

3. PROPOSED STUDY

Textiles would be used to explore a sympoietic approach of making through material choices, pattern design, fabrication methods, and digital simulations. Textiles and textile processes have proven to be an excellent platform to explore complex ideas; due to their hierarchical structure, they can be programmed to create complex shapes of variable properties and performance (Menges & Reichert 2012). The research will run in parallel strands. One that explores the creation of interdependencies and situated practice—creating alliances through the making of the textiles under a sympoietic framework (Figure 1). This means examining making, programming the material by considering the relationality of material—maker—local material signification—material agency. The second strand would examine in parallel scientific and computational methods for the fabrication and material programmability of the textiles. The following methods would be employed to achieve the second part of the exploration.

4. METHODS

The methods would be explored in parallel, each informing the other to examine their interrelations and inter-actions through a sympoietic making methodology. The three key elements can be seen as relational to the main elements of producing craft - material, technique, tools and make input (Figure 2).

- *material—material programmability*: looking in-depth into understanding the material properties and potential of material programmability; and examining what it could mean for the maker to design and fine-tune the material itself based on the concept of the project.

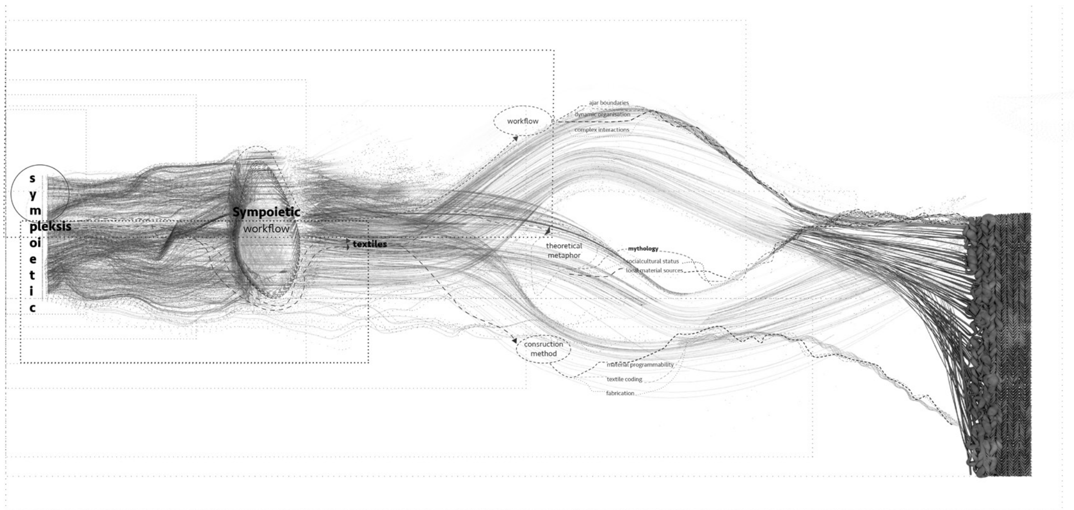

Figure 1: Sympoietic Pleksis, thesis outline diagram: theories-concepts-fabrication ‘woven’ together. Source: Author 2021.

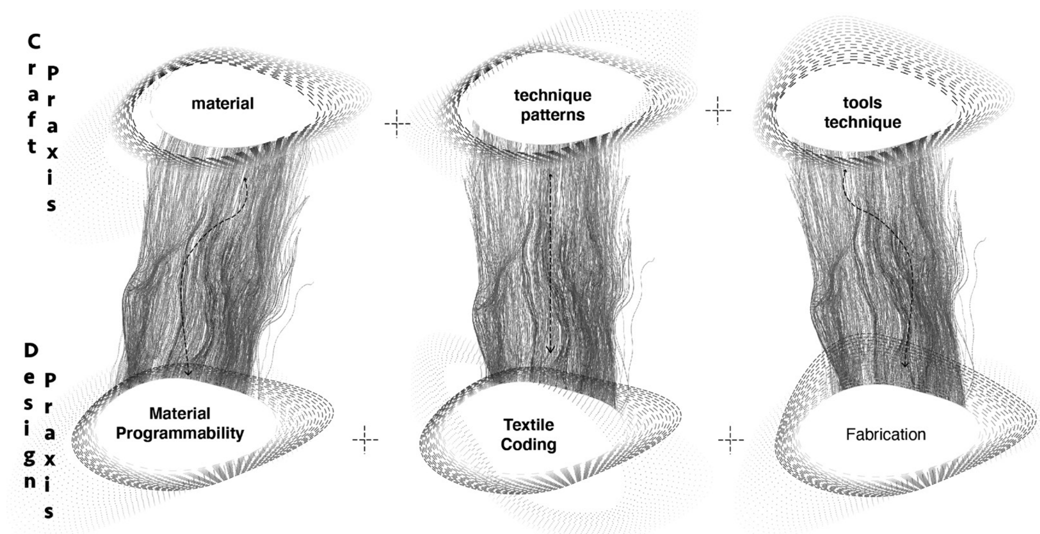

Figure 2: From craft praxis towards expanding digital craft practice. Source: Author 2021.

- *technique—textile coding*: examining various textile-making techniques and the impact the technique and pattern would have on the final form. This could be explored through physical making and through simulations. Textile coding relates to programming the textiles’ performance by understanding the fibers’ agency and various textile techniques and their effect on the form. The explorations of patterns can be examined to express and explore the relationalities of the maker with the fabric, its materiality, and its locality, as per Donna Haraway’s Navaho Weaving example.
- *tools—fabrication*: testing various fabrication methods and tools to scale up the process.

As part of this exploration, it would be key to explore and record how one process affects the other and at which point. Spider diagrams would document the relationships between material, technique, and tools to map the process. Paul

Loh has tried a similar method using diagrams to examine the workmanship of risk and certainty during mass and craft production by conducting semi-structured interviews of artists (Loh et al. 2016).

4.1. MATERIAL PROGRAMMABILITY

In the last decades, there has been a vast number of advancements and literature around material systems, material agency, material programming, biomaterials across disciplines of material science, chemical engineering, architecture, textile and product design (McQuaid, Becker, & Beesley 2005; Oxman et al. 2010; Ahlquist & Menges 2013). Material ecology, a term coined by Neri Oxman defined as:

An emerging field in design denoting informed relations between products, buildings, systems and their environment. Defined as the study and design of products and processes integrating environmentally aware computational form generation and digital fabrication, the filed operates at the intersection of biology, material science and engineering and computer science with emphasis on environmentally informed digital design and fabrication (Oxman 2014).

She also uses the term “variable property” design to describe a design approach and methodology in which material assemblies of varying properties correspond to multiple and continuously varied functional constraints. In this approach, the properties of the materials are used strategically to generate the form (Oxman et al. 2010). This principle is explored in the project form follows flow looking at the potential in architecture to tune and program the material to create a complex, continuous structure with variable stiffness. For example, in the project biopolymers extruded from airtight barrels show elastic and plastic behavior depending on the consistency of the material (Oxman 2015). Furthermore, based on similar principles in the field of textiles and fashion, bio-yarns are created with the use of similar substances, testing a variety of consistencies to create sustainable yarns with various properties.

In the textile and fashion industry, several projects started to push for sustainable solutions for creating composite materials or yarns through biological processes. For example, Bastian Beyer’s in his Ph.D. thesis, explores the potential of solidifying knitted structures through biological solidification with the use of a bacteria which produces a calcite layer on the structure and binds it together (Beyer & Palz 2019). Also, a recent project at Central Saint Martins by Jen Keane in which weaving and production of bacterial cellulose have been combined to create a homogenous form (Jen Keane—MA Material Futures n.d.).

The above projects signify the beginning of a new era in which materials with tuned properties are part of the design form-finding method to create a multi-performance form responding to predefined criteria. The research would examine how we could explore the interconnected relationships with the maker, the making process, and its relationship with the environment through material programmability. The critical part would be to identify the composition of the thread, as natural but also as an artificial fiber, which can be programmed to respond to predefined stimuli. The fiber can be seen as a filament used to create spaces through knitting, weaving, binding, patterning, connecting, intermingling, and can happen with various materials of different states. It would be crucial also to examine the relationship the materials have with their signification and their relationship with the ecological and socio-cultural environment.

The main part of this process would be to identify a material pallet of fibers. This could comprise existing fibers and composite fibers and investigate development making tunable fiber bio-filament (Figure 3). There are two main aspects to explore. Firstly, the performance of the fibers and in particular the parameters that would be explored would be a) the type of yarns structure used:

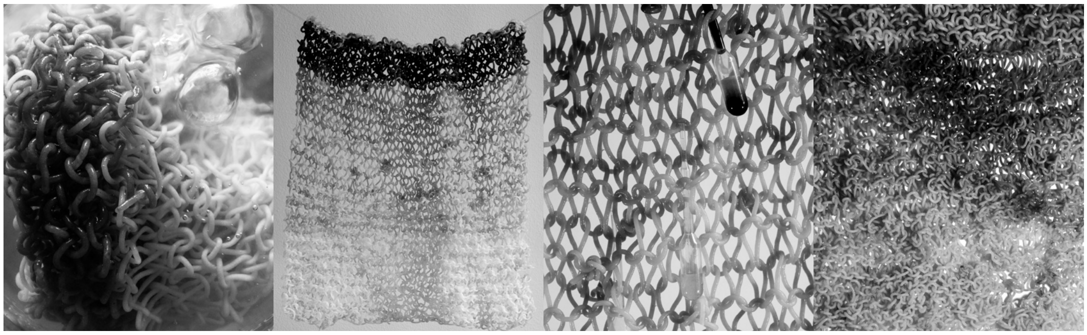

Figure 3: Making and experimenting with bio-yarns infused with living marine algae to explore the relationship between our environment, the textile, and the microorganisms. Source: Author 2021.

monofilament, multifilament, ply yarn, covered yarn, spun yarn, b) tensile strength and elongation of textiles, c) bending stiffness, d) drapability, e) response to stimuli (i.e., moisture, measure the shrinkage rate). Secondly, various mixing protocols for the creation of tunable biopolymer filaments. The making of the biopolymers is of great interest because the materials can be tuned to relate to required local and environmental conditions. The materials used would be water-based-composites of biological ingredients which tend to be environmentally responsive (Ling 2019). The materials can be "bio-based", such as casein, chitosan, cellulose, pectin, sodium alginate and "bio-active", such as algae. There are multiple challenges in working with biopolymers, such as the strength of the filament, diameter of the filament. These would be addressed by testing multiple recipe consistencies and curing methods with the input from material scientists. The behavior of the fibers would be measured and recorded to feed the simulations and form finding process.

4.2. TEXTILE CODING

There is a clear connection between the computation and the textile pattern, as each knot could be translated directly into the digital environment (Popescu et al. 2018; Tamke et al. 2021; Narayanan et al. 2018; Tamke et al. 2021). This makes it a powerful tool to work with and has great control over the final output. Also, the granularity of the data and its instant relationship with the physical world can relate to McCullough point on digital craft and connection to data.

Computational methods would be used to design the patterns and understand the fabric's behavior and response to various stimuli. The data from the material tests would be used to inform the behaviors of the models. The simulations and computations would be used both to inform the design fabrication, predict the textile behavior and act as a speculation tool. The speculation part would be used as a medium to enhance the imagination and envisage possibilities (Figure 4). McCullough's regards the medium as something which affects human senses in a matter that commands our attention and stir our imagination (McCullough 1996). According to Doy, craft encourages imagination and is a powerful agent "the ability to imagine a better word equipped with the capacity to act, is to craft and object with intentionality and purpose" (Doyle & Forehand 2017).

The key computational method that would be used is Grasshopper, for creating the pattern and conducting the structural analysis through Karamba and simulating the behavior of the textile (Figure 5). Furthermore, Houdini would be used to conduct the simulations of the textile behavior, such as the impact of the pattern on the form, how various material turnability can affect the form (for instance, part of the structure might shrink or change color) and as a medium to extend our imagination. Finally, the explorations would lead to a re-coded textiles-pattern aesthetic.

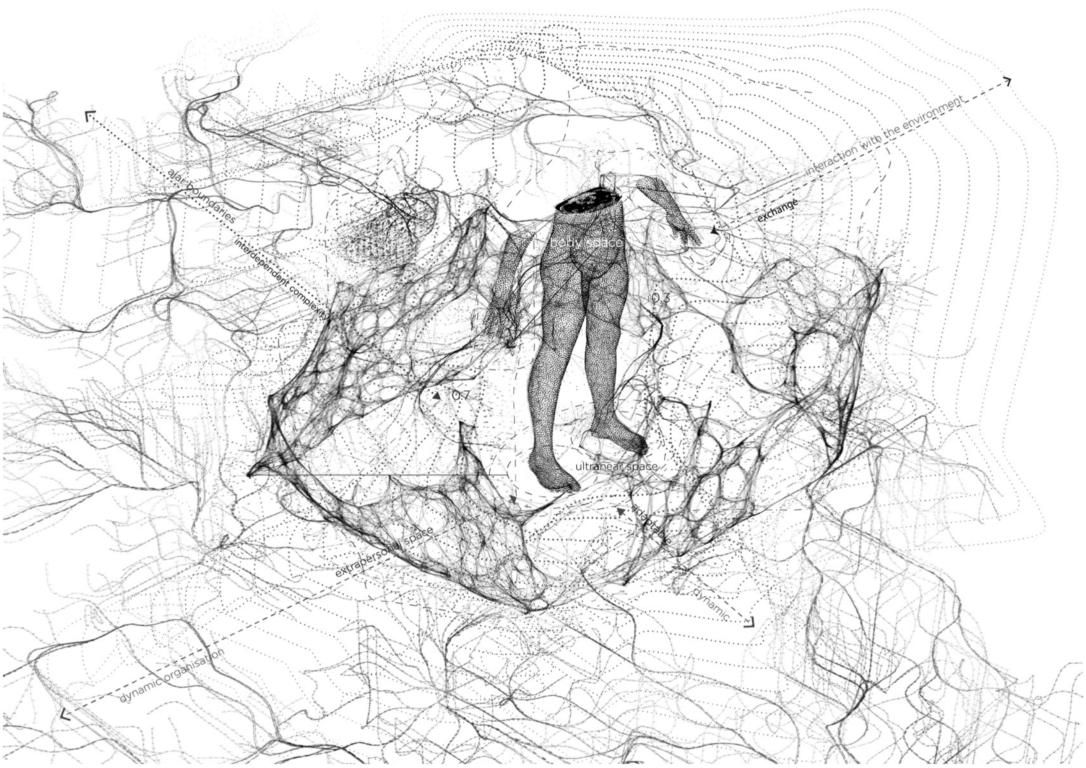

Figure 4: Exploring through Houdini, the behaviour of the fabric and producing speculative drawings that explore the inter-relationships of weaving- material-body- environment. Source: Author 2021.

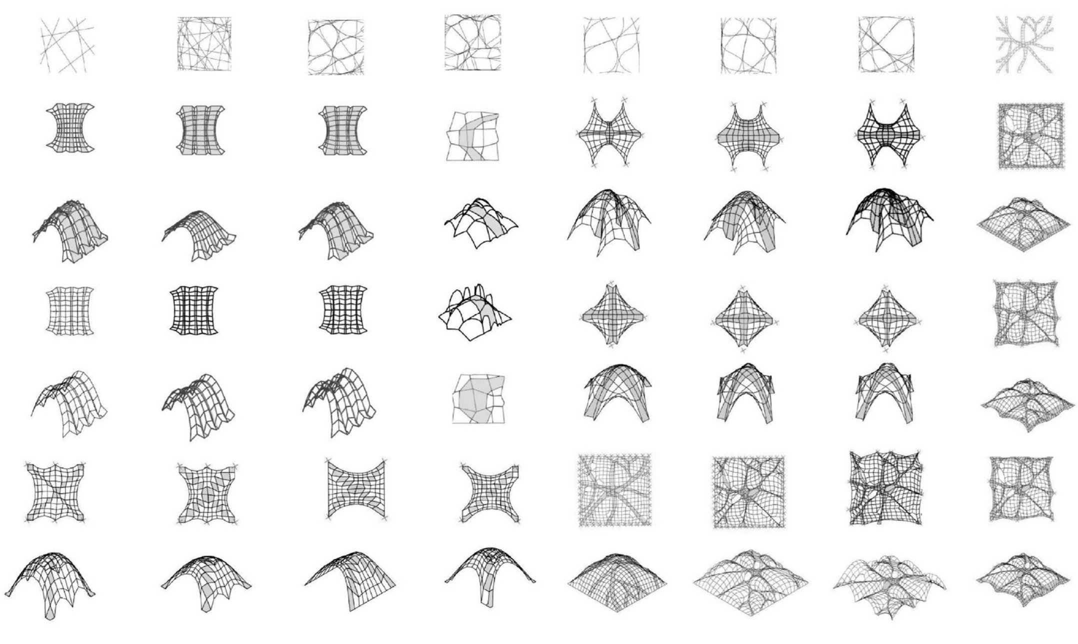

Figure 5: Exploring fabric behaviour & activation in grasshopper. The impact of the pattern and of material properties (in particular shrinkage) on the final form. Source: Author 2021.

4.3. FABRICATION

This phase is closely related to the material testing, the textile coding. It will occur in parallel with the other two and will be an iterative process. An important part is testing and setting up methods for scaling up the processes. Architectural textiles would be constructed by exploring various fabrication methods, materials, patterns, their impact on the final form and their interdependencies with the maker and the environment. A fundamental part of this step would be to use cutting-edge technology such as robotics and high-end knitting machines to test and explore the scaling up of the process. Robotics can also extrude the bio-yarn filament to create continuous yarns of varied thicknesses. There would be two main challenges for using existing knitting machines on the prototypes with the bio-yarns. The first one would be the tensile strength of the yarns, and the second would be the yarns' thickness. Knitting machines have a set thickness they can withstand. Thus, depending on the prototype needs, there would be an opportunity to create a simple system or tool to support the requirements to reach the desired output.

There could be multiple challenges for scaling up the process, such as the fibers' size, how the technique used gets translated to a larger scale, and the limitations that might come with the use of tools. It will be key to understanding how the selected materials can work together, and mixing techniques could be needed. A few examples of the techniques that would be considered are looking at: a) spacer fabric structures and how they could be used in an architectural context b) looking at ways of locally solidifying parts of the textile to act as structural support, this could be through the programmability of the fibers themselves c) using the shrinkage of the biopolymers to test if it could create tension within the structured) testing mixed techniques such as weaving within the structure, bending active elements, or using pneumatics and foams to stabilize parts of the structure. All these choices would be made possible when their initial material tests and simulations start.

These steps would come together to produce a series of architectural textiles and speculative drawings that would narrate and explore novel ways of thinking and fabricating architecture.

CONCLUSION

The main aim of this paper was to present a brief overview of the background knowledge of craft by looking at the interrelationships between making, maker, material, and tool. Furthermore, looking at understanding the autopoietic and sympoietic systems as a way of expressing and exploring such relations. Through developing such an understanding, we would be able to create and expand on new cultures of architecture and digital craft. Textiles would be used as a medium of exploration to examine these inter-actions. An initial framework is described based on how the study is intended to be conducted. The project requires input from multiple disciplines such as material science, architecture, computations, engineering and could introduce original perspectives to each field and shed light on those intricate relationships. Finally, it will seek to provide new perspectives and a critical re-evaluation of the textile-based material practice in architecture through a lens of an "architect–weaver–teller–a co-produce".

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THE CONTROL, COMMUNICATION AND FUZZY LOGIC OF ARCHITECTURAL PRODUCTION

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> In the workshop or laboratory, the spoken word seems more effective than written instructions. Whenever a procedure becomes difficult, you can immediately ask someone else about it, discussing back and forth, whereas when reading a printed page you can discuss with yourself what you read but you cannot get another's feedback. Yet simply privileging the speaking voice, face-to-face, is an incomplete solution. You both have to be in the same spot; learning becomes local. Unscripted dialogue, moreover, is often very messy and wandering. Rather than getting rid of print, the challenge is to make written instructions communicate—to create expressive instructions.[1]

Situated at the nexus of the environments of architectural design and architectural construction, this paper explores the relationship architects have with the building site. An architect's primary output is the drawing, but in order to become an "expressive instruction" during its use at the building site, architectural drawings are augmented and/or subverted via a connected system of control, communication(s) and fuzzy logic during the translation to construction. The paper will therefore answer the question: How does an Architect adopt notions of control, communication and fuzzy logic during the construction of an architectural project? Three historical examples are used as vehicles to probe the meanings of control, communication and fuzzy logic in architectural production.

Keywords: Fuzzy logic, cybernetics, drawing, making, construction, site office.

1. CONTROL

A building site is an important place for architects and architecture. At its most basic the building site is the place, and moment, a drawing is translated into a building. But the building site is also a place of learning and has a rich history as an extension of the architect's office. The interaction between the building site and the architect's office is well documented.

Often sent to the building site to draw, record and paint projects under construction, John Soane's pupils would ". . . learn about design, construction and the play of light in a building."[2] "They had instructions to study the contrast between the dark mausoleum and the light of the gallery carefully. At this stage the building was unfinished—the bare brick is still to be plastered and decorated."[3] The separation, and relationship, between the design environments of the building site and office can be seen clearly in the painting from 1812 (Figure 1).

> Note that the pupil has made a bench and drawing table out of two planks on a trestle. He has even covered the bench with his handkerchief to protect his white trousers.[4]

The painting of 1812 depicts one of Soane's students sitting in a makeshift office, a self-defined space for the designer on the building site. A hybrid space containing site and office, calm and mess, drawing and making. A historical depiction of a "site office" and a clear signal that the building site provided an essential learning experience for an architect. The painting explores the intersection between the act of drawing and the act of construction. The material and atmospheric considerations of dust, noise and conversation are referenced through the inclusion of the builders' ladders, and how the operations of the building site could influence the process of producing a drawing.

Using ideas communicated through drawings, the building site is a domain of physical materials, motion and complexity—a physical environment that can be difficult to navigate and understand. For the architect, the building site has always been a place of learning, a place to understand the meaning of drawing and its intersection with making, and, always a place that provokes further consideration of what a drawing should mean and a trigger for a shift between modes of thought.

Figure 1: Painting of Soane pupil at work at Dulwich Mausoleum. Source: By courtesy of the Trustees of Sir John Soane's Museum'. Artist Unknown 1812.

The architect's drawing is a device used to control the production of a building. Architects desire to understand the building site because without an understanding, control is not possible, lost even. There is an abundance of knowledge on the building site, manifest in different forms, but not present or possible to experience in the architect's office.

The image of the student hints at a deeply embedded culture of learning at Soane's office. His students are dispatched to the site to study construction and, presumably, to help inform them how they will make architectural drawings in the future. This is the pre-mechanical and pre-photographic age so the amount of time spent on site would have been a significant investment. Watercolor paintings of this quality offer a visual record of the importance that was attributed to this

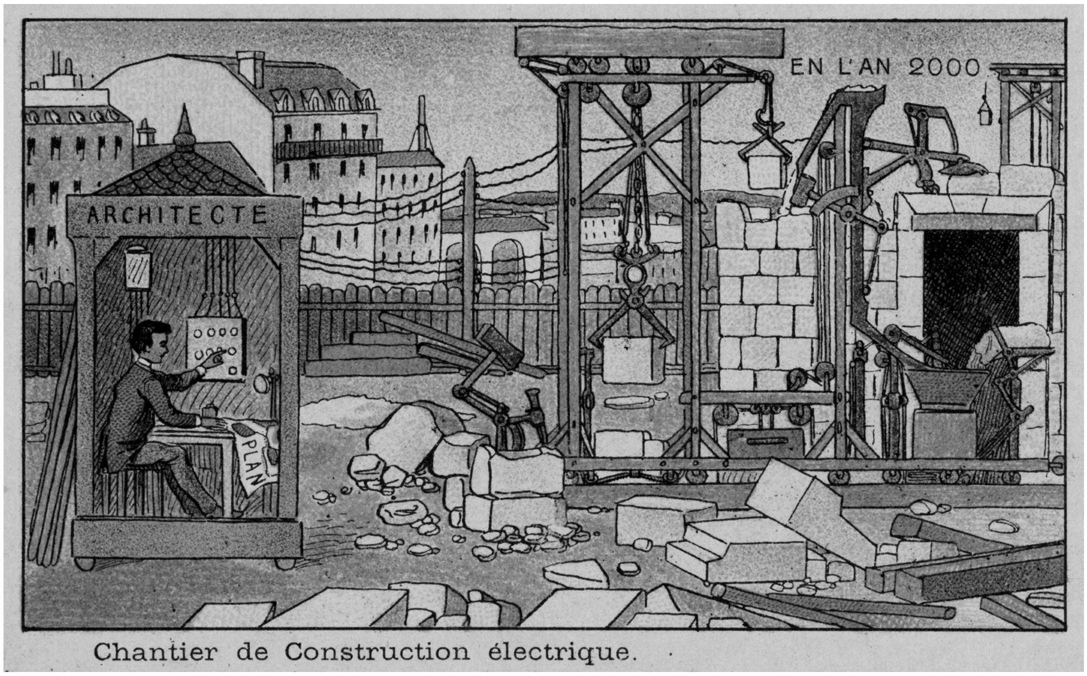


Figure 2: Chantier de construction électrique / The electrical construction site. Source: The National Library of France, Villemard 1910.

way of educating young architects. The connection between drawing, making and construction is resolved by the architect's occupation and presence on the construction site to "to learn about design, construction and the play of light in a building"[5] but also, we can assume, to foster a way of making drawings for future projects. It was a means to connect the office and the building site. It is interesting to note, however, that Soane's students are clear to maintain their social status in the picture by wearing the clothes of an architect and member of the middle class.

2. COMMUNICATION

Villemard's illustration from 1910 "The Electrical Construction Site" (Figure 2), shows the building site and architect's office as the same place, another depiction of a site office. Sat in a purpose-made office booth, the "Architecte" can be seen operating mechanical, quasi-robotic devices, to assemble the building from his seated position. Using his drawing as a guide he is directing the mechanical devices with a control panel of buttons. He is connecting the drawn world with the physical material environment, and becomes the maker alongside his role as the architect. By dissolving the boundaries between traditional disciplines of those who draw with those who make, the image anticipates the future and a new way of producing architecture and communicating drawn intent.

It is also, for its time, a profound political statement. The roles of the working and middle classes within architectural production are represented in one person, and furthermore, the image is a reflection of a new paradigm of making in the 20th century that uses mechanical means of production.

The Villemard image highlights the designer's need for control over the communication of information and instructions to the building site. This dress code is similar to that depicted in the Soane painting, but Villemard proposes a middle-class professional engaging with physical construction in such a direct way that it offers a change of perspective on what an architect could do. The rchitect is getting his hands dirty, so to speak, but more importantly, is in close proximity to the act of construction. The architectural drawing is also a prominent feature in the image, perhaps defining the importance of information at the core of power in architecture, and the architect's position as a result.

Control, communication and authorship are at the heart of operations on the building site. The realization that the architectural drawing does not guarantee a precise destination for an architectural project is a significant moment in the practising life of an architect. At times seen as a negative characteristic of architectural production, the loss of control by the architect over the materialization of their work is usually reconciled with experience, and the idea of a project being made up of multiple authors becomes a normal way to think.

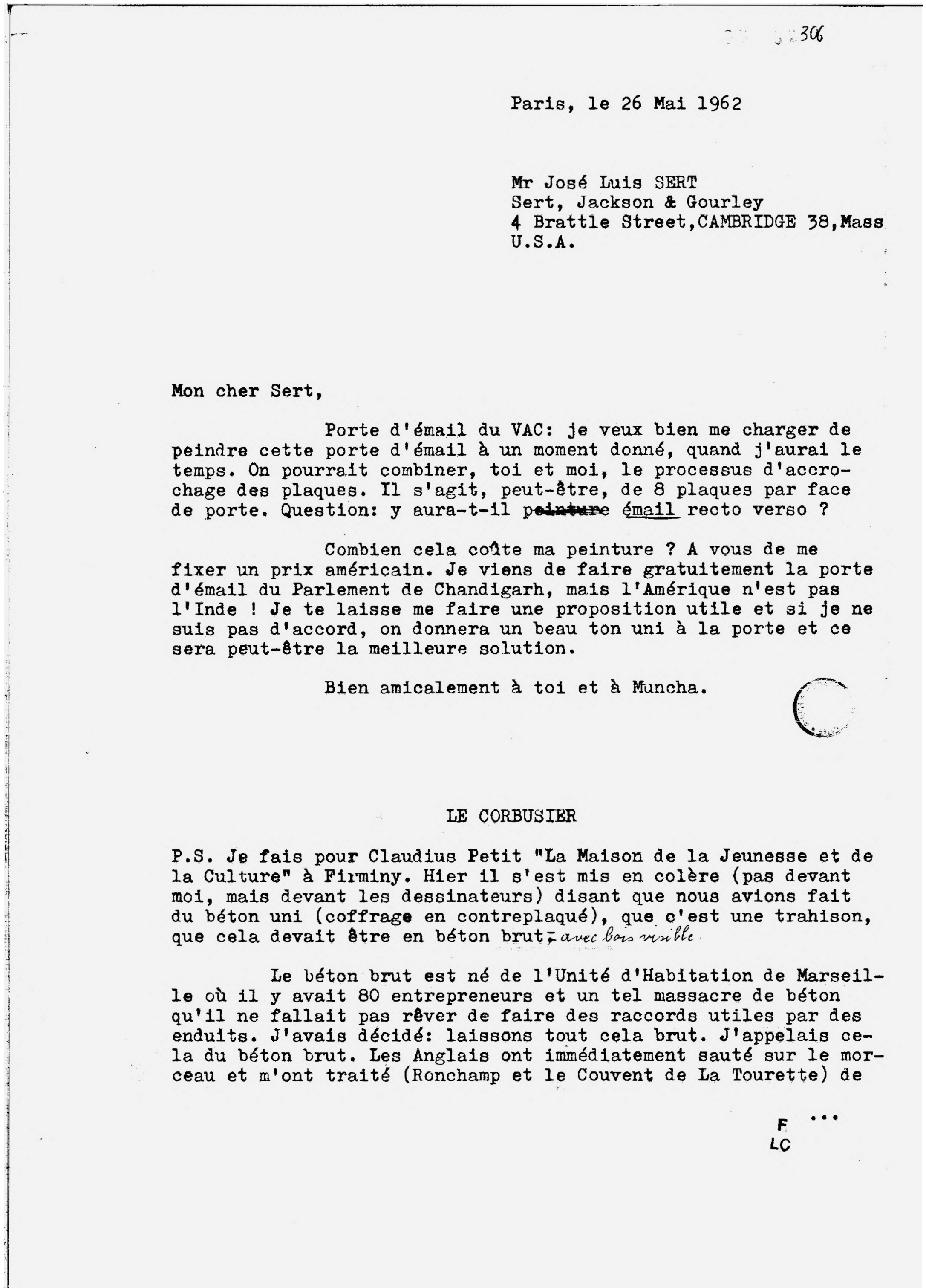
3. FUZZY LOGIC

The statement "All dimensions to be checked on site. Any discrepancies or omissions to be brought to the attention of the architect immediately," or similar outside the UK, is a present and prominent feature of a title block on an orthographic architectural drawing.

This statement is unambiguous and is a declaration intended to offer a degree of harmony between the dimensional relationships of the environments of the building site and the architect's office. The clarity of language and intent signals how high a priority the pursuit of harmony, or architect's control, is. In essence, it presents an opportunity to calibrate the drawn work of the office with the physical environment of the building site, and in doing so augments the drawn information with the character and workings of a physical context. Even though a process of calibration between these environments is important, a degree of improvisation and agility remains at the heart of architectural design and construction in this context—it has to. This improvisation and agility, I think, are the critical ingredients for a successful dialogue between the very different environments of the building site and the architectural office. An unwritten fuzzy logic is at play when these two environments interact.

The effect of translation from drawing to building, the perils of communication between site and office, was also not lost on the modernist architect Le Corbusier either. His Unite d'Habitation in Marseille is a case in point. Le Corbusier wrote a letter to his friend and collaborator Josep Luis Sert in 1962 (Figures 3, 4 & 5). In the letter, Le Corbusier makes reference to the construction of the Unite d'Habitation in Marseille, and the 'brutal concrete.' Le Corbusier openly laments his lack of control during construction and the unintended physical outcome of the in-situ concrete due to the "massacre of 80 contractors."[6] The built outcome was considered acceptable by Le Corbusier, reframed as intentional, and an example of a new way of building using in-situ "beton brut" exposed concrete. The agility of "fuzzy logic" certainly ruled in the Marseille project; but it also represents anexample of an architect manipulating the narrative of the construction process to present a more palatable position of drawn intention and built outcome being identical twins, and the Architect as sole author.

The case study highlights the importance of construction tolerances as a collaborative tool used by all design disciplines, an interdisciplinary tool that facilitates the blurring of traditional disciplinary boundaries. A tool that blurs the meaning of what an architect, engineer, and builder are. Allowing them, almost, to be the same person simultaneously. The specific conditions created by the use of construction tolerances are fundamental to achieving an architectural outcome, and further highlight the idea of fuzzy logic governing how success is measured on a built architectural project. Construction tolerances provide a 'place' for the imagination to thrive, a place for the fast and loose to co-exist.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Paris, le 26 Mai 1962

Mr José Luis SERT
Sert, Jackson & Gourley
4 Brattle Street, CAMBRIDGE 38, Mass
U.S.A.

Mon cher Sert,

Porte d'émail du VAC: je veux bien me charger de peindre cette porte d'émail à un moment donné, quand j'aurai le temps. On pourrait combiner, toi et moi, le processus d'accrochage des plaques. Il s'agit, peut-être, de 8 plaques par face de porte. Question: y aura-t-il ~~peinture~~ émail recto verso ?

Combien cela coûte ma peinture ? A vous de me fixer un prix américain. Je viens de faire gratuitement la porte d'émail du Parlement de Chandigarh, mais l'Amérique n'est pas l'Inde ! Je te laisse me faire une proposition utile et si je ne suis pas d'accord, on donnera un beau ton uni à la porte et ce sera peut-être la meilleure solution.

Bien amicalement à toi et à Muncha.

LE CORBUSIER

P.S. Je fais pour Claudius Petit "La Maison de la Jeunesse et de la Culture" à Firminy. Hier il s'est mis en colère (pas devant moi, mais devant les dessinateurs) disant que nous avions fait du béton uni (coffrage en contreplaqué), que c'est une trahison, que cela devait être en béton brut, avec bois visible

Le béton brut est né de l'Unité d'Habitation de Marseille où il y avait 80 entrepreneurs et un tel massacre de béton qu'il ne fallait pas rêver de faire des raccords utiles par des enduits. J'avais décidé: laissons tout cela brut. J'appelais cela du béton brut. Les Anglais ont immédiatement sauté sur le morceau et m'ont traité (Ronchamp et le Couvent de La Tourette) de

F ...
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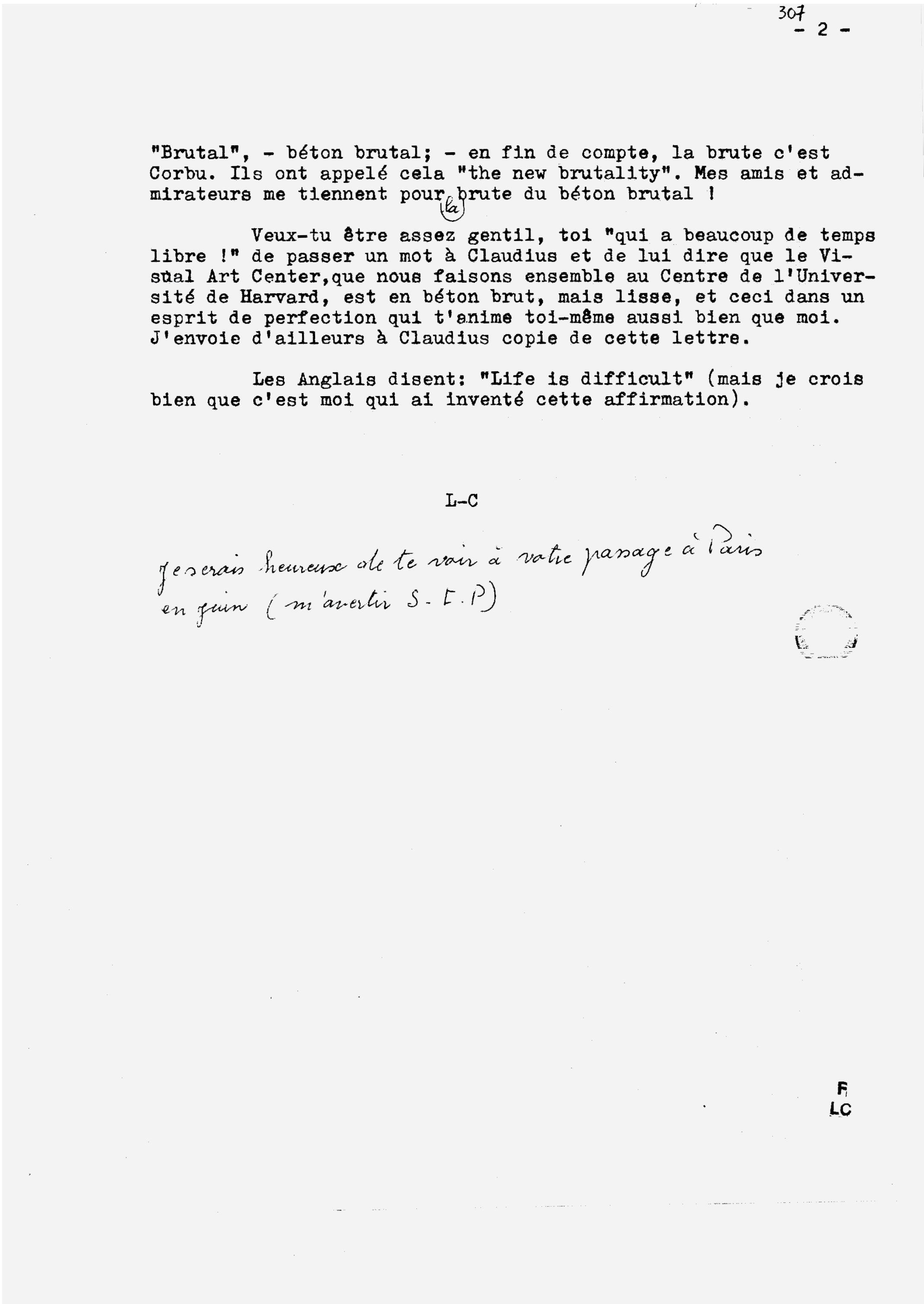
Figure 3: Letter from Le Corbusier to Josep Luis Sert. Source: Ref G3-2-306-001 La Fondation Le Corbusier 1962.



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- 2 -

"Brutal", - béton brutal; - en fin de compte, la brute c'est Corbu. Ils ont appelé cela "the new brutality". Mes amis et admirateurs me tiennent pour la brute du béton brutal !

Veux-tu être assez gentil, toi "qui a beaucoup de temps libre !" de passer un mot à Claudius et de lui dire que le Visual Art Center, que nous faisons ensemble au Centre de l'Université de Harvard, est en béton brut, mais lisse, et ceci dans un esprit de perfection qui t'anime toi-même aussi bien que moi. J'envoie d'ailleurs à Claudius copie de cette lettre.

Les Anglais disent: "Life is difficult" (mais je crois bien que c'est moi qui ai inventé cette affirmation).

L-C

Je serais heureux de te voir à votre passage à Paris en juin (m'avertir S.V.P)

F
LC

Figure 4: Letter from Le Corbusier to Josep Luis Sert. Source: Ref G3-2-306-002 La Fondation Le Corbusier 1962.

Paris, May 26, 1962

Mr José Luis SERT
Sert, Jackson & Gourley
4 Brattle Street, CAMBRIDGE 38, Mass
U.S.A.

My dear Sert,

Enamel door for the VAC: I'd be happy to take care of painting this enamel door at some point, when I have the time. We could work together to put up the panels. It's probably around 8 panels for each face of the door. Question: will there be enamel on both sides?

How much for my paint job? I'll leave it up to you to suggest an [appropriate] American price. I just finished an enamel door for the Chandigarh Parliament for free, but America is not India! You propose something and if I'm not in agreement, we'll just give a nice even tone to the door which might be the best solution.

Best wishes to you and Muncha.

LE CORBUSIER

P.S. I'm doing the Maison de la Jeuness et de la Culture in Firminy for for Claudius Petit. Yesterday he flew into a rage (not in front of me but in front of the draftsmen) saying that the smooth concrete (in plywood formwork) we've done is a betrayal, that it should have been raw concrete [done in wood plank formwork] with the wood [imprint] visible.

Raw concrete was born out of the Unité d'Habitation in Marseilles where there were 80 builders and such a massacre of concrete that one couldn't even dream of plastering. I decided: let's leave all this raw. I called it raw [*brut*] concrete. The English immediately jumped on this bastardizing it (with reference to Ronchamp and the Couvent de La Tourette) as 'brutal' — brutal concrete — at the end of the day, the brute, that's Corbu. They called this 'the new brutality.' My friends and admirers take me for the brute of brutal concrete!

Would you be so kind, you who 'have a lot of free time!' as to pass on to Claudius that the Visual Arts Centre that we're doing together at Harvard's University Centre is in raw concrete but smooth and smooth in a spirit of perfection that not only I but indeed you too find moving. I'll also send Claudius a copy of this letter.

The English say: 'Life is difficult' (but I think despite the fact it was me that invented this affirmation).

L-C

I'll be happy to see you when you come by Paris in June (let me know please)

Figure 5: Letter from Le Corbusier to Josep Luis Sert. Source: Ref G3-2-306-001&002, La Fondation Le Corbusier 1962. Translation into English by Rebecca Loewen, 2018.

4. THE (ARCHITECT'S) OFFICE

The office in architecture comes in various guises. There is a variety of definitions that are used to suggest how an office makes drawings and interacts with the construction processes of architecture. The words Architects, Architecture, Atelier, Workshop, Studio and Design are commonplace, but what do they really mean in relation to the actions within an architect's office? And how do they inform the architect's position in relation to the building site?

They offer us some insight into this positioning and the attempts that are made to demarcate the boundaries between architects who make information,architects who construct, and architects who do both.

Atelier, Workshop and Studio

Places to make 'stuff', experiment with materials, methods of making and the processes that inform their usage. Used to define an architect's office when the intention is to engage with the physicality of architectural construction, an attitude to architecture that is beyond the notations of a drawing on paper.

Architects, Architecture and Design

Perhaps more common, the words have become somewhat blurrier over time in defining the true role of the office they are representing, maybe using more subtle ways to define their ways of communicating with the building site.

As mentioned earlier in the paper, there is a hybrid environment that occupies the space in-between the 'building site' and the 'office'—known as the 'site office', a spatial hybrid.

More recently, the Covid19 pandemic has forced an alternative context onto architecture practices. The traditional physical environment has been dispersed and substituted with an alternative digital environment. Offices have become digitally connected through Zoom, MS Teams etc. Only a laptop (or smartphone) and an internet connection are required to establish a connection to an office community, albeit in a very different environment. Geographical location is no longer important and the physical space beyond the home, no longer essential. It is unclear if this will permanently change the nature of communication between architect and contractor, or the relationship between the environments of the building site and the architect's office. The question is what are the implications of this shift?

Firstly, it would be useful to explore and discuss the notion of expectation and what is a reasonable expectation in terms of the information contained in and on an architectural drawing. With its roots in words such as "skill" and "judgment" the word "reasonable" is linked, professionally, to the obligations and knowledge beyond that of a layperson. In the professional context of architectural practice and building construction, the skilled execution of knowledge and the reliance on academic and industry training are what drives the action of an architect and how they carry out their duties.

Skill and judgment are what, then, drive the production of information for construction in architecture, and are expressions of knowledge. If the drawn outputs produced by an architect are viewed through a binary lens of right and wrong, the architect has no room or place for intended ambiguity in the information they produce for construction—but we know that this is not true. Contingency, ambiguity and planned imprecision are important components of the design and construction process. The ability to judge a given situation of a project requires not only skill but also experience. The architect, therefore, develops a knowledge and understanding of 'what is reasonable' when executing a drawing. Or if they choose to do so, the location of ambiguity has to be very precisely defined and

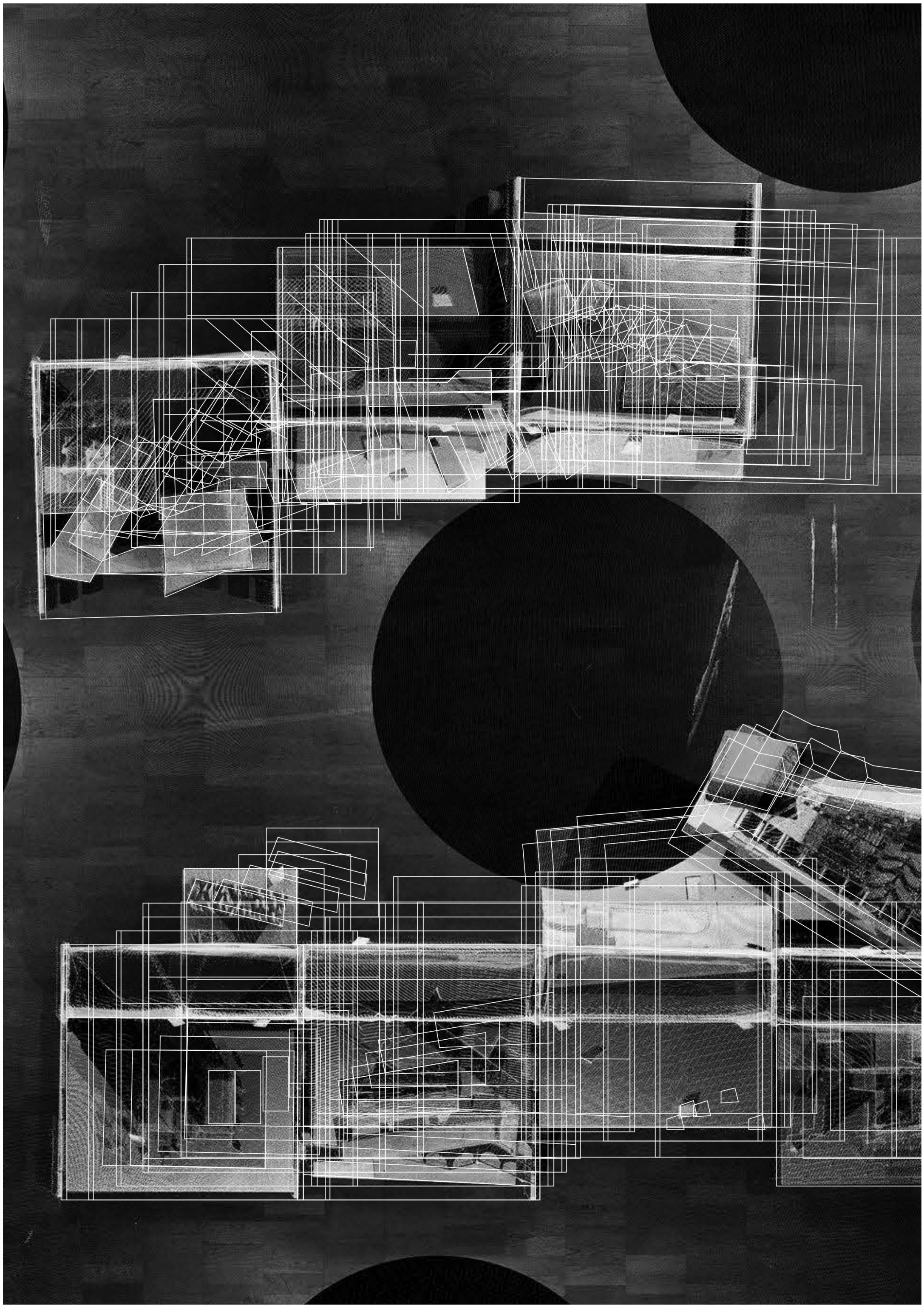

Figure 6: ‘There or Thereabouts #1’ Experimenting with imprecision through drawing, making, and scanning. Source: Paul King, Sheffield 2018.

managed. Some would say that there is a need for at least a degree of ambiguity, or contingency, in the drawn information used for construction on site. This is because 'he drawn' and 'the made' belong to different design environments and their relationship is not as straightforward as we like to think it is.

The definition of the word reasonable is clear and imprecise at the same time. Specific context seems to be the most important driver here. The imprecision I refer to seems to offer the scope for a variety of correct outcomes that are simultaneously defined as reasonable. By extension, and logic, the nature and meaning of the word reasonable at any given time, and context, can be described as fuzzy.

CONCLUSION

There are several ways to interpret and conclude this paper. I believe the central conclusion is one of an appreciation and understanding that fuzzy logic, ambiguity, contingency and planned imprecision are central driving forces in the production of architecture (Figure 6).

An unwritten, fuzzy, agreement between those involved in a project supersedes the drawing as the authority for a project. Even the precision of dimensional accuracy is called into question on a project, in that fuzziness reconciles a built outcome with its drawn intent.

> In general, I try and distinguish between what one calls the Future and 'l' avenir' [the 'to come']. The future is that which—tomorrow, later, next century—will be. There is a future which is predictable, programmed, scheduled, foreseeable. But there is a future, l' avenir (to come) which refers to someone who comes whose arrival is totally unexpected. For me, that is the real future. That which is totally unpredictable. The Other, who comes without being able to anticipate their arrival. So, if there is a real future, beyond the other known future, it is l'avenir in that it is the coming of The Other when I am completely unable to foresee their arrival.[7]

Jacques Derrida states this clearly when highlighting that two futures are possible, 'Le Futur' and 'L' Avenir'. We like to think that Architectural production sits neatly within the definition of 'Le Futur' but really Architectural production tends to sit better with the concept of 'L' Avenir'. Moving from drawn intent to built outcome, or Architectural production, is unpredictable and imprecise but we pretend it is not.

ENDNOTES

1 Sennet, R. 2009. *The Craftsman*. London. Penguin
2 www.soane.org
3 www.soane.org
4 www.soane.org
5 www.soane.org
6 Le Corbusier. 1962. Letter to Josep Luis Sert Ref G3-2-306-001&002. France. La Fondation Le Corbusier.
7 E. White, 2007. *A Passage toward the Other: The Legacy of Jacques Derrida (1930-2004), European Legacy*. Online. Routledge

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EXPLORING THE CRAFT OF SEWING MACHINE-FACILITATED NOVEL EARTHBAG GEOMETRIES

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Pennsylvania State University

The earthbag, or flexible-form rammed earth wall system, is a low-tech building system that can be used to quickly erect emergency shelters for disaster relief or, alternatively, to construct "do-it-yourself" homes within the context of self-building construction. Because the required building materials are affordable and the construction method easy to replicate and teach, earthbag construction is more accessible than comparable building systems that require certifications. This study aims to explore the impact of machine-facilitated bag craft on earthbag building processes, with regards to bag production, sewing craft and reducing on-site tooling. Following a literature review, a design-as-research methodology approach with a sewing machine is used to replicate existing earthbag geometries and generate novel geometries, varying in bag material and production process. The first part of the study catalogs bag fabric material behavior when sewn, instructions for sewing existing and new geometries, and selects one novel bag prototype, the Surprise-Star, as a case study for preliminary stacking assessment. The second part of the study catalogs the craft experience of modified earthbag geometries intended to substitute existing tools used on-site, which culminates in an assessment of the feasibility of sewn novel earthbag construction.

Keywords: Earthbag construction, sewing craft, do-it-yourself, earthbag production.

1. FRAMING THE RESEARCH

1.1. BACKGROUND AND RATIONALE

Earthbag construction is a type of rammed earth building method that utilizes the earthbag's material flexibility and capability to support earth as it is transported, stacked, compressed, and hardened on site. The conventional earthbag wall system consists of earth-filled bags that are tamped and strengthened with barbed wires between each course that strengthen the wall's tensile strength (Khalili & Vittore 1998). The bag itself serves as an alternative to traditional wood forms and is easier to replicate and mass produce. In addition to their inexpensive cost, earthbags often utilize locally sourced earth, effectively reducing or eliminating energy use when transporting materials to the building site (Wojciechowska 2001). Due to the simplicity of its construction process, earthbag construction is an affordable and easily replicable building system that can be erected quickly (Geiger 2009). Its quick and simple building methodology makes earthbag construction suitable for responding to disasters. Within the context of craft, earthbag building techniques are passed down by experts in training workshops and "do-it-yourself" guides, making it more accessible than building techniques that require certifications.

Because the earthbag is primarily considered as a container for carrying earth, it is underdeveloped as an architectural element with regard to spatial expression and quality. Currently, earthbag geometries can be categorized into two types: single-unit bags laid in a stacked course, and tube bags that coil in layers (Hunter & Kiffmeyer 2004). The flexibility of the bag material, which varies between burlap and polypropylene fabric, allows the earth to be sculpted into organic forms and domes (Khalili & Vittore 1998). With the aid of external forms, earthbag geometries can be manipulated into curves and keys for arched openings. Sculpting earthbags in this way, however, occur on-site and after the bags have been filled and begets the question: is there a way for the earthbag to be transformed off-site and before the bags are filled? Could this eliminate the need for additional tools, forms, or materials used to construct the earthbag wall on-site?

As a form of craft that is also democratically accessible, machine sewing, in this study, is regarded as the fastening of textile objects together with needle and thread, and the hand-making skill associated with it. The sewing machine is considered in this study as a vehicle of craft accessibility that shares parallels with conventional earthbag construction: (1) both incorporate standardizing tools for democratized use among many types of users, (2) increased usability through adaptive design, (3) teachability to the less-skilled, (4) material variability in craft, and (5) celebration of the user's capacity in hand-operated crafts. This research aims to explore how machine-facilitated earthbag crafting can impact earthbag building processes, with regards to bag production, sewing craft and reducing on-site tooling through the creation of alternate bag geometries.

1.2. METHODOLOGY

Following a literature review of existing earthbag construction guides, which include "do-it-yourself" and emergency applications, explorations on sewing machine-facilitated earthbag geometry were conducted in two parts. The first part focuses on understanding the behavior of fabrics, both conventionally and unconventionally used in earthbag construction, when sewn with a machine. Primary design explorations intended to increase tactile experience in bag-making involved replicating existing earthbag geometries with alternate materials, such as cotton fabric, canvas tarp, medium-duty woven polypropylene fabric, and spandex. Conventionally-used materials, such as low-duty woven polypropylene fabric and burlap are examined in the same manner. After replicating existing earthbag geometries and understanding shape relationships during the bag sewing process, a novel Surprise-Star geometry was generated and selected for further examination for potential application in bag-to-bag stacking relationships, with a focus on understanding how changes in geometry can begin to impact the building construction process and the resultant wall. The second part of the research focuses on earthbag modifications and their feasibility within the scope of "do-it-yourself" construction, with regard to craft difficulty, material consumption, and replicability. Preliminary prototype bags were designed and replicated with a sewing machine, with the goal to specifically reduce on-site tooling, such as eliminating a bag stand, during the construction building process.

2. CRAFTING ALTERNATE EARTHBAG GEOMETRIES

Since fabric weaves perform differently due to variations in thread size, material, directionality, and shape, it was essential to first understand the behavior of the different fabrics when assembling earthbags on the sewing machine. Differences in the physical characteristics of the weave impact how the fabric is cut, handled, and stitched during the sewing process. Within the scope of conventional earthbag construction, earthbags are made from woven polypropylene or burlap fabric (Hunter & Kiffmeyer 2004). Each material possesses its own advantages and disadvantages that impact the construction of the earthbag wall and stitch depending on the fabric weave. For example, the flat weave of woven polypropylene makes the fabric more durable to abrasion than burlap fabric, which is woven from twisted jute string. While burlap fabric is natural and biodegradable, its rounded threads and loose weave makes the fabric unsuitable for holding fine particulate earth fills (Wojciechowska 2001). For the research, conventional materials handled include burlap and low-duty polypropylene fabric. Unconventional fabric materials handled in the research are medium-duty polypropylene and painter's tarp fabric.

2.1. HANDLING AND SEWING EARTHBAG FABRIC MATERIALS

As mentioned previously, burlap fabric is woven from jute string, which is an organic and sustainable material. The loose weave makes single-line stitching less ideal when attempting to sew burlap fabric together. Instead, zig-zag stitching is more appropriate for making burlap fabric earthbags. Compared to polypropylene, burlap fabric is heavier and more expensive (Wojciechowska 2001); the bulkiness of the fabric makes sewn hems and folds thicker and comparably less precise than sewing similar folds on polypropylene.

Low-duty woven polypropylene when cut is easy to unravel, and the material loses its weave when the cut edges have not been sealed. The resulting instability of the fabric's cut edge complicates the sewing process because a consistent stitch cannot be applied to the loosened material. To properly seal the edge, an adhesive layer should be applied to the weave and pressed with heat. Heat must be applied through a flat-press method to hold the weave while the adhesive bonds them together because the polypropylene material tends to contract and crinkle when exposed to heat.

Medium-duty woven polypropylene is the same material as the low-duty material with the addition of an adhesive layer on both sides of the fabric. Because it is made from three layers—woven polypropylene bonded between two plastic adhesive layers, the fabric is more durable when cut and easier to sew together. When cutting with a straight-edge scissor, a seamstress can glide the tool across the fabric with less resistance and catch than the more unstable low-duty version. The flat weave allows many stitches to be applied to seams—for simple sewing, single-line stitches were primarily used when handling this material.

The canvas tarp or painter's tarp is a woven rough cotton fabric with a plastic membrane underside that prevents moisture from seeping through the fabric. The cotton weave is also treated to reduce unraveling and adhere to the plastic membrane, allowing it to maintain its shape when cut. The fabric is easy to sew, lightweight, and, due to the plastic membrane, can hold its shape slightly better than plain woven cotton fabric. This material, however, does not hold its shape as well as polypropylene. Compared to the burlap, the canvas tarp has a tighter and thinner weave, making single-line stitching suitable for sewing it together.

2.2. RE-CONSTRUCTING THE EARTHBAG SHAPE

Another element of the bag construction is the shape of the earthbag, which in this study was geometrically deconstructed and assessed for material consumption. Prior to assembly on the sewing machine, individual parts were measured and cut from larger material sheets. Similar bag geometries were observed to vary in sewing complexity and material consumption, despite having the same dimensions, material, and size. The bag geometries were reproduced at 1:4 scale and the bag dimensions mentioned in this paper will refer to the intended full-size earthbags for the purposes of instruction. Dimensions and same-shape pieces were limited to 45cm (18in) widths and 76cm (30in) lengths, which are derived from the conventional 50lb polypropylene earthbag sizes noted by Hunter and Kiffmeyer (2004) as well as common hessian-bag width by Wojciechowska (2001). Variables include the number of pieces and edge-to-edge connections for each geometry.

The Sack or Pocket geometry consists of two rectangular pieces that are overlayed on top of each other and sewn along three edges. This geometry is the conventional geometry that is used in earthbag construction, both in off-the-shelf products and repurposed items of similar shape (i.e. – animal feed bags or rice sacks). Alternatively, it can also be constructed from a singular rectangle piece that is double the length; a piece that has a 45cm (18in) width and 152cm (60in)

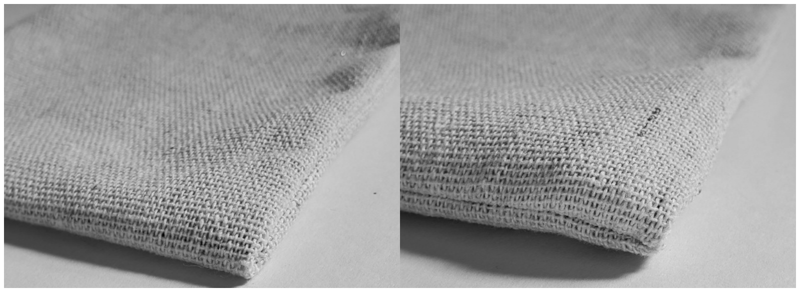

Figure 1: Side-by-side photographs of folded end (left) and two-piece (right) end condition. Source: Author 2022.

length can be folded in half lengthwise and sewn along the two edges adjacent to the fold. Each version results in a two-sided bag that is flat when empty, as shown in Figure 1. Although both sewing processes yield the same bag geometry with the same amount of fabric material, the single-piece version requires fewer cuts and less sewing thread.

The U-panel geometry, which is derived from construction methods used in polypropylene factory-packing bags, is constructed from overlapping two 45cm (18in) width by 197cm (78in) – subdivided by a 76cm (30in), 45cm (18in), and 76cm (30in), length rectangle pieces perpendicularly in cross orientation. The total overlapped area in the center is a 45cm by 45cm (18in by 18in) square. A single-line is stitched diagonally on the square, running from corner to opposite corner. Another line is stitched on the remaining corners to create an X that fixes the rectangle pieces together, as shown in Figure 2. The remaining 76cm (30in) edges are sewn together so that the resulting geometry is a five-sided rectangular prism with an open top.

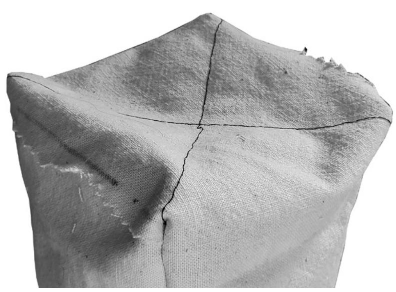

Figure 2: Crossing two single-line stitches to attach planar surfaces together. Source: Author 2022.

The Four-panel geometry, derived from another polypropylene factor-packing bag variant, is constructed using four 45cm (18in) width by 76cm (30in) length rectangle pieces, or panels, and one 45cm by 45cm (18in by 18in) square bottom piece. Each rectangle piece is sewn to another rectangle along their 76cm (30in) long side to create a four-sided open rectangular prism shape. The square bottom piece is sewn to close one of the sides, creating a five-sided rectangular prism with an open top. Compared to the U-panel geometry, which possesses identical surfaces, this geometry utilizes less material, but requires more total parts.

2.3. CASE STUDY OF THE SURPRISE-STAR DERIVATIVE GEOMETRY

To reiterate, the first part of the research sought to explore the manipulation of same-shapes to create different earthbag geometries. As hinted before with the Sack/Pocket, U-panel, and Four-panel geometries, the same and nearly-similar rectangle and square shapes can be used to generate different configurations or methods of sewn bag construction as long as they share the same measured edges. Following the logic of same-measured edges, the 45cm (18in) measurement was adjusted to be a factor of all measured edges to allow for all edges to be sewn proportionally. One possible geometry resulting from this change is the Surprise-Star geometry. The prototype is 1:4 scale, but the following measurements will refer to the intended dimensions for full-sized earthbags.

The Surprise-Star geometry is constructed from two 45cm width by 90cm length (18in by 36in) rectangle pieces and uses the same amount of material as the Pocket geometry. Each rectangle piece is folded in half along its 90cm (36in) edge and sewn along one of the newly generated 45cm (18in) edges, from the fold to the corner. This transforms the rectangle pieces into pinched cone geometries that have an opening profile of two 45cm (18in) edges and one 90cm (36in) edge. One cone is then partially inverted in a manner so that the unsewn edges perfectly overlap with the inside edges of the other cone. Then one 45cm (18in) and 90cm (36in) overlap is sewn, leaving a 45cm (18in) opening. The resulting geometry is an eight-sided polyhedron that can be manipulated once more to form a six-sided polyhedron, as shown in Figure 3.

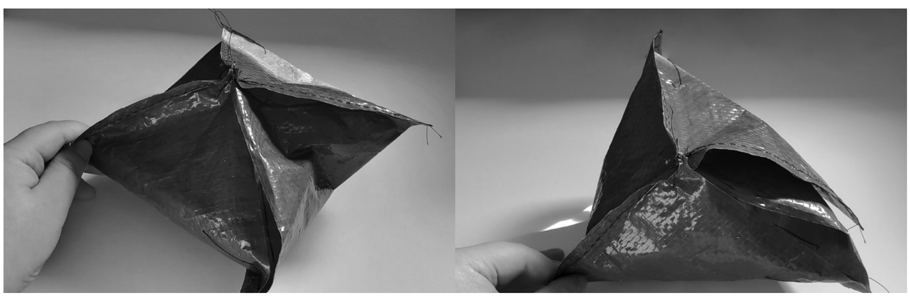

Figure 3: *Surprise-Star* transformation from four-points (left) to three-points (right). Source: Author 2022.

In conventional earthbag construction, when stacking Sack/Pocket bag geometries, the stacking surfaces are aligned relatively parallel to each other and tamped so that the top surfaces are even and level. When transporting U-panel and Four-panel geometries, the bags, which are rectangular and orthogonal, can be stacked on top of each other evenly. In contrast, the generated Surprise-Star geometry does not have a continuously flat surface for parallel stacking. Therefore, to observe the relationship between Surprise-Star earthbags and potential reductions of on-site tooling, additional Surprise-Stars were produced, filled with the same medium, and arranged in various wall configurations at a rudimentary level. In this case study, the medium-duty woven polypropylene Surprise-Star earthbags were selected for study and replicated following the described instructions.

To understand how this geometry can influence the building process, the Surprise-Star earthbag courses were laid in a manner to take advantage of the geometry of the individual bag. The pyramidal top of the eight-sided Surprise-Star earthbag, when arranged side-to-side with an identical bag generates a valley surface condition that can potentially serve as a pseudo form (a three-dimensional template of sorts) for a sequential course. If lower earthbag courses could support and isolate upper courses in a manner that prevents slippage, could a Surprise-Star earthbag wall eliminate the use of barbed wire and rebar within the construction? Simple stacking exercises were used to assess the feasibility of the geometry in various wall configurations: line, L-shape corners, T-shape perpendicular joints, and 2 by 2 squares.

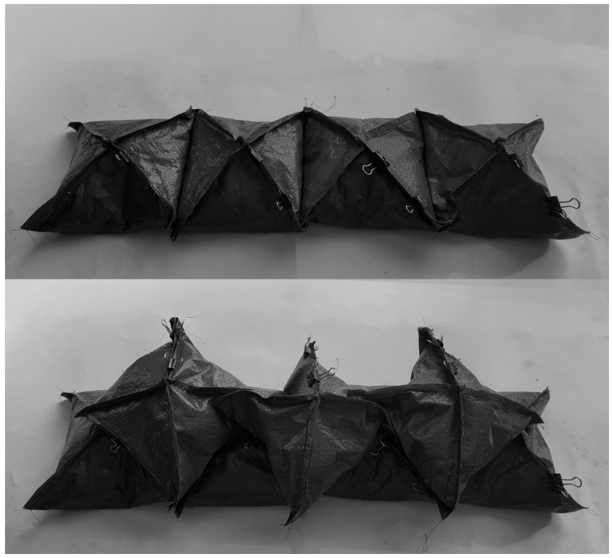

Figure 4: *Surprise-Star* valleys can support other *Surprise-Star* earthbags. Source: Author 2022.

When arranged orthogonally in a line, the Surprise-Star bags create a valley-and-hill form along the top surface of the earthbag wall course. The valleys can serve as a supporting form for the next course, albeit in a different orientation; the second course in the line arrangement features Surprise-Star bags that are rotated 45 degrees to fit into the valleys, as seen in Figure 4. In the third course, the bags are rotated 45 degrees again to create an orthogonal arrangement like the first course in the wall. To summarize, the odd courses, as a result, are orthogonal while the even courses feature bags rotated 45 degrees in the wall.

When arranging the corner in an L-shape, the first course of the Surprise-Star earthbag stack can be neatly arranged because the profile of the bags in the plan is rectangular. In the following course, the Surprise-Star bags are not able to fill in the corner of an irregular valley condition there. As a result, by the third course, the corner of the wall begins to deviate from the layout of the first course. A rigid corner material to support the Surprise-Star as a filling medium or increasing the thickness of the wall to two Surprise-Star bags can give the corners more stability. Alternatively, when arranged in a T-shape, the presence of a perpendicular wall provides the primary wall with stability when stacking, despite the upper layer deviation observed in the L-shape array. Similarly, the corners can be strengthened with a supporting material, such as chicken wire or metal mesh, or with wall thickening (Geiger & Zemskova 2015).

The Surprise-Star earthbags, when stacked in a 2 by 2 square, are comparably more unstable the further the layers rise above the ground. The uneven distribution observed in the L-shape array is multiplied with the introduction of three more corners in the square, causing more slippage between earthbag layers, as seen in Figure 5. This slippage aligns with stacked sandbag behavior, particularly in structures lacking tensile strength (Khalili & Vittore 1998). On that note, the eight-sided Surprise-Star sewn from polypropylene is not ideal for a 2 by 2 formation. The pile can be strengthened with the addition of supporting rigid material or with buttressing elements (the former option distorts its spatial identity as a column, however).

Reflecting upon the Surprise-Star geometry, the undulating polyhedral form of the Surprise-Star wall contrasts greatly with the smooth planar surfaces of conventional earthbag walls, offering a different spatial expression with regard

Figure 5: Gradual slippage of *Surprise-Star* earthbags in a 2 by 2 square alternating stack sequence (left to right). Source: Author 2022.

to contrast and texture. Yet, as the Surprise-Star wall is built vertically, the layers deform in a manner that increases irregularity within the wall, particularly with regard to unfilled space and slip-prone surfaces. This could be remedied with a different fabric material, earthbag fill, or a secondary supporting system, such as mesh or ties, to hold the bags in place, as suggested by Geiger and Zemskova (2015). This shows that the combination of the Surprise-Star geometry, medium-duty woven polypropylene fabric, and dirt medium is not effective in eliminating barbed wire, rebar, or similar supporting components from the earthbag construction. However, arising from the Surprise-Star exploration was not only a novel earthbag geometry as a product, but also an altered earthbag construction process that was expanded to include bag-making and sewing craft.

3. EARTHBAG MODIFICATION AND DIY CRAFT FEASIBILITY IN CONSTRUCTION

The next phase of the research sought to understand the significance of earthbag craft and production within the context of “do-it-yourself” making processes by cataloging novel prototypes derived from manipulations of conventional earthbag geometry. In “do-it-yourself” earthbag construction, earthbags are often purchased off-the-shelf or recycled from approximately 45cm by 76cm (18 inch by 30 inch) sack-shaped bags (Geiger 2009). Prospective builders are recommended to acquire misprinted commercial bags or recycled feed bags to save money prior to the building construction (Hunter & Kiffmeyer 2004). “Do-it-yourself” earthbag building construction has a frugal and resourceful connotation associated with the act of self-building. Therefore, the cost of materials and the effort invested in hand-making the earthbags are considered in bag production. All the prototypes share the same starting 45cm by 76cm (18 inch by 30 inch) dimensions, TERA 80 sewing thread, and single-stitch seams. The variables will be the supplementing material used to modify each earthbag prototype and two types of polypropylene fabric. The introduction of modifications to the base 45cm by 76cm (18in by 30in) earthbags sought to explore ways in which tools could be eliminated during the on-site building process. The earthbag prototypes were constructed at 1:2 scale but the paper will refer to the intended full size for purposes of instruction.

3.1. REDUCING TOOLS

The Drawstring modification requires open edges of the base geometry to be folded and sewn around a string, which can be jute, nylon, or any alternate material, that is free enough to pull and cinch the edges closed. The addition of a drawstring part allows the earthbag to carry more amounts of earth, and be sealed and resealed. Prototypes using the Drawstring modification could reduce the number of earthbags used in the wall in exchange for generating heavier and more packed bags.

Figure 6: An emptied *Bi-Cinch* prototype opening detail (left) and filled side view (right). Source: Author 2022.

Alternatively, while the Drawstring modification requires an edge to create a string-wrapping hem, the edge of the base geometry can be cut freely on the earthbag. One example of an alternate design is to reposition the bag's opening to run midway across the 76cm (30 inch) length, bisecting the geometry. The addition of Drawstring modifications in the bisecting center of the bag geometry transforms the conventional Sack/Pocket geometry into a folded one, named Bi-Cinch, as shown in Figure 6. The centered fold allows the earthbag, particularly if sewn from a semi-rigid material such as woven polypropylene fabric, to stand up by itself or hang on a rigid line or pole. As a result, this geometry simultaneously eliminates the need for a bag stand and allows the earthbag to be supported by a simpler supporting apparatus. Additionally, since this geometric manipulation involves the Drawstring modification, the Bi-Cinch prototype is also capable of containing more earth.

The Corner-stitch modification is created by stitching two adjacent corners along a closed 45cm (18 inch) length to create a folded loop, as shown in Figure 7. Fixing two corners of the geometry together curves the end while also creating a handle on the earthbag without adding supplementary materials. Furthermore, the creation of a handle or loop on the geometry eliminates the need to puncture the earthbag with rebar when reinforcing the wall. Instead, vertical supports can be inserted into the loops to hold multiple bags in place; the introduction of vertical support around the Corner-stitch modifications also allows the earthbags to be stacked axially.

The Embedded stick modification is characterized by sewing hems along the surface of the base earthbag geometry and threading dowels inside them. The hems are sewn to be at least twice the diameter of the dowels to allow

Figure 7: A schematic *Corner-Stitch* modification on a commercial low-duty woven polypropylene earthbag. Source: Author 2022.

enough space for the new materials to be embedded into the fabric. The insertion of dowels within the surface of the geometry adds rigid edges to the earthbag that will not deform when packed with earth. Depending on the placement of the dowels, an earthbag surface can be modified to reduce slippage between layers.

3.2. MATERIAL CONSUMPTION AND HANDICRAFT

In exchange for the prototype's potential to reduce or eliminate on-site tool use in earthbag construction, the new geometries, as mentioned previously, add materials to the earthbag. The Drawstring prototypes, for instance, require one or two strings to pull the earthbag shut. Supplementing strings, not only need to be measured to an appropriate length, but they need to be threaded into the earthbag either during or after the sewing process. When threading the drawstring post-sewing, a needle or threading tool, such as a hook or straw, needs to be used; depending on the tool, the hem dimensions need to be adjusted accordingly, as shown in Figure 8.

The Bi-Cinch prototypes, because they use two Drawstring modifications, require double the amount of string. Doubling the material doubles the amount of time required to assemble that part, meaning more time spent threading the string through the added hems. Conversely, the Corner-stitch prototypes, because they only require sewing the corners of the original bag geometry, only consume a minute amount of thread during the sewing process.

The Embedded stick prototypes, on the other hand, require multiple hems to be sewn into the surface of the earthbags and a proportionate number of supplementing dowel materials. Depending on the number of modifications within each earthbag, the Embedded stick prototypes consume a lot of material, time, and effort in precisely sewing the correct lengths and threading dowels. Furthermore, the Embedded stick modifications, if intended to reduce slippage, do not outperform the conventionally used barbed wire, and can also be substituted by changing the bag material with a more frictional surface.

3.3. REPLICABLE CRAFT FEASIBILITY

All the earthbag prototypes in this study were mass-produced with the sewing machine and followed defined instructions for replication. To increase accessibility by providing instructional flexibility, there were two versions of bag-making guidelines for each prototype: 1) from sheet fabric and, 2) modifying existing bags; all earthbags were modified from existing off-the-shelf polypropylene sandbags or from pieces measured from sheet material using a template. Within the scope of replicable "do-it-yourself" craft, using a template allows non-polypropylene materials to be used for sewing new earthbags while repurposing off-the-shelf products allows quick minute changes via modifications. Using a template

Figure 8: Photo of a commercially available threading tool, or straw, threading an earthbag hem. Source: Author 2022.

facilitates easier marking, cutting, and trimming of earthbag fabrics and increases the craft accessibility of sewn earthbag production to less-skilled hands.

With regards to the individual prototypes and modifications, instructions that had simpler steps and fewer supplementing materials were easier and faster to replicate. For example, the Corner-stich prototypes did not require many additional materials to be inserted into the earthbag. This meant that not a significant quantity of materials needed to be handled during the bag crafting process, which is notably less than the Embedded stick prototypes, which require more finesse in handcrafting. Similarly, the Bi-Cinch prototype, because it is essentially a combination of two Drawstring prototypes, requires builders to make the modification twice on the same geometry.

Complications during the crafting process were linked to material properties. For example, when repurposing off-the-shelf sandbag products, which are optimized for cost and disposability, difficulties in sewing the polypropylene resulted in more time being spent attempting to prevent the fabric from unraveling. While it is possible to apply and heat adhesive layers to stabilize the low-duty woven polypropylene fabric, it is simpler to purchase or use medium-duty polypropylene fabric. The option to select more durable fabrics, while more expensive than repurposing bags, makes crafting the bags easier and more manageable.

To clarify, this does not delegitimize low-duty polypropylene, however. Instead, the instructions sampled in Chapter 2.2 Re-Constructing the Earthbag Shape, by explicitly only defining fabric parts and shapes, leave the possibility of using fabrics not mentioned in this paper. The act of sewing earthbags by hand is a more intimate way for builders to process their materials; through continuously selecting, feeling, interacting, and working with fabrics, the sewing machine, and geometries, builders increase their knowledge and crafting skills with each sewn bag.

4. CONCLUDING REMARKS AND FOLLOWING RESEARCH

This paper sought to investigate how using the sewing machine to create novel earthbag geometries can change the earthbag construction process in terms of bag production and reducing the use of tools on the construction site. The sewing machine served as a vehicle for creating geometries that replaced on-site tooling with off-site bag modifications that added value to earthbag craft, reflecting a direct impact of the sewing machine on the construction of the resultant wall. Added value to earthbag craft includes the handicraft experience associated with experimenting and handling different materials, testing stitches, and planning how to construct individual bags. Sewing alternate earthbag geometries gained value within tactile craft-learning while simultaneously attempting to improve on-site earthbag construction.

The primary focus of this research sought not to explicitly improve the performance of the resultant earthbag wall, but rather explore how changes in on-site construction processes can be facilitated through the craft of actively manipulating earthbag geometries. Production of the novel earthbags generated in this research also sought to increase accessibility through the tactile understanding of materials, sewing craft, and knowledge formulation within the context of "do-it-yourself" earthbag building and bag-making that can be shared with others, hence the initial abstraction of earthbag geometries to assembled sheets.

In terms of open questions, while the research investigated preliminary considerations of earthbag craft, geometric manipulations, and tool substitution, it did not investigate another core component of earthbag construction: namely, the earth medium used to fill the bags. In conventional earthbag construction, the earth varies depending on the site, making each earthbag building intimately related to the environment it is placed. The stability of a compressed earthbag unit depends on the stabilization of the earth mixture, which can be strengthened with cement or clay. Furthermore, the presented research did not include tamping or discussion on compressive forces on the earthbag geometries. Future stages of the research, therefore, incorporated filling the novel earthbags with naturally stabilized earth that was available locally and tested varying tamping strategies during wall-building construction processes (Leung 2022).

The methodology for future work included a framework that compared the on-site construction parameters of conventional earthbag and similar wall systems, which was used as a benchmark for evaluating the suitability of novel earthbag prototypes as modular units intended to support compressive forces. This framework included the conventional earthbag system, SuperAdobe coiled earthbag system, hybrid earthbag systems, and rammed earth. Taking into consideration an expanded building process that includes machine-facilitated earthbag production, sewing craft and earthbag replicability of the earthbag prototypes were assessed; this included strategies used to improve bag production and efficiency, such as alternate sewing techniques and the use of standardized templates. Then, physical simulations of subsequent novel prototype-walls were built to include a stabilized earth mixture and ramming. During the construction of each wall, it was important to document how the geometry changed in three parts: (1) immediately after being filled with earth, (2) after ramming within the wall, and (3) while supporting the weight of earthbags on top. Most importantly, the research conducted outside of the work presented in this paper assessed prototyped earthbags, not in terms of modular earthbag performance, but in terms of improving safety and labor during on-site earthbag construction

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KNITTED TENSILE MEMBRANE TENSEGRITY HELIX-TOWER

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This paper explores the development and research of knitted tensile membranes used within tensegrity structures. The research explores the historical context of tensegrity, as well as contemporary precedent projects. The final design explores a workflow and novel prototype for a tower using bending active helix-shaped rods connected and held in suspension with the knit membranes. This structure explores the possibilities for lightweight deployable construction methods, as well as the resulting structural integrity of tensegrity modules. The process of design and fabrication is a feedback loop between physical and digital models, at each phase scaling larger to create more precision and accuracy in design prediction. Furthermore, through this process designer's intuition and knowledge about working with the materials is developed. The final design is lightweight and generates aesthetic qualities, which are representative of the distribution of forces on the material. The design resultantly creates a large volume and spatial presence for using very few materials.

Keywords: Textile, tensegrity, membrane, structure, knitting.

1. INTRODUCTION

Knitted textiles are not typically used as a performative material. In this case study, knit membranes are explored as a participating part of a tensegrity structure. There are many precedents for tensile membrane architecture, although these examples are typically found as lightweight roofs and building skins. In these cases, the textile membranes create an enclosure and are held up with a combination of a rigid structure or using tensioned steel cables. Meanwhile, tensegrity models are made with linear struts and cables. The load transfers between tension and compression members to create a balanced system where the compression members do not touch one another and are held in constant suspension by the tensioned elements (Pugh 1976).

The objective of the design in this research is to replace the tensioned cables with a knitted tensioned membrane to create a hybrid model of tensegrity and tensile membrane structure. The process throughout this research explores the use of knitted textiles as these tensioned membranes. Resulting in the need to develop a unique workflow that explores a method of feedback from digital design to physical studies, and computational physics simulation. The methods for predicting knit membranes are not very advanced and thus this workflow hopes to overcome these deficits by gradually scaling the design through a multi-phased digital and physical process. At each point in the process, different methods of evaluation inform the next phases of the process creating an informed method of working where the designer develops knowledge and intuition.

The resulting prototype is a 2.74 meters (9 feet) helix structured tensegrity tower. The design explores the possibilities of using membrane tensegrity structures, which are ultimately lightweight, deployable, and at a small architectural scale. The resulting volume of space generated by the design is large in comparison to the volume of raw materials used. The assembly process for the final construction was simple and took no tools to put together. The prototype structure was developed and fabricated while Virginia Melnyk was an artist in residence at Arts Letters and Numbers.

2. TENSEGRITY

2.1. HISTORY

Tensioned structures are for the most part a modern development, made possible due to the advancements in building materials. Historically, many structures were built with stone, and bricks which are only structurally stable under compression forces. Wood is one of the few traditional materials used in architecture that has tensile properties. Although most traditional wood-designed buildings are not using it specifically for their tensile property alone.

A few examples of traditional tensioned structures are those of rope bridges, which often required large amounts of annual maintenance (Pugh 1976). These structures used natural fibrous materials which would degrade over time and have size limitations. Modern steel cables have made tensioned structures a more viable large-scale structural option, as the material is strong and long-lasting.

2.1. DEFINITION

Tensegrity was developed by three key designers, Richard Buckminster Fuller, David Georges Emmerich, and Kenneth D. Snelson. Although there were other designers also exploring these types of structures earlier, the three fore mentioned designers are most commonly credited (Gomez-Juaregui 2010). Also, it is Buckminster Fuller who coined the term tensegrity, a contraction of tensional integrity (Burkhardt 2008).

Anthony Pugh's definition of tensegrity from his book An Introduction to Tensegrity:

> A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space (Pugh 1976, 3).

It is important to note that in this definition Pugh does not refer to struts or cables, which are often found in tensegrity but are not a requirement. As in some cases, struts could be replaced by planar surfaces or bent members, as well as cables could be replaced by membranes. Therefore tensegrity is for the most part a structural system.

2.3. CHARACTERISTICS AND ADVANTAGES OF TENSEGRITY

Tensegrity structures have many advantages. A few that are integral to this research are that tensegrity is very lightweight. It is also a self-stressing system whereby the higher the stress the more load-bearing the structure will be. This is described in comparison to a balloon. Whereas a balloon inflated fully will react little to external pressure forces, yet a balloon that is half-filled with air can easily be squashed and deformed. Yet, once the force is removed the balloon returns to its stable rounded state (Pugh 1976). This allows for structural resilience as it can flex and again return to its equilibrium state. Meanwhile, the amount of deformation is directly dependent on the amount of force to begin with, the stronger the base force the more stable and resistant to deformation the structure is. As a feature of this characteristic tensegrity modules are sensitive to vibrations and dynamic loading which transfers throughout the structure. Tensegrity modules also are self-stable, meaning they are not dependent on gravitational forces for their structural integrity; meaning they hold their form no matter which orientation they are positioned. Furthermore, elemental tensegrity modules can also be joined and combined together to create larger tensegrity networked structures (Gomes-Juaregui 2010).

2.4. MEMBRANE TENSEGRITY

Although tensegrity is most often seen with struts and cables, as mentioned in the definition of tensegrity, it is not dependent on these elements. It is only the relationship of the compression and tensioned members working together as a system that creates a tensegrity structure. There are some important precedent examples to note of current research exploring tensegrity, membranes, and bending active elements.

The Hybrid Tower developed by CITA, the Center for IT and Architecture at the Royal Danish Academy, explored a bending active Glass Fiber Reinforced Polymer (GFRP) rod structure as well as a knitted textile membrane in this tower design. The structure uses the bent rods as an interconnected network of members, crossed together in a diagonal grid. (Ramsgaard Thomsen 2015). Cables are also used to pull the membrane into tension. The design for the tower expresses a workflow between digital and physical modeling, as well as post-construction analysis.

The Dynamic Assemblies Lab at Singapore University of Technology and Design has explored several structural developments. One recent exploration is a membrane tensegrity pavilion built in 2019. In this structure, a single knitted membrane with linear struts placed in a particular arrangement on the membrane creates a structural shell pavilion (Gupta 2020). This structure uses the tension in the membrane to support the struts and transfer the load.

The BetA pavilion developed by Diane Davis-Sikora and Rui Liu uses bending active compression elements, as well as knitted tensile membranes. Their structure uses bent GFRP rods in the formation of bending active tetrahedrons. The rods are connected at their ends creating the tetrahedron shape, thus the bent members in this case are acting as a network rather than as independent elements. In their design, a triangular knitted textile is connected at the corners. This textile is then used in tension to combine one module to the center of the next creating the tensegrity system in their design (Davis-Sikora 2020).

The final example, using bending active GFRP rods, textile PVC membranes, and polyester belt cables, is the “Form Follows Tension” structure built as part of the 2012 IASS by researchers at Technische Universität München. Their design explores membranes as an active part of the tensegrity module. The structure consisted of four modules, which included two bent rods, one membrane that connects the ends of the rods at opposite corners, and cables connecting the center of the rod to the end of the opposite rod (Schling 2015).

There are of course many other case studies available but not worth mentioning in relation directly to this research. These presidents set up a good basis on to build. Taking the knowledge of how to work with tensegrity with bending active rods as well as knit membranes. In these precedents, the focus was on different features. As well they often included the integration of cables.

3. RESEARCH

3.1. KNIT MATERIAL

With the precedent examples of tensile and tensegrity structures, this research project hypothesized that bending active elements and knit textiles could work together as tensegrity modules. And that two or more of these modules could be combined together to create a larger structure. To develop a design like this, it was necessary to develop an understanding of the materials to be used. To do this several studies were done first at a small scale before they could be further explored at larger scales. This workflow was found to be a successful workflow between material and computational design from the precedents as well as in this project, when working with knitted materials.

Knit material is not typically used for large-scale tensile structures because it has heterogeneous elastic properties. Where the knit material does not stretch evenly across the surface. Most tensile structures use woven materials, which are not as stretchy, and are coated with waterproofing to provide a barrier from the elements. The knit material to be used on this project is very porous since the knit was created on a standard domestic 4.5mm needle gauge machine. The stitch length is also set to 6 and knit with 1 ply cotton yarn. This means that depending on the knit would still have small visible small holes based on the looping structure and would not be water or airtight.

These small holes are a result of the weft knitting structure. Weft knitting is the most common form of knitting machine as they use a horizontal bed of needles and draw yarn across the bed creating rows of stitches. The looping structure of the material results in its elastic properties, as the loops permit the yarn to shift and slide between each other creating stretch and tension in the yarn. This slippage of yarn allows for some of the loops to get larger and others to become smaller, creating heterogeneous elasticity across the material (Figure 1). This is more noticeable when tensile forces are applied to the material. The amount of slippage that can occur is dependent on many parameters, such as stitch length, yarn thickness, and yarn fuzziness which causes friction in the yarn material.

Knit material is also quite strong because of this looping structure. When a single yarn is pulled it can easily break. But when it is knitted together the forces are distributed across the material and many strands of yarn, causing it to be able to withstand much more tensile force.

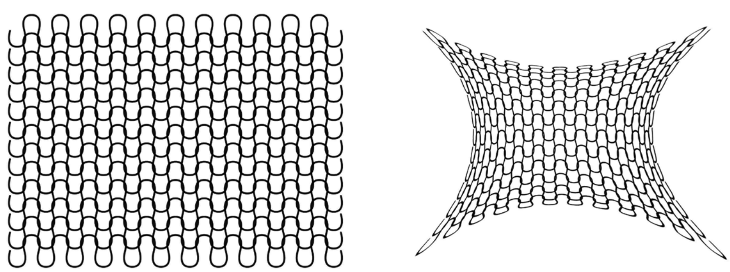

Figure 1: Image of knit structure compared to knit in a tensile state. Source: Author 2022.

3.2. KNIT STUDIES

The initial studies started by exploring the knit material by creating material swatches with different stitch lengths and yarn types (Figure 2). These swatches were generated on a Brother Ameno KH 836E domestic knitting Machine with a 4.5mm needle bed. With these swatches, the designer is able to develop an understanding of the possible materials and different constraints and properties of the resulting textile. The relationship between the designer and the material understanding is an important part of the method and workflow for this research.

It was decided to work with cotton yarn as in the swatch tests, its performance had less elastic properties within the yarn itself, leaving most of the elasticity in the textile to be from the looping structure of the knit. The stitch length used was 6, because it is in the middle range for the domestic Brother knitting machine, which is not too tight or too loose. Tighter stitch lengths caused jamming and breaking of the yarn while loser stitch lengths were prone to dropping the yarn. The middle range stitch length allows for some movement of the yarn between loops, but not too much, allowing the textile to reach tension across the surfaces when stretched, distributing the tensile load.

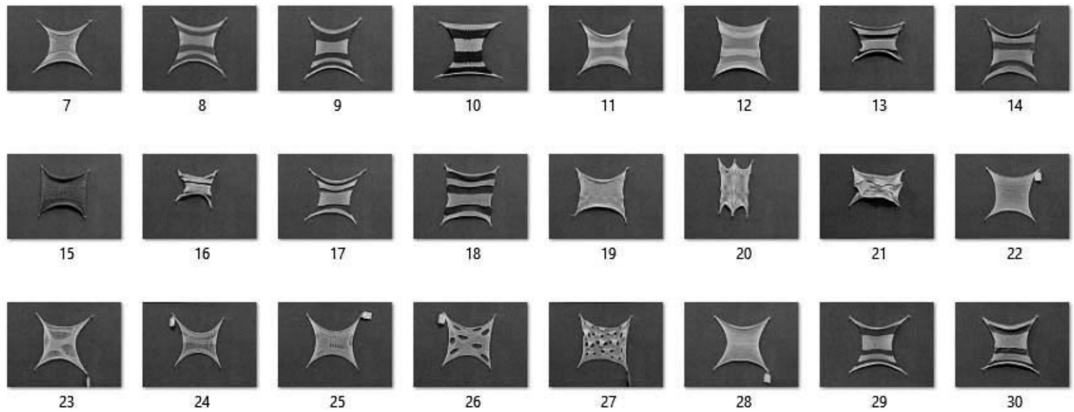

Figure 2: Image of different sample knits in different materials and stitch lengths. Source: Author 2022.

3.3. TENSEGRITY MODULES

The first models with knit tensile tensegrity explored different structural organizations using linear struts and bending active rods, made from PTEG pipes. In these small models, the rods are held in suspension by the membrane and do not touch one another (Figure 3). The forces in these models can be expressed in the membrane in tension and the bent rods in compression. These iterative models proved that a membrane could replace the tension cables that are typically seen in tensegrity modules. As well as the whole surface, not just the edges of the membrane is being tensioned.

These models were made by hand and the scale of materials was based largely on digital models from Rhinoceros 3D as an estimation of material size and length. Although these Rhinoceros 3D models were only for design and did not simulate elasticity or predict structural performance. As with these models, the number of stitches and length of compression members were measured from the Rhinoceros model as an estimate. This estimate was based on the swatches which measured 50 needles by 50 rows. Thus an estimate could be made as to what the general dimensions should be with the same materials.

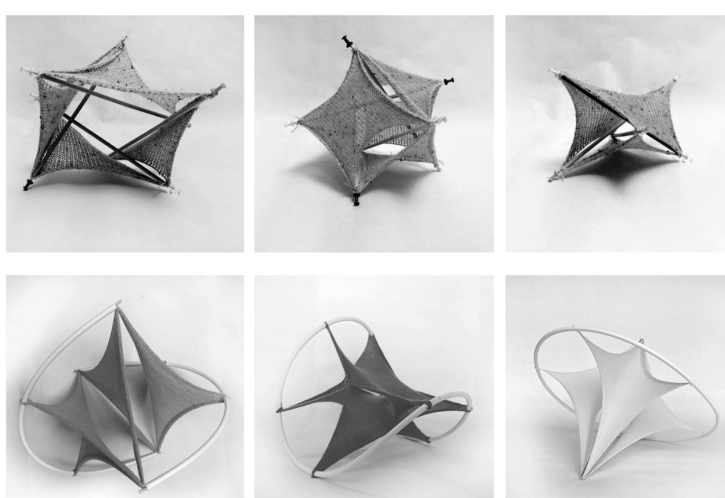

Figure 3: Image of knit tensegrity module studies. Source: Author 2022.

3.4. SIMULATION

The next step in the design process was to create more complex digital simulations of the designs using the Kangaroo2 plugin in Grasshopper for Rhinoceros 3D. For the simulation, a mesh surface is set to have each mesh edge as spring. The mesh is subdivided into inches to allow for an understanding of how much each mesh edge may represent a set amount of knit stitches. From the physical knit swatches it can be known how many stitches would make up a 2.54 cm by 2.54 cm (1 inch by 1 inch) area of knit material given the selected stitch length and material.

Furthermore, the physical swatch samples are used to determine the proportions of elasticity, by measuring the test material in a relaxed state and in a tensioned state. Understanding of how knit stretches are studied here, as knit material reacts differently when tensioned from top to bottom, then from side to side. In this case, the corners of the knit would be used to attach to the structure, and the knit needed to be measured when equally pulled at all four corners. These properties from the sample swatches are measured in a relaxed state and again in a tensioned state. The measurements are then used to help inform the input data for the digital Kangaroo2 model (Figure 4). The mesh edges are organized based on their different directions and location in the material and set to different spring lengths, which mimicked the physical tests. The horizontal mesh edges represent the knit rows or courses and stretch differently than the vertical mesh edges, which represent the interlocking loops or wales of the knit.

Additionally, the top and bottom edges of the knit, which are the cast-on and bind-off, are more constrained than the vertical edges. In the simulation, these are also set as different spring lengths. Moreover, the knit material does not usually scale exactly 1:1. When trying to predict larger models from small swatches, it is important to allow a small factor of variation between scaling the models to larger prediction models. This percent of variation is based on experience and learned knowledge the designer had accumulated through the sampling and testing in this research. Ultimately, the digital simulation allows the mesh to be tensioned by the bent rod members in the design and creates a balanced state of tensegrity. The design is similar to the small studies made with rods and textiles, and can be used to determine dimensions for scaling up the designs into larger models. And further the understanding of the material and design process.

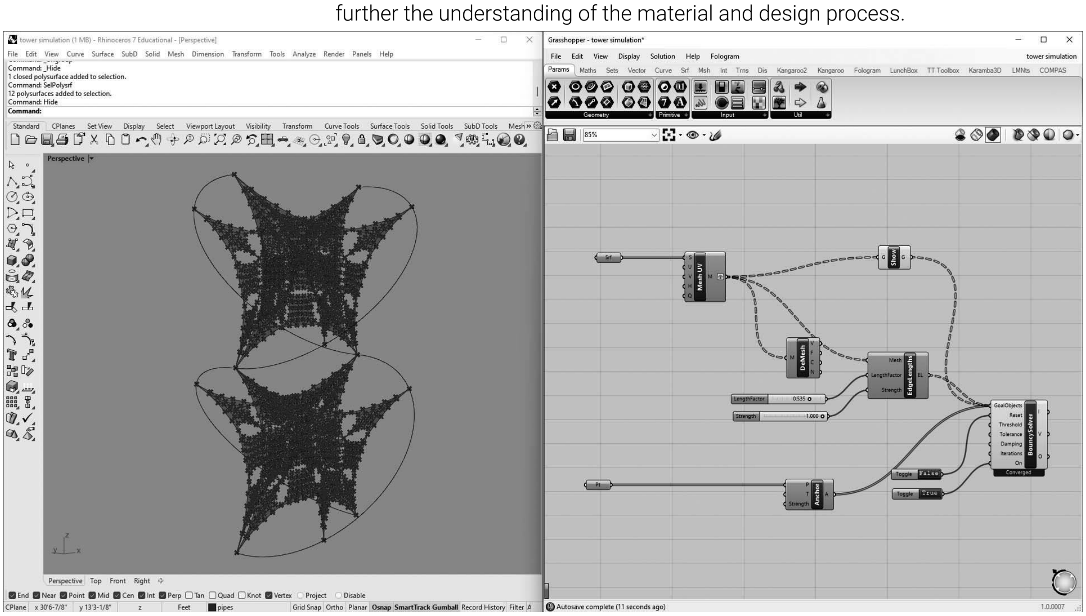

Figure 4: Image Grasshopper Rhino Simulation. Source: Author 2022.

3.5. LARGER MODEL

After the digital simulations of a larger-scale proposal were made, a physical phase of testing was necessary to determine the accuracy of the digital predictions. The predictions were used to take the information from the smaller scale models and determine the possible sizes and dimensions for the larger design. The next model would be around twice the size of the original model. Based on the scaling of the proportions and simulation in Grasshopper, an understanding of how many courses and wales would need to be knit to produce material so that it would stretch to the desired size. The resulting sample consisted of three knit panels that were 160 needles by 120 rows and the bent rods would be two 1.22 meters (4 feet) PETEG pipes.

The result showed that the design was able to somewhat successfully estimate the necessary sizes and material properties when scaled up to a larger size. Although some important observations took place. At a larger scale, the flexibility of the PETEG rod was too much and it did not create enough bending compression force to make the structure stable. Resulting in it being too flexible and not rigid enough to pull the textile into full tension. This determined that the bending rods would need to at least be more rigid, and later were replaced with PVC rods. Since the knit was not pulled fully into tension it was also noticeable where slack areas and tighter areas would occur across the membrane. This allowed for some assessment and information on how to adjust the design to provide better performance across the material. The simulation was adjusted to make the knit even slightly smaller than the original prediction. Ultimately the module was supporting its weight and was able to successfully transfer load between the membrane and the compression members creating a tensegrity module.

4. HELIX-TOWER

4.1. HYPOTHESIS

The objective for the final structure was to make a tower by stacking multiple of the previously studied and designed tensegrity modules together to create a vertical tower-like structure. The hypothesis is to use the bending active tensile textile and tensegrity to create a large structure using very few raw materials. By using textiles the material is lightweight and expands creating a large surface area and visual enclosure to the volume. This structural organization is novel as it is using no cables, and the membrane surfaces act as tensile elements. Although when attaching the two modules together, the bending active members are connected end to end. This although does not break the tensegrity module as the members are now acting as two compression members in a spiral rather than four “C” shaped members.

4.2. SCALE AND DESIGN

For the final structure, the goal was to create a 4.5 meter (13.5 foot) tall tower by stacking three of the modules on top of one another. Unfortunately, due to the height limitations of the available space and time constraints for the fabrication and construction, the design would end up being only two modules stacked and would be 2.74 meters (9 feet) tall.

The scale of the proposed structure was based on available materials. Using off-the-shelf PVC rods, so as not to create any waste material keeping them at the original size. The structure would use four, 3.048-meter (10-foot) rods, which would be connected with a coupling fastener end to end. The Rhino 3D simulation was then scaled to fit these size dimensions and proportions. Creating a prediction of how much knit material would be needed to fit the proposed design. The PVC rods would also be pre-measured at the connection points for the material and marked with eye hooks for attachment. This would help streamline the assembly process.

The textile when scaled in the digital simulation predicted that the knit would need to be 396 by 264 for the necessary stitch count for the design. This would be too large to be knit on the domestic Brother knitting machine. Therefore the design subdivided the membrane into nine smaller pieces that would be attached together to make the larger necessary pieces. Given the understanding of the material and its variation in elasticity, the information learned from the large-scale model was used to adjust the simulation for the final. This also helped predict the new necessary sizes of the smaller subdivided knit pieces. To avoid issues of sewing the panels together affecting the elasticity in the knit material, the proposal was to only attach the panels at the corners and not along all the edges. Expecting that the load would still transfer through the material along the X, Y, and diagonal axis. The new subdivided design used nine smaller pieces to create the panels that would provide the tensile membranes for the structure. When the material of these panels stretches openings are created as they are not sewn edge to edge and this creates an even more dynamic and porous membrane expressing the forces of elasticity in the material.

In the simulation, each knit panel responded differently to forces formed by slightly different geometries. As the edge panels would stretch more than the center panels. The panels that are located to either side in relation to the bending active member, tended to stretch into a diamond shape. Which led to the sizes of the panels slightly varying to respond to these different measurements found in the simulation. The smallest panel resultantly was 108 needles by 72 rows. The middle size is 120 needles by 80 rows. And the largest panels which would be used for the center membrane and arranged on a diagonal of the side membranes were 132 by 88 rows. This variation in panel sizes was arranged to help emphasize and support the natural form of the elasticity of the material. The pieces needed to be attached facing the same way so that the orientation represented the direction of stretch that was previously studied and designed in the simulation.

4.3. CONSTRUCTION

All fifty-four panels of textile were knit and attached at the corners to make the final six panels needed for the design. The corners were marked with small tags noting which corner of the structure to attach to. Since the panels were not symmetric and their orientation was dependent on the direction of the stretch in previously studies. This was important since this variation in knit direction and panel size is not visible to the naked eye.

The final construction of the tower took less than 30 minutes, from start to finish. The first two textiles are attached to the first bent rod. Then the middle textile and the third textile are attached to the second rod. Once they are attached, what was a small amount of material pops up to fill the space and form the first module. The second PVC rods are attached to the ends of the first module with the PVC coupling. While the module is laying on its side the next three pieces of textile are connected to the new rods bending them into place. Since tensegrity structures are a self-stable system gravity, they can be built on its side and do not affect the structural integrity of the modules. Once fully attached the structure is lightweight enough that an individual can pick it up and rotate it into the desired vertical position. The weight of the overall construction is 8.9 kilograms (17.6 pounds). The final structure stands on the two ends of the rods and the three bottom edges of the textile membranes (Figure 5).


Figure 5 time-lapse video stills of the construction process: Author 2022.

4.4. RESULTS

The final structure stands on its own although, the weight of the material forces the rods to compress at the base more than at the top. This was not accurate in the prediction models but was obvious in the final physical construct. Although this deformation did provide a larger edge for resting place on the two rods which touch the ground, making the structure more balanced (Figure 6).

Resultantly the structure is also still a bit flexible since the knit material is not held fully tensioned. The material visually deforms resembling the movement of forces across the surface. Making the center portions of the knit remain softer and somewhat flexible, which is different from the precedents of typical tensioned membrane structures, which pull the whole membrane is tensioned to such an extent that it becomes almost rigid. This allows for the softness of the structure, which can be pushed and manipulated by visitors. Having similar residual effects to the balloon example described earlier in the paper. However, as with all tensegrity structures, they are self-stressing and their stiffness depends on the material proprieties as well as the level of tensioned stress. Thus this structure does hold its geometry and will recoil back to its equilibrium state. The PVC pipes used are not as sturdy as they are needed for a more rigid structure to be in full bending force. This is not necessarily a design flaw as a change in material and the amount of tension applied could create a more rigid structure. Yet the dynamism of tensegrity in this model's structure allows for these dynamic reactions to be part of the design result and its return to a predetermined form proves that the structure does have stability.

4.5. NEXT STEPS

Although the size of the design did have to be reduced based on space and time constraints, further exploration into larger prototypes and stacking more modules together is the next desired phase of research. Furthermore, advancements can be made to use GFRP rods, similar to many of the precedent examples, which would have more bending resistance and be more stable, avoiding the extra flex seen in the results of this prototype. As well as more precision in the material could be developed, to achieve more overall balanced tension across the membrane. A denser knit material could also be useful by using CNC knitted membrane to provide more specificity and control in the design rather than the single jersey knit that was created for this prototype on a domestic knitting machine.

The overall process of starting with small studies, and using this information to inform the digital simulations through measurement and visual study also worked successfully. Although there was also some added information from experience such as when scaling up the proportions would not be 1:1, and those

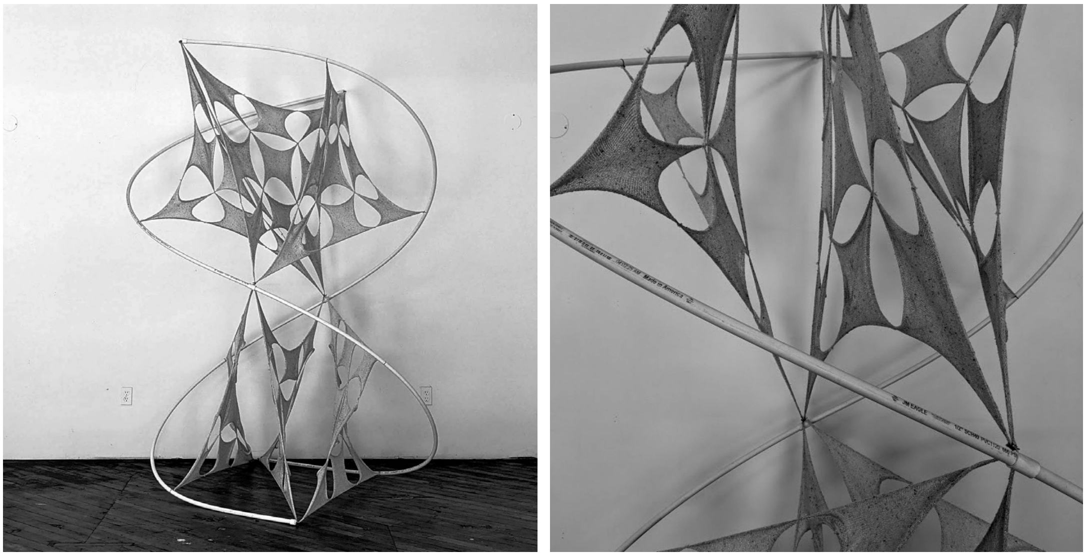

Figure 6: Images of the final structure. Source: Author 2022.

intuitive minor adjustments had to be taken into consideration. The consecutive scaling up from small-scale models to a medium-scale mock-up, before the construction of the final, was also successful as different material and physical information was learned at each phase and able to be applied to the final design.

CONCLUSION

The overall proposal to create a new structural design that uses bending active and membrane tensegrity modules stacked together to create a helix-tower structure was successful. The design hypothesized that using lightweight materials could produce visual and spatial impact with very low material resources. The prototype design resultantly is quick and easy to assemble and can be done by an individual person.

The developed workflow also proved to be successful. Through this process, not only is the data implemented into the computer but also there is natural learned information through the experience that the designer generates as they work closely with the materials. The process also involved consecutive scaling up from material swatches to small-scale models to medium-scale mock-ups, before proceeding with the construction of the final. This process also involved several points to adjust information in the computer as well as physically.

Although, space and the size of the knitting machine were ultimately constraints. They eventually provided opportunities to explore different aspects of the design such as breaking down the membranes into smaller panels. In conclusion, the structure did produce the desired objectives. The exploration of creating a new knitted membrane tensile tensegrity model did generate an easily deployable structure that provided a large volume with minimal material usage and was very lightweight. This provides a strong impact on how we build with these materials and structural systems. Creating new possible design methods as well as construction fabrication methods for these lightweight structures. Ultimately, there is more to be explored and developed to make these models viable at larger architectural and building scales.

ACKNOWLEDGEMENTS

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FROM PHYSICALLY KNITTED MODELS TO CALIBRATED DIGITAL SIMULATIONS: A WORKFLOW BASED ON THE BEHAVIOR AND GEOMETRY OF THE KNITTED TENSIONED STRUCTURES

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The author of this paper proposes a workflow that is developed based on the behavior and geometrical characteristics of knitted textiles. The overall goal is to enhance the implementation of knitted tensioned structures for architects and architecture students to use this material during the design process. The workflow includes eight main steps that are not necessarily in sequence: 1) Rough illustration of the overall form, 2) Developing knitting diagram for the desired shape, 3) Knitting physical models, 4) Physical form finding, 5) Digital simulation, 6) 3D scanning, 7) Overlapping form found and 3D scanned meshes, and 8) Calibrating digital model. The output of this process would be a tuned digital mesh that could be used as an input for further structural analysis, such as external wind/snow loads.

Additionally, the author highlights the different architectural form development strategies using knitted textiles. The emphasis is on understanding knitted textiles characteristics through making and elaborating the methods to input material behavior and geometry into digital simulations. The digital model is then calibrated using optimization methods to approximate its physical counterpart. Knitted textiles are new architectural materials that offer potential such as flexibility and seamless 3D knitting. Such characteristics allow for the development of more complex shapes, however, making predicting the behavior and shape of these materials more challenging. In general, there is a spectrum of possibilities to develop an architectural form using knitted textiles. At one extreme, one can knit a planar shape using stretchy yarns or knit patterns. At the other end, a final shape can be knitted to the exact desired form with non-stretchy yarns and patterns. Nevertheless, there are some other possibilities in between. A form can be knitted in a rough, simplified, and semi-3D shape, and then by implementing external forces, the final shape will emerge. Form development with simplified knitted shapes is the focus of this research. The author will explore the methods to correlate physical modeling with digital simulations of tensioned knitted textile structures by making samples and digitally simulating the models.

Keywords: Knitted textile, form finding, prediction, initial shape, form development, calibration, 3D scanning.

INTRODUCTION

Although dominant material in textile design/industry, knitted textiles are new materials in architecture. Flexibility, multi-directionality, and interconnected structure of the knits are essential properties of knitted textiles, allowing these materials to be considered for developing more complex architectural shapes. However, successful implementation of knits in architecture requires a deep understanding of their structures for making architectural forms.

Form development using knitted textiles requires consideration of three embedded scales in the structure of knitted fabrics, including micro-, meso-, and macroscale (Oghazian and Vazquez 2021). Microscale is the scale of one stitch, or one loop made by moving continuous yarn through previously made stitches. The adjacency of multiple stitches will create a piece of textile that adds structure to the fabric and it is called mesoscale in this research. The overall form of the models made of aggregated parts of mesoscale materials or using a seamless knitting technique is called macroscale.

Developing the overall form for the desired shape is challenging because there is no unique method for generating the form. Taking advantage of the characteristics of the knitted textiles, one can knit a form in a spectrum of possibilities, and based on the method chosen, different knitting diagrams will be generated, and therefore, knitting machines with specific capabilities are required. Implementing knitted textiles in textile design reveals different form-fitting strategies based on the body dimensions and curvatures such as studies by Kaspar (2019) and Yang (2010). Similarly, in this research, I elaborate on the various form development approaches to fit architectural forms and shapes.

1. FORM DEVELOPMENT WITH KNITTED TEXTILES

Knitted textiles are used broadly as materials for developing 3D shapes in textile design. In the last two decades, these materials have started to be used in architecture due to many potentials of knits and advancements in CNC knitting (Ahlquist 2015; Sabin 2013; Thomsen, et al. 2016). This section highlights different approaches to developing forms within these research areas.

Developing knitted tensioned forms with knitted textiles depends on the initial shape knitted, level of the elasticity of the textile and forces applied. The first two elements are also dependent on the yarn type, knitting patterns, and the tension applied to the yarn during the knitting process. Based on the many implementations of knitted materials in literature, the author argues that the shape and the behavior of 3D knitted structures for developing tensioned structures can fall in a spectrum of full force/no form to full form/no force, as illustrated in Figure 1.

This means that textiles can be knitted in a planar shape made of either stretchy materials or knit patterns that add to the elasticity of the textiles (Figure 1_Left). These knitted materials must be under full external force to get the final shape. The methods used by Baranovskaya, et al. (2016), McKnelly (2015), Ahlquist (2015) belong to this category. On the other extreme, textiles are knitted in a desired 3D shape without needing an external force or minimum force to obtain the final form (Figure1- Right). Methods developed by Liu, et al. (2020), Popescu, et al. (2018) are representative of this category. In this approach, the yarns used for making the models should have the least elasticity, and the patterns should add no stretchability to the knitted textile. Generating diagrams is more complicated in this method, and there are some limitations to developing the mesh configurations depending the typology of the overall form and possibility of the knitting the whole structure seamlessly (Liu, Li, and Yuan 2020). The third approach is to knit semi-3D shapes in a rough initial shape with a simple mesh configuration. The models between the two extremes need a proportional force/form to obtain the desired

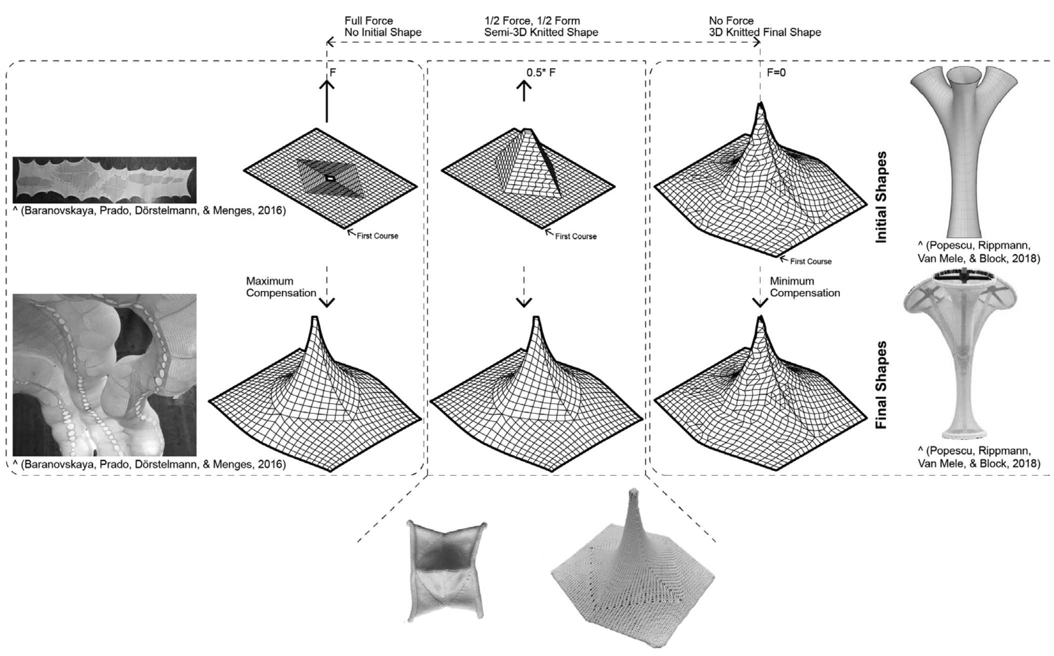

Figure 1: Spectrum of approaches in architectural knitted tension structures using knitted textiles. Source: Revised based on Oghazian, et al. 2021. Additional images from Baranovskaya, et al. (2016) and Popescu, et al. (2018).

shape. The third approach is the focus of this research, where we will get a relaxed shape out of a rough and simplified knitted textile. The most advantage of this approach is that the digital simulation is much simpler and compared to the two ends of the spectrum, it is possible to knit the forms with simple tools such as pegboards, looms and hand-held knitting machines as well.

There are differences regarding the knitting diagrams, knitting processes, and the knitting machine potentials required for knitting the models associated with each of the aforementioned methods. For example, the left category of Figure 1 requires a change in the knit structure for one course and within different courses. Although the shape is planar, for obtaining the desired shape under external force, the textile should have a gradient effect, such as varied looseness in different sections of the fabric. The right category of the spectrum in Figure 1 also requires manipulation in the knitting of different parts of the model by putting stitches on hold and transferring the stitches between two beds of the knitting machine. Therefore, two ends of this spectrum will benefit a lot from CNC knitting machines and their capabilities for automatic knitting. However, other approaches in-between require adding some level of 3D dimensionality to the textile of the consistent knit structure which makes them easier to knit and are knittable with more simple knitting machines, pegboards, and looms.

The overall tensioned form is dependent on the initial shape knitted and the force applied. If we could formalize the correlation between the initial shape, final shape, and the force required to obtain such shapes, then it would be easier to develop complex architectural tensioned forms considering architectural and structural requirements. In the following of this section, the author elaborates more on the differences between these three form development strategies. Finally, a workflow is proposed to enhance the study of knitted textile structures for developing architectural forms.

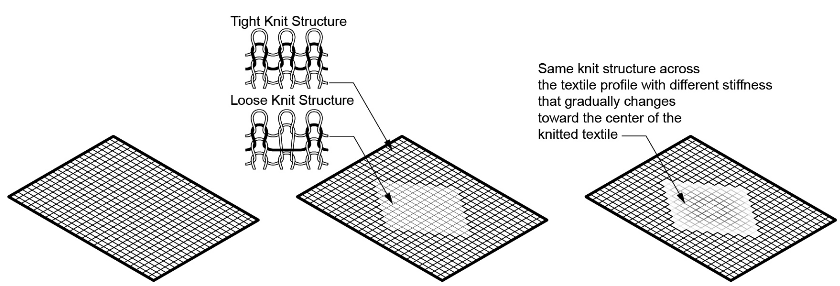

Figure 2: Variations in structure of knitted textiles to change its behavior. Left: Simple knit structure across the model; Middle: Change of pattern in the middle of the textile; Right: Change of tension settings in the middle of the textile. Source: Author 2021.

1.1. PLANAR INITIAL SHAPE

Yarn type, knit structure (patterns made of a sequence of different stitch structures), and tension applied on the yarn during the knitting process by yarn holder and carriage are some of the main elements that affect the looseness and initial quality of the overall knitted textile. Such qualities also affect the shape and curvature of the models that emerge after applying external forces. In this approach, the initial shape is a planar surface knitted flat. A basic model in this category is a planar shape with a consistent pattern across the knitted textile structure. Using a monotonous pattern, it would be hard to manipulate the behavior of the textile for a particular overall shape. Therefore, the textile could be graded by differentiating the looseness in different sections of the textile, either by changing the tension settings, stitch structure or yarn thickness. Figure 2 shows some of these different strategies.

1.2. SEMI-3D AND ROUGH INITIAL SHAPE

The second approach is to knit a semi-3D and rough shape and then apply external forces to obtain the desired shape. In this approach, the final shape is dependent on both the initial shape knitted and the external force. However, the dependency of the final form on each of these elements is different based on the closeness of the strategy to either ends of the spectrum. Figure 1- middle shows one case study of a rough 3D knitted cone that is seamlessly attached to a planar rectangular fabric. The more detailed process of physical form-finding, digital simulation, and calibrating a digital model for a tensioned knitted textile model that belongs to this category of form development strategies will be presented in section 2.

1.3. FULLY 3D INITIAL SHAPE

The third approach is knitting the full 3D shape exactly as desired. This approach will minimize the compensation and external forces required to fixate the final form. However, the elasticity of the knitted textile should be decreased. Research in textile design shows the possibility of generating adequate diagrams for making complex shapes considering the potential of knitting machines such as Shima Seiki, as proposed in a study by Narayanan, et al. (2018) and McCann, et al. (2016). However, there are limited platforms for architects to design and generate such diagrams. Popescu, et al. (2018) has developed an algorithm that creates a distribution of stitches for patches of complex forms. Cockatoo, a plugin for Grasshopper, recently offered by Max Eschenbach, is an open-source software toolkit for generating 3d knitting patterns from NURBS surface and mesh geometry (Eschenbach 2021). Figure 3 illustrates different stitch distributions generated using this tool. However, not all the configurations are suitable for knitting. Knittability of the models using the diagrams generated by this plugin is the subject of another ongoing research. It should be also mentioned that it is difficult and in some stitch configurations it is even impossible to knit the model using simple and manual knitting machines because it requires to keep track of the stitches that should be stayed on hold or transferred between the beds within each course and between the beds.

In summation, regardless of the approaches mentioned above, the model's overall size will be affected by the type of the yarn, knit structure, and tension applied to the yarn during the knitting process. By changing the method of developing the initial shape, the level at which each element affects the behavior of the tensioned knitted textiles might differ. Additionally, based on the control users seek to have on the overall form, either of these approaches might be implemented during the design process. In this research, we are looking at enhancing the use of knitted textiles for architects and architecture students

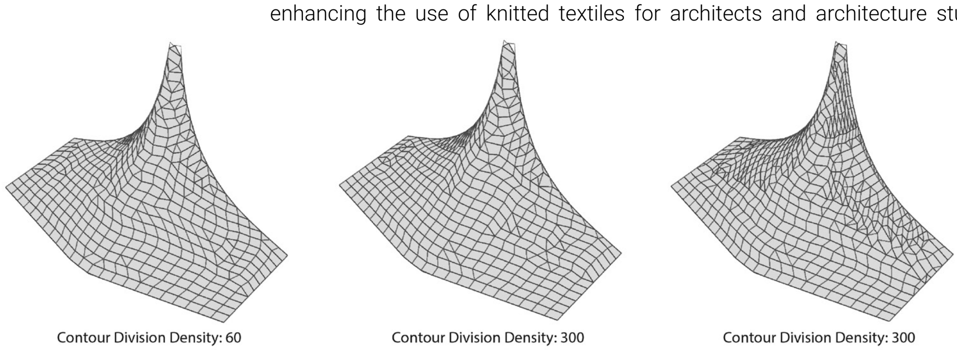

Figure 3: Stitch distribution over the half of desired 3D form using Cockatoo plugin in Grasshopper developed by Eschenbach (2021). Source: Author 2021.

for form development in the simplest way. The available tools for making the knitted samples significantly affect the approach chosen for developing such forms. Therefore, we emphasize the middle category as one of the methods of generating 3D architectural forms using simple devices. In the next section, a workflow is introduced that highlights consecutive processes from physical to tuned digital models for this kind of tensioned knitted textile structure.

2. A WORKFLOW FOR IMPLEMENTATION OF TENSIONED KNITTED TEXTILES

In this section, a workflow for developing tensioned knitted textiles is introduced. The process is illustrated in Figure 4.

The method includes eight main steps that are not necessarily in sequence. 1) Rough illustration of the overall form 2) Developing knitting diagram for the desired shape, 3) Knitting physical models, 4) Physical form-finding, 5) Digital simulation, 6) 3D scanning, 7) Overlapping form found and 3D scanned meshes, and 8) Calibrating digital model using optimization techniques.

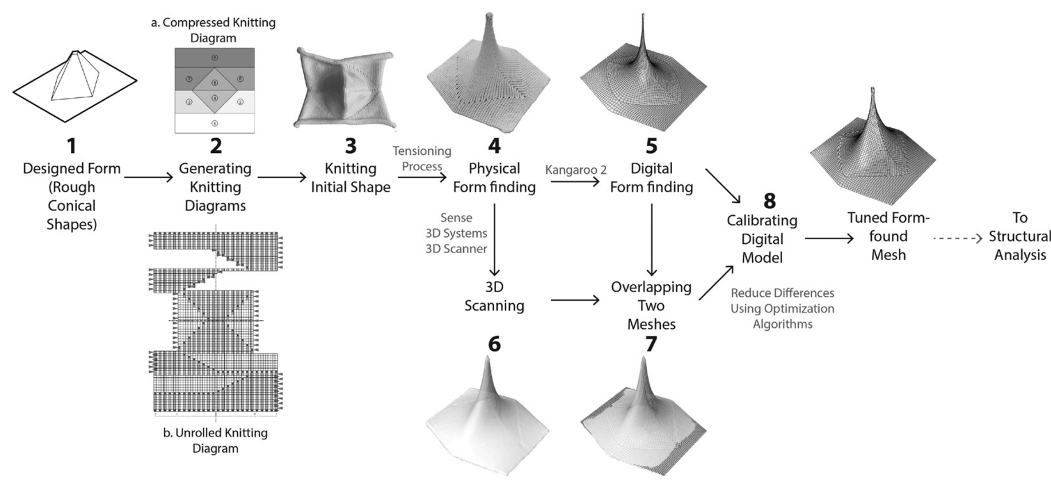

Figure 4: A workflow from physical modeling to the digital simulation of knitted tensioned structures. Source: Author 2021.

2.1. KNITTING PROCESSES AND PHYSICAL FORM-FINDING (STEPS 1,2,3,4)

The physical form-finding of the tensioned knitted textiles comprises the first four steps of the workflow. For a desired conical shape, a rough shape is generated first, and the knitting diagrams are designed. There are two types of graphs for this step: the first is a compressed diagram that helps to understand the sequence of knitting the different parts of the model (Figure 4- step 2, diagram a), and the second diagram is the unrolled diagram that illustrates the process of making every individual stitch (Figure 4- step 2, diagram b). In this study, a simple single-bed Silver Reed knitting machine is used for making the samples. Therefore, it was essential to generate the knitting diagram in a way that is knittable by this machine. After knitting samples, the boundary conditions and the external forces are defined to give the final shape to the flexible knitted piece. This process is called physical form-finding. These four steps are shown in Figure 5 for different double conical shapes knitted with the same machine and the same pattern.

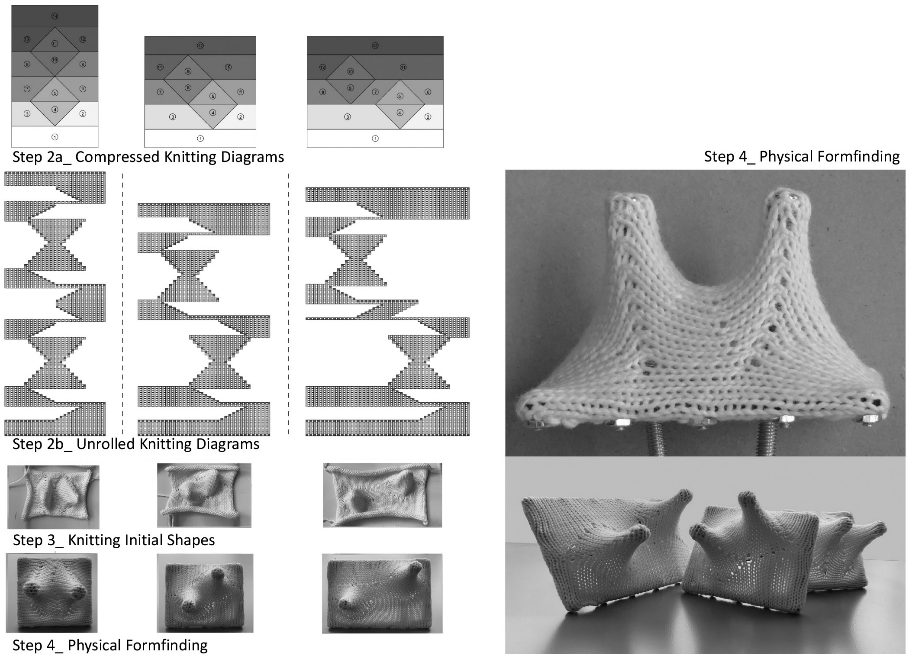

Figure 5: Generating knitting diagrams, knitting, and physical form finding for different double conical shapes. Source: Author 2021.

2.2. DIGITAL SIMULATIONS (STEP 5)

The fifth step of the workflow is digital form-finding. Knitted textiles are flexible materials that possess some level of uncertainty in their behavior because of the characteristics that emerge in the formation process. Therefore, it is challenging to input such properties during the simulation process. Tools such as Kangaroo 1 and 2, which use Dynamic Relaxation and the Projective Constraint method, respectively, are immensely powerful for explorative form-finding of flexible materials. They require the user to specify lengths and stiffnesses or related model properties to get an accurate representation of the tensioned shape. The digital modeling at this step is based on the model developed in our previous research using Kangaroo 2 (Oghazian, et al. 2021). To simplify the simulation process, a quad mesh face is used to represent a stitch. The change of the length and stiffness of these mesh edges are in which the properties of the knitted textiles under the tension are input during the form-finding process.

2.3. CALIBRATION PROCESS (STEPS 6,7,8)

In the digital model developed for simulating the knitted textile models by Oghazian, et al. (2021), the values for the length factor and stiffness are adjusted manually. To automate the process and tune the digital model, a calibration process is developed that requires 3D scanning of the physical models. This 3D mesh and the formfound mesh will then be overlapped. An objective is defined to minimize the distance between the two meshes. For this step, the implementation of different optimization plugins is studied as tools for tuning the digital model. The length factor of the meshes is the variable, and the cumulative distance between the meshes is the objective of the optimization process. A more detailed comparison between the performance of different optimization algorithms for this model can be found in Oghazian, et al. (2022). In the calibrated model presented in Figure 4 at step 8, GN-ORIG-DIRECT-L from Radical/ DSE plugin is used as the best optimization algorithm for this process.

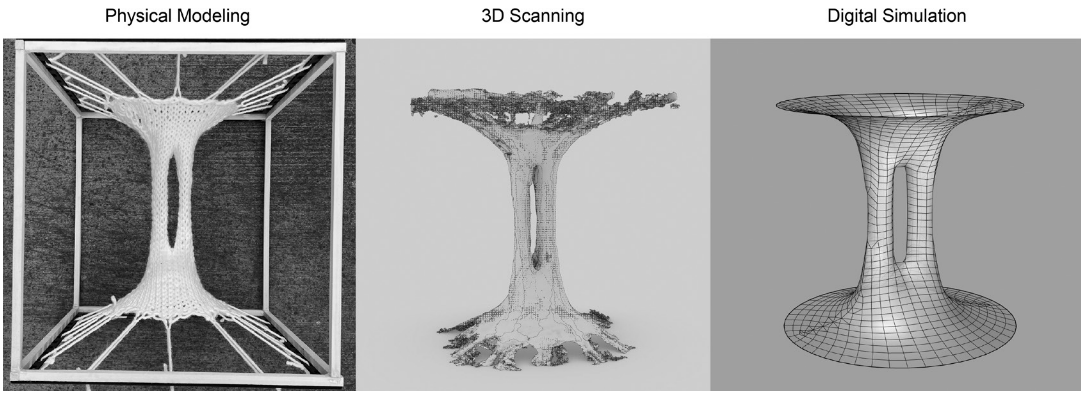

Figure 6: Physical Modeling, 3D scanning, and Digital Simulation. Source: Yu Shi.

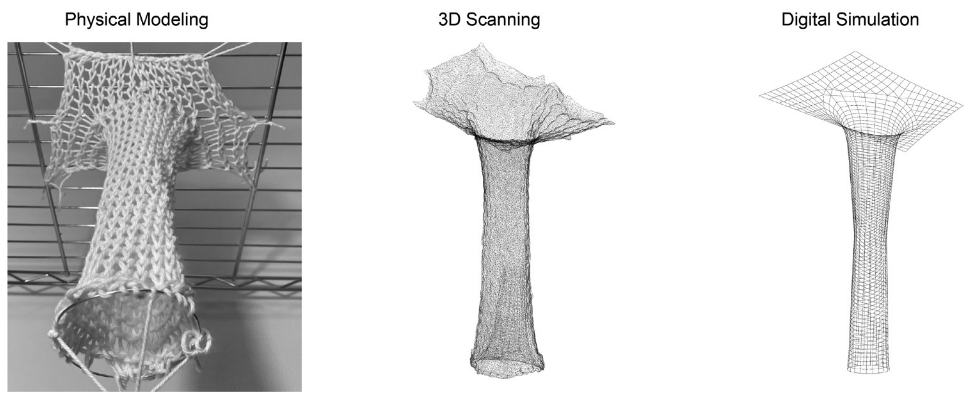

Figure 7: Physical Modeling, 3D scanning, and Digital Simulation. Source: Daniel Robert Pawluczyk.

The output of the process is a tuned mesh that can be used as an input for structural analysis. It is important to have a reliable formfound mesh to do the structural analysis and study the behavior of the material under external loads. The whole process was validated through the development of different knitted tensioned structures within a Design Research Studio (DRS) course for Lightweight Tensioned Structures that was offered by Felecia Davis and the author at Penn State University during Spring 2021 and 2022. Two examples of the initial projects are illustrated in Figures 6 and 7.

3. CONTRIBUTION

In this research, different form development strategies using knitted textiles are introduced. Additionally, a workflow is proposed that includes various processes from physical modeling to tuning digital simulations for developing 3D architectural forms using knitted textiles and knitting techniques. The process is mainly illustrated for the models that have a semi-3D rough knitted initial shape and are dependent on both the initial shape and external loads to obtain the final tensioned shape. However, the whole process is applicable to developing any form of development approach discussed in the paper.

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SENTIENT SPACES: INTERPRETING BIOFEEDBACK INTO ENVIRONMENTAL SYSTEMS TO MITIGATE THE SEVERITY OF PHYSIOLOGICAL SYMPTOMS IN ANXIETY DISORDERS

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Harvard University

While anxiety disorders remain the most pervasive mental illness in the United States, few therapeutic solutions have incorporated strategies for dealing with both cognitive and physical symptoms. This is particularly challenging due to the often context-driven trigger of panic and the rapid and exponential onset of such physiological symptoms. With technological advancements for real-time physiological measurements becoming increasingly precise, along with new research highlighting their relationship to cognitive state, there lies great potential for current forms of treatment to be accompanied by real-time alterations to the qualities of our built environment. Sentient space is positioned at the intersection of psychophysiology, cognitive psychology, and environmental design, to put forth a study proposal that questions how spatial systems such as light, temperature, and air quality can be informed by individuals' physiological signals to, in turn, provide real-time relief to the physical symptoms associated with anxiety disorder.

Keywords: Anxiety disorder, psychophysiology, cognitive psychology, responsive environments, sensory stimuli.

INTRODUCTION

Anxiety disorders are the most common mental illness in the U.S., affecting 40 million adults, or 18% of the U.S. population. Even though anxiety disorders are highly treatable, only about 37% of those affected receive treatment due to forms of therapies being often associated with high monetary cost and social stigma, rendering them inaccessible or undesirable (ADAA 2021). Anxiety is characterized by the anticipation of a future threat and often results in chronic and persistent worry, which is multifocal, excessive, and difficult to control. Anxiety affects women twice as likely than men, and often is comorbid with stress, depression, insomnia, and other mental disorders. Featured most prominently with anxiety disorders are panic attacks, which represent a particular type of fear response. Additionally, the World Health Organization reports that anxiety disorders are the most common mental disorder globally and, along with depression, account for the leading cause of disability worldwide (WHO 2021). Several studies have identified both the psychological and physiological symptoms of anxiety disorders which span from signs of autonomic arousal, muscle tension, and insomnia to overthinking, indecisiveness, and inability to concentrate on a task (American Psychiatric Association 2013).

Currently, the most common forms of treatment for anxiety disorders include pharmacotherapy, such as benzodiazepines (e.g., Valium), selective serotonin reuptake inhibitors or serotonin-norepinephrine reuptake inhibitors (e.g., Prozac), and psychotherapy, such as cognitive behavioral therapy (CBT) which looks to treat anxiety through behavioral relaxation techniques and to reconstruct patterns of thinking that foster anxiety. Combined, these forms of therapy substantially improve quality of life in anxiety patients (Bandelow 2017). However, despite these treatments showing promising results around the long-term effects of anxiety disorder, little research has been conducted on therapeutic strategies for alleviating physiological symptoms, particularly those initiated by panic attacks or aggravated by environmental conditions.

Beyond the barriers of monetary cost and social stigmatization of anxiety disorder therapies is the absence of therapeutic strategies which address physiological traits associated with anxiety disorders, which often initiate or exacerbate the presence of cognitive-based symptoms. This is especially evident in the presence of panic attacks, whose symptoms primarily are physiological: palpitations, accelerated heart rate, sweating, shaking, shortness of breath, chest pain, nausea, chills or heat sensation, and feeling dizzy. While physiological responses vary between episodes of panic attacks and anxiety disorders, several studies have identified that the most common symptoms are associated with autonomic arousal, and muscle tension (American Psychiatric Association 2013). Despite the tracking of these signals becoming increasingly easy to identify with wearable devices such as the Empatica E4 wristband or the Fit Bit Sense (Empatica 2021; Fitbit 2021), little has been studied in the use of such personal metrics in altering one's environment to alleviate symptoms of anxiety disorders and provide immediate support.

Many environmental triggers of panic attacks vary between patients and are often associated with personal stressors experienced throughout their life; however, some cues show repeated association with the induction of panic attacks within patients suffering from anxiety disorders.

It is important to note at this point that for this paper, the term "environmental cues" will be used to define qualities of our built environment, such as thermal comfort, light, noise, smell, and other spatial qualities. More specifically, we will look at the correlation between heat (Asnis 1999), light (Chinazzo 2021; Chamilothori 2019; Verywell Mind), and air quality (Asnis 1999; Bandelow 2017; Verywell Mind 2021) and how the interpretation of our biosignla inform these environmental conditions to result in proactive alterations in our surroundings.

Positioned at the intersection of psychophysiology, cognitive psychology, and environmental design, this paper contributes to our knowledge of the role of sensory stimuli on mental health and, more specifically, in this case, to symptoms of anxiety disorder. It is hypothesized that by leveraging technological advancements in physiological signal tracking, more proactive spatial systems can be designed to mitigate the severity of symptoms and provide an alternate real-time therapeutic treatments.

1. BACKGROUND

1.1. PHYSIOLOGICAL SYMPTOMS

The Diagnostic and Statistical Manual of Mental Disorders (DSM), along with a number of papers, present a list of cognitive and physical symptoms associated with anxiety disorder and panic attack specifiers (American Psychiatric Association 2013, Bandelow 2017; Lader 1980; Katsis 2011). Some of the most common symptoms are skin conductance, heart rate variability, blood pressure, respiration, body temperature, muscle tension, and pupil dilation. The majority of these physical responses are directly triggered by one of our two branches of our nervous system. These two systems are our sympathetic nervous system (SNS), also known as our "fight or flight" response, and our parasympathetic nervous system (PNS), which controls our "rest and digest" response. The reason for physiological responses such as heightened heart rate, pupil dilation, heightened respiration rate, or peaks in skin conductance to appear during panic attacks is due to the fact that these systems are directly triggered by the sympathetic branch of our nervous system, which is the bodies way to prepare for a threat, or emergency. This response from the SNS is fairly sudden and can rapidly escalate the magnitude of these physiological signals until communication from the parasympathetic branch kicks in to regulate the potential magnitude of such threat or stressor (APA 2012) (Figure 1).

Studies that look specifically at heart rate variability (HRV), which is a measure of how healthy one's communication between the SNS and PNS branches are, have shown a significant association between reduced HRV and anxiety disorder,

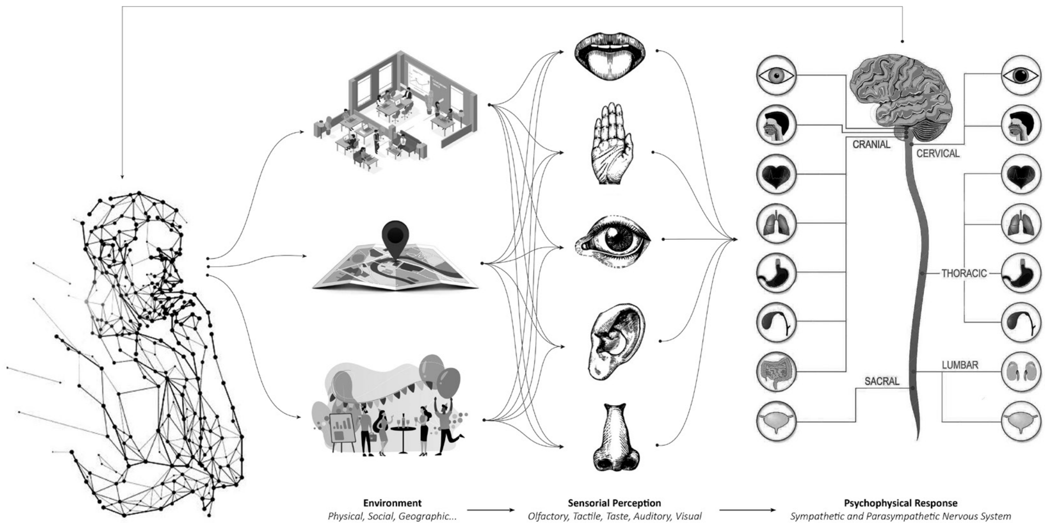

Figure 1: Diagram illustrating the feedback loop between environmental and sensorial cues that impact our nervous system and influences our psychophysiological response. Source: Author 2022.

suggesting that autonomic neurocardiac integrity is substantially impaired in such patients (Kim 2016; Chalmers 2014; Campos 2019). These findings shed light on a possible explanation of why those suffering from anxiety disorders, particularly those who also experience panic attacks, find it so difficult to calm down actively. Essentially, their nervous system is not processing the "rest and digest" appraisal of a scenario, allowing for physical symptoms to escalate and perpetuate. Despite cognitive behavioral therapy (CBT) showing promise in promoting calming strategies and modifying thinking patterns to soothe in-the-moment causal responses to panic or stress, we often see this falling short in new patients overwhelmed by the physiological symptoms (Otte 2011). This is especially true when such physical responses are being amplified by environmental conditions such as the severity of light in the space, thermal conditions, or air quality. In order to help mitigate the severity of physical symptoms, often due to an impaired autonomic nervous system, this study proposes to question the influence of external conditions on the amplitude of such physiological metrics, as well as patients' perceived ability to cope in a stressful scenario.

1.2. ENVIRONMENTAL TRIGGERS

As seen in the section above, there is an undeniable link between mind, body, and our environment, yet the study of sensorial stimuli in the aggravation of symptoms related to anxiety disorder is greatly limited. Although one could arguably go through all aspects of our built environment and denote how each element, from scale to materiality, has some relative impact on our mental state, for the purpose of this study we will be looking at the effect of light, heat, and air quality in relationship with the physiological signals presented above (Figure 2).

The visual system is arguably the most pervasive sense in humans and on which we rely on to build the primary understanding of our surroundings (Pallasmaa 2012). Perhaps the most influential aspect of our visual system on well-being is our intake of light and its necessity in regulating our circadian rhythms and melatonin production. This correlation is crucial since difficulty sleeping is a comorbidity of every anxiety disorder and plays a significant role in how patients can manage both their cognitive and physical symptoms (Harvard

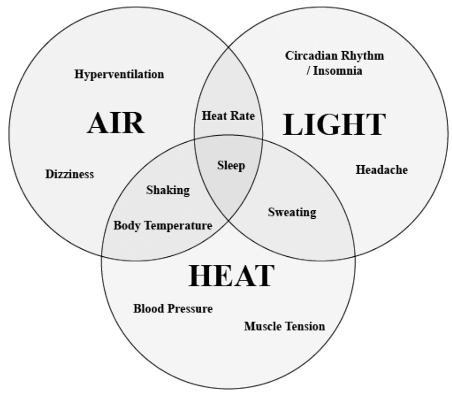

Figure 2: Diagram illustrating correlative symptoms of panic attacks and environmental conditions. Source: Author 2022.

2011; Kalmbach 2016). It was not until 2003 that scientists discovered the intrinsically photosensitive Retinal Ganglion Cells (ipRGC), which, unlike the other cells in the retina, are photosensitive and contain the photoreceptor chemical melanopsin (Berson 2003). Most importantly, these cells are what help humans synchronize their circadian rhythms with the solar day and are correlated with other behavioral and physiological responses to environmental illumination. Other than the highly influential role light plays on our sleep and, thus, overall health, light color, intensity, and spectral content have been seen to impact heart rate, skin conductance and even influence our perception of temperature (Chinazzo 2021; Chamilothori 2019).

Secondly, the influence of light has been the impact of environmental conditions, such as room temperature, humidity, and air quality (levels of Co2), which demonstrate not only detrimental effects on physical health, but also mental health. A study conducted by Asnis et al. found that patients with panic disorders described hot weather and humidity as potential triggers of their panic attacks (Asnis 1999). While several other studies have highlighted the link between air pollution and mental health, indoor air pollution contributes more and more to our daily exposure of Co2 levels (Zhou 2021, Colligan 2021). Beyond the cognitive detriment poor air quality and severe temperature changes cause, is the contribution such factors can make to physiological symptoms of anxiety and panic. Rapid changes in skin temperature and sweat induction are two common occurrences during a panic attack which, depending on the conditions of the room itself, can either be aggravated further, or subtly alleviated. Additionally, one's rate of respiration is known to heighten when under panic, often referred to as hyperventilation, which can lead to low levels of carbon dioxide in the blood and other physical symptoms of dizziness, fainting, nausea, etc. If the air that one is rapidly inhaling is itself deficient in oxygen, or saturated by humidity, this will additionally cause further detriment to the person experiencing symptoms of panic.

With adults now spending 87% of their time inside buildings, it is impossible not to consider the enormous impact our environmental conditions have on mental health (Klepeis 2001). While we continue to live among these spatial qualities every day, with little thought behind their contribution to our mental well-being, it is time to not only recognize their impact on all facets of health, but additionally begin to consider their malleability as opportunities to promote emotionally conscious spatial experiences.

2. METHODS

2.1. SUBJECTS

Three Groups of Participants will be recruited for this study: Group A (subjects suffering from an anxiety disorder, with little indication of panic attacks), Group B (subjects suffering from anxiety disorders, and frequent panic attacks), and Group C (Random control - subjects exhibit no symptoms of anxiety disorder or panic attacks). These subjects will be recruited through association with the School of Psychology, and advertisements. Subjects must be 18 years of age or older. Subjects who meet the definition of anxiety disorder with or without the presence of panic attacks will be based on criteria from the fifth edition of the Diagnostic and Statistical Manual for Mental Disorders (DSM-5) (American Psychiatric Association 2013). Subjects that meet these criteria will additionally take the Beck Anxiety Inventory (BAI) to assess the intensity of physical and cognitive anxiety symptoms during the past week. Subjects with scores above 16 will be recruited for either Groups A or B (Beck 1988). To be sorted between Group A and B, these subjects will take an additional questionnaire assessing the comorbid presence of panic attacks based on symptoms for the panic attack specifier in the DSM-5. Subjects taking psychotropic medication such as antidepressants or benzodiazepines for the last seven days before the assessment will be excluded. Additionally, subjects will be excluded if taking any drugs that affect the response of their autonomic nervous systems, such as beta-blockers or anti-arrhythmic agents, or exhibited substance abuse or dependence. Healthy controls, Groups C, will undergo the same screening as Groups A and B and will only be recruited if exhibiting no psychiatric diagnosis associated with the DSM-5. A partial explanation of the study and its specific procedures will be given to all participants, and written informed consent will be obtained before proceeding.

2.2. PROCEDURE

The study will take place in a controlled space on campus. The controlled variables of this space will be light intensity and spectral content (blue or red light), room temperature, and air quality (humidity and levels of C02). These variables will be directly controlled by the interpretation of the subjects' physiological signals, which will indicate signs of autonomic arousal. Based on the findings from previous research highlighted in the literature review above, the alteration of the variables will depend on the associated desired physical response to these environmental conditions. For example, decreased blue light intensity when pupil dilation and heart rate is elevated from the participant's baseline.

Participants will arrive at the location, and before being briefed on the task, they will complete they put on the Empatica wrist device and are asked to wait calmly in a waiting room for 10 minutes (Empatica 2021). During this time, subjects will sit quietly in a soft chair in a sound-attenuated room, and asked to relax. This will allow for calibration of the device to occur and a per-subject baseline to be assessed. After the initial calibration phase, the subjects will be brought into the neutral room, which will be equipped with integrated systems for controlling light, temperature, and air quality. Subjects will be told not to worry about possible fluctuations they might notice in their environment since the room is equipped to change throughout the day. Once seated, participants will complete the first self-assessment evaluating their current levels of perceived stress, anxiety, and valence. Once done, subjects will begin the two-minute math test they are asked to perform, also referred to as the serial seven tests (Karzmark 2000; Hayman 1942). The test requires participants to continuously subtract 7 from an initial number as rapidly as they can for a time period of two minutes (e.g., initial number given= 86, -7 = 79, -7 = 72, -7 = 65, -7 = 58…). The participants are told when their answers are incorrect and must alter their answers to continue. They are also informed of the time remaining every 30 seconds. After completing this task, participants will get two minutes to “recover” from the test before proceeding to the second phase, which is image stressors. In this section, subjects will be asked to imagine a personally stressful scene for two minutes. When done, participants will be presented with the second self-assessment report of their perceived levels of stress, anxiety, and valence.

2.3. PSYCHOLOGICAL EVALUATION

Subjects are required to fill out several questionnaires throughout the study. First, to determine eligibility to participate in the study, all subjects will fill out a questionnaire determining their symptoms associated with Anxiety disorder and Panic attacks based on the fifth edition of the Diagnostic and Statistical Manual for Mental Disorders (DSM-5) (American Psychiatric Association 2013). Additionally, subjects in Groups A and B will be asked to complete the Beck Anxiety Inventory (BAI) and will only be eligible for the study if their score is higher than 16 (Beck 1988). During the test, two questionnaires will be presented, one before the stress-inducing task, and one after. These questionnaires will be identical and follow the State-Trait Anxiety Inventory (STAI), specifically form Y, which evaluates subjects’ current state of anxiety, asking participants how they feel “right now” (Julian 2011; Spielberger et al. 1983).

2.4. PHYSIOLOGICAL EVALUATION

In order to continuously collect a series of physiological data, the subject will be equipped with the FDA-approved Empatica E4 wristband, which allows for unobtrusive, long-term assessment of the physiological signals (Poh 2010; Empatica 2021). This device collects the raw signals of electrodermal activity (skin conductance) measured in microsiemens (μS), peripheral skin temperature measured in Celsius (°C), blood volume pulse, and heart rate measured in beats per minute. Although other physiological signals, such as pupil dilation and respiration, will not be measured, they will be assumed correlated with the automatic response from the sympathetic nervous systems. For the analyses of changes in skin conductance, temperature, and heart rate, a mean value over a 5-second period will be evaluated to determine fluctuations that occur from the subject’s initial baseline. Heart rate variability will be calculated through the SDNN time domain metric, the Standard Deviation of the normal beat-to-beat intervals (IBI) (Cacioppo 2007; Shaffer 2017). This time domain metric is measured in ms and represents short-term variability, in this case the most recent ten beats.

3. DISCUSSION

The prediction for this study rests on the assumption that subjects suffering from anxiety disorders, particularly those who suffer from panic attacks, have associated physiological symptoms. Although this is certainly the case for symptoms of panic attacks, this is not always the case with subjects suffering from anxiety. In fact, one study found little difference between participants with a generalized anxiety disorder (GAD) and healthy controls in their psychophysiological responses (Hoehn-Saric 1989). While another measuring physiological reactivity in patients with a social anxiety disorder (SAD) found that reactivity was dependent on the context of the subject’s appraisal, suggesting that it is more a matter of reframing stress arousal as a positive coping tool (Jamieson 2013). These studies demonstrate that the fundamental component of anxiety disorders is the personal context. Beyond the evident unique qualities every person suffering from anxiety disorders face based on genetics, upbringing, and social environment are those of skin conductance, sensitivity, external health conditions, physical activity and more. These all make the assessment particularly difficult for both psychological and physical symptoms appraisal and need to be accounted for as ulterior factors.

Another limitation of this study is the length for which participants undergo stress tests. Adding up to a total of four minutes, participants are unlikely to reach the extent of their physiological symptoms in such little time. Additionally, although the tasks at hand have demonstrated efficacy in inducing stress, this response is again highly dependent on a person's experience and might be beyond the scope of what triggers heightened anxiety in that particular subject. With this in mind, the study designs could incorporate a pre-study questionnaire in which participants indicate personal stressors so that the task can be catered more specifically to each participant.

Lastly, it is important to note that this type of sensory therapy is not looking to replace current forms of pharmacological and cognitive-based treatments but rather provide an additional antidote that would be integrated into individuals' personal surroundings to specifically address in-the-moment physiological cues of anxiety and panic. Being founded on the principle that our physical environment plays a significant role in our well-being, this work seeks to leverage the scale and subtly of spatial qualities to offer a novel approach to biofeedback-informed therapy.

CONCLUSION

Although anxiety disorders are composed of both cognitive and physical symptoms, surprisingly little research has been done to mitigate the severity of physical symptoms at the moment of panic or induced stress. Therapy techniques such as CBT promote cognitive strategies for dealing with anxiety in the moment however are not always sufficient in successfully subsiding the amplitude of such physical sensations, which often are rapidly triggered and grow exponentially (Otte 2011). With technological advancements for real-time physiological measurements becoming increasingly precise, along with new research highlighting their relationship to cognitive state, there lies great potential for current forms of treatment to be accompanied by real-time alterations to the qualities of our built environment. This study looks to begin exploring this relationship between mental health and spatial systems to expand the potential for our built environment to respond proactively to one's cognitive state.

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RESPONSIVE BUILDING PERFORMANCE: A CASE STUDY OF ELECTROCHROMIC BUILDING ENVELOPES

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Building envelopes play an important role in the building performance of energy efficiency, thermal insulation, and visual comfort. Controlling solar radiation and daylight through responsive building envelope systems is an emerging sustainable strategy to improve building performance. The effectiveness of responsive building envelopes depends on the dynamic properties of building envelope materials and control algorithms. Architects and researchers are exploring possible ways to integrate responsive electrochromic (EC) glazing materials in building envelopes and testing the dynamic impacts on building performance (DeForest et al. 2013; Hamidpour and Blouin 2018; Eleanor S. Lee et al. 2013). Up to now, the research has tended to focus on control logic, rather than on the responsiveness of the building envelope itself. The modeling of responsive behaviors of an electrochromic building envelope system is challenging due to the dynamic properties of the electrochromic materials and unpredictable behaviors. In this paper, we proposed a case study using four different electrochromic glazing materials to test the impacts of responsiveness on building performance in terms of visual comfort and energy saving for the climate conditions in Tampa, FL. We developed a novel approach, Dynamic Sequence Modeling (DSM), by which these responsive EC building envelope behaviors can be simulated. The simulation results are then used to feed our Supervised Machine Learning (SML) algorithms to enable prediction under changing weather conditions. The SML algorithms are promising avenues to solve this type of predictive learning problem (Murphy 2012). Our SML algorithms seek to optimize performance with altered responsiveness of our EC building envelopes, as a generally capable agent to predict effective responses given similar weather conditions to the learned representation of the climate model. We find that all three responsive building envelope variants demonstrate large improvements in both energy and visual comfort performance compared to the static building envelope. In three EC alternatives, where each has different tint responsiveness, the cooling and heating energy loads were reduced by 54.36% on average, and the illuminance measures had almost the same mean values close to the visual comfort threshold. The most responsive 4-mode EC had the least absolute deviations. On the other hand, the prediction accuracy of supervised machine learning models decreases as the complexity of tint responsiveness (tint mode) increases in electrochromic building envelopes. Our study demonstrates the impacts of responsive electrochromic materials on building performance. Moreover, we show that the complexity of responsiveness decreases the prediction accuracy for SML-based building control of dynamic materials.

Keywords: Building envelope, electrochromic glass, supervised machine learning, building simulation.

INTRODUCTION

From time to time, people tend to overlook the importance of decisions we make in designing, integrating, and operating our building envelope systems. Glazing-materials-based building envelopes have accumulated and amplified impacts on the overall user visual comfort experiences and building energy efficiency. The electrochromic (EC) glazing materials, which we are interested in here, are a type of smart glazing material that has dynamic optical properties and a switchable interface. Electrochromic materials are able to change their color or their optical characteristics in response to an applied voltage(Granqvist 1995). The original study of electrochromic materials can be traced back to S.K. Deb with the early research of electrochromism in 1969 (Deb 1969). Thirty years later, Carl M. Lampert published a paper in which he wrote about the characteristics of chromogenic materials, considering possible applications for improving a building's energy efficiency (Lampert 1984). Since then, more and more evidence has been found in the application of EC in buildings as a promising material for optimizing lighting and energy efficiency of glazing-based building envelope systems (E.S. Lee and Tavil 2007; Aste, Compostella, and Mazzon 2012; Aldawoud 2013; DeForest et al. 2017). With the development of Building Information Modeling (BIM) and simulation approaches to the study of dynamic building performance (Negendahl 2015). With these validated deterministic models and pre-defined activities control functions to represent and visualize building performances, we gain deeper understanding of the relationship between natural and built environmental systems. However, dynamic materials (DM) and phase-changing materials (PCM) provide new possibilities for the optimization of building design and operations (Rauh 1999). There are clear difficulties in adopting the new building materials and technologies, which lie in the incompatibilities of the modeling, design, integration, and evaluation of dynamic materials to the conventional static building models (Casini 2018).

The review of precedent studies regarding the application of EC application as dynamic building envelopes in various locations suggests that using EC could be beneficial to the energy saving of the building, as well as the visual comfort of the occupant. On the other hand, in most cases, the performances differentiate due to variance of EC properties and selection of control strategy in the face of given or unknown climate conditions. There is a trade-off problem between energy efficiency and natural daylighting regarding dynamic glazing. Considering both dimensions, a number of control strategies have been developed in the literature for controlling the EC building envelope. The findings of these studies for evaluating the performance of the EC were mostly based on experiments or simulations. For energy performance investigation, the evaluations of EC glazing depended on several cross-sectional case studies focused on energy load measurements or estimation. For the studies assessing the performance of EC according to its daylighting or visual comfort, some temporal and spatial visual comfort metrics are created and used in both quantitative and qualitative research designs. However, few quantitative types of research have been done to decipher the dynamic patterns of EC with the association of environmental variables from a statistical perspective. Most current studies do not include a time series analysis of environmental variables, nor do they discuss how the simulation performance of EC building envelope with historical weather data could be translated to real solutions under random climate conditions. These research works of control strategy for building glazing systems have several limitations concerning the modeling and learning of EC behaviors, while supervised machine learning allows us to effectively structure the systematic logic between EC and key environmental variables to gain capacities of pattern recognition and eventually control the dynamic building performance. For the supervised machine learning methodology, there are minimum adjustments to the model setup and features required for learning tasks regardless of when and where the EC buildings are situated. The total number of simulation data for performance optimization will be correlated to the accuracy of EC pattern recognition. This SML methodology is based on the statistical analysis of training data to minimize the effort required in solving the EC pattern recognition problem. The identified patterns for EC dynamic behaviors are derived from the optimized overhead simulation. The spatial and time elements are interconnected through this theoretical framework, which is crucial for high-level references on the dynamic EC building performance during the design and modeling process, and in the integration, analysis, and evaluation of post-occupancy experiences.

1. MATERIALS AND METHODS

In our project, we proposed a case study comparing four EC building envelope variants in terms of energy and daylighting performance and decipherability of operation patterns. The following two sections have been designed to prepare two key steps for evaluating of dynamic building performance (energy and daylighting) and supervised machine learning of EC behaviors.

1. 1. A CASE STUDY OF EC INTEGRATED BUILDING ENVELOPES IN TAMPA, FL

1.1.1. VARIANTS OF ELECTROCHROMIC BUILDING ENVELOPES

A parametric designed generic office building model with a net floor area of 153.06 square feet was created with Rhino® and Grasshopper®. Three representative EC building envelope variants were integrated with the building model: 2-Mode EC, 3-Mode EC, and 4-Mode EC of which properties are demonstrated in Table 1. The optical and insulation properties of the building envelopes were modeled in accordance with the manufacturer's specifications. EC optical properties, which are highly relevant in buildings' energy and visual comfort performance were discussed in detail under seven categories: visible light transmission (Tvis), radio frequency (Rf Ext.), solar radiation transmittance (Tsol), Light Reflectance interior range (%Rb Int.), solar heat gain coefficient (SHGC), rate of non-solar heat loss(U-factor), sensitivity (Tdw-K).

EC Glazing	%Tvis	%Rf Ext.	%Rb Int	%Tsol	SHGC	U-factor	Tdw-K
Static Mode	60	16	14	33	0.41	0.28	15
2nd Mode EC	18	10	9	7	0.15	0.28	5
3nd Mode EC	6	11	9	2	0.1	0.28	2
4nd Mode EC	1	11	9	0.4	0.09	0.28	0.6

Table 1: Electrochromic Glazing Material Specifications. Source: SageGlass®.

Given the fact that our simulation study does not intend to investigate any architectural design or system factors other than the EC glazing, we keep other simulation setting identical with each comparative model for focusing on the impacts of EC dynamics on building energy and daylighting performances.

To quantitatively evaluate the impact of EC building envelopes, extraneous environmental variables and geographical context were controlled in the simulation iterations of comparative models. To demonstrate EC potentials in the extremely hot conditions found within the U.S., Tampa was selected as the sample city for our case study. Electrochromic building envelopes are particularly desirable for cooling-dominant climate areas with high solar radiation. As our selected site, Tampa, FL represents the typical hot climate on the eastern sides of the North American continent, characterized by subtropical high temperatures in long summers (avg: 4.9 months) and mild temperatures in short winters (avg: 2.7 months). The annual temperatures in Tampa typically range from 52°F to 90°F as shown in Figure 1.

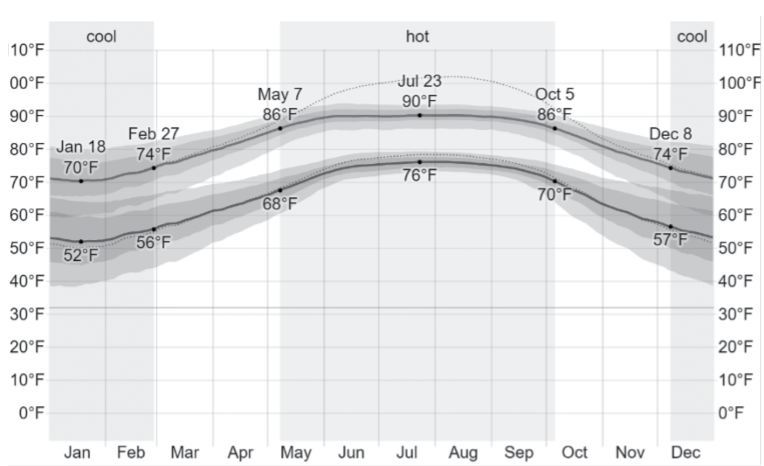

Figure 1: Hourly temperature visualization in Tampa, FL. Source: NASA 2022.

1.1.2. SIMULATION MODELING OF DYNAMIC BUILDING ENVELOPES

The simulation research framework was used and validated in previous research projects (Tällberg et al. 2019). The procedural logic can be summarized as EC building envelopes are first constructed to run the simulation with extended static modes of EC. A post-processing script was developed to examine the hourly simulation data and populate it as new time series sequences, matching the dynamic behaviors of EC. The process ensures that our models approximate closely with the dynamic nature of EC building envelopes. In this study, the simulation workflow consists of three parts in the context of Tampa, FL:

1. Create hypothetical building models with EC variants' discrete phase material properties.
2. Run ClimateStudio® to perform energy and daylighting simulations with the Tampa weather file by connecting to EnergyPlus® and Radiance®.
3. Sequence hourly simulation results to generate dynamic building envelope behavior.

Our comparative simulation research design with four building models is to demonstrate how much improvement we can achieve by each optimized EC building envelope compared to the static glazing scenario. A precedent study provided an overview of the control optimization of EC glazing materials with different optical properties data (Oh et al. 2018).

1.1.3. SUPERVISED MACHINE LEARNING FOR PATTERN RECOGNITION OF EC BUILDING ENVELOPES

The normal tasks for using supervised learning are establishing a model from a set of existing instances and utilizing the model to effectively predict certain label features (here is EC mode) for some unknown instances. After we successfully generate the simulation data set of each EC building envelope, we randomly split the data into two parts: a training set (90%) and a test set (10%). The training instances are sparse simulation data points at random working hours across the year. Three-time series environmental variables are identified as training features. The testing instances are used to evaluate the deciphering performance of the SML model for EC pattern recognition.

Conventional building simulations require accurate knowledge of the state of the model and environment conditions and become ineffective with dynamic models in changing environments. Therefore, we developed a post-processing script to integrate dynamic models in simulation and then used supervised machine learning to deal with uncertain outdoor environmental conditions. We analyzed all relevant environmental variables in the weather file and conducted dimensionality

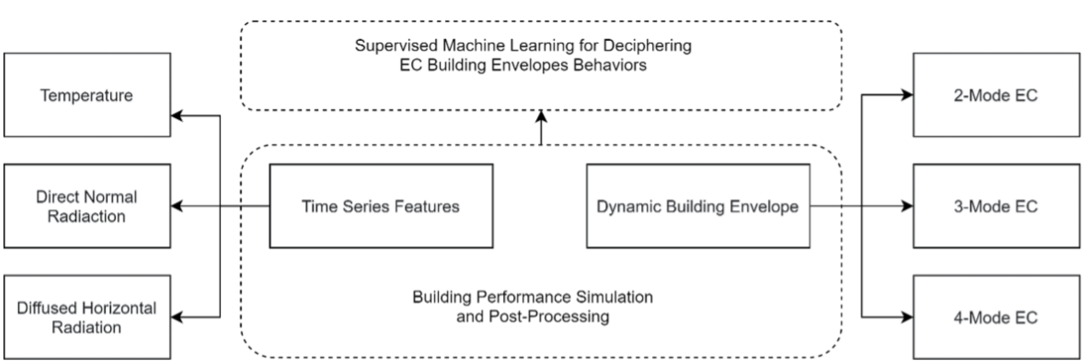

Figure 2: A schematic outline of our simulation modeling process and SML architecture. Source: Author 2022.

reduction to improve the computation efficiency of SML. Seasonal and daily cycles embedded with the time series features are categorical information that needs to be engineered for SML to understand the temporal patterns. The parametric modeling process makes our supervised simple machine learning algorithm applicable to various pattern recognition tasks. An adaptive machine learning approach is preferred for linking the building simulation knowledge with SML to solve the dynamic building performance problems, since the state of the model and natural environmental conditions are more uncertain. Figure 2 illustrates this integration process, we have established a methodology towards a hybrid approach to the electrochromic building envelope systems, blending the benefits of simulation with machine learning. Our framework concurrently engages the development of parametric modeling, simulation of the dynamic building envelope, and analysis of building energy and daylighting performance comprehensively.

2. RESULTS

2.1. SIMULATION COMBINED WITH TIME SERIES ENVIRONMENTAL CONDITIONS

All the simulated energy performance results generated in this study confirm the energy-saving potential of electrochromic building envelopes in Tampa, FL. As mentioned earlier, simulations were run in parallel to understand how EC properties effect affects energy consumption. In this section, these annual performances were resampled as the smoothed weekly scale to compare with each other. Figure 3 shows the buildings' annual total operational energy demands without the EC (Static Glazing) and with EC variants considered. Results showed that the energy demand was significantly higher when the EC dynamics were not taken into account. While the difference in 3 EC building envelope alternatives was relatively small (8.47 %), this difference was around 54.36 % in static glazing building envelope and the average of all EC variants.

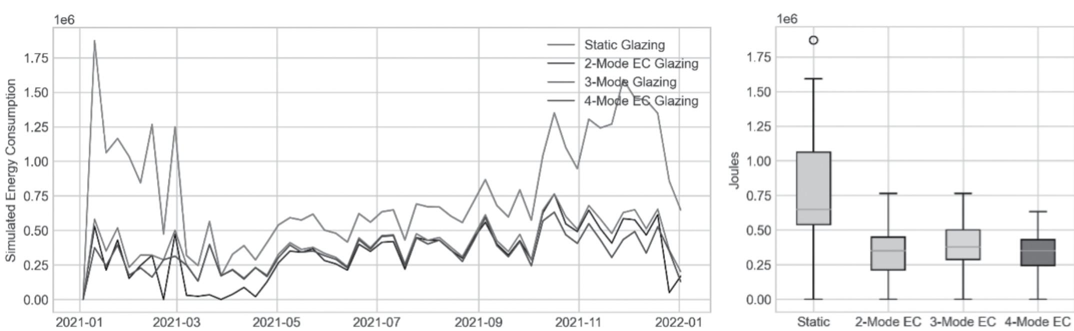

Figure 3: Annual energy performance for each EC building envelope. Simulation of the dynamic building envelopes effectively reduced energy consumption across all settings with the least median under 2-Mode EC. Source: Author 2022.

In the case of the static glazing considered, when 2-Mode EC was compared, a decrease of up to 57.73 percent was observed in annual energy consumption. When the same comparisons were made for 3-Mode and 4-Mode EC, a decrease of up to 48.89 and 56.44 percent in energy consumption values were measured respectively.

The daylighting performance in terms of indoor illuminance was also simulated separately. Figures 4 on the following page show these daylighting simulation results. When EC dynamics were not considered, the results indicated that the indoor illuminance could easily cause visual discomfort with its high daily and seasonal volatility compared to the situation in which EC was used. In annual comparisons, the effect of EC dynamics in winter (solar altitude at its minimum) became more evident. However, these simulated energy and daylighting performance comparisons may not be a convincing method to assess the actual benefit of EC building envelopes because the weather conditions will not be given as the pre-knowledge in real-world scenarios. The randomness of natural environmental variables, an important point that should never be overlooked with dynamic materials, needs to be factored into the equation for optimizing the performance of dynamic building envelopes.

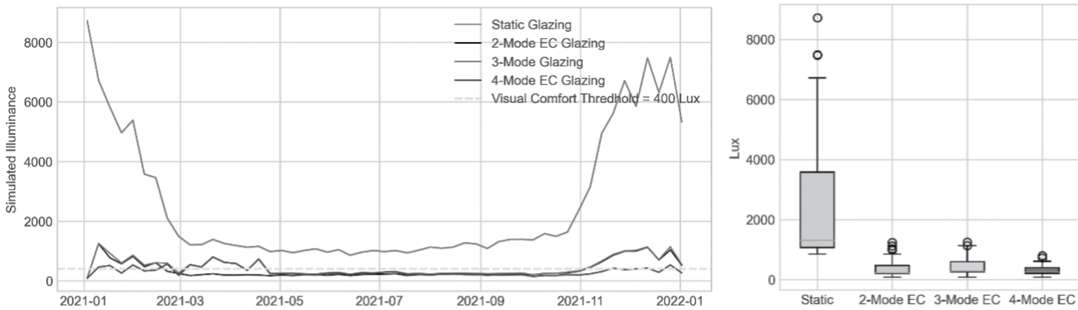

Figure 4: Annual daylighting performance for each EC building envelope. Simulation of the dynamic building envelopes effectively reduced excessive lighting across all settings with the most consistent performance under 4-Mode EC. Source: Author 2022.

2.2. SML CLASSIFICATION OF EC PATTERNS

We conducted randomized testing on the SML for classifying dynamic patterns of all EC building envelope variants. The results show that the precision of classification is inversely related to the complexity of EC behaviors. The SML we tuned achieves a competitive 98.32% classification precision in the 2-mode EC dataset.

EC Glazing	Precision	Recall	F1-score	Support
Static Mode	-	-	-	-
2nd Mode EC	0.9832	0.9829	0.9821	234
3nd Mode EC	0.8732	0.8760	0.8741	234
4nd Mode EC	0.7762	0.7735	0.7733	234

Table 2: Classification precisions on EC dynamic behaviors. Source: Author.

By visualizing the temporal pattern of simulated EC behavior and summarizing the classification performance in Figure 5 on the following page, we found that (a) training an SML model using dynamic simulation data is generally well suited for the pattern recognition of all EC building envelops (b) the learning scheme for less dynamic material shows better results (c) for learning from high dimensional data points, 2D visualization of temporal

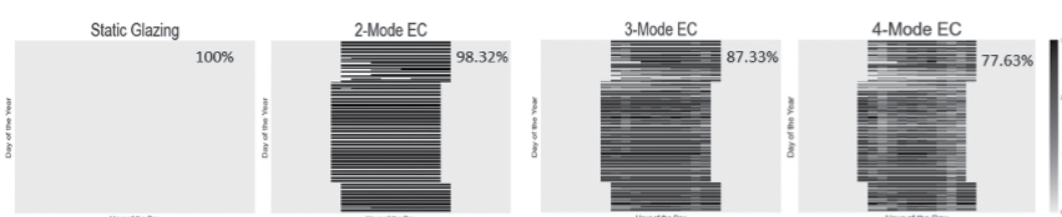

Figure 5: SML weighted precision of classification of EC dynamic behaviors. Source: Author 2022.

or spatial distribution would not be sufficient to show the hidden patterns of EC dynamic (d) as the development of EC materials, the operational decision boundary (Mode of EC) will continue to expand from discrete to linear. There would be a possibility that the training datasets from the simulation can only be sparsely annotated. Then pre-processing methods will be needed for machine learning from these missing or partial EC mode labeling to continue to improve the classification performance.

CONCLUSION

In this article, we have demonstrated the responsiveness of a spectrum of EC building envelopes in Tampa, FL, and how well we can predict the responsiveness. As discussed in the previous sections, dynamic glazing materials, especially electrochromic glazing, have become the material driving factor for the next generations of high-performance building envelopes. The responsiveness of dynamic glazing material is of great significance for improving building performance. This study focused on understanding the impact of responsiveness on the energy and daylighting performance of the building models. The simulation results show that all EC building envelopes with different responsive levels improve visual comfort and energy efficiency, and the performance variance decreases as the responsiveness increases. However, the predictability and controllability decrease as the responsive operation patterns of electrochromic glazing materials get more complicated. The accuracy is still low to using the machine learning approach to decipher responsive EC operations based on simulation data. Further explorations of environmental data are warranted to enhance the predictable responsiveness of electrochromic glazing integrated building envelopes to develop robust modeling and learning techniques for responsive building envelopes.

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TOWARDS A BIOREMEDIATION BUILDING ENVELOPE SYSTEM FOR IMPROVED AIR QUALITY

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According to the World Health Organization and the European Environment Agency, air pollution is the biggest environmental health risk today (European Environment Agency n.d.; Neslen 2018; United Nations Economic Commission for Europe, n.d.). Although general pollutant levels have improved in the last few decades, it is only recently that certain types of highly toxic human-made pollutants have been emitted in unprecedented quantities, primarily in developing regions. Moreover, within these geographic regions, the global population is estimated to double by 2050. The climatic context in most of these predominantly unindustrialized economic territories favors natural ventilation and the seamless interaction between indoor and outdoor space. Still, these areas mainly rely on mechanical systems to homogenize atmospheric living standards. Air conditioning systems produce wasted heat that alters the microclimate of buildings' surroundings, while creating additional air pollution exhausted by the running cycles of equipment. To disrupt this vicious cycle of energy expenditure and air pollution replenishment, this research proposes a hybrid air purification modular ceramic system for building envelopes in regions where fiscal means are limited, and natural ventilation is a viable option, to regulate both exterior and interior atmospheric pollution. The objective is to create a low-tech, high-value system, conceptualized as a combination of mechanical components, with the effectiveness and sensitivity of biological organisms. This infrastructural strategy serves as a site of inquiry towards the potential amelioration of local urban pollution airstreams in the developing world. Through an extensive analysis of air pollution bioremediative systems' attributes and a series of research initiatives, several variables of the proposed system were substantiated. The probable impact factor of the system on the projected global population was also investigated with qualitative and quantitative work, defining the potential regions complying with the system's hypothesis criteria. Air pollution levels and urban air velocity thresholds were further characterized for specific cities inside the boundaries of these regions. Computational Fluid Dynamics parametric experimental work investigated air velocity-related issues that would be evaluated under established air exchange rates to further streamline the design features of the core modular system's ceramic plant host component. While with this work, the technical applicability of the proposed system is established, the intention was not only to provide an explicit technical solution, but also to suggest an encounter with cultural settings based on the premise that when people lose their relationship with the environment due to air pollution, they also lose their societal cohabitation and cohesion patterns.

Keywords: Air pollution, air quality/inequality, bioremediation, envelope-system.

1. THE NEED FOR VIABLE AIR POLLUTION CONTROL BUILDING SYSTEMS IN DEVELOPING REGIONS

In recent years, air pollution has been inextricably linked to the changing physiology of the human body (Schell et al. 2010). Air pollution has already affected the way we have evolved as a species. Although pollutants have been emitted into the atmosphere throughout history, either by biogenic or technogenic origin, it is only recently that new types of highly toxic and noxious human-made pollutants have been emitted in unprecedented quantities. In a 2012 report, the World Health Organization (WHO) estimated that 7 million premature deaths annually are linked to air pollution, characterizing the adverse effects of air quality on the human organism as the world's largest environmental health risk (Jasarevic, and Osseiran 2014; European Environment Agency, n.d.; Neslen, 2018; United Nations Economic Commission for Europe n.d.). According to the United Nations (UN), the world's population, currently numbered around 7.6 billion people, will increase to 9.8 billion by 2050, with nearly 90% of the increase concentrated in Asia and Africa. As the world population continues to grow and urbanize primarily in regions with challenging economies, so are the ambient air pollution-associated problems. The WHO indicates that the majority of air pollution-related deaths

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occur in South-East Asia, Africa and some Western Pacific regions. In fact, nearly 92% of air pollution-related deaths occur in low and middle-income countries (World Health Organization 2016; Katsouyanni 2013).

The intensification of air pollution problems in developing regions is mainly due to the outsourcing of industrialized manufacturing processes from capitalist-oriented markets to economies where the cost of human labor is grossly undervalued. Other contributing factors include the lack of infrastructure that deals with rising levels of air pollution, and the lack of relevant legislative policy that prevents citizens from using alternative fuels, like biomass, for their household needs. Nevertheless, within those geographic regions, the population is estimated to double by 2050 (Mannucci, and Franchini 2017; Shanmugam, and Hertelendy 2011).

2. THE PREMISE OF PHYTOREMEDIATIVE BUILDING ELEMENTS

This research proposes solutions for reducing air pollutant concentrations in the urban airstreams of regions with developing economies and mild climatological conditions by augmenting natural ventilation, contrary to the more popular but energy-intensive mechanical ventilation. Through comparative analysis of phytoremediative systems for indoor and outdoor air pollution, as well as experiments in computational fluid dynamics (CFD) and other studies, the analysis concludes with the design of a low-tech biomechanical phytoremediation envelope system. The proposed vertical hydroponic system is a hybrid in the sense that it combines organic plant life along with mechanical components that are strategically instrumentalized to augment the growth of plant life. It is also hybrid since it is used for both indoor and outdoor phytoremediation, eventually reducing air pollutant concentrations in urban ambient air.

An essential parameter in the realization of the proposed system is the role of an augmented natural ventilation complex, which supports the right volume and velocity of airflow to sustain organic life while also regulating air pollution control. As is well established, there are natural and mechanical ventilation systems, yet the aim in this particular research is to enhance the performance of natural airflow with passive formal means like the use of solar chimneys. This decision is critical as it requires as little external energy as possible to augment and orchestrate airflow for pollution control and indoor climate control and is also easily implemented worldwide at a low cost. The system is primarily focused on performing under natural ventilation conditions, yet under certain environmental conditions, it requires the assistance of low-energy active components, such as room air extraction fans, which can support an adequate air purification and circulation rate. Contrary to the majority of existing systems that perform as extensions of mechanical systems or as fully automated mechanical systems with the addition of biotic components, the proposed approach is redefining the envelope of the building in order to take full advantage of the regional environmental flows while at the same time regulating the indoor and outdoor air streams (Lau 2015; Wang, and Zhang 2011). Consequently, this augmented natural ventilation system is designed and developed under the premise that it will use materials in the most environmentally sustainable way, which could be locally sourced. It takes full advantage of its envelope integration in reducing watering and artificial lighting needs. At the same time, its acquisition and maintenance cost would be feasible for less financially affluent people since it could perform in multiple levels from air biofilter to thermal regulator to building enclosure. Overall, this line of research investigates the following two questions and related subjects around them:

1. Can we envision an integrated building system that would be feasible to construct and function in the naturally ventilated environment of an emerging

economy; a system comparable to existing indoor phytoremediative systems in terms of air pollution control but more interactive in terms of its exchange with outside environmental flows? Additionally, could we control the microclimate around such systems through a design approach incorporating plant evapotranspiration and solar heat regulations through plant shading?

2. If a low-tech, high-value phytoremediation system is a viable option for the region, how might this affect the public life of the built environment? Additionally, what kinds of transformative effects might such a system have on existing building typologies, specifically how they relate to and accommodate their inhabitants?

The underlying assumption behind both these questions is that such a system would require direct exposure of buildings to external environmental flows designed to perform within the framework of economic constraints in developing regions. Additionally, there are multiple factors to consider in terms of the embodied energy of the system, the life cycle of its components, or the source-origin of its raw materials. More importantly, one would need to evaluate its significance within a broader socio-political value structure particular to the geographic region under consideration in order to limit to an absolute minimum, the necessary use of mechanical apparatuses in the built environment.

3. MECHANICAL VERSUS BIOLOGICAL VENTILATION SYSTEMS

Although a big part of this work is data-driven and scientifically substantiated, the assumption suggests an alternative building system as a response to air pollution but also critiques a larger context: the establishment of building practices abiding exclusively by Western capitalist-oriented market modes and the logic of uniformity and expedient optimization that in most cases disregards the environmental patterns of specific geopolitical territories (Bachman 2003).

Around the globe, oversized mechanical air conditioning systems are used unilaterally to homogenize atmospheric standards of living. Other than the obvious high embodied energy usage of these mechanical systems, the byproducts of their provided services come in a multitude of forms; from excessively produced, wasted heat that alters the microclimate of the building's surroundings to additional air pollution that is exhausted by the running cycles of the equipment. As a response to this vicious circle of energy expenditure and air pollution replenishment, this research work proposes a hybrid air purification system (EPA 1991; Raji et al. 2015; Sung 2016).

Architecture has not always been as heavily dependent on mechanical systems as it is today. Less than a century ago, natural ventilation was the prevailing method for revitalizing stale air in interior spaces. Advancements in building systems and materials, along with energy conservation requirements, have radically reshaped the building industry throughout the last few decades. With the assumption that buildings can be completely isolated from the outside, the industry invested in and promoted envelope systems as artificial barriers of separation, heavily equipped with and dependent on mechanical ventilation systems. With the rise of atmospherically-controlled buildings, universal typologies of physiological living standards related to building codes emerged assuming that they would support and accommodate a universal inhabitant (De Dear, and Brager 2002; Heating et al. 2004; Larsen et al. 2020; Simonson et al. 2002).

Within this mechanical paradigm, the capital invested in environmental control systems, as a percentage of the total cost of construction, has increased more than five-fold in the past 100 years, from 5% to 27% (Kieran and Timberlake 2004). Regarding energy consumption, Heating, Ventilation, and Air Conditioning (HVAC) systems account for circa 40% of the total energy used for the building sector (U.S. Department of Energy 2015; Westphalen, and Koszalinski 2001). Furthermore, when we consider the functional life cycle analysis of buildings within the context of increasing concerns regarding toxic and non-renewable material consumption, it becomes evident that research on systems for environmental control and how they interact with the building envelope has become today more relevant than ever, especially for their deployment in the suggested regions.

Traditionally, in biomes where natural ventilation is permitted, for example, the Mediterranean basin, the distinction of indoor/outdoor air that characterizes the built environments of many Western cultures is inconceivable (Klepeis et al. 2001). Instead, natural ventilation is the prevailing mode of air conditioning, whether conducted passively or actively using fans. In the western world, air pollution has become detrimental, to an extent, in the way buildings are designed; it has also greatly affected patterns of urban habitation. My objective is thus to create a phytoremediative building system that could potentially provide an effective countermeasure to air pollution, allowing for natural ventilation and, ultimately, positively affecting modes of living in an urban setting.

4. BIOGEOGRAPHICAL CONTENT AND SOCIO-ENVIRONMENTAL AMBIENT AIR POLLUTION TRENDS

If we make a close empirical examination between the regions that the UN predicts to witness the most extensive urbanization and population growth, with the regions that demonstrate high levels of air pollution, we will see that these are the same regions that have traditionally developed architectural/habitational typologies that favor the seamless interaction between indoor space and the exterior environment (The Global Health Observatory, n.d.; United Nations & Department of Economic and Social Affairs, Population Division, 2015 2017). In other words, areas that are predicted to urbanize rapidly and are, in most cases, climatically suitable for natural ventilation; however, due to rising levels of air pollution, these areas will most likely have to rely on mechanical ventilation systems if there is no alternative proposal provided (Arnfield 2016; Petersen et al. 2021). The cost of such implementations would be high, leading to partially unpolluted, or over-sterilized air supplies through the Heating, ventilation, and Air Conditioning (HVAC) filters, but most importantly to a significant alteration of urban living isolation that would negatively impact the culturally traditional habitation patterns.

Beyond this empirical overview, three research initiatives were developed to accurately establish variables that geographically define the regions mentioned and the projected number of people that could benefit from implementing the proposed natural ventilation bioremediation system.

The first initiative is a visual mapping of parameters analyzing the human health impact of air pollutants, their primary origin, relative concentration space around a building, and the corresponding normalized air quality standards provided by several governmental and non-governmental regulatory agencies worldwide (Figure 1). In addition, an HVAC systems filter analysis was also established for these pollutants. The findings indicated that even the higher efficiency filters like an Ultra-Low Penetration Air filter (ULPA) have limited removal efficiency when the particle size of non-biological pollutants is smaller than 0.1μm. Another important piece of information from this study was the discovery that air pollution standards were often significantly different among various agencies, with many of the pollutants not having established standards, while the ambient air pollution guidelines for human health from the United Nations—World Health Organization (UN-WHO) proposing the lowest concentration levels of air contaminants per time of exposure overall.

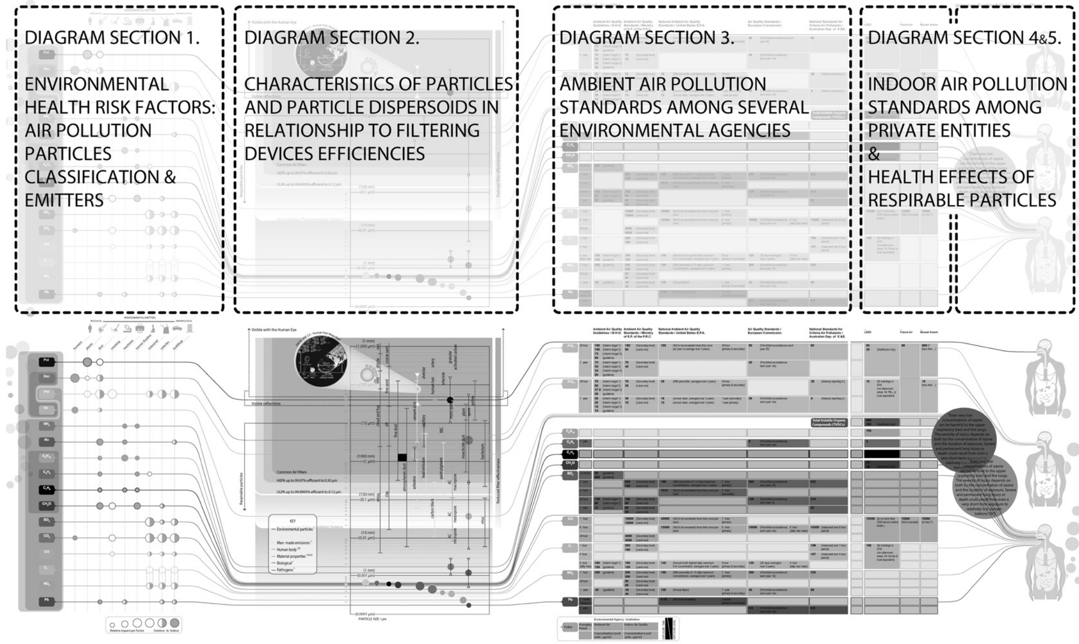

Figure 1: Multivariable diagram associating air pollution sources and standards, health severity of individual pollutants, and HVAC filters efficiencies. Source: Author 2018 in collaboration with: CASE students Anna Dyson et al.

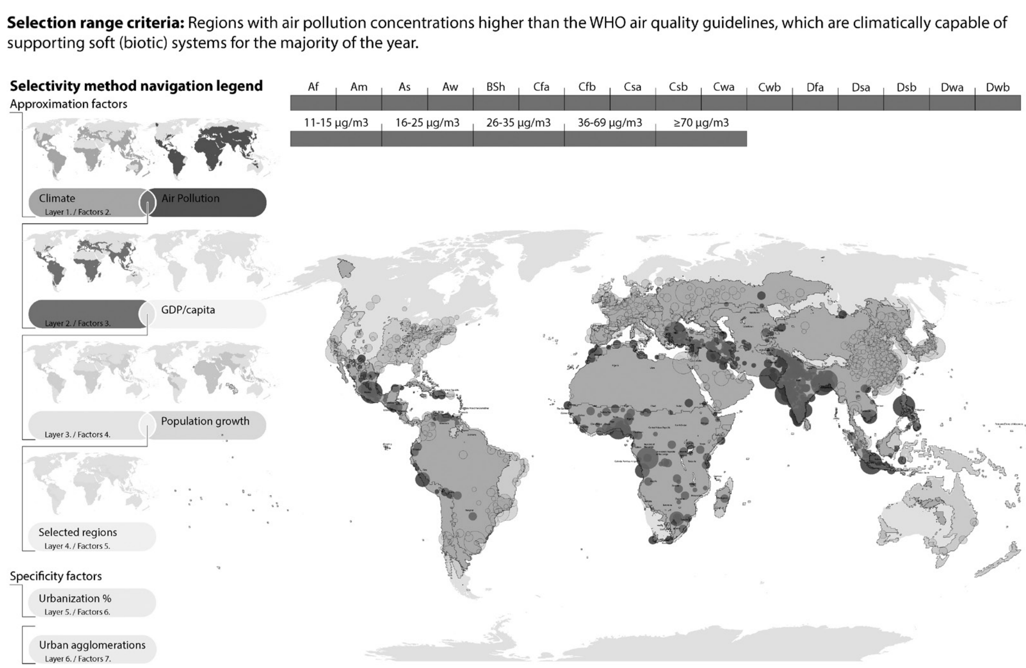

Figure 2: Global map of regions under selection criteria for the proposed system applicability and impact factor to projected population growth. Source: Author 2021.

Based on these findings, a second initiative was formed that used quantitative and qualitative data in the form of several maps with resolution at 0.5° (or ~50 km) (Figure 2). For the first section of this initiative, four main maps were used in a geospatial Venn diagrammatic study, where the final selected map area resulted from the exclusion of the non-mutual areas. The four global maps used for this stage of the initiative were a climate map based on the Köppen-Geiger climate and ecosystems condition classification, an air pollution map of annual median concentrations of fine Particulate Matter (PM2.5) above the UN-WHO standards guideline, a Gross Domestic Product (GDP) per capita map and finally a natural population growth map of countries (Kottek et al. 2006; The World Bank Group, n.d.; United Nations, and Department of Economic and Social Affairs, Population Division 2017). The criteria used in each map for the appropriate selection of the geospatial data sets represented were based on the research's hypothesis that the hydroponic planted system proposed would require climatic conditions that would not prohibit a plant from growing in the envelope of a building in terms of regional annual temperature and air-water content. As for the GDP/Capita, thresholds were set below the poverty thresholds set by the U.S. Department of Health & Human Services for individuals for 2019 (U.S. Department of Health and Human Services n.d.).

The sequence of the maps used was marginally altered from the research's hypothesis for a hybrid bioremediative envelope system that could be implemented in developing regions with mild climatological conditions and air pollution problems and where the local population is projected to increase. The main reason behind this sequence inconsistency was the assumption that a low-tech system like the one proposed does not necessarily mean that it is also a low-value system only for developing regions. Although unpopular in many financially affluent areas, natural ventilation has many benefits in terms of energy reduction. In fact, an almost 60% total primary energy reduction could be saved if offices in the commercial building sector apply natural ventilation strategies (Baker & Steemers 2000) (Figure 3).

Finally, after the graphical representation of the global regions under compliance with the selected criteria, two additional maps are imposed over the selected regions as factors of specificity to define the impact factor of the system further. Evaluation of numbers of the projected population increase in the next 78 years until 2100 are established through population growth projection studies from the UN.

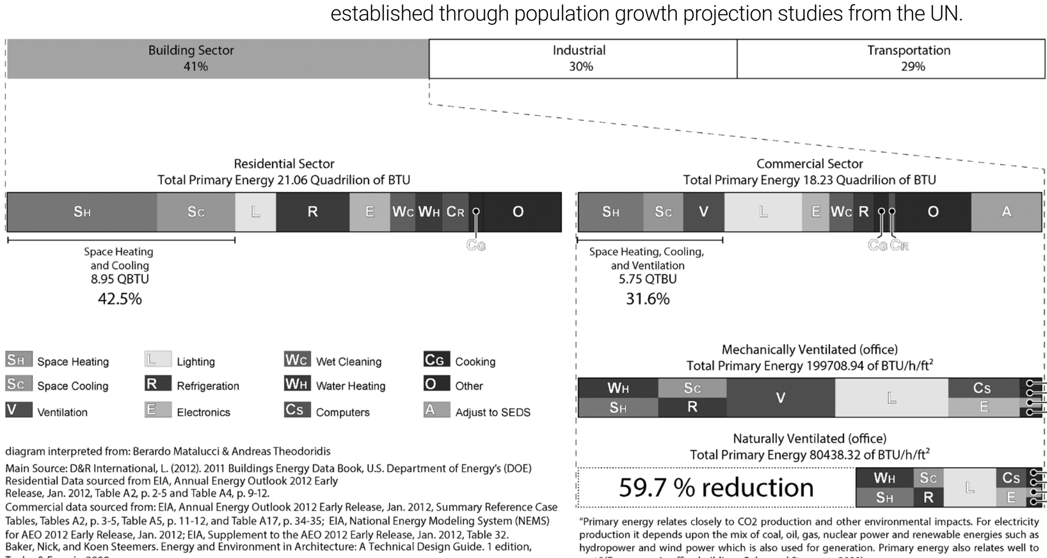

Figure 3: Potential primary energy reduction of naturally ventilated buildings for the commercial building sector of U.S. Source: Berardo Matalucci & Author 2020.

Following the outcomes of the previous initiatives, the third one was conducted to investigate diagrammatically and numerically the climate and air pollution concentration trends in the atmosphere of cities inside the boundaries of the previously designated global areas (Figure 4). The main scope of the inquiry was to verify the relative urban air velocities required to disperse air pollution concentrations below the UN-WHO recommendation guidelines for Particulate Matter (PM10). Particulate Matter was selected for this initiative as a baseline pollution indicator since it is considered by most environmental agencies, including the U.S. Environmental Protection Agency (EPA) and the E.U. European Environment Agency (EEA), as one of the most common criteria pollutants for setting ambient air quality standards.

Three cities from three different continents were selected to be studied, which are Mexico City from North America, Athens from Europe, and Delhi from Asia. Annual detailed data archives of 2018 were used from the corresponding national agencies for weather and air pollution. For instance, in the case of Athens, air data were used from the Hellenic National Meteorological Service with a resolution of three hours, 2920 data points in total, and 8736 hourly data points were obtained from the European Environment Agency for air pollution. After the required post-processing of the data to the necessary form for diagrammatic analysis and display, a series of timeline and bar chart diagrams of several resolutions were developed for each city. For this line of work, the wind direction was not as important of a factor to consider, especially considering it can vary significantly across the scale of an urban setting. Some of the anticipated trends, such as the lower air pollution concentrations as the wind speeds got higher, were the first ones depicted by the graphs. After an extensive analysis of the charts, a more detailed and appropriate conclusion would be that the graphs generally show a negative correlation between wind speed, temperature, and air pollution concentrations and a positive correlation between relative humidity and air pollution concentrations. These results suggest that while wind speed might predominate general pollution levels on a day-to-day basis, temperature and humidity are better indicators of pollution trends within the daily cycle

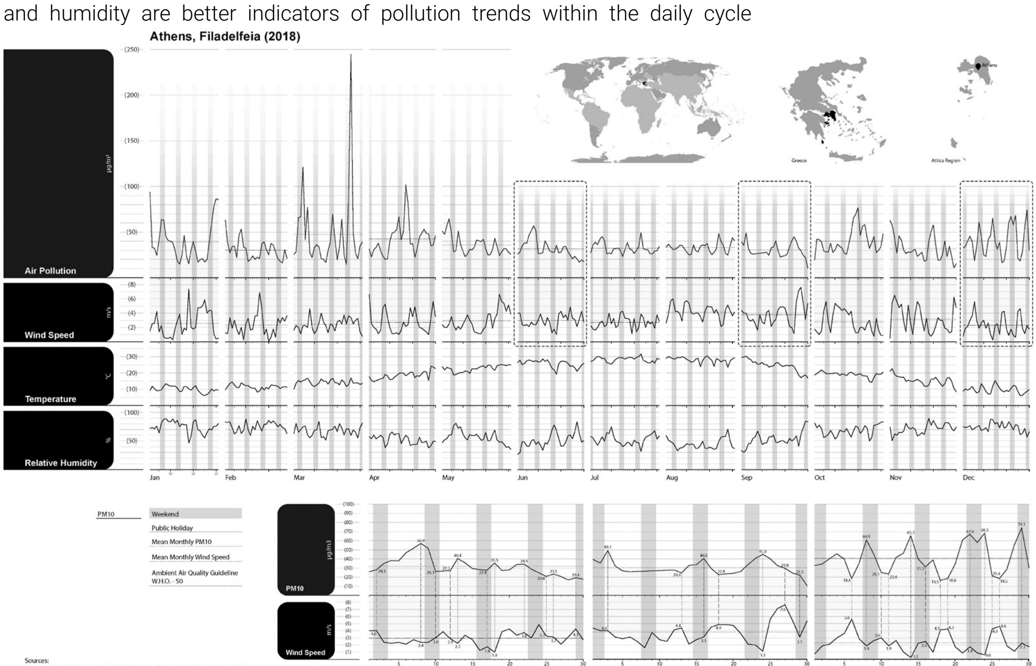

Figure 4: Urban air pollution to environmental variables association diagram for Athens. Source: Author 2021 in collaboration with: Daniel Ruan.

and that the concentration of pollutants generally follows the cycles of human activity; however, meteorological factors have a significant impact on air quality. For instance, during the weekends in Athens or during the national holidays in the winter days, since people spent time inside their homes burning solid fuels to warm their spaces, pollution levels were spiking. Nevertheless, these studies numerically suggested that above wind speeds of 3.5-4m/s, air pollution levels are getting below the 50 μg/m3 concentration for PM10, indicated as the lower interim target level for daily average time exposure by the WHO (The Global Health Observatory n.d.).

5. LITERATURE REVIEW OF PHYTOREMEDIATIVE BUILDING SYSTEMS

The current systems in the market or those still in development for experimental purposes are primarily divided into two main categories for indoor and outdoor space systems (Figure 5). Besides this classification, they come in different sizes and manifestations, from small portable to the scale of a plant pot, to a whole wall installation with a partially indoor systems integration to entirely independent standalone exterior space installations.

Indoor space systems come in various physical sizes following entirely different approaches, from standalone structures to fully integrated, and manually regulated to fully automated. Two typical examples of standalone systems are the first version of the Active Phytoremediation Wall System (AMPS) experimental prototype created at the Center for Architecture Science and Ecology (CASE) and the commercial N-series systems that NAVVA produces (Aydogan 2012; CIAT 2019; Kallipoliti 2018; Naava n.d.; NAAVA 2020; Polidori 2010). These systems are portable, not attached to the floor or the walls, and they have inherent modularity that allows them to take different sizes and volumes. At the same time, everything required for the system to perform is provided from the apparatus itself. Both systems have their own structural components, lighting and watering system, and subsystems with pumps, air fans, sensors, and actuators regulating the circulation of air, fluids, and humidity. Unless the specific device version is not equipped with manually refilled fluid tanks and rechargeable batteries, then the device's container room should be provided with a regular electricity socket required to plugin, and a water installation with drainage pipes for the circulation of fluids.

On the other side of the spectrum, the integrated systems coexist with the building's mechanical systems installations. The most recognizable systems of this typology are the ones of Dr. Alan Darlington of NEDLAW with the indicative commercial name "Living Walls," which have been installed in building lobbies worldwide (A. Darlington 2015; A. B. Darlington et al. 2001; Nedlaw 2016). Also, the latest instantiation of the AMPS prototype, has been installed in the Public Safety Answering Center II in the Bronx, NY (PSAC II) and mounted on the ground floor main lobby wall (SOM n.d.). The system's front side is directly interacting with the long side of the lobby main transitioning corridor as a typical passive green wall commonly used in interior spaces. However, its unseen mechanical side is expanded in a dedicated space on the back of the wall. This space is used to monitor and maintain the wall, which is transformed into a fully functional automated, active wall dragging air through its plants' rhizosphere for regulating and conditioning air quality levels of the space for one of the crisis decision-making rooms. Although the lighting source for the PSAC II AMPS system is still individualized to each plant and attached in each interchangeable module, the system's water and air handling components are directly controlled and integrated into a continuous mechanism with the more conventional mechanical systems of the building's HVAC. Installations like the one briefly described above are mainly possible to reach this level of interconnectivity in new constructions

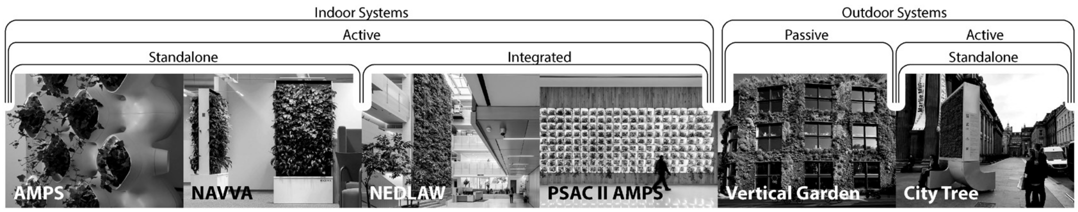

Figure 5: Categorization of phytoremidiative systems. Source: Author 2022.

or extensive retrofits that will plan the necessary requirements in the early design and construction building phases. In less extensive renovations and existing spaces, standalone systems would probably adapt better with less disruption in the fundamental building systems.

Current outdoor systems are mainly divided into two categories, passive and active. Although passive outdoor phytoremediation systems are not considered as air purification systems alone, contrary to the active ones, which force the air through specific routes, we will include them for the purposes of this review. They are the only ones currently described as outdoor biotic systems in the related literature, except for a singular active outdoor air-forcing standalone system. The most renowned representative of exterior phytoremediation systems is the botanist Patric Blank whose work with passive green walls named "Vertical Garden - Mur Végétal" and green spaces attached to building walls' exterior (Bianchini n.d.; Blanc et al. 2008; Blank n.d.; Kmieć 2014; Nurnberg n.d.). Blank's "vertical gardens" are primarily felt-based additions to existing building facades interacting with the surrounding building environment more directly but always with the supplement of an envelope component that acts as the substrate for the plants to grow. Since these types of "green walls" are placed outdoors, their mechanical lighting and watering requirements are minimized almost entirely. Depending on the region's climatic conditions, it may require additional water that is usually a dripping irrigation system on the top of the wall, with a gutter on the lower part for collection and recirculation of the excess water. "City tree" is the only outdoor active system in existence so far and, as its name suggests, is a standalone vertical fully automated greening system (Mok 2020; Patel 2018; Splittgerber & Saenger 2015; urbanNext 2018). "City tree" is a ground-placed system equipped with its own irrigation and air-handling system, while solar panels provide its energy. The system uses moss as its primary plant-growing substrate and an abundance of sensors for

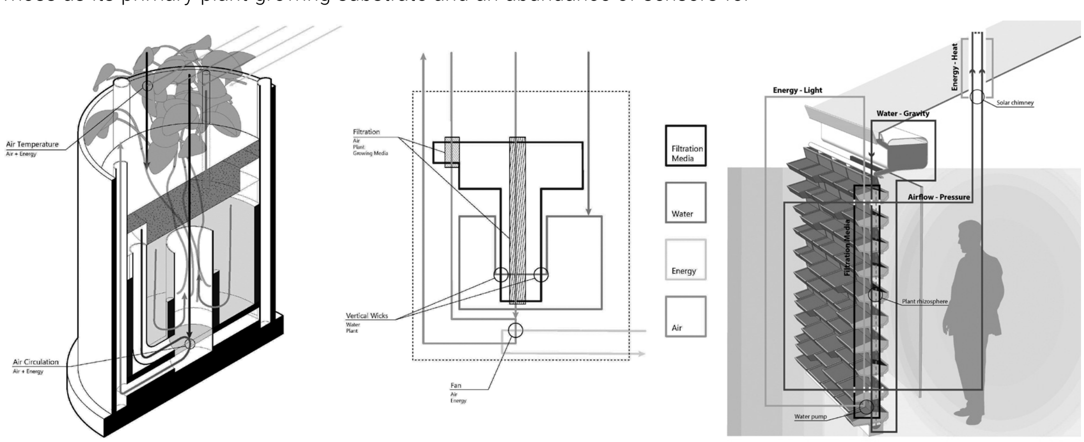

Figure 6: Schematic representation of flow interactions analysis for indoor planter - active phytoremediation system "Airtron" (Wolverton et al., 1989) and proposed system for developing regions (AMPSc). Source: Author 2018 in collaboration with: Alison Notation.

remotely monitoring its performance and maintenance requirements (Kohlstedt 2017; Priday, and Scott 2018).

All these hybrid systems have in common their prescribed services of air quality, sound absorption, space microbial inoculation, and biophilia, among others. The biological organism, most usually a plant and rarely moss or algae, is the acting agent for all the system's services. The organisms, nevertheless, need to be supported literally and figuratively by the mechanical part of the system since their survival depend on the artificial environment's performance. Therefore, in addition to keeping plants in place with structural elements and vessels with growing media—mainly a combination of inert small-size substrates or types of felt and/or other artificially made porous material—such systems require the regulated and consistent provision of light, water, nutrients, treated or untreated air in order to keep plants alive and thriving. Overall, all required system inputs are based on the interaction of three main elements: energy, water, and air (Figure 6). Their combination, manipulation, and treatment with the necessary equipment, such as water pumps, air fans, electricity cables, irrigation tubes, and lighting sources create the conditions to keep the plants alive, effectively illuminated, watered with nutrients liquids, temperature, and air velocity regulated and with a specific volume of air dragged through their rhizosphere.

6. PROPOSAL: THE AMPS BRICK

Following the literature review of phytoremediation systems and their corresponding design attributes, it becomes evident that most systems are based on a logic extracted from the mechanical services era that we live in by prioritizing the mechanization of the system's design and development. There is, therefore, a growing need to reinterpret passive ventilation systems in traditional architectural practice as an adaptation strategy to regionally established architectural typologies. There is also a growing need for the development of a system that does not rely exclusively on technological instrumentation: a system easy to adapt, fabricate, and support in different regions of the world, which lack the financial means not only to install a complex and expensive imported system, but even to service it and maintain it.

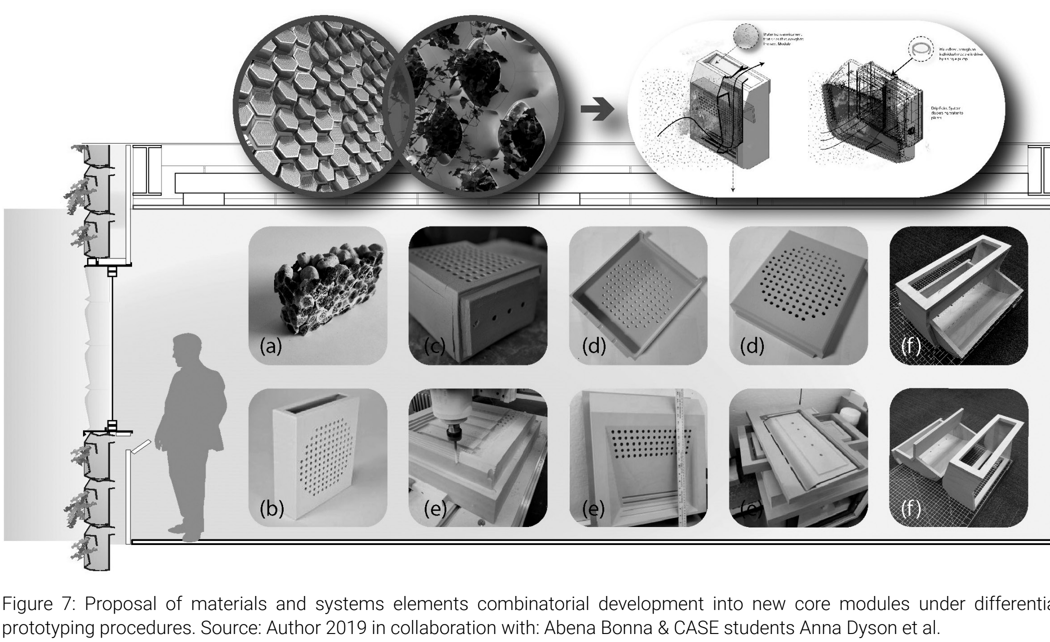

Figure 7: Proposal of materials and systems elements combinatorial development into new core modules under differentiated prototyping procedures. Source: Author 2019 in collaboration with: Abena Bonna & CASE students Anna Dyson et al.

The proposal is thus a low-tech high-value proposition using locally sourced materials, reducing the carbon footprint and saving embodied energy, associated with importing materials from other continents. It is critical to create phytoremediation systems that minimize development costs, unnecessary expansion of expertise needed for assembly, and additional construction assembly components between the several material layers.

In this light, the proposed indoor-outdoor hybrid system, tentatively termed as the "AMPS brick" (Figure 6), uses clay as its primary structural component, which is a material already used in abundance as a wall infill or weight carrying material in more conventional structures (Vollen 2010). Walls composed of AMPS bricks take the shape of interchangeable modules that can be subtracted for maintenance from the indoor side of the wall. AMPS bricks are locally sourced, made from materials abundant in every region of the world, and assembled with easy manufacturing techniques in existence already, familiar with local communities, as in the construction of bricks, roof shingles, plumbing systems, floors, and wall tiles.

The AMPS brick reinterprets the Active Modular Phytoremediation System (AMPS) and the advanced Eco Ceramic envelope system (EcoC), both previously developed at the Center for Architecture Science and Ecology (CASE) (Figure 7). These two prototypes indicate the need for the development of a more reliable method to integrate the material substrate designed to support plant growth. There is a clear need to explore alternative design methods that would minimize excess material in order to amplify the module's capacity to support a wide variety of plants (Figure 8). Further, it would be highly beneficial if the overall system of modules were not designed as a standalone structure, but rather as units capable of maximum integration into the rest of the building system and its site-specific and more ambient environmental flows.

AMPS was specifically conceived as an alternative approach to mechanically dependent building systems that amplify plants' inherent air-cleaning capacity to improve indoor air quality (IAQ), while simultaneously decreasing energy consumption and minimizing the use of conventional air filters

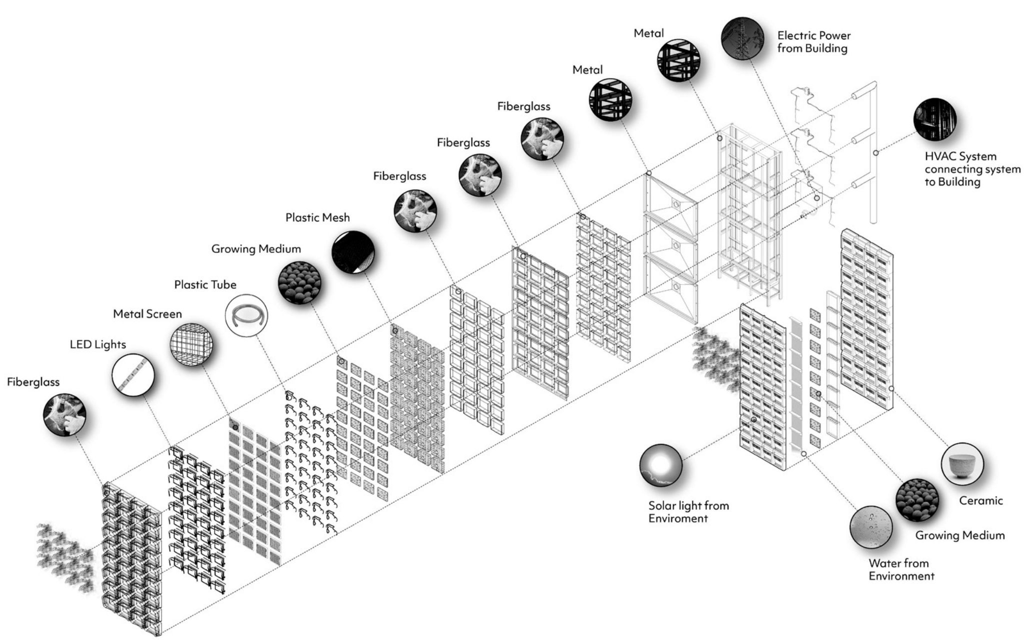

Figure 8: Material and assembly analysis of existing and proposed systems. Source: Author 2018 in collaboration with: Abena Bonna.

for mechanically ventilated buildings (Polidori 2010). Nevertheless, AMPS was designed, constructed, and tested to perform within buildings that have limited interaction with outside environmental flows. It is, therefore, primarily conceived as an extension of a typical mechanical (HVAC) ventilation system (Wang, and Zhang 2011). Although based on the research outcomes of AMPS, this research work primarily focuses on climates that permit natural ventilation, thus making a significant shift in how such a system can be designed and implemented. This approach favors natural ventilation, questioning mechanical systems that completely isolate a building from its environment.

Since the proposed system takes advantage of environmental flows such as rain, the orientation of the growing medium is not vertical, but in inclination with the overall module directing the water collected to the bottom lower center part and then through a series of small water irrigation holes to the one below. Certain precautions should be taken into account in terms of plants' water requirements, depending on the biome intended to perform. Subsequently, the watering system is a drip irrigation gravitational system similar to the ones used by Patric Blank in his green walls; it means that in biomes with a higher content of atmospheric water, plants prone to water should be placed higher in the wall to avoid overwatering. However, for more arid biomes, plants that have higher watering needs should be placed lower in the wall since, in addition to the irrigation system's water, the rainwater collected from the modular bricks in higher parts of the wall would eventually be directed to the lower water collection tank.

Along with the considerations mentioned above, probably the most critical functions of a system primarily focused on air quality were those related to optimizing the module design for ambient and indoor air integration. As a means of addressing this challenge, digital design and fabrication techniques have been employed to expedite the initial testing phase and reduce the cost of production. Additionally, parametric CAD (computer-aided design) models that utilize computational fluid dynamics (CFD) software have been developed to predict the airflow properties and pressure changes characteristic of the new type of typical module. (see fig.9) These wall figures were used to a digitally emulated single pass airflow through-chamber to test the main modular wall component parametrically in a CFD matrix diagram with three different air velocities under four growing media porosities. Each module design was evaluated for its streamlines optimization for maximum pollutants retention in the plant's rhizosphere, while achieving the necessary volumes of air going through the wall according to the established air

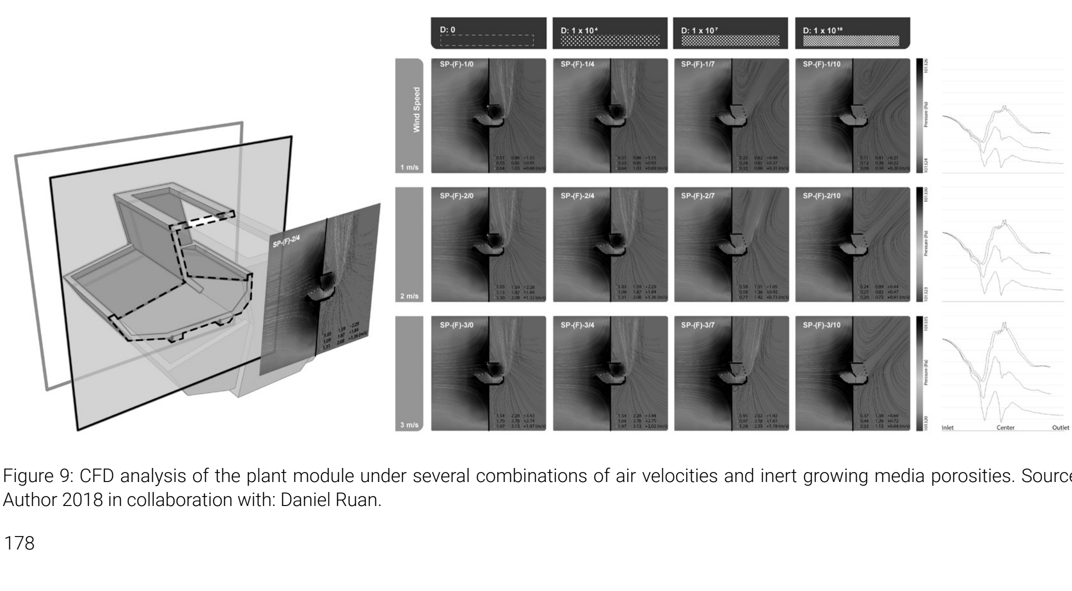

Figure 9: CFD analysis of the plant module under several combinations of air velocities and inert growing media porosities. Source: Author 2018 in collaboration with: Daniel Ruan.

exchange rates under the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) et al. 2013). The three air velocities used were selected based on the previously done studies of urban air velocities to pollution levels in the three cities (Figure 4). All three were under the 3.5-4m/s level recognized as the condition in which urban air pollution levels are not dispersed in safety levels. As for the matrix axis testing the growing media porosities, the first column was the module without a porous material, and then three states of porosities from the equivalent of gravel to the equivalent of dense soil.

In the testing of various module types, five parameters have been used to establish evaluation criteria: a) the geometry of the brick module that contains plant life and a growth medium; b) the porosity of the growing medium of the plant life, in terms of the air volume that may pass through it; c) the air velocity that is channeled in the module for testing; d) the streamlined airflow pathway through the module and virtual chamber; and e) the pressure differential created around the module under different design, growing media porosity, and air velocity conditions. The findings of this analysis will be further evaluated through the production of a physical 1/1 model of the new phytoremediation system proposed previously and assembled from "AMPS bricks" built on a real site in Greece. This full-scale prototype will enable interaction between users and the prototype in a public setting and will further the scope of the research from the laboratory to the field. Finally, it will be evaluated whether or not the system would function effectively for plants to survive in their host module through real life, full-scale application in the context of two locations typical of a natural ventilation biome, those of Chania, Greece, and Limassol, Cyprus. Each location would likely provide significant data, as it relates to different temperature and humidity levels, demonstrating the efficiency and sustainability of this application in terms of plant growth.

CONCLUSION

After substantial research on air quality phytoremediation strategies, it may be asserted that the applicability and the multitude of benefits of a phytoremediation-based building system are strong and can no longer be ignored. The recent iteration of the AMPS system, from the scale of the laboratory to an integrated large-scale building system for the new public safety answering center II (PSAC II) of New York City in the Bronx, is another vote of confidence in the multitude of benefits that the rhizosphere of plants and the related microbial communities could play in the environmental health of building occupants. The possibilities for augmenting the benefits of a natural system that has evolved for thousands of years are limitless. At the same time, our restricted knowledge of the evolutionary mechanisms surrounding microbial communities and plant ecosystems could be a limiting factor for marketing the system to a broader audience, given that it does not currently comply with the established metrics and standards of air pollution strategies established exclusively based on mechanical engineering research.

Work on this specific area of research is currently performed from our research cohort to characterize the microbial communities and to upgrade the metrics used for evaluating complex building systems in the totality of their performance. With two papers accepted in the ASHRAE forthcoming conference—although in its infancy—the results of this research are already too promising.

The Center for Disease Control and Prevention (CDC) estimates the majority of Americans spend approximately 90% of their time indoors. In other parts of the world, this percentage might be smaller, and the indoor space of structures is not as isolated from the exterior environment (Centers for Disease Control and Prevention & U.S. Department of Housing and Urban Development 2006; Klepeis et al. 2001). This does not mean that air quality (AQ) problems are minimized, as in many instances, the absence of viable remediation options could result in the exacerbation of air pollution. There is a need to move beyond the dichotomy of indoor and outdoor air quality and transition to natural ventilation and ambient air quality (AQ) mentality for places where the climate may support it. The suggested interdisciplinary work will attempt to dematerialize this dichotomy with the use of phytoremediation techniques that will impact the quality of users' life in space and reintroduce traditional living patterns in civic space. The breathing envelope solution—under development—has the potential not only to create the conditions necessary to alter the pollution concentrations surrounding air streams, but also to offer a living system that may grow over time into a localized ecosystem that will regulate the quality of life in the environment via the control of local microclimates and their corresponding parameters. Especially in regions with challenging economies, phytoremediation ecosystems could establish a new manufacturing paradigm, building on vernacular systems with exceptional airflow, shading, and civic value. Such systems might transform urban environments into networks of living, breathable buildings rather than accumulations of isolated mechanical building bubbles that exploit the environment for the benefit of temporary IAQ gains.

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MATTER, MATERIALIZATION, AND BIOMATERIAL FUTURES

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The material landscape of architecture is shifting. Architects are increasingly engaging in material systems design, no longer relying on mere specifications to address the materialization of architectural form. All the while, the climate crisis demands that the field develop new solutions to reduce energy consumption and forces us to reckon with the carbon footprint of the materials that make up our built environment. As a result, designers are often developing materials that are bio-based, utilize waste feedstocks, or water-based formulations to keep carbon costs to a minimum. By stepping away from industrialized materials, material behaviors, such as warping, shrinking, and curling, have re-entered the fabrication process and must be contended with. Furthermore, living materials disrupt any notion of determinism or "specification" and instead must be cared for and catered to guide the organisms towards desirable outcomes. New methods for robotic fabrication suggest ways that material realities may be fed back onto the design process, enabling new material expressions, and suggesting a shared design agency through adaptive construction methods. These developments defy the hylomorphic hierarchies of form and matter that have been present in architectural production since the Renaissance. Here, we will investigate how novel biomaterial systems are challenging existing practices of materialization and the nature of matter in architectural design.

Keywords: Biomaterials, bio-fabrication, robotic fabrication, cyber-physical systems, new materialism.

1. CLIMATE FUTURES AND BIO-MATERIALITY

The inescapable reality of the climate crisis is starting to materialize in our present moment, supplanting years of pessimistic projections and warnings that we should be doing more, but failing to communicate the consequences adequately. We can now watch through the media or our very eyes as landscapes burn, hurricanes batter and flood more frequently, coral reefs bleach, and heat and drought begin to displace vulnerable populations from increasingly unlivable regions. Architecture and the built environment play an outsized role in this drama – up to 40% of global carbon emissions may be attributed to the built environment (Abergel et al. 2019). While reducing energy consumption has been the topic of much research for the last 20 years, the UN Environment Programme recently published a report finding that 11% of global carbon emission can be linked to the extraction, manufacturing, and transportation of construction materials (Abergel et al. 2019). This embodied carbon energy constitutes a significant portion of the total carbon costs of the built environment. Even when replacing an older single-family home with a new, more energy-efficient one, it takes an average of 50 years of energy savings to repay the carbon costs associated with its construction (Frey, Dunn, and Cochran 2011). This predicament has led some architects, in what can only be understood as a sort of professional suicide, to reconsider whether we should build at all (Idenburg 2011; Malterre-Barthes 2022). However, the demand for new housing alone is set to rise in the next 30 years, as the population will reach 10 billion by 2050, and the global household size is trending downward. As a profession, we need to interrogate how we build and the materials we build with to reduce the embodied carbon footprint of our built environment.

While the 2000s saw a surge of interest in sustainability in architecture, that interest waned throughout the 2010s but is finally starting to see a resurgence. An example of this new generation of climate-focused researchers is Phillipe Block of ETH Zurich's eponymous Block Research Group. One of Block's research agendas as a structural engineer focuses on reducing the amount of concrete used in multi-story constructions by re-engineering the concrete floor slab to save weight and material. Compared to a typical floor slab, the BRG slab saves up to 70% of the material, close to one-third of the building's entire structural mass (Block et al. 2020). Block's critical insight is that, while it is much maligned for its high total carbon footprint, the problem with concrete is not so much with the material but the way we use it. Measured by weight, concrete has quite a low carbon footprint. However, to save on the financial (and, to an extent, environmental) cost of formwork, we design blocky, standardized slabs and beams with concrete containing excess weight and material, which drives up carbon costs.

While concrete's carbon footprint is only low compared with steel, plastics, and other industrialized materials, biomaterials are attractive because the original biological organisms that comprise them function as a carbon sink, absorbing carbon from the atmosphere naturally through photosynthesis. Some biomaterials even reach carbon negativity, sequestering more carbon during their lifespan than is required to produce the building material. However, the balance can be tenuous. Trees raised in responsibly managed forests have time to sequester enough carbon to make their wood products carbon negative. In contrast, wood from poorly managed forests is typically carbon positive, having its negative carbon balance overtaken by kiln drying and transportation costs (Law et al. 2018). In addition to the use of wood and other species as a dimensional material, scientists have made significant progress in replacing the petroleum-based compounds used for plastic production with bio-based feedstocks. Bioplastics can replace their petroleum-based counterparts in a 1:1 manner but feature a lower carbon footprint. They have even been used to manufacture high-performance applications, such as automotive parts (Mohanty et al. 2018). However, due to their extensive chemical processing, these bioplastics will never reach carbon parity, and many are not compostable or degradable.

New advances at the intersection of material science and synthetic biology have recently unveiled new biocomposites that leverage synthetic chemistry and biology in collaborative ways. Scientists have begun to look to smaller and smaller biological units as their feedstock to construct new material systems from the bottom-up. As an example, researchers have constructed bulk materials by condensing individual tobacco cells into stock forms through compression molds (Roumeli et al. 2022). The new approaches of bio-fabrication and Engineered Living Materials look past the simple harvesting of biological feedstocks to begin to develop ways in which biological processes might form, assemble, or bind the material itself or deliver new functionalities (Nguyen et al. 2018). Mycelium is a classic example of this concept, as the living fungi are grown in place to bind together loose fragments of cellulose-rich plant material into a usable product. Researchers are also pursuing this work at the nano-to-micro scale by using micro-organisms. Bacteria have been introduced to grow self-reinforcing, nano-scale cellulose networks within a 3D printed material system (Schaffer et al., 2017). Furthermore, other biological organisms may be included in the material to impart novel, ongoing behaviors through their metabolic functions, such as the destruction of Volatile Organic Compounds (VOCs) in the air.

Many architects and designers have started to engage in the process of bio-material design, exploring new material systems with low-to-negative carbon footprints. However, fabricating with biomaterials—or in the case of bio-fabrication, living materials, such as mycelium—presents unique technical challenges and forces us to question many long-standing notions of the relation between matter, design, craft, and materialization. Many biomaterials express unique characteristics from individual to individual, have variations in mechanical properties based on their growing conditions, or are acutely sensitive to environmental conditions at the time of fabrication. Living materials disrupt any notion of determinism or "specification" and instead must be cared for and catered to guide the organisms towards desirable outcomes. From a technical standpoint, these materials' behaviors must be accounted for in the fabrication process in ways that are difficult to predict or simulate. In this way, living and biomaterials undermine the Aristotelian notion of inert matter that has largely underpinned architectural discourse for centuries and instead hews closer to a Ruskinian material dynamism that supports his ideals of craft-based construction.

Next, we will show how these biocomposite materials, which represent an important tool to combat the climate crisis, give us a clear opening to reconsider materiality in the built environment. The issues of craft and materialization in the digital era will be investigated through the lens of active materials.

2. ON CRAFT, MATTER AND MAKING

2.1. MATERIALIZATION, REPRESENTATION, AND ERROR

The first aspect of design and construction that a heightened mode of material dynamism disrupts is the materialization of design. Since Leon Batista Alberti developed our current model of architectural authorship based on drawing, the materialization of those drawings—our construction and fabrication processes—has been siloed from the design process (Carpo 2011). Alberti's distinction between building and design had far-reaching implications, first and foremost, that construction processes relied on information to be encoded and decoded through the form of orthographic notation. For Alberti, the design of the building found on paper and the physical building itself are notationally identical to bestow the authorship of that building onto the architect. Alberti renders the architect as someone who can "project whole forms in mind without any recourse to the material" (as cited in Ingold 2013). Thus, from Alberti forward, design is transformed into an immaterial act.

The immateriality of design is reinforced by the nature of the notation system that the architect hands to the builders. The orthographic drawing set features only geometric information. Achim Menges argues that building based on geometric notation alone has two effects—it renders the material as a passive recipient of form and understands construction as merely the materialization of a wholly pre-designed product (2015). Tim Ingold's interpretation of this paradigm is that "The architect, then, conceives the lineaments of the structure, while the builder's task is to unite the structure with the material." (2013). This separation raises the question, what is lost when an architect is not forced to contend with the dynamism of the material world?

Francesca Hughes sees the distance that architects keep from the materiality and building processes as the critical driver for their obsession with precision, and its opposite, error. For Hughes, dimensioning a brick wall to six decimal places when the workers are bound to be wearing heavy gloves to assemble it speaks to a desire for a level of precision or control that was never possible (2014). When the assemblies inevitably fail to meet this level of precision, the error is assumed to be from the material. This reinforces an Aristotelian view of the form-matter divide, where a pure form is to be comprised of a subservient material. The advent of digital technologies and CAD/CAM processes only reinforces this hierarchy as CNC machines offer extreme levels of precision to the designer. However, the precision of the machine does not equate to the precision of the part. Materials expand and contract with heat and humidity, often in dramatic ways. The material may also deform during the fabrication process—wood may chip or splinter during milling, or material may sag during 3D printing. The assumption that the level of precision offered by the software and by the machine will be perfectly translated to the material is a false one. As the High-Definition issue of AD explored through LiDAR 3D-scanning, the as-built conditions of our digitally fabricated assemblies always deviate from their idealized digital form (Sheil 2014). Even with industrialized materials, material behavior and the stubborn pull of gravity are forces to reckon with.

2.2. DIGITAL CRAFT

Thus, the notion of digital craft is currently rife with contradictions. While digital fabrication specialists often speak of their work in terms of craft, the reality of their methods represents a limited portion of the Ruskinian notions of craft. Ruskin believes that craft, as both a moral and aesthetic imperative, is in touch with and speaks to the dynamism of the natural world. An artisan takes cues from the materials they are presented and works through the material's particularities and tendencies, like the grain of marble or the tendency of wood to swell and curl when soaked. Lars Spuybroek, writing along the lines of Ruskin, insists that "we only have to sympathize with the technological tendencies present in matter itself" to reestablish both craft and a matter-oriented theory of ornament (2016). While Richard Sennett argues that nearly anything may be considered craft, he still states that craft is anchored in a tangible reality and is linked to the "intimate connection between the hand and the head." (2008).

On the other hand, there is almost no influence from the material on a traditional CAD/CAM process. For a standard CNC milling operation, the digital model is set into a generic solid that represents the stock material. As most CAD software platforms rely on the NURBS modeling paradigm, which simplifies all solids to only their boundary representation (more commonly referred to as a BRep), it is impossible to represent the material's interior structure in the software. Toolpaths are then generated over this homogeneous stock volume with minimal input about what kind of material is to be milled. Finally, the machine carries out these instructions in a pre-defined manner without any process feedback. The machine has no way to slow down as it approaches a knot in the wood, it cannot surmise if a part of the object is unstable and will flake off during the routing, and perhaps most damningly, the machine does not even know if it is contacting the material that it is attempting to mill. 3D printing operations can be similarly fraught, with no feedback to know whether the print is warping, sagging, or deforming as it is being constructed. As it stands, we have almost no off-the-shelf tools to incorporate material realities into a digital design or digital fabrication process. This digital fabrication model is a one-way process incapable of responding to the material condition and only projects pure forms onto it. Thus, our current digital fabrication workflows are designed exclusively for an abstract version of materiality—a materiality of generic sameness that is personified by the industrialized, homogeneous materials kept in stock at digital fabrication labs. Therefore, the notions of digital craft are the same pursuits of ever-higher levels of precision inherited from modernism, but with nostalgic overtones. Alberti's quote about architects projecting whole forms without recourse to the material is as true today as when it was written.

3. TO BIOMATERIAL FUTURES

3.1. WHEN MATTER IS NOT INERT

This lack of feedback from the real world into the fabrication process severely limits how we might fabricate with living and biomaterials. Many biomaterials being used in large-scale applications are water-based formulations, as they carry much lower carbon footprints than other bio-based materials, which are chemically cross-linked or encapsulated in a synthetic polymer matrix. Water-based biomaterials are mixed into a wet or slurry state and then condensed and dried into a structural material. These materials are especially popular as they can be easily amended to work in direct ink write (DIW) or liquid deposition modeling (LDM) additive manufacturing processes. During the fabrication process, the biomaterial will shrink as it loses water, but at rates dependent on the atmospheric humidity, the geometry of the part, and the biochemistry of the original organism. This shrinkage is problematic for any additive manufacturing process as the lower layers of the print will begin to shrink mid-print, potentially causing alignment issues with the upper layers. Additionally, differential shrinkage across the part can lead to cracking or misalignment with other parts in the assembly. Due to the competing factors and differences between material batches, it is incredibly challenging to build a model to predict how the biomaterial will behave during the fabrication process. Machine learning would be well-equipped to handle this challenge. However, machine learning models are only effective when they have been trained on thousands of samples, making the data collection process onerous.

Living materials are even more indeterminant in their bio-fabrication processes. Their growth is reliant on environmental conditions such as temperature and humidity, the availability of nutrients, and competition with other micro-organisms in the environment. While measures can be taken to assure constant atmospheric conditions and nutrient availability, gauging the health of the starter colony or the presence of other microbes is challenging in large-scale bio-fabrication. As a result, there is wide variability in the growth rates of living materials, which affects performance metrics down the line. Furthermore, bio-fabrication processes extend the threshold of what is typically considered the fabrication process. Monitoring and caring for living organisms are just as important as the forming process and knowing when a material is ready for harvest or has stopped growing can be a difficult judgment call as well.

However, these biomaterial systems can also be seen as only one example of active matter. The field of smart materials has been developing materials that act as either a sensor or an actuator in response to changing ambient conditions, as evidenced by the wealth of research investigating bi-layer materials that actively change shape. The dynamism of matter present in these materials calls for a new mode of materializing design.

Ultimately, we must recognize that the fault lies not with biomaterials or any other material that exhibits active, discernible behaviors but instead with our assumption that construction materials are comprised of inert matter. As anyone who has detailed an expansion joint will attest, this assumption has always been convenient but false. The prevalence of new biomaterials simply exposes the false assumptions that our fabrication systems are based on. This, however, is not an argument against digital technology nor a call for a return to handicrafts. Instead, we must find ways to translate material into information, such that the algorithms that drive digital fabrication technologies are not reliant on geometrical information alone. Through the transmutation of matter into information, we can develop advanced fabrication processes that upend the hylomorphic paradigm of form over matter.

3.2. NEW FORMS OF AWARENESS

Achim Menges laid the groundwork for a materially-aware computational construction model that he termed “cyber-physical systems.” (2015). Rather than the open-loop model wherein all machine instructions are pre-computed and followed unambiguously, the cyber-physical system creates a closed loop of information with a network of sensors. The sensors endeavor to give the fabrication process information on the workspace, materials, and progress of the assembly. This model uses information on the material to parametrically adjust process parameters, tool paths, and action sequences in response to the material realities. In this way, fabrication decisions are made based on the unique nature of the materials present in the workspace, and the process can account for divergences between the idealized assembly and the physical one. Menges also argues that the open-loop model avails the possibility of considering materialization as a generative part of the design process. In the cyber-physical model, the design can evolve as the process unfolds, holistically uniting design and materialization. This fabrication method is compared to Kostas Terzidis' distinction between computerization and computational design processes (2006). Computerization refers to the replication of manual tasks within a digital environment, while computational is the exploration of indeterminant processes.

One of the earliest examples of these closed-loop processes was by a team at the University of Stuttgart in their ICD/ITKE 2014/2015 Research Pavilion. The project robotically laid carbon-fiber tape on the interior of an inflated formwork until a rigid shell was formed and the formwork could be deflated and taken away. To compensate for inaccuracies and deflections in the inflated formwork, the team equipped the robotic end effector with a pressure sensor to know when they were in contact with the inflated surface and could start laying tape (Vasey et al. 2015). In this way, the robot has an awareness of the elements in the workspace, which it must be in contact with for a successful tape-laying procedure. Other research at Autodesk's Technology Centers explored how closed-loop robotic assembly processes might be brought to actual building construction practices by using computer vision to assist with the assembly of prefabricated facade panels. Equipping the robot with a 3D camera, it could locate the cladding elements for the façade in the workspace, select one of the available module sizes, and assemble the cladding into an unplanned façade pattern (Tish, King, and Cote 2020). While this project uses standardized materials, the process of materialization influences its final design.

New sensing regimes will need to be explored to transmit information about the biomaterial state to the fabrication process. 3D cameras can be used to monitor shrinkage or to check for material deformation during fabrication. Weight and moisture sensors are useful for monitoring water content during the process. Additionally, thermal cameras can be used to monitor drying as the surface temperature of an object will slowly rise from the dew point to the ambient temperature as water leaves the surface. New tools for monitoring living materials are yet to be developed. The timber industry uses technologies such as Near Infrared (NIR) spectroscopy, acoustic propagation, or even Computed Tomography (CT) scanning to nondestructively test wood elements or standing trees to estimate their internal density or modulus of elasticity (Schimleck et al. 2019). Similar techniques will need to be developed for living materials to test when growth networks of mycelium, for example, have reached their desired density or strength.

Adding living and minimally processed biomaterials further instrumentalizes the cyber-physical fabrication method by expanding the range of material behaviors to which the cyber-physical system may respond. Working with biological materials is not a determinant operation, but rather more a process of coaxing or guiding the materials into shape. A closed-loop process that can adapt and respond in real-time to the indeterminant nature of these biomaterials, to their whims and tendencies, is the only feasible way to fabricate with these materials. In future research, when other organisms are introduced that grow self-reinforcing networks or self-actuate in response to atmospheric conditions, the cyber-physical model becomes increasingly productive as the two intelligent systems may collaborate in the form of conversation. In this way, the cyber-physical model leads to a product that is the result of a shared agency between the designer, process, and material. With this model, we may finally reach the latent potential of a digital craft.

CONCLUSION

The reality of our climate crisis forces us to reconsider the industrial traditions and technologies that have brought us to this point. However, it is a mistake of the environmental discourse to focus only on what must be given up and on the necessary frugality. In what is admittedly a techno-optimistic position, there is much to be gained by developing novel biomaterials with low-to-negative carbon footprints. It is clear that a shift in how we conceptualize matter and materialization has already been underway through research on cyber-physical systems, one that can be expanded to encompass more types of material behavior. This research reframes computation as a method to explore materialization and matter, working with specific and dynamic notions of materiality rather than the abstract ones that were common during industrialization and in the first generation of digital fabrication. In many ways, biomaterials that exhibit a dynamic behavior do not change these conversations as much as they instrumentalize them. Cyber-physical systems may feel like an intellectual project when explored firmly in a realm of industrialized, homogeneous materials. Biomaterials, especially those that are used while still living, make the dynamism of matter inescapable, leaving no other choice than to cater to their whims and tendencies through a closed-loop fabrication method. What is critical is that our engagement in these new modalities of computational materialism occurs in support of efforts to solve our climate crisis. We may find promise in this future of increasingly hybrid conditions between the technological and the natural.

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“SUBORDINATION” IN MODERN THAI ARCHITECTURE, 1960S-1980S: CASE STUDIES OF CRYPTO-COLONIALISM

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Joseph P. Salerno’s Design of Siam InterContinental Hotel on Rama I Road in Bangkok, Thailand (1966). Source: *Lexi Belle Racing, The United States.*

This paper offers an examination of crypto-colonial discourse in Modern Thai Architecture from the 1960s to the 1980s. It argues that the transplantation of western Modern architecture in Thailand initiated a neo-colonial cultural dynamic as the architects’ creations were subtly subjected to an American Cold War agenda established in the Southeast Asia region since the 1950s. According to the recent scholarship of Thai postcolonial studies, the term *Crypto-colonialism* is applied to Thailand based on its unique form of political marginality. This theory characterizes Thailand’s relation to the West as being a technically independent though essentially tributary nation-state because the country was materially dependent on western economic and political power (Herzfeld 2002, 900-901). This research thus looks at the “subordination” characteristics of Modern Thai architecture from the 1960s to the 1980s, when western powers, especially the United States, imposed their culture upon that of Thailand to undermine or deny its existence. Its analysis shows that, during these Cold War years, urban infrastructure and the hospitality industry in Bangkok and its suburbs grew rapidly due to American economic aid as well as to the need to provide accommodations for western tourists and the American military presence. The architectural design of this period was dominated by spatial concerns that reflected the new and powerful influence of the United States over traditional Thai architectural planning. By tracing the historical consolidation of Modern architectural consumerism in Thailand and the works of American architects who were working in Thailand during the 1960s and the 1980s, this research will challenge the idea that colonial discourses were only confined to countries or regions that were directly occupied by western nations.

Keywords: Crypto-colonialism, post-colonialism, Thailand, The United States, subordination.

INTRODUCTION

At the close of the Second World War, the United States had supplanted the European colonizers of the imperialist era as the dominant world power. U.S. policymakers were relatively inexperienced in Southeast Asian affairs, and the region posed a dilemma. American sympathy for the post-war nationalist movements in Asia was in direct opposition to the close diplomatic ties between the United States and the western colonial powers which still controlled much of the region, such as Britain, France, and the Netherlands. As relations deteriorated with the Soviet Union, the American government feared that the independence of former European colonies in Southeast Asia might create a power vacuum, which communists could exploit to their advantage (Norland and al et. 1997, 68). However, in the case of Thailand, the only independent state in the region, the U.S. took no risk in breaking with its European allies. From Washington’s point of view, Thailand had only declared war on the western powers because of Japanese coercion, and therefore deserved to receive American assistance.

From the 1940s onwards, the United States became Thailand’s new foreign patron, supporting the country with various kinds of aid, far greater than anything the country had received during the colonial era. While France and Britain had focused on their colonies and had never taken more than a peripheral interest in Thailand, the U.S. seized on Thailand as an ally and a base for countering the spread of communism in Asia (Baker and Phongpaichit 2014, 139). To retain Thailand as an American “free world” ally during the Cold War, the U.S. helped to revive and strengthen Thai military rule, promoted Thai development by boosting economic growth through private capitalism, and pushed the mechanisms of the nation-state more deeply into Thai society in order to assure that the country successfully set up its “national security.” Under this regime, a new elite group emerged, consisting of ruling generals, senior bureaucrats, and the heads of new business conglomerates (Baker and Phongpaichit 2014, 139). Strengthened by the ideology of “development” and unconstrained by “democracy,” American businesses were able to exploit both the Thai people and the country’s natural resources on a new scale, leading to a significant and fundamental change in urban planning and Thai architectural form.

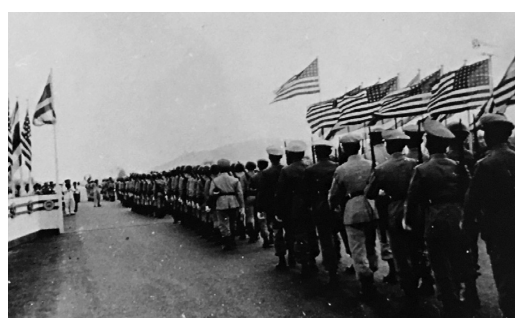


Figure 1 (left): Opening ceremony of the Pak Thong Chai-Kabinburi highway in December 1965, presided over by Prime Minister Thanom and U.S. Ambassador Graham Martin. Source: Warren 2007.
Figure 2 (right): A march by members of the U.S. construction battalion. Source: Warren 2007.

1. THAILAND IN THE COLD WAR

1.1. AMERICAN MILITARY AID TO THAILAND DURING THE COLD WAR

When Dwight D. Eisenhower assumed the presidency in 1953, he committed to a hard stance against communism in Asia and echoed the Thai government’s dismay over French moves toward a negotiated settlement in 1954. He warned of a “domino effect” in Southeast Asia, predicting that if one nation fell to communism, the others would surely fall in turn (Norland and al et. 1997, 95). In July 1953, the U.S. National Security Council pronounced Thailand an “anti-communist bastion,” from which to “extend U.S. influence—and local acceptance of it—throughout the whole of Southeast Asia” (Fineman 1997, 173) (Figure 1 and 2). The flow of U.S. aid to Thailand continued through the 1950s, especially in the form of funds for highway and airport construction (Figure 3 and 4). The U.S. began to fund $13.6 million to build a highway project in 1954. This 400-kilometer highway was built in order to link Bangkok with Korat and the rest of Northeast Thailand. Successfully, completed on July 10, 1958, this “Mittraphap Road” or “Friendship Highway” shortened the drive from Bangkok to Korat by about 150 kilometers and helped improve communications with the Northeast (Norland and al et. 1997, 97). Moreover, the assistance in developing the Thai airports also began in 1954. Airfields at Korat, Takhli, Phisanuloke, Udon Thani, Chiang Mai, Phuket, and Bangkok’s Don Mueang received new communication equipment, lighting, and navigational systems. In summary, approximately half of the U.S. technical aid between 1954 and 1960 was allocated for transportation projects. While the emphasis on building transportation facilities reflected the concerns for national security, particularly in the Northeast, the new roads and airports also stimulated economic development, a high priority for Sarit’s government.[1] Thailand had thus become a U.S. client-state under military rule, although this resulted in a severe division between the army and the police within Thailand’s ruling junta.

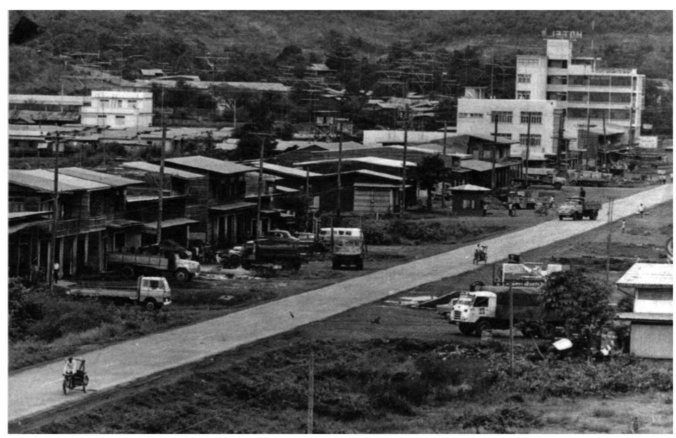


Figure 3 (left): Prime Minister Thanom Kittikachorn and U.S. Ambassador Graham A. Martin opened the Chachoengsao-Kabinburi Highway in February 1966. Source: Norland and et al. 1997.
Figure 4 (right): The city of Takhli near the American-built airbase in Nakhon Sawan province. The U.S. military presence transformed numerous upcountry towns and provinces. Source: Algie and et al. 2014.

1.2. AMERICAN ECONOMIC AND EDUCATIONAL AIDS ON THAILAND DURING THE COLD WAR

Amid a crisis of cultural transition in the mid-fifties, Field Marshal Sarit Thanarat seized power from the political experiments of Phibun forcible regime. The Thai commoners were caught between the old order of the royal ruling elite and this new Phibun regime, with its project to build Thai nationalism. Traditional societal bonds were loosening. The expected democratic institutions were developing unexpectedly slowly, while Phibun’s attempts to unite the country through a resurgence of Thai tradition were too weak to promote real nationalism. In these circumstances, Sarit chose an ideal moment to take power. His regime offered a clear way forward through the tangled questions of traditional values and national identity.

Earlier in 1947, President Truman introduced the word "development" in his first televised presidential speech, which Sarit Thanarat perceived and interpreted it as a key concept of the U.S. global mission. He adopted the term as a new, powerful justification for the power of the nation-state, and translated this American "progress" by coining a new Thai word, *phatthana.* He then positioned *phatthana* at the center of his policy objectives: "[O]ur important task in this revolutionary era is to *phatthana*, which includes economic development, educational development, administrative development, and everything else" (Baker and Phongpaichit 2014, 14). Based on this new concept of *phathana* or progress, Thailand's economic program was permanently shifted from Phibun's nationalism to Sarit's private-sector capitalism in the 1950s.[2] Due to the government's policy of welcoming foreign investments, Thailand was drawn more deeply into a more complex geopolitical situation involving Japan, China, and the western powers; and because of Thai involvement in the Vietnam War, Thailand was often accused of having abandoned their traditional independence or neutrality in foreign policy in favor of close identification and involvement with a single great power, the United States (Wyatt 2003, 277). The more threatened the Thai felt by circumstances in Indochina, the more they turned to the United States, the only great power with both the strength and the will to assist them.

From the second World War onwards, the United States did not restrict its post-war involvement with Thailand to economic matters. U.S. policies also emphasized the importance of "national security," as they sought to further their national security ends by molding Thailand into a nation-state conducted upon American social principles. Educational aid, provided to modernize the population, also served as a means of acculturation. This American educational aid produced a set of paradigms of social life that distorted the fundamental fabric of Thai society and was used to manipulate the Thai people. These paradigms served to accelerate the extension of American academic values and programs within Thai universities, and at the same time, this "cultural imperialism" deterred the growth of indigenous scholarship (Bell 1980). According to Peter Bell, a specialist on economies of developing countries who have examined the character and purpose of American scholarship on Thailand after the Second World War, American influence has been the single most important element in the pattern of social change in Thailand. It has affected the evolution of the class structure, the economy, political institutions, and external relations (Bell 1980) (Figure 5 and 6). This attempted Americanization was at the core of the ideal of "Cold War cosmopolitanism," in which American aid was subtly used to cultivate a "cosmopolitan" ethos in artists, writers, filmmakers, and others involved in creating a nation's culture (Klein 2017, 281). Creating cosmopolitanism was a major objective for Americans waging the cultural Cold War in Asia, and the American foundations and scholarship opportunities set up by Washington were the primary instruments for doing so (Figure 7 and 8).

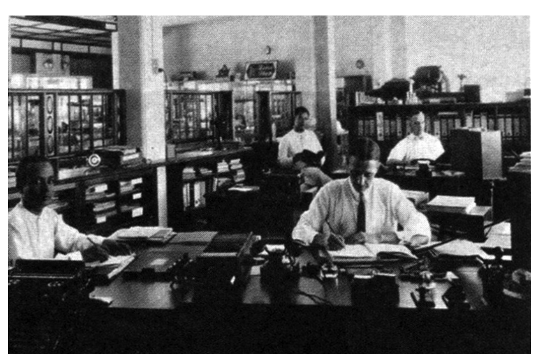
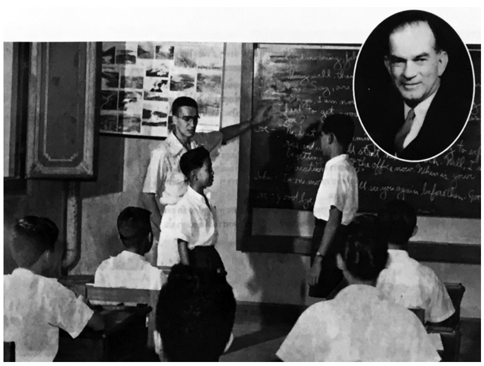


Figure 5 (left): Image of the U.S. Trade Center in Bangkok taken in 1960. Source: Harrison Forman, UWM Libraries.
Figure 6 (right): Expat at work in Bangkok in the early 20th century. Source: Algie and et al. 2014.

However, this shift of scholarly paradigms could not have happened in Thailand had there been resistance from the locals, particularly in the ruling classes. Because this group was aligned with Sarit's belief in the value of technocrats, they actively endorsed the virtues of modernization and stability in Thailand and invited American specialists of all kinds to act as advisors of new governmental agencies created in the late 1950s and early 1960s, in order to rationalize capitalist development.[3] It was certainly the case that the U.S. saw its role as "steering" Thailand's development, and it arrogantly attempted to influence the direction of policy in almost every area of social planning. Like the European "civilizing mission," American Cold War cosmopolitanism was able to manipulate foreign culture in desirable directions. However, it could not succeed without the help of the nation's rulers, who were responsible for imposing this broader cultural shift and acted as local agents to bring in foreign models imbued with civilizational importance to the country.



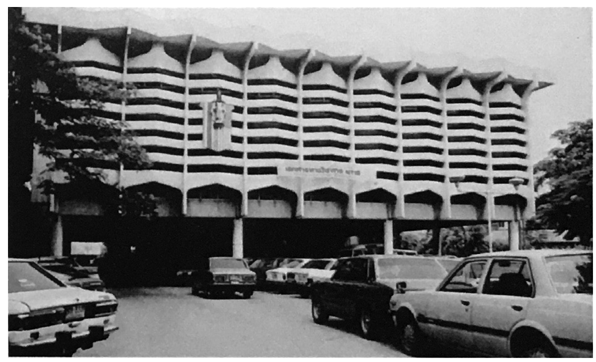


Figure 7 (left): Fulbright exchange student from the U.S. teaching English to Thai students. (Insert photo) Senator J. William Fulbright, the program founder. Source: Norland and et al. 1997.
Figure 8 (right): Krisda Arunvongse na Ayudhya's concrete-fin brise-soleil technique that was used in the design of the American University Alumni Language Center building (AUA building). Source: Warren 2007.

1.3. CULTURAL SHIFT DURING THE COLD WAR ERA

The effects of the Cold War extended through nearly every aspect of Thai national life. It brought large segments of the Thai population face to face with the outside world in unprecedented ways. The economy was pumped up with American dollars, and hundreds of thousands of Thais became dependent on the American presence for their livelihoods. Additionally, the Vietnam boom brought widespread corruption, and commercialized vice teemed in the hotels and honky-tonks clustered around the U.S. air bases both in Bangkok and Udon (Wyatt 2003, 279). New Phetchaburi Road became an "American strip" lined with bars, nightclubs, brothels, and massage parlors. Don Mueang airport added a new runway to accommodate jet planes to serve foreign visitors, which grew rapidly from only 40,000 in the late 1950s to over 600,000 by 1970 (Baker and Phongpaichit 2014, 148). As disruptive as these surface-level changes were, the effects of the American era in Thailand ran much deeper. The economic attraction of the city, particularly the service sector, changed the fundamental way Thai social relationships are constructed. Young women and men from farm families went to the city to learn English and work as waiters, bartenders and hotel desk clerks, prostitutes and masseuses, tour guides, and souvenir shop clerks. When there, they were exposed to a kind of rapid access to western culture, ideas, values, and fashions that had previously been limited to only the small group of Thai elites. With western tastes and fashions came new social ideologies, encompassing sexual morality, ideas of romantic love, and a cult of youth that supplanted the traditional respect for seniority.

2. THE GOLDEN ERA OF THAILAND’S TOURIST INDUSTRY AND BUILDING CONSTRUCTION

Thailand’s emergent tourist industry also took off during the 1960s, starting with the opening of the Tourism Authority of Thailand in 1960. This was intended to expand business sectors related to travel and tourism. Sarit hoped to make this a major focus of Thai efforts, urging the nation that “the promotion of tourism can be best achieved for the benefit of our people and our country only when every government office, individual enterprise, and the people themselves give their full co-operation and support” (Algie and el at. 2014, 187). By the mid-1960s, the Thai tourism industry was still supported by the American war effort, with somewhere between 11 to 16 percent of total visitors composed of U.S. soldiers on leave from Vietnam. This specific Rest and Recreation (R & R) demographic spent twice as much money as the average tourist—the liberal spending was fueling growth in many areas, particularly in the sex industry (Figure 9 and 10). The period from 1965 to 1969 was the golden era of building construction in Thailand, as the tourist boom created massive new demand for hotel rooms, with 14 luxury or international-class hotels in construction in Bangkok (Vimolsiddhi and el at. 1993, 99-101). In 1966 alone, 2,500 hotel rooms were added to a city with fewer than 800 a decade previously, along with roads, airstrips, coffee shops, and palatial dwellings for high-ranking foreigners and nouveau riche Thai.

Figure 9 (left): American servicemen on R&R leap ashore into the arms of Pattaya’s “Hawaiians.” Source: Baker 2014.
Figure 10 (right): Tourists sunbathing at the pool of the Dusit Thani Hotel, opened in 1970. Source: Algie and et al. 2014.

Americans played a significant role in developing the Thai tourist industry. The first of a long list of American hotel chains arrived in Bangkok with the opening of the Siam InterContinental hotel, partly owned by Pan American World Airways (Figure 11).[4] This striking building with multi-tiered tiled roofs rising to a central peak was located on 26 acres of land in the heart of Bangkok. Its form reminds some people of a volcano and others of a traditional hat worn by ancient Thai royalty. Tellingly, it was located on the part of a 43-acre site belonging to the royal family. This site also houses Wat Pathum Wanaram, built by King Rama VI in 1857. The hotel, offering 411 rooms and a variety of dining and conference facilities set in a lushly tropical landscape, remained a distinctive landmark for nearly three decades before it was removed to make room for Siam Paragon shopping center, which opened in 2005. The government-owned Erawan Hotel (Figure 12), located a few blocks away, had been torn down several years before and was replaced by the Grand Hyatt, another American chain. Still, other noted names entered Thailand in the following years, including Hilton, Marriott, Sheraton, Regent, Holiday Inn, Westin, and Conrad (Warren 2006, 64).

Figure 11 (left): Joseph P. Salerno's design of Siam InterContinental Hotel on Rama I road (1966). Source: Lexi Belle Racing, The United States.
Figure 12 (right): The Erawan Hotel, in 1960, operated by the government-owned company The Syndicate of Thai Hotels and Tourists Enterprises. Source: The American Geographical Society Library, University of Wisconsin-Milwaukee Libraries.

2.1. A FLOURISHING IN THE CAREERS OF ARCHITECTS IN THAILAND

The building boom led to the flourishing of the architectural profession in Thailand. Due to the rising economy and the number of Thai architecture graduates who successfully completed a five-year bachelor's degree, newly hired personnel in Thai architectural firms increased by approximately 90 per year. These students were taught a Modern architectural curriculum by western-educated Thai architects, who themselves had directly received their education from Modernist masters such as Frank Lloyd Wright, Walter Gropius, Mies van der Rohe, Louis I. Khan, and others (Figure 13 and 14). As Vimolsiddhi remarks in *Development of Concepts and Architectural Patterns*, between 1958 and 1972 more than half of the Thai architecture professors went to study in the United States and obtained a master's degree (Vimolsiddhi and et al. 1993, 99-101). Not only did Thai architects benefit from this boom, but foreign architects, especially Americans, also received commissions in Thailand during this period.

Figure 13 (left): CIMC building, designed by Cornell and UPenn graduate Dan Wongprasart, who was once Louis Khan's apprentice (1979). Source: Thailand Creative and Design Center 2008.
Figure 14 (right): House for Khun Tritip Telan in Hua Mak, Bangkok, designed by Dan Wongprasart (1972). Source: The Association of Siamese Architects.

3. MODERN THAI ARCHITECTURE IN 1960S-1980S

3.1. THE ERA OF AMERICAN ARCHITECTS IN THAILAND

The era of American architects in Thailand began with the opening of the architectural firm Bourne Associates International in Bangkok, led by the architect John W. Rifenburg who was later set up a new company with Rirk-rit Kaewvichien, registered under the name *Rifenburg and Rirk-rit Architects* (Tiptus 1996, 377). Rifenburg was renowned for his interior designs, including the Oriental Hotel (1876, renovated in the 1960s), the Siam InterContinental Hotel (1966), the Montien Hotel (1967) and for his architecture, as seen in the Fedders building (1976) (Figure 14), Siam Bayshore in Pattaya (1976) (Figure 15), and Baan Kai Mook Condominium in Hua Hin (1990). The Louise Berger Group, Inc. was another in the small group of American firms to receive commissions in Thailand prior to 1965 due to the US-Thai OICC military agreement.[5] [6]

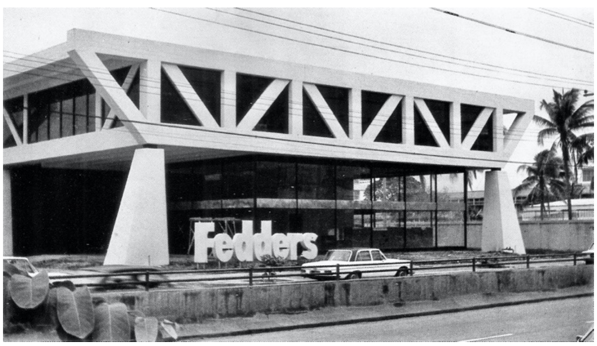


Figure 15 (left): The Fedders building, designed by Rifenburg and Rirk-rit Architects, was already demolished (1976). Source: Architecture + Engineering + Construction magazine 1976.
Figure 16 (right): The design of Siam Bayshore hotel in Pattaya (1976). Source: Rerkdee Potiwanakul.

The majority of Louis Berger’s construction activities in Thailand can be classified, in general, as being for the U.S. military purposes, including facilities constructed under the Military Assistance Program (MAP). Berger’s civilian projects included facilities constructed for the Agency for International Development (AID) (The Comptroller General of the United States 1968). Because of the continuing interest of the U.S. Congress in their own activities in Southeast Asia, the U.S. supported substantial dollar expenditures for facilities in Thailand, which increased military construction activities in Thailand dramatically within a few years.[7] In early 1966, in anticipation of large increases in construction work, the U.S. Department of Defense (DoD) mobilized two cost-reimbursable contractors from the United States to Thailand. By June 30, 1967, an estimated $165 million worth of construction had been assigned to these contractors, including to Louis Berger firm.

Among more than 40 projects undertaken by Boughey and his firm, a number have become modern landmarks of Thailand. In undertaking an investigation of the Louis Berger Group and Boughey’s works, Thai architectural trends from the American Era offer excellent examples of American cultural transplantation. Among them, Thai-government commissioned architecture provides several obvious cases in point, leading to an insight into the dynamism and mechanism of the period of Thai subordination to America. The previous portion of this chapter provides the political, economic, and cultural context which sets the stages for the following discussion of architecture, examined in detail through the following case study.

3.2. DON MUEANG AIRPORT: A CASE STUDY OF "SUBORDINATION" CHARACTERISTICS IN MODERN THAI ARCHITECTURE

Construction of *Don Mueang Airport* began in the reign of King Rama VI, a few years after aviation was introduced in Thailand, while the country was still called "Siam." In 1948, the government elevated Don Mueang Airport to international status, but it was not until seven years later that the name was changed to Don Mueang International Airport. Since the very first day of its construction, Don Mueang International Airport has been famous as an important node of Southeast Asian air transportation, a strategic connecting point to all continents. The airport was also known for its standard and efficient management, which is trusted by all international airlines (Figure 17 and 18). It was overseen by the Airports Authority of Thailand or AAT, founded in 1979.[8] Shortly after the AAT assumed responsibility over the three other regional airports, Chiang Mai, Hat Yai, and Phuket, the agency realized the urgent need for airport development to cope with the rapid growth of air traffic. They designed the Bangkok International Airport Development Plan in two phases, with phase I spanning 1980 to 1989 and phase II covering 1989 to 1990.[9] The engineering-architectural firm of Louis Berger was hired to study, design, and supervise the construction of a new terminal, air cargo facilities, and a parking garage at Bangkok's Don Mueang International Airport in September 1989 (Warren 2006, 65-66, and Airports of Thailand 1991, 2-3).

Figure 17: Don Mueang International Airport once named "Bangkok Airport" (1968-71). Source: Pantip.com.

Pursuant to the contract signed on January 24, 1990, the Louis Berger Group's responsibilities included: generating medium-term and long-term master plans for all the four airports operating under the AAT; evaluating the current short-term plan for efficiency of integration into the new master plan; evaluating the ways in which the AAT could assist the new master plan; forecasting the importance, size, and timeframe for construction of the second international airport; training AAT officers in producing the airport master planning and airport future-development plans; and reporting the financial feasibility. The firm proposed three new directions for the master plan for Don Mueang Airport. The first was that the airport should be renovated to be able to serve the public until the year 2010, with allowances for some building removals and expansions. The second proposal was to improve the existing conditions of the airport so as to serve the public until the year 2000, without any demolition or new construction. The third plan was to enhance the abilities of the current airport to serve the public until the secondary international airport was done. The additional construction in

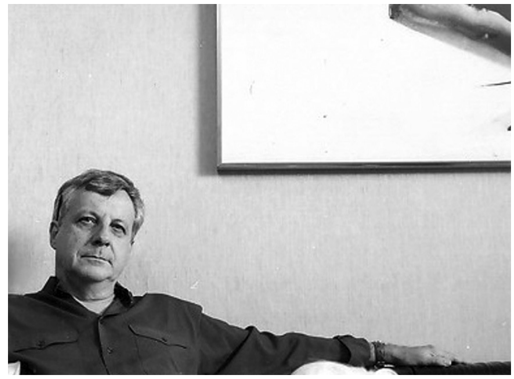


Figure 18 (left): *Don Mueang* International Airport's terminal, designed by Robert G. Boughey under Louis Berger Group. (1968-71). Source: Warren 2006.
Figure 19 (right): Robert G. Boughey, who came to Thailand in the late 1960s with Louis Berger Inc. and opened his own architectural firm in 1973. Source: Prabhakorn 2010.

this proposal would be arranged similarly to the first proposal (Airport of Thailand 1991, 2-6). The committee selected the second proposal for the project due to the lesser construction requirements.

Decades earlier, Pottsville Pennsylvania native Robert G. Boughey came to Thailand as the chief architect of the International Division of Louis Berger, Inc. (Figure 19). He had enumerated the specific challenges of designing an airport for a Southeast Asian setting. In the January-February issue of *T-AB* magazine in 1971, he explained,

> [T]he usually large groups of non-passenger meeting and seeing off travelers at Asian air terminals, and the differences between Thai and Western customs and immigration procedures posed unique challenges for an American engineering firm. … The response involved designing essentially two airports in one. A bi-level concept separates arriving and departing passengers, within a single building to alleviate congestion and allow rapid, one-way passenger flow. By means of a high-speed overpass from the adjacent highway, departing passengers arrive and remain on the second level from baggage check-in through aerobridge aircraft embarkation. Arriving passengers disembark on a second level concourse and proceed down ramps to retrieve baggage from giant carousels. … Preliminary design began in December 1968. Then Pan American announced that Bangkok was on the itinerary of its new Boeing 747, and design had to be greatly accelerated. Although the scope of the project was amplified several times during this period, final design documents were completed and submitted within six months. The final estimate for construction exceeded five million U.S. dollars, more than double the original appropriation (Warren 2006, 65-66).

Though the Berger firm was asked to train Thai architects to design the future airports, and though their work came in at the double the original cost, the American firm was nonetheless hired to complete the master plan of Thailand's second international airport, Suvarnabhumi Airport, opened in 2006.[10] Shortly after the opening of Suvarnabhumi Airport, Thai officials decided that Don Mueang would still need to handle domestic commercial flights due to faster-than-projected air traffic growth throughout Asia. AAT, later renamed Airports of Thailand Public Company Limited or AOT, determined that using the existing facilities at Don Mueang would increase the flexibility needed to handle the growing air traffic demands before Suvarnabhumi Airport could be expanded.[11]

This project was one of the causes of the controversy among Thai architectural professionals who objected to hiring westerners as designers of Thai iconic buildings. Members of the Thai architectural society were separated into three groups according to their reactions to the project. The first group was able to accept the GATT free trade agreement, which allowed foreign architects to come and work in Thailand without any restrictions.[12] They argued that certain complex buildings and advanced techniques required experts with specific knowledge and technical skills, and in these cases it could be vital to seek foreign technicians.[13] Manoon Leewiraphan argued that "there are some building types that require western architects to handle, for example, the international airports, especially the *S*uvarnabhumi Airport. We have to admit that this category of buildings needs specialist services with experience and expertise, similar to meeting specialist doctors" (Pussadee 1996, 392). The second group did not object to having *farang* carry out certain Thai architectural works, but insisted that the designs needed to be controlled by Thai rules and regulations. On the opposite side, feelings of professional suppression ran deeply and brought the third group of Thai architects to advocate for an entire prohibition of foreign architects working in Thailand. Krisda Arunvongse explains that

> this problem occurs because the commissioners do not give as many credits to the Thai architects as that they are giving to *farang* (westerners), and it is hard to change their thoughts to believe in us that "they will lose more money if hiring foreigners. Besides, those westerners are not familiar with our weather conditions, local materials, and quality controls of the Thai blue-collar workers." … Moreover, the fascination with *farang* reflects what Thai owners appraise as their social value to express themselves as having high-class taste and use it as a labelling to display their own manifesto. This kind of norm is really hard to change (Pussadee 1996, 398).

Figure 20 (left) and 21 (right): Samui International Airport, designed by Thai architectural firm named Habita (1989) Source: Habita Architects 1996.

In fact, some of the regional airports in Thailand were designed entirely by Thai architects and were much praised by foreigners who remarked that their planning and characteristics truly reflected the Thai identity and climate. Koh Samui Airport, which opened in 1989, the same year that the renovation of Don Mueang Airport was completed, is often described by visitors as "the most beautiful airport in the world" (Figure 20 and 21). The Samui Airport was designed by the Thai architectural firm Habita. It was intended to fit sensitively into its natural surroundings while being environmentally friendly by employing local materials such as palm, wood, and rattan, together with a largely open-plan layout negating the need for air conditioning. Its terminal combines the ambiance of a Polynesian resort with contemporary Thai design elements, impressing visitors with its minimalistic architecture (Airport Technology 2007). Koh Samui Airport has won several awards for its design, notably gaining first place in the Outstanding Architecture competition held by the Association of Siamese Architects in 1998 and a Board of National Environment Award for aviation environmental protection and awareness in 1989. The reception of this project makes it clear that prejudice against Thai design and technical skill can be groundless and that Thai architectural patrons (especially government commissioners) have often simply been blinded by the allure of the West and *farang* goods.

Another remarkable story regarding the subordinate position of Thai professionals took place in 1975 when the Ministry of Education was searching for an expert to design the Science Center for Education Planetarium. The Ford Foundation, both the sponsor and consultant of the project, suggested a western-graduated Thai architect, Dr. Sumet Jumsai, and introduced him to the Thai educational authorities as a museum design specialist. The Thai ministers were surprised and they wished to know why a Thai expert had been proposed rather than a *farang.* In an interview in *Satapanik Siam,* Sumet expressed disappointment and sorrow for the Thai architectural profession, in that even the Thai authorities looked down on people from their own nation (Pussadee 2996, 383). These instances affirm Pattana's argument that the Siamese/Thai has consistently been active in seeking *farang* expertise and influence rather than purely receiving it passively. It also confirms that since the beginning of the quest for *siwilai,* Siamese/Thai agents have chosen to employ the discourse of *farang* as a tactical method for locating their cultural and national selves, alongside and against the historically interweaving western-initiated projects such as colonization, modernization, and globalization (Pattana 2002, 60). Beginning with Siam's royal elite in the nineteenth century, continued by military dictators and bureaucrats through the twentieth century, and now driven by middle-class consumers and the mass media, the consumption of *farang* goods aroused a sense of cosmopolitan pleasure, which marked emerging new cultural identities and confirmed social status (Pattana 2002, 68). However, this created an opposite pole for those Thai who were not selected to participate in the building of their own nation and culture too much—a feeling of disgrace, subordination, and inferiority for being less admirable or less "civilized." Ultimately, it confirms that the traditional forms of hierarchy continue to form an important part of the psychology of Thai peoples' minds, which would become a fundamental part of Thai statecraft and, in the end, its propaganda.

CONCLUSION

By the early 1960s, change was already in the air in Thailand on both the political and the economic fronts. Field Marshal Plaek Phibunsongkhram and his head of police, Phao Siyanon, had been deposed and sent into exile by General Sarit Thanarat. Thailand was under the firm control of the military, receiving United States aid to revive and strengthen its rule. Bangkok had begun to show some signs of its extraordinary future growth, and the American presence was more obvious than it had been in the pre-war days. In order to recruit more nations into the Free World camp during the Cold War, the U.S. became Thailand's new foreign patron, having seized on the nation as an ally and a base for opposing the spread of communism in Asia. The Euro-centric colonial concept of "*khwam charoen* (progress)" and its local interpretation, the cultivation of a new kind of national citizen, was thus replaced by the U.S.-derived concept of "*phattana* (development)" and its more precise focus on economic development through private enterprise (Baker and Phongpaichit 2014, 165). More and more Americans were coming to Thailand as tourists, members of groups like the Peace Corps, and military personnel based in the country or on rest and recreation leave from the Vietnam War. Greater numbers of young Thais were going to the U.S. for their studies. They returned with more than simply a degree in architecture, engineering, or science and a taste for such American fashions as blue jeans. (Warren 2006, 54). The Thai "development" hence was boosted mainly by money flow, ideological commitment, bureaucratic infrastructure, and political links offered by U.S. patronage.

Among all the United States-funded projects, the commissions for new constructions in Thailand between the 1960s and the 1980s were one of the most evident, proving a long range of "subordination" discourse that never faded away from Thai governmentality. The Thais, no matter whether ruling elites or commoners, occupied a subordinate position relative to the West. This subordinate position is not only visible in economics and law, where so-called treaties of "free trade and friendship" such as the 1855 Bowring Treaty with Britain and the 1962 Rusk-Thanat Agreement imposed unequal trading relations and extraterritorial legal regimes on Thailand. It is also revealed in the government-commissioned construction projects assigned to American architects through the 1950s, the OICC military agreement, and the 1982 General Agreement on Tariffs and Trade (GATT). It is in these domains of international politics and economics that Thailand's loss of autonomy vis-à-vis the West, particularly the United States, is most visible and where the country looks most like a colony.

The socio-political circumstances of the period between the 1960s and the 1980s certainly affirm the subordinate relations of Thailand to the West. This was particularly manifested in three ways. First, *farang* and *tawan-tok* were seen as indicators of "civilization" and became the bars of achievement of the elites' desire to be modern and civilized. All the instances shown in this research encompass the "westernization" of the image of the Thai ruling nobilities in linguistic and spatial terms, with the created western image serving the dual purpose of increasing Thailand's prestige in an international arena and the establishment of the government's authority over the domestic territory. The second manifestation was a direct result of the first: it became impossible to conceptualize Thai identity or Thainess separately from civilization and modernization in regard to *farang* and *tawan-tok*. This reverse orientalist, i.e., occidentalist, practice in the Thai case studies reveals ways in which an auto- or crypto-colonizing elite voluntarily adopted strategies of power from the West at a time when the latter was a dominant political and cultural force in the region; there were distinct gains to be made from doing so (Harrison 2010, 16). The third effect of this enforced self-modernization of Siam/Thailand to appease the West was of benefit to the ruling Bangkok elite in terms of the increased centralization of the state, which it implied. As a consequence, the institution of the Thai ruling elite shored up its strength under external imperial incentives, turning instead to an assumption of augmented "other" powers over its own selves in this imitation of colonial rule. As long as Thailand wished to play a part in the western-dominated world order, the country had no choice but to maintain its subordinate relation to the West.

ENDNOTES

1 Field Marshal Sarit Thanarat staged a coup in 1957, which replacing Plaek Phibunsongkhram as Thailand's prime minister until Sarit died in 1963.

2 Upon Sarit's return to Thailand on September 20, 1958, Sarit dissolved the parliamentary system, citing the threat of communism. This second attempt to seize power, he explained, was a revolution rather than a coup. At the same time, he announced his plans to improve Thailand's economic well-being. Sarit relied on American advice and strategy to implement his plans. The word "*phattana*" was increasingly preferentially used in all official documents, and further developed to be the terms like "*phaen phattana*" (Kullada 2003, 59).

3 The new governmental agencies that the American consultants assisted included National Economic Development Board, Board of Investment, Ministry of National Development, etc.

4 Along with tourists, many of Bangkok's new hotels catered directly to the U.S. military personnel working in Thailand. The May 1969 issue of *Investor* magazine noted that "the Chavalit, which opened in 1966 with 300 rooms, took the U.S. personnel in 1967 and has since turned itself into an apartment house for long-term lease … the Chao Phraya [has] 230 rooms for sergeants." By 1972, three years after the U.S. began reducing both the military presence and aid spending in Thailand, the World Bank estimated that 20,000 Thais worked in the hotel industry alone (Jim Algie and et al. 2014, 187).

5 The Louis Berger Group was founded in the United States in 1950 as civil engineering consultancy. It expanded rapidly both in the United States and overseas. In 1959, an Architectural Division was established in Europe and subsequently extended to some fourteen foreign countries in Latin America, Africa, Europe, and the Far East. The work of the Architectural Division has been completely diversified, embracing the design of buildings of all types with particular emphasis on public buildings, auditoria, and buildings designed for exhibition purposes. It has attracted a number of international architects of repute as well as some brilliant young architects who have already demonstrated exceptional ability in the design of unique buildings. This included Robert G. Boughey, a chief architect of the Bangkok Office (Jewkes 1966).

6 In the 1950s, the United States Department of Defense assigned responsibility for contract construction in support of military assistance and military construction in regions around the world to the three major branches of defense: the Army, the Navy, and the Air Force. The Navy was assigned as the Department of Defense contract construction agent in Southeast Asia, among other regions. The Navy, therefore, established its first contracting officer in Southeast Asia with the Officer in Charge of Construction (OICC), Thailand, located in Bangkok, in December 1955, and in 1958, the name was changed to OICC Southeast Asia in order to encompass the construction work undergoing in Thailand, Cambodia, Laos, and Vietnam (Tregaskis 1975, 13, and Seufer 1968).

7 The United States construction activities in Thailand began in 1956, consisted of the construction of facilities for joint use in the common defense of the United States and Thailand. The original construction was performed primarily by the use of local fixed-price contracts. The initial dollar input was relatively small. However, as of June 30, 1967, the U.S. construction program had increased to about $337 million in construction projects, and the greater part of the work was being accomplished by U.S. military troop construction forces and civilian U.S. contractors (The Comptroller General of the United States 1968, 4).

8 The Airports of Thailand Public Company Limited, formerly a state enterprise, was founded on July 1, 1979, under the name “Airports Authority of Thailand—AAT.” As a result of the government’s privatization policy in 2002, AAT became a registered public entity and changed its name to “Airports of Thailand Public Company Limited or AOT” (Airports of Thailand under the Patronage 2011, 44-45).

9 The Phase I of Bangkok International Airport Development Project (1980-1989) placed emphasis on the upgrading and modernization of all facilities at the airport. This was to bring it up to international standards. A major long-term project was initiated with a capital investment of 5,074 million baht. After its completion, the airport was annually able to handle approximately 16 million international passengers, 2 million domestic passengers, and 532,000 metric tons of cargo. The above-mentioned development of the Bangkok International Airport resulted in greater efficiency and the raising of standards to those of other international airports. However, AAT was following the growth of air traffic closely, especially in 1987 (which was the Visit Thailand Year), and found out that further expansion was needed. As a consequence, Phase II of Bangkok International Airport Development Project (1989-1990) invested 637 million Baht in various projects. The first was the extension of the east runway for long-haul aircraft landing and taking off with the maximum load. The second was the expansion of cargo warehouses, and the third was the installation of a Y position boarding bridge. Phase III and IV followed. (Airports of Thailand 1991, 2-3; Airports of Thailand 1998, 171; and Warren 2006, 65-66).

10 The architectural part of the Suvarnabhumi Airport was designed by the Chicago-based architects, Murphy/Jahn, the winner of an invited international competition held in 1994 (Dixon 2007).

11 On behalf of AOT, the International Civil Aviation Organization contracted Louis Berger to prepare a traffic allocation strategy for the two airports and a plan for their future development. Louis Berger proceeded with a revised master plan that included: a statute review; inspection and appraisal of airside and landside facilities at both airports; passenger surveys; a strategic plan for air traffic allocation; comprehensive airport planning and design parameters; landside and airspace capacity analysis and planning, including simulations, a land-use and facility plan, an environmental impact study; and alternatives for airport development, including financial assessments (capital and operational expenditures) (WSP (former Louis Berger) 2021).

12 *General Agreement on Tariffs and Trade,* or *GATT,* aims to liberalize and achieve greater security in world trade through reducing or eliminating tariff and non-tariff barriers and provides a forum for negotiation over current international trade issues, thereby contributing to economic growth and development. The General Agreement has a number of provisions that deal particularly with the trade interests and needs of developing countries; some of these provisions were reinforced as a result of the Tokyo Round of multilateral trade negotiations in GATT, which concluded in 1979. Thailand became the 88th Contracting Party to GATT on November 20, 1982 (Thailand Joins GATT, 1982).

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LABORATORIES OF ENVIRONMENTAL KNOWLEDGE

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This essay narrates the story of three mid-to-late-century North American laboratories that produced architectural knowledge regarding the environment. For each laboratory, this essay describes the physical location of inquiry, institutional setting, instruments of investigation, biography of the principal investigator, and the publication that summarized the findings of the laboratory work. Through these descriptions, the essay attempts to identify how each investigator leveraged the model of the laboratory to situate their work in their respective cultural milieu.

Keywords: Laboratories, architecture, environment, Victor Olgyay, ASHRAE, Ralph Knowles.

INTRODUCTION

In the introduction to the 1998 publication Picturing Science, Producing Art, Caroline Jones, and Peter Galison questioned the conditions within which objects are made visible in culture and how such visibilities are characterized as science or art (Jones & Galison 1998). This essay is prompted by, responds to, and continues this line of inquiry. It asks how environmental knowledge has been made visible in architecture, and how such visibilities allow transmission of knowledge to and from architecture and its cognate disciplines. Specifically, it narrates the story of three mid-to-late-century North American laboratories where architectural knowledge regarding the environment was produced.

This essay approaches each laboratory as five distinct and interrelated sites of inquiry. The first site is the laboratory as a physical space. The locality, adjacency, and physical characteristics of the laboratory are recounted here to provide a sense of place and physical form. The second site is the laboratory as a research institution. This site is intricately linked to the first yet provides an opportunity to ask a distinct set of questions such as: Why was the laboratory established, by whom, who funded it, and to whose benefit? The third site is the primary instrument of investigation. Here, the essay describes each of the key instruments' design, physical construction, and operation. The fourth site is the biographical information of the principal investigator. This section characterizes each of the principal investigators by identifying their place of origin, professional training, and contribution to the respective fields before and after their time spent at the laboratory. The fifth and last site is the set of visual and written documents produced from each practice. This section investigates the process in which findings from each practice were formatted into knowledge in various forms of publication. References cited, linguistic and graphic choices, venue, and format of publication are delineated to ask the following questions: How was knowledge documented, and what kind of contribution has it made to the field? In the last section, this essay contemplates the significance of the laboratory as a model of architectural knowledge production.

1. PRINCETON ARCHITECTURAL LABORATORY

1.1. PRINCETON ARCHITECTURAL LABORATORY, PRINCETON, NJ

The first laboratory in question is the Princeton Architectural Laboratory during the Olgyay brother's tenure from 1953 to 1957. At the laboratory, Hungarian-born architect brothers Victor and Aladar Olgyay imported applied principles from biology, engineering, and meteorology to demonstrate an analytical approach to architectural design in response to climatic conditions. In addition to using this venue for academic research, they used the laboratory as a consulting venue for several high-profile contemporary architectural projects. Victor Olgyay's 1963 publication Design with Climate was the summary of his and his brother's work at the laboratory, and it remains influential—particularly to the discipline of building science—to this date.

The Architectural Laboratory at Princeton University was built on the periphery of the campus in 1949. This laboratory was designed by Jean Labatut—a French-born architect who arrived at Princeton in 1928 and taught until his retirement in 1967— two graduate students Robert S. Taylor and Paul M. Rodda, and faculty members Henry Jandel and William Shellman Jr. (Clarke 2013). The Architectural Laboratory was a spatial expression of Labatut's pedagogy. In a 1952 interview, Labatut described The Architectural Laboratory as a unique place where one can experiment with values of color under natural as well as artificial lighting conditions and test the relationship of architecture to the physical environment (Daily Princetonian 1952).

The laboratory consisted of a series of additions to an existing polo stable that had been used as a site of experiment for architecture and engineering students. Labatut and the team added a triangular-shaped extension and a large glass box mock-up space, and a small hallway connecting the two. The southern and northern walls of the triangular extension were fitted with large spans of plate glass. The roof of this room contained a Plexiglass dome to let natural light into the space, which doubled as a testing device to approximate lighting conditions for architectural models. The components of the radiant heating system used to heat this space were painted in bright colors to serve as an instructional tool in environmental controls. Each of the curtain wall panels could be removed and replaced with a different type, and full-scale mock-ups of architectural details were often hung from the frame. The laboratory space was replete with contemporary theater equipment such as scaffolding, rigging, lamps, block, tacking, etc. for the purposes of visual testing of various scales of architectural models (Clarke 2013).

The laboratory was a venue for seminars and experiments by the likes of Louis Kahn, Buckminster Fuller, and Richard Neutra in the early 1950s. One of the earliest results from the laboratory was the design of the Church of the Four Evangelists, a circular glass structure with murals designed by French liturgical painter André Girard. The model of the church was produced and tested in the lab and the large open space of the laboratory was used to test the colors and composition of the murals (Clarke 2013). While the laboratory was designed specifically for this sort of phenomenological experiment, it also attracted experiments in building systems and structures that more closely emulated engineering inquiries of the time. It was in this laboratory space that the Olgyay brothers constructed their thermoheliodon—originally intended to be called the climatron (Castro 2018).

1.2. THERMOHELIODON

From 1953 to 1957, Hungarian-born architects Victor and Alardar Olgyay carried out a series of experiments at the Princeton Architectural Laboratory using the thermoheliodon. The construction of the machine was funded by the National Science Foundation, an independent United States government agency formed in 1950 to support fundamental research and education in all non-medical fields of science and engineering (NSF 2021). The Olgyay brothers designed a machine that would allow simulation of infinitely variable climatic conditions and rapid prototyping of architectural form. This laboratory machine consisted of two major components: the testing apparatus and the instrument panel.

The testing apparatus was an enclosed Plexiglass dome placed on top of a cylindrical base. Inside the dome, scaled architectural models were placed on a

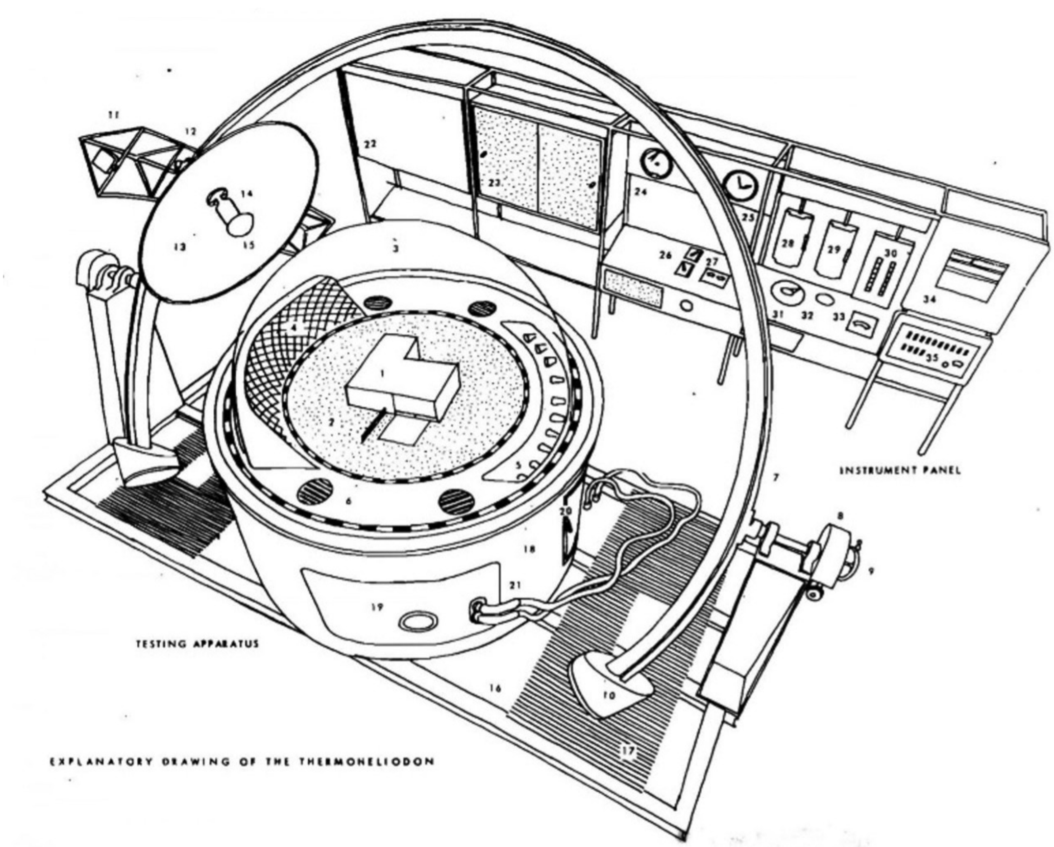

Figure 1: Illustration of the thermoheliodon. Source: Olgyay 1963.

circular four-foot-diameter sunken pan that was filled with soil. Olgyay brothers used soil native to the location of proposed buildings in order to ensure “proper thermal relations” between the model and the ground (Olgyay 1963). Architectural models placed inside the dome were fitted with a thermistor for interior heat measurements and a thermocouple to measure the exterior (still inside the Plexiglass dome) temperatures. This dome was equipped with an air inlet that directed air over the experimental area, an air outlet to recirculate air-conditioned with heating coils, and four-300-watt incandescent lamps to simulate diffuse sky radiation by reflection from the dome’s inner surface (Olgyay 1963).

A latitude ring—a track for the sun’s path—was placed outside of the dome. It was designed to be adjusted to the desired latitude by a crank for tilting the track. A geared motor drove the sun around the latitude ring. Time was scaled to 1/36th, each hour truncated to 100 seconds, and a full test ‘day’ of 12 hours—a 180-degree rotation of the ‘sun’—took 20 minutes. The ‘sun’ was a 5000-watt incandescent bulb with a polished aluminum parabolic reflector to produce parallel rays (Olgyay 1963).

A few feet away from the testing area was an instrument panel equipped with a chalkboard panel, compartments and additional shelves for storage, temperature and relative humidity gauge, a clock geared to run at a scaled time (1 hour = 100 seconds), and various controls for the heaters, lamps, fan, sun-motor housed inside the cylindrical base of the testing apparatus (Olgyay 1963).

Using the apparatus, the Olgyays were successful in determining ideal solar orientation, volumetric relations, design of intricate shading systems, and material choices based on abstract thermal performance values. As the name of the device suggested, Olgyays' goal was to accurately calculate the thermal performance of a building through modelling. However, thermal capacity of materials and interior climatic conditions were conditions that could not be scaled, despite their continued attempt to correct the error through complex calculations (Barber 2014).

1.3. VICTOR OLGYAY

Victor Olgyay was born in Budapest in 1910. He studied English at the Royal Hungarian Institute of Technology in Budapest and completed an architectural degree at the Scuola Superiore Di Architettura in Rome, Italy in 1936 ("Victor Olgyay Collection 1939-1991 Olgyay, (Victor) Collection" 2021). Victor Olgyay and his brother Alardar already had an established career as architects in Hungary when they moved to the United States in 1947 to teach at Notre Dame University upon Marcel Breur's invitation. The Olgyays joined the Department of Architecture at the Massachusetts Institute of Technology as Research Associates two years later. Their research and publication on climatic analysis and design of suburban buildings gained them a reputation as climate experts, which afforded them numerous consulting positions. In 1953, the brothers were invited to Princeton University as Research Professors and began their work at the Princeton Architectural Laboratory (Barber 2013). The Olgyays used this venue and the thermoheliodon for their professional consulting work for contemporaneous architectural projects such as Josep Lluis Sert's Peabody Terrace, Breuer's UNESCO building, and Walter Gropius' plan for the University of Baghdad (Barber 2014). The Olgyay brothers' work at the laboratory ended in 1957, which also marked the end of their professional partnership.

1.4. DESIGN WITH CLIMATE, 1963

Victor Olgyay's 1963 publication 'Design with Climate: Bioclimatic Approach to Architectural Regionalism' was the summation of the brothers' work with the Thermoheliodon at the Princeton Architectural Laboratory. In this publication, Victor Olgyay wrote that the 'success of every design must be measured by its total effect on the human environment,' and that the man remains the module—'the central measure'—in all approaches (Olgyay 1963). The first reference Olgyay cited in outlining this bioclimatic approach was the work of Ellsworth Huntington, an American geographer at Yale University known for a collection of studies on the correlation between climate, geography, and human behavior.

Huntington conducted a study of a factory in Connecticut that correlated climatic data and workers' productivity. This so-called physiological research on the performance of factory workers led to Huntington's map depicting the distribution of human health and energy around the world based on climate. Regions around Western Europe and the American East Coast and Midwest were considered the most productive regions, whereas the Latin American, sub-Saharan African, South and Southeast Asian regions were considered to have the lowest human productivity (Huntington 1915). The core justification for Huntington's troubling measure of civilization was the correlation between climatic variability and racial characteristics. The graph that accompanied Huntington's Connecticut study was uncritically reproduced in Olgyay's 'Design with Climate'.

In the late twentieth century and early twenty-first century, geographers have widely condemned such theories of environmental determinism as justification for Western colonialism, imperialism, and racism (Gilmartin 2009). Huntington's work has recently been appropriately criticized as a 'meteorological Taylorism' (Fleming 1998). Acknowledging the Olgyay brothers' role in importing antiquated biases into architecture under the name of scientific development is timely. The more troubling aspect, however, is that these concepts were indeed accepted as scientific knowledge without critical examination and are now deeply embedded in the twenty-first-century architectural knowledge and practice in North America.

One of the most enduring concepts associated with the diagram was the ‘comfort zone’ which described a condition in which ‘minimum expenditure of energy is needed to adjust himself to his environment’ so that ‘most of his energy is freed for productivity’ (Olgyay 1963). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)’s definition of thermal comfort bears a striking resemblance. It is defined as:

> that condition of mind which expresses satisfaction with the thermal environment . . . where the body’s effort at temperature regulation is minimized (ASHRAE 2020).

While the formulas have been refined and additional variables were added, the conceptual underpinning remains virtually unchanged and yet unexamined.

2. THE ENVIRONMENT LABORATORY

2.1. THE ENVIRONMENT LABORATORY AT 7218 EUCLID AVENUE, CLEVELAND, OH

The second laboratory is the Environment Laboratory run by the American Society of Heating and Ventilating Engineers (ASHVE), in operation from 1951 to 1961 in Cleveland, Ohio. The work at this laboratory was focused on developing quantitative standards of acceptable thermal conditions in buildings which eventually became codified as ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. This document was first published in 1966 and continues to be in use today with regular revisions and updates.

The American Society of Heating and Ventilating Engineers (ASHVE) had maintained a research laboratory since 1919, when the first laboratory was set up in facilities of the United States Bureau of Mines in Pittsburgh, PA. In 1944, ASHVE Research Laboratory was relocated to Cleveland, Ohio. After two years of using a leased space, in 1946, ASHVE purchased a historic Queen Anne-style mansion at 7218 Euclid Avenue to house the Research Laboratory. At this location, ASHVE established the Environment Laboratory in 1951, lauded as the ‘newest and, perhaps, most important facility for fundamental research on panel heating and cooling’ (‘ASHVE Opens New Environment Laboratory’1951).

7218 Euclid Avenue was one of the surviving mansions of the previous era of prosperity. The property was built in 1887 by Richard N. Allen, a Massachusetts railroad engineer. The design of the house followed the typical contemporary examples of Queen Anne style with the abundance of bay windows, steeply pitched irregular roof shapes, patterned shingles, and asymmetrical façade (Dubelko 2021). It was generously set back from the Medina sandstone paved avenue, and a meticulously maintained lawn filled in the space between the avenue and the house.

ASHVE purchased the mansion in 1946 from The Grand Lodge of Ohio, Order of Sons of Italy who had been in possession of the property since 1934. By this time, most of the mansions on Euclid Avenue — formerly known as the “Millionaire’s Row” — had been torn down or converted to other uses. The American Society of Heating and Ventilating Engineers established a national research laboratory dubbed the Environment Laboratory here in one of the surviving mansions. The construction and operation of ASHRAE laboratories were funded by the National Institute of Health, a United States government agency responsible for biomedical and public health research (NIH 2021).

HEATING AND VENTILATING ENGINEERS OPEN ENVIRONMENT LABORATORY

November 1 marked the opening of the ASHVE Environment Laboratory, the heating engineers' newest and, perhaps, most important facility for fundamental research on panel heating and cooling.

The Environment Laboratory is a large room in which the temperature of all room surfaces and portions of each surface can be controlled separately, so that it is possible to simulate a variety of combinations of cold and warm walls, windows, floors, and ceilings. To simulate a corner room of a building, two walls can be cooled to desired temperatures, while some portions of these walls can be held at a lower temperature to act as glass areas.

The room will be used as follows:

1. To measure the method of the exchange of heat between the surfaces of the room and the air in the room as they are affected by temperature of the surfaces, temperature and humidity of room air, rate of ventilation, character and location of room surfaces.
2. To determine the influence of radiation on human comfort.
3. The room may also be used for a study of the removal of heat by means of heat-absorbing panels.
4. Evaluation of the effect of different interior surface finishes on the performances of panels.

The laboratory is necessary to the ASHVE four-part research program on panel heating and cooling: (1) heat distribution within and behind the panel, (2) heat transfer between the panel and the space in the room, (3) comfort conditions, and (4) controls.

Above: exterior of the laboratory showing the instrument console, entrance to crawl space underneath the stairs, and dehumidifier and duct work. The ceiling can be raised or lowered. Right: 175 heat flow meters like this, made of bimetallic foil separated by plastic spacers, will measure how much heat is picked up or given off by the room surfaces. Lower right: the two shining pipes are perforated ducts for introducing air to simulate infiltration; behind the pipes are polished shields to direct air away from the walls. Lower left: rear view of aluminum panels with copper coils

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Figure 2: Photographs of the Environment Chamber reproduced in Architectural Record. Source: 'ASHVE Opens New Environment Laboratory' 1951.

2.2. THE ENVIRONMENTAL CHAMBER

Placed inside this laboratory was the Environmental Chamber, a room-sized machine composed of coil-heated-and-cooled panels and a console cluster. The Environmental chamber was 3.66m (12ft) wide by 7.32m (24ft) long and had a ceiling height adjustable from 2.43m (8ft) to 3.35m (11ft). All interior surfaces were made of aluminum panels. Copper tubes attached to the back of each panel controlled the surface temperature as heated or chilled liquid was passed through the pipes. With this method, they were able to achieve surface temperatures that ranged from 4.4°C (40°F) to 65.5°C (150°F). Perforated inlet strips were located between the ceiling panels to supply conditioned air into the chamber, and a continuous slot at the floor around the perimeter was used to return the air (Jaax 1967).

The control room was a separate room that housed a combination of electronic and pneumatic control equipment. It included graphic control panels for the air circuit and the liquid circuit, lights that indicated parts of the system in operation, and a monitoring interface for air and liquid temperatures at various locations along the circuitry. The relative humidity was measured by an aspirated psychrometer that was shielded from radiant heat inside the test chamber. Dry and wet bulb temperatures were measured in the room with an aspirated psychrometer with mercury thermometers. Air velocities were measured with a hot wire anemometer. All measurements were taken at one-hour intervals (Jaax 1967).

The testing method was a refined version of what American engineers (and members of ASHVE) F.C. Houghton and C.P. Yaglou had started as early as 1923 (Houghton & Yaglou 1923). Test subjects were asked to spend three hours inside the chamber, maintaining a certain activity level under controlled thermal conditions. Test subjects reported approximately 1 hour before their scheduled testing times to get dressed in the uniform in the pre-test room. During this preparatory phase, a registered nurse recorded the test subject's age, height, weight, pulse rate, oral temperature, and a summary of their recent physical activity. After this physical examination, for 30 minutes, they were 'indoctrinated' (Jaax 1967) to the purpose of the test and how to use the ballot that listed seven possible thermal sensations—cold, cool, slightly cool, neutral, slightly warm, warm, and hot. The purpose of the test was to determine the effect that various temperature and humidity conditions have on 'exercising human beings' (Jaax 1967). Upon entering the chamber, subjects were asked to walk up and down the steps placed inside the chamber, walk around for 5 minutes, and sit down at the table placed in the center of the room. At the end of the first hour, and each half hour thereafter, subjects were asked to indicate their "impression" of the thermal sensation they felt on the ballot. Subjects could study, engage in quiet conversation, or play cards within the testing chamber. Smoking was allowed, but they were asked to keep it to a minimum. After the three-hour duration was over, subjects reported to the adjacent physiological monitoring room. This monitoring room was equipped with instrumentation for measuring skin temperature, rectal temperature, and heart rate. For participating in the study, the subjects were paid 5 USD (Jaax 1967).

In 1961, the research laboratory was closed "due to financial reasons" (ASHRAE 1995). The maintenance of the laboratory was no longer a priority for a newly formed organization called the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) that had absorbed ASHVE. Shortly following the merger was the establishment of ASHRAE headquarters in the United Engineering Center in New York. The new space was in a twenty-story tower just across the street from the United Nations headquarters and designed by Shreve, Lamb & Harmon Associates, an American architecture firm best known for designing the Empire State Building. This building housed major engineering societies based in the United States and was 'designed to symbolize the dignity and achievements of the engineering profession' ('New United Engineering Center to Be Erected on United Nations Plaza' 1957). The building was designed to provide spaces for 'engineering meetings and committee activity,' private dining rooms and cafeteria, enlarged library and publication facilities, and exhibition space to showcase 'the rapid advances in engineering' to be 'interpreted for the general public' ('New United Engineering Center to Be Erected on United Nations Plaza' 1957).

2.3. AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) was formed in 1959. This organization was created by the merger of the American Society of Heating and Air-Conditioning Engineers (ASHAE) founded in 1894 and the American Society of Refrigerating Engineers (ASRE) founded in 1904. The merger was intended to develop a series of industry regulations on a global scale, focused on thermal conditional and ventilation in contemporary buildings.

One of the main precursor organizations, the American Society of Heating and Ventilating Engineers (ASHVE), was founded by an American engineer Hugh J. Barron in September 1894 in New York City with 75 charter members. In their first regular meeting, the society's constitution and by-laws were adopted, which outlined the objectives of the society meant to guide its future work. The objectives included the establishment of professional and administrative protocols, as well as moral standards for the members of the society. In the same meeting, American engineer and a notable member of the Christian Science Church, Edward P. Bates, was installed as the first president of the society. In his first address to the society, Bates characterized the society as public benefactors whose work will 'benefit all classes' (Comstock, Stephen & Spanos 1995,). Except, he was adamant in his call to avoid those who were not deemed to be qualified engineers, and only sought those who are 'men of character and reasonably ambitious of success,' and 'men who will think, study, and work until they see the fruition of their hopes' (Comstock, Stephen & Spanos 1995). Bates closed the address by arguing that the work of this society will be 'to the credit and the good of the race' (Comstock, Stephen & Spanos 1995).

The creation of the larger organization of the American Society of Heating, Refrigerating and Air-Conditioning Engineers in 1959 was an extended effort. At stake during the merger was the claim of the industrial domain. During the thirty odd years between the first proposal to the realization of the merger, the resistance primarily came from individuals who were interested in only limited segments of the industry—ice and cold storage, domestic refrigeration, steam and hot water heating industry—who feared the obsolescence of their professional domain. Air-conditioning engineers were at the helm of this merger. And it was no accident that 'ventilating' was omitted from the new acronym in favor of air-conditioning.

Since its inception, ASHRAE has been a powerful lobbying force for the industry that aligned itself closely with the United States Government. As the organization frames it, ASHRAE was called upon by the United States government to take a major role in energy management during the oil crisis of 1973. This also led to ASHRAE's involvement in the United States Department of Energy's implementation of the Emergency Building Temperature Restrictions Program in 1979. In 1982, ASHRAE opened a Washington, D.C. office, to 'strengthen the liaison with the U.S. Federal government' (ASHRAE 1995). Under President George H.W. Bush's administration, ASHRAE received a record $2.3 million in research funds, as part of the Energy Policy Act of 1992. ASHRAE has now grown into an organization with 57,000 members in more than 132 countries worldwide that authors technical standards related to building services engineering, energy efficiency, indoor air quality, and sustainable development that are widely accepted. It has also assumed the responsibility for funding research projects and offering continuing education programs to licensed engineers and architects ('Home | Ashrae.Org' 2021).

Leveraging the popularity of the newly invented air-conditioning system, mechanical engineers in the United States quickly banded together to create a well-funded and visible organization. In the seminal 1960 publication 'The Architecture of the Well-Tempered Environment', British architectural critic and writer Reyner Banham posited the rise of the hermetically sealed 'mechanized envelope' as a 'predominantly American history' (Banham 1969) related to Willis Carrier's invention of the modern air conditioning system. Banham criticized the Modernist effort to 'devise a style that would 'civilize technology' while the American engineers had devised a technology that would make the 'modern style of architecture habitable by civilized human beings' (Banham 1969).

2.4. ASHRAE 55, 1966

ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy is an American National Standard published by ASHRAE that establishes the ranges of indoor environmental conditions to achieve acceptable thermal comfort for occupants of buildings. It was first published in 1966, revised in 1974, 1981, 1992, 2004, 2010, 2013, 2017, and 2020 (ASHRAE 2020). In it, the comfort zone is defined as the combinations of air temperature, mean radiant temperature, and humidity that are predicted to be an acceptable thermal environment at specific values of air speed, metabolic rate, and clothing insulation (ASHRAE 2020). And this was one of the key engineering concepts that were introduced by Olgyay to the architectural discourse. This term was first formally defined by American engineers F.C. Houghton and C. P. Yaglou in a series of articles published in the American Society of Heating and Ventilating Engineers (ASHVE) transactions in 1923 (Houghton & Yaglou 1923).

3. THE NATURAL FORCES LABORATORY

3.1. THE NATURAL FORCES LABORATORY AT HARRIS HALL, 825 BLOOM WALK, LOS ANGELES, CA

The third laboratory is the Natural Forces Laboratory at the University of Southern California which operated between 1967 and sometime in the early 1970s. The laboratory was a series of design studios for third-year undergraduate architecture students created by Ralph Knowles, Emmet Wemple, and Pierre Koenig. It was designed to enable students to develop equipment and simulation techniques for the performative evaluation of historical building forms and generation of novel forms.

The Natural Forces Laboratory was located inside Harris Hall, a romanesque-revival style building designed by Ralph C. Flewelling and dedicated in 1940 at the University of Southern California. Arthur C. Weatherhead, the first leader of the school of architecture formed in 1925, characterized his effort at USC as a prolonged experiment. Weatherhead emphasized 'habits of visualizing three-dimensional forms' early in the curriculum as a 'modern approach" to the study of design (Weatherhead 1941). In doing so, all the project programs were written around local situations that students in the early years of design education could easily comprehend. For the more advanced students, the focus on local context allowed students to develop their work to the level of working detail drawings and speculations on the mechanisms of building finance. Weatherhead considered this a necessary parallel to the 'dramatic and colorful presentations' as he sought to foster the ability to balance a 'well-developed imagination and the technical skill to express it' (Weatherhead 1941).

In 1961, a Bauhaus-trained American architect Samuel Hurst was appointed the dean of the USC School of Architecture and Fine Arts. Hurst brought Ralph Knowles with him from Auburn University in 1963, and Pierre Koenig in 1964. Ralph Knowles would take over as the interim dean after Hurst's retirement in 1973 ('School of Architecture 100-Year Anniversary Spotlight: Ralph Knowles' 2019), and Pierre Koenig would go on to serve as the director of the school's building science program from 1980 to his death in 2004. The school's Building Science Group has included Knowles, as well as Douglas E. Noble, Marc Schiler, Karen M. Kensk, Goetz Schierle, David Brindle, and Konrad Wachsmann.

The Natural Forces Laboratory was a design studio that was reconceived as a laboratory for controlled design experiments that began in 1967. This ecological design laboratory was furnished with custom machines for experiments with lighting, wind, and water dynamics. The studio was largely funded by a grant from the National Endowment for the Arts for $25,000. Knowles considered the studio as 'a kind of forerunner to what became the building science program' ('School of Architecture 100-Year Anniversary Spotlight: Ralph Knowles' 2019). The three educators worked with third-year undergraduate architecture students to develop equipment and simulation techniques for the performative evaluation of historical building forms and generation of novel architectural forms in response to ecological forces. The third-year architecture design studio was furnished with simulation tools that were designed, built, and used by students as integral components of the design process. 'Sun machines, wind tunnels and water tables of various types' (Knowles 2011) were set up alongside traditional drafting tables in the studio space. Pierre Koenig primarily dealt with the impact of wind, Emmet Wemple with water, and Ralph Knowles focused on the impact of sunlight on form (Witt & Reznich 2018).

3.2. HELIODON

Ralph Knowles' heliodon was much simpler than the thermoheliodon of the Olgyay brothers. Unlike the machine at Princeton laboratory that sought to emulate all possible ecological parameters and their thermal consequences, the Knowles' heliodon was only concerned with the aspect of solar movement and its perceptual effect on buildings. It also lacked the elaborate control and readout cluster that accompanied the machine at Princeton. In 1965, prior to the official launch of the Natural Forces Laboratory, Knowles and students at the USC built a large-scale version of this heliodon. This heliodon consisted of a light source, a large latitude ring made of an aluminum track, a smaller aluminum track that served the same function as Olgyays' 'month-bridge,' and two stacked wooden platforms all supported on an H-section steel foundation (Chen 2008).

The larger aluminum track was supported at two pivot points, connected to a pair of large sprockets to allow latitude adjustments. However, the tilt-rotation of the track was often locked to the 34.0522° N of Los Angeles, California. The smaller aluminum track was clamped perpendicularly onto the larger track to allow adjustment of the sun position for different months of the year. The light source was a parabolic aluminized reflector bulb (PAR), a type of bulb that produces a highly directional beam (Chen 2008). This type of light was often used for theatrical lighting and automotive headlamps. While Olgyays manufactured an elaborate parabolic reflector for their light source to simulate the directional light of the sun, by the time Knowles was setting up the studio, this type of light had become commercially available. This light source was mounted on the smaller aluminum track that traveled along the main track. While motorized, the operation of the heliodon and the speed of the sun's movement was manually controlled

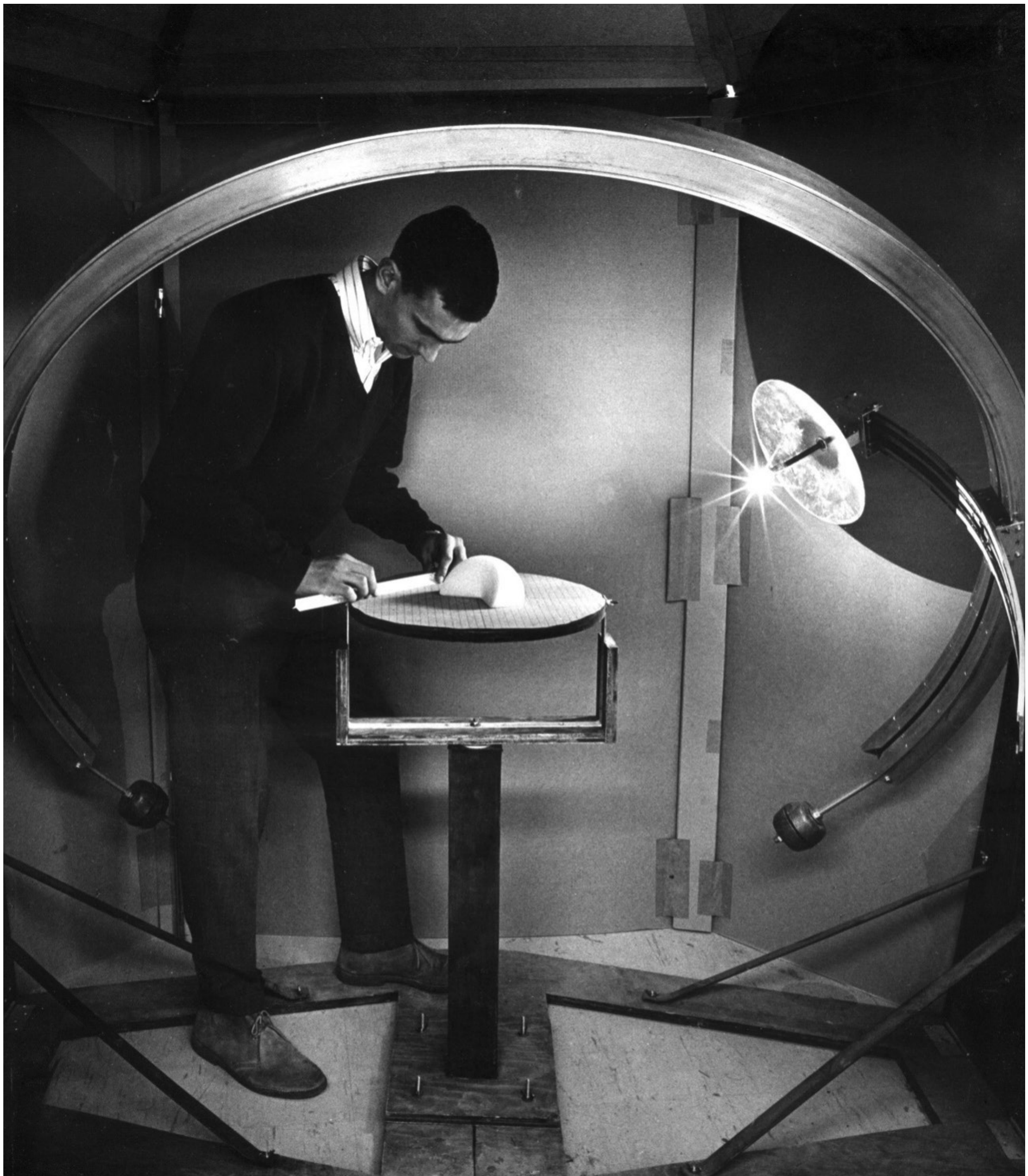

Figure 3: A student testing his model inside the cardboard enclosed heliodon. Source: Witt and Reznich 2018.

unlike that of the thermoheliodon at Princeton. The investigations carried out using the heliodon were primarily recorded by observing and photographing architectural models placed on this wooden platform. Rather than temperatures recorded via a collection of thermocouples and thermistors, the output of the heliodon was iterative sets of architectural models and photographs that captured diverse shadow conditions.

3.3. RALPH KNOWLES

Ralph Knowles received his Bachelor of Architecture degree from North Carolina State University in 1954. He took classes offered by Buckminster Fuller and Eduardo Catalano, two figures that Knowles credited for shaping his early career as an architect (Witt & Reznich 2018). At the time of Knowles' enrollment, Fuller was continuing his research on the cardboard dome housing project for the United States Marine Corps with students and faculty members. Eduardo Catalano was experimenting with non-traditional building forms, perhaps best exemplified by his 1954 Raleigh House with a hyperbolic paraboloid roof structure ('Catalano House: Raleigh, North Carolina' 1955).

After graduating from North Carolina State in 1954, Knowles followed his mentor Eduardo Catalano—an Argentine architect with a focus on novel structural forms—to work in his office in Cambridge, MA. Knowles finished his master's degree in architecture in 1959 at MIT. There, Knowles completed a joint thesis titled 'A Prototype Structure' with engineer Stanley Steinberg, advised by Eduardo Catalano. This was a structural research project regarding the development of a prototype structure that was 'systemized through the geometric ordering of surface' (Knowles & Steinberg 1959).

Following his studies at MIT, Knowles began teaching at Auburn University in 1959, where he continued to consider the design studio as a platform for research. Funded by a series of grants from the Container Corporation of America—the same company that funded Buckminster Fuller's cardboard housing projects for the US Marine Corps—Knowles explored design potentials of cardboard as a structural material and formwork for concrete (Witt & Reznich 2018).

In 1962, Knowles received a grant from the Graham Foundation for Advanced Studies in the Fine Arts, then directed by John D. Entenza. With this support, Knowles began to develop his own methodologies for measuring the impact of ecological forces on buildings. Knowles organized studios at Auburn that focused on the concept of differentiation as a 'continuity of instantaneously observed differences in the condition of related parts or differences recognized in the same part or arrangement of parts over time' (Knowles 1974, 5).

This line of research began as a response to Kevin Lynch's 1960 publication The Image of the City. Lynch had worked together with painter and photographer Gyorgy Kepes on a five-year-long project from 1954 to 1959, titled 'Perceptual Form of the City.' As directors of MIT's Center for Urban and Regional Studies, Lynch and Kepes addressed the legibility and imageability of the American city through an individual's perception of the urban landscape, through an extensive series of black and white photographs, field notes, interviews, data collection, and hand-drawn maps.

Knowles observed that Lynch and Kepes' concepts of imageability and perceptive association lacked a rational, generative framework. Knowles collaborated with his Auburn University colleague William K. Turner to search for 'rational design criteria that would provide clues to orientation in the urban environment' (Knowles 1974, vii). In this search, Knowles and Turner developed systems of structural planes of varying size, shape, and orientation that responded to natural forces. This renewed focus on ecological forces was influenced by James Marston Fitch's 1948 publication American Building, in which Fitch argued that the ultimate task of architecture is to interpose itself between man and the natural environment (Fitch 1948).

Knowles argued that his work at Auburn conceptualized a "building as an ecological form' that is differentiated in response to natural forces. Further, he argued that the new aesthetic was distinguished from that of Modernism which sought a universal expression of form (Knowles 2011).

Ralph Knowles began teaching at the University of Southern California in 1963. Beginning in 1967, Knowles continued his inquiry into ecological form generation funded by a grant from the National Endowment for the Arts. In 1968, Knowles received a second grant from the National Endowment for the Arts, enabling him to conduct a large-scale case study of diversified settlements in Owens Valley, California. This was a study of a large-scale application of principles that were emerging from the Natural Forces Laboratory that correlated building form with natural variation. The stated purpose of this study was to reduce energy expenditures in responding to natural variation at a regional scale using building form (Knowles 1974). Owens Valley was chosen as a case study subject for its hydrogeological diversity and the wide range of ecological conditions that involve heat, light, water, and wind.

3.4. SUN RHYTHM FORM, 1981

After the territorial scale investigation, Ralph Knowles returned to more focused research on developing the concept of a solar envelope from 1976 to 1981. This body of research culminated in the 1981 publication Sun Rhythm Form. In this publication, regional ecological analysis and mapping were notably absent. Instead, the relational form-response framework was further theorized and tested against prototypical and repeatable conditions. Among the concepts that continued to evolve from the Owens Valley work was the consideration of buildings in simple 'terms of the form of the enclosure or the envelope' (Knowles 1974). For this next phase of investigation, Knowles aligned his definition of envelope with the one used in zoning practices in the US. Therefore, Knowles shifted his focus from the regional ambitions of ecological planning projects towards intervention on existing legal structures that effectively governed building height and bulk in a locally specific manner. In this publication, Ralph Knowles proposed the concept of the solar envelope as 'the volumetric limits of building that will not shadow surroundings at specified times' (Knowles 1981). This envelope was constructed according to the daily and seasonal paths of the sun in relation to the site's latitude, size, shape, slope, and orientation. Thus, Knowles claimed that the solar envelope is 'a constructed synthesis of time and space' (Knowles 1981).

This research publication was funded by the Design Arts Program of the National Endowment for the Arts (NEA) through two separate grants to develop and explore the concept of solar envelope zoning. In addition, in 1980 and 1981 the Community and Consumer Branch of the Solar Energy Research Institute (SERI)—a government-owned organization funded through the United States Department of Energy, now known as the National Renewable Energy Laboratory (NREL)—granted Knowles two separate contracts to develop strategies and test applications of the solar envelope zoning concept. This governmental support required production and submission of two separate research reports. In 1980, part of the work of Sun Rhythm Form was repackaged into Solar Envelope Concepts: Moderate Density Building Applications by Knowles, specifically focusing on the design of residential building types. In 1982, Solar Envelope Zoning: Application to the City Planning; Los Angeles Case Study was produced by the City of Los Angeles in which the contents of Sun Rhythm Form were summarized and evaluated by the Department of City Planning for the purpose of examining the feasibility of implementing Knowles' concept of solar envelope zoning.

CONCLUSION

The three laboratories featured in this essay—The Princeton Architectural Laboratory, ASHVE's Environment Laboratory, and the Natural Forces Laboratory at USC—qualified as laboratories in the extended and figurative sense of the word:

> something likened to a scientific laboratory, esp. In being a site or center of development, production, or experimentation (OED Online 2021).

A laboratory was originally 'a room or building for practice of alchemy and the preparation of medicines' (Oxford English Dictionary 2021). The etymon of the word is the post-classical Latin word 'laboratorium' which described a workplace. Later, this term began to describe a room or building 'equipped for carrying out scientific experiments or procedures', especially for the 'purposes of research, teaching, or analysis' (Oxford English Dictionary 2021). Here, it's important to note that the laboratory was always understood to be a venue of knowledge production and dissemination, and a space of collaboration.

The laboratories at Princeton and USC were primarily architectural design studios that were modeled after science. A studio is defined as 'The workroom of an artist, sculptor, photographer, etc.' (Oxford English Dictionary 2021). This word has its origins in Italian, and is a lexical cognate between German, French, and English as well. This definition was in concurrent use in the European context since the Renaissance. It is also related to the noun study that describes:

> A room in a house or other building, intended to be used for private study, reading, writing, etc., esp. by one particular person (Oxford English Dictionary 2021).

Before the seventeenth century, study also was used to describe 'A place of learning; an educational establishment' (Oxford English Dictionary 2021). The disappearance of this earlier meaning of study is partially elucidated by American art historian Svetlana Alpers, as she characterized the self-depicted studios of seventeenth-century European—primarily Dutch—painters. Despite the realities of the studios as places of work for students, assistants, models, and maids, painters who represented their studio spaces did so from a 'solitary's view' (Alpers 1998, 404) that sustained a fiction of the isolated and singular artistic genius.

Rather than verifying the accuracy of scientific knowledge produced by each laboratory, this essay attempted to focus on their cultural contributions. Each principal investigator positioned themselves at the boundary conditions of laboratory and studio practice to capture the attention of a new kind of audience interested in the scientization of art. Thus, the thick description of each laboratory is an attempt to elucidate the myriad physical, administrative, technical, personal, and political concerns involved in developing a body of knowledge that we now recognize as the discipline of building science.

For the principal investigators featured in this dissertation, the laboratory-studio was an instrument to perform elaborate sets of translations to import scientific knowledge and manipulate them into new knowledge in the domain of architectural inquiry. The shifting dynamic between science and art has always been correlated to the evolution and creation of audiences. The three laboratories featured in this essay could hardly be considered one of the earliest examples, and I cannot claim to provide a comprehensive history of building science through their stories. However, the stories provide glimpses into the conscious migration from the studio to the laboratory as a form of resistance against an established model of practice and the body of knowledge it produced.

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FROM PHYSIOCRACY TO A NEW PRODUCTIVE RURAL CHINA

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This paper examines the reception and impacts of Western ideas of the "agrarian" in China. In particular, it traces how the agrarian philosophy of the Physiocrats traveled across space and time and how this line of thinking influenced the Chinese urban-rural transformation at the turn of the twentieth century. The paper examines Adam Smith's interpretation of the Physiocracy, and how the agrarian idea was embedded in the liberal school of political economy. By tracing the significant role of Fukuzawa Yukichi and Liang Qichao in cross-cultural borrowing, the paper reveals the Western "agrarian" roots within the concept of "local self-government." As the paper suggests, it was this line of thought that influenced the state regeneration in early modern China. As a representative case, Zhang Jian's village-ism and his agrarian practice in Nantong are presented as the epitome of the local self-government movement in the early twentieth century, which marked one of the first rural modernization efforts in China. By tracing the intellectual transmission of the idea of the "agrarian," the paper aims to unpack the connotation of the "agrarian modern" as an alternative to the mainstream model of high-dense cities and depopulated countryside. This paper offers a perspective to situate the urban-rural transformation in early modern China in a global context without the conventional West-East divide.

Keywords: Agrarianism, agrarian modern, rural transformation, urban-rural continuum, China.

INTRODUCTION

This paper grew out of an intellectual journey contemplating China in the twentieth century. Against the backdrop of foreign penetration and the fall of the Qing dynasty, it has become a widely received approach to read the whole century as part of a perennial search for modernity. In the spatial domain, this century-long endeavor of modernization is widely described as an urbanization process. However, history also witnessed moments when a few reformers repeatedly returned to their commitments to rural alternatives. Instead of focusing on the centralized schemes of city-making and industrial production, a series of reform projects indicated a shared belief that an agrarian Chinese modernity could be realized from the bottom up.

The agrarian reformers that I am referring to are a set of names loosely distributed across the political spectrum: Zhang Jian, Sun Yat-sen, Yan Yangchu, Tao Xingzhi, Liang Shuming, Zhou Zuoren, and Mao Zedong. Despite their hugely different political ideologies, they all shared an increasing, if not consistent, concern about the rural masses. They all noticed, though to varying degrees, the potential problems of a city-based modernization, and demonstrated a conviction that modern state-making in China had to start from the rural people and communities. For them, the agrarian reform was not simply urbanizing the countryside or making the hinterland modern in the same way as the cities. Instead, they saw distinct modernity from the potentially mobilized villages.

To be sure, we do not want to confuse these agrarian pursuits with any nostalgia for the rural idyllic. "Agrarian" in this paper refers specifically to a path to modernization that does not presuppose the mainstream mode of urbanization. Indeed, one might argue that the agrarian movements are deeply entrenched in China's agricultural society, and thus profoundly influenced by a wide array of cultural traditions. And yet, it is equally critical to notice that the agrarian efforts in question were ultimately committed to new modes of production and governance that embraced values of science, technology, and democracy. Such ideas of the agrarian modern, though very much unknown to most Chinese by the turn of the century, had been widely disseminated in the West. The first school of modern agrarianism dates back to the second half of the eighteenth century, when a group of French economists, commonly known as the Physiocrats, built a theory of the "rural economy." The very modern ideas behind the twentieth century Chinese agrarian movements were, to a great extent, an outcome of cross-cultural borrowing. To truly understand the agrarian efforts in China, a series of names are equally important: François Quesnay, Thomas Jefferson, Henry George, Fukuzawa Yukichi, John Dewey, Peter Kropotkin, Saneatsu Mushanokōji, Karl Marx, Karl Kautsky, and Vladimir Lenin.

Indeed, the space here does not allow us to cover all these chains of thoughts. Strategically, this paper shall focus on one major agrarian reform, and the history of ideas that took shape long before the reform project came into being. In particular, it traces how the agrarian philosophy of the Physiocrats was introduced to China, and how this line of thinking, which was incorporated into the local self-government movement, influenced the Chinese urban-rural transformation at the turn of the twentieth century.

1. FRANÇOIS QUESNAY AND A TRANSFORMING FRENCH COUNTRYSIDE

Any serious look at the school of the Physiocrats has to start from the historical context of eighteenth century France. Before Quesnay, Mercantilism had been the dominant school of economic thought for centuries (Gide and Rist 1915). They saw foreign trade as the primary source of wealth. The government was granted absolute rights to direct and regulate the whole process of trade. By the early eighteenth century, the huge debt and sharp decline of farm produce drove the kingdom into a remorseless financial system. Suffering from falling prices and heavy duties, the poor could barely make ends meet. Many landowners abandoned their property, leaving large tracts of arable lands wasted (Higg 1963).

The worrying condition of the late *ancien régime* began to draw criticism from economic writers at home and abroad. By the 1750s, the growing interest in the English political economy led to a famous debate over the grain trade. However, it was François Quesnay who effectually consolidated all these influences, and set up a school of agrarian philosophy. For Quesnay, curing the sickness of a state would require a thorough understanding of the "physiology of social order," and it was the objective economic law that would determine how wealth was to be distributed across different sections of society (Meek 1962). To make this "natural" economic order legible to others, Quesnay designed a chart, famously known as the *Tableau Économique* (Quesnay 1894). In the three columns of the Tableau, economic activities take the form of circular flows traveling between cultivators, proprietors, and manufacturers. Agriculture stands as the only sector capable of producing an annual surplus, with the other industries being "sterile." As Quesnay explained, the country's opulence would primarily depend on the extent to which the wealth absorbed by the right-hand column of the "sterile industries" could make its way back to the left. One of the highest priorities for the state was to dedicate a larger portion of capital to agriculture. To maximize the benefit of the "natural laws," economic activities should be freed from mercantile obstacles. A free grain trade and a simplified taxation system would be the key to relieving the burdens levied upon the poor peasantry.

By the late 1750s, Quesnay started to hold regular meetings at Versailles for a small group of persons sharing interests in the political economy. The meetings turned out to be an effective tool to popularize his ideas and earned him important disciples, such as Marquis de Mirabeau, who wrote extensively about Quesnay's theories, and Pierre Samuel du Pont de Nemours, who edited Quesnay's writings and became the chief editor for the school's major periodicals (Higgs 1963). These efforts soon paid off. By the early 1760s, the liberal philosophy of the Physiocrats had generated huge impacts among the intellectuals. The two edicts enacted in 1762 and 1764 virtually put an end to any restrictions on the internal grain trade (McNally 1988).

And yet, the Physiocracy was not simply an economic doctrine solely focused on taxes and grain trade. As the school developed, it was increasingly confronted by the central question regarding state-society relations—the tensions between the interests of the liberalized individuals and the state welfare. As David McNally reminded us, the publication of *Philosophie rurale* in 1763 marked a turning point from which the political dimension of the Physiocracy became more visible (McNally 1988). For Quesnay, as for all the Physiocrats, the proper functioning of the economic laws would require a "well-ordered" institutional framework. While they all supported economic liberalism, they also agreed that a preexistent social arrangement would be the key to preventing self-centered individuals from tearing society apart (Quesnay 1915). For the Physiocrats, the best form of this social order was what they termed "legal despotism," a centralized monarchy strictly checked by "the spirit of natural laws" (McNally 1988). Thus the two-fold and even seemingly paradoxical theory of the Physiocrats: on the one hand, they celebrated the individual right to property and the liberal pursuit of self-interest; on the other hand, they prioritized agricultural investment as opposed to commerce and manufacture, left little doubt about the monarchical system, and claimed that only a unified state could provide a pre-condition where the individual pursuits would contribute to the general welfare.

Both aspects of the physiocratic doctrine significantly influenced the French territory. Despite being an absolute monarchy, France in the *ancien régime* had been quite divided in many ways. Across the provinces were various systems of laws, taxation, and administration. For the Physiocrats, their agrarian ideal was to transform this fragmented territory into a unified kingdom grounded on the bedrock of agriculture. Not only did they directly contribute to the laws of free trade during the school's heyday, but the impact of their general theory also lingered long after Quesnay's death. From 1774 to 1776, Anne Robert Jacques Turgot, who had been closely associated with the school, was appointed as Controller-General of Finances, and further carried the physiocratic political economy into practice (Higgs 1963). In 1775, he directed du Pont de Nemours to draft a memorandum examining the fragmented local government and proposing a "national regeneration" scheme for the king (du Pont 1913–23). For Turgot, it was due to the poorly organized administrative system that the individuals of the kingdom had little sense of their responsibility to the state. To develop a public spirit, Turgot proposed a standardized local administration system and a national council responsible for the education of the general masses (du Pont 1913–23). Although Turgot fell from power before he could put this in place, the idea of state-making, particularly in this memorandum, profoundly influenced the national territorial reorganization in the French Revolution (Higgs 1963; Drinkwater 2020). From 1789 to 1791, the National Assembly eliminated the traditional provincial boundaries and redivided the nation into 83 *départements* (figure 1). Unlike the old system, the *départements* were given similar size and the exact same institutions, with each further divided into districts, cantons, and communes. On the one hand, by dividing the nation into more than 44,000 communes, this system reconstructed a decentralized and interconnected rural-urban territory that celebrated a liberal economy and local autonomy (Woloch 1991). On the other hand, it effectually unified and standardized the preexistent regional varieties and offered a powerful channel through which the localities were subordinated to the state as a whole.

2. PHYSIOCRACY INTERPRETED AND DISSEMINATED VIA ADAM SMITH

The far-reaching influence of the Physiocracy is reflected in Adam Smith's celebrated *The Wealth of Nations*. According to his biographers, not only did Smith visit Paris and attend the Physiocrats' regular meetings during the heyday of the school, but he even intended to dedicate the book to Quesnay, had the

Figure 1: The French départements in 1790. Source: Wikimedia Commons.

latter not died shortly before its publication (McNally 1988). In his Book IV, Smith compared the two existing systems of political economy—the mercantile system and the system of the Physiocrats (Smith 1904). While, for Smith, the superior occupation of agriculture does not necessarily render the other industries completely barren, he pays a generous tribute to the Physiocrats' liberal thinking. As Smith puts it, the physiocratic system, "with all its imperfections, is perhaps the nearest approximation to the truth that has yet been published upon the subject of political economy" (Smith 1904, 2: 176).

Indeed, compared to the physiocratic vision of an agrarian economy grounded on an absolute monarchy, Smith holds a far more laissez-faire position. However, the very lineage between the two reveals Smith's political economy beyond a mere model of self-seeking individuals—the model for which he is widely known. Smith never downplays the central place of agriculture for economic improvement (McNally 1988). Nor does he neglect the possible erosion of the social relations in a society of free markets. For Smith, while the sovereign is to be restrained from intervening in any private economic activities, the state must take on the duties to protect society from external violence and internal injustice (Smith 1904). As argued by Smith, only within this state-maintained, well-ordered institutional framework could the individual pursuits of self-interests safely contribute to society's general interest. Such "economic liberalism" benefiting both individuals and the state is not unlike the paradoxical two folds within the Physiocracy.

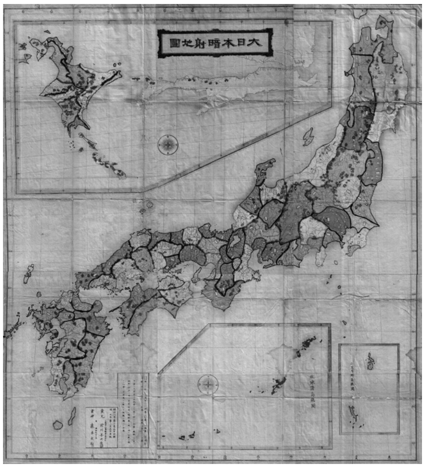
Through Smith's writings, the theory of the Physiocrats was made available to a broader audience. It was through *The Wealth of Nations* that the Physiocracy was introduced to Yan Fu (1854–1921), who later translated the book for the Chinese audience (Pi 2000; Borokh 2012; Smith and Yan 1929). Moreover, it was also based on Smith and the Western school of political economy that Meiji Japan was able to develop its own theory of state formation, which in many ways envisaged a modern agrarian state built upon interconnected localities.

3. ENLIGHTENED LOCAL AUTONOMY BY WAY OF MEIJI JAPAN

Learning from Japan is an essential feature of China's path to modernity. The renowned Meiji Enlightenment (1868–1912) provided an ideal Eastern model of gaining wealth and power through the benefits of the West. Fukuzawa Yukichi (1835–1901) was one of the first who systematically introduced the liberal school of political economy to Japan. Not only did he open the first economic course ever held in any Japanese institution, but he also published an extensive list of books for the general audience (Sugiyama 1994). While the doctrine of liberalism and individualism is evident throughout his writings, the interpretation of Fukuzawa bears a strong nationalist bent. For Fukuzawa, Western theories need to be understood within the specific context of his time, and the ultimate goal of such learning is to gain strength and confront Western countries. On the one hand, he repeatedly argues for economic activities free from government interventions, emphasizing equality between individuals and nations. On the other hand, he stresses every citizen's duty to the state, and contends that the Smithian free-trade doctrine does not apply everywhere. For Fukuzawa, international free trade with equal benefits to both sides could only be an unrealistic ideal unless the hearts and minds of the Japanese people were adequately enlightened (Sugiyama 1994). The acute priority, therefore, lay in popular education and institutional reforms.

It was with this mindset that Fukuzawa extended his economic theory to the broader realm of state-making. Before the Meiji era, Japan was based on the *han* (domain) system, with the whole empire divided into estates controlled by feudal lords (Kamiko 2010a). The early Meiji government replaced the feudal domains with a new system of prefectures and districts (*ku*) (figure 2). While this new system of administration hugely facilitated state-building programs such as tax collection and military conscription, it also led to an excessive centralization of the state power. In 1876, Fukuzawa wrote *Bunkenron* (On Decentralization of Power). Citing Alexis de Tocqueville, the essay drew a distinction between "administrative power" and "political power," arguing for the distribution of the former through elected local assemblies (Kim 2005). For Fukuzawa, not only would this local administration ward off the power abuse of the central government, but it would also help train the populace for public participation. According to Fukuzawa, the assemblies would be responsible for a series of welfare initiatives, ranging from constructing roads and dikes to managing public health and local police (Kim 2005). Such an idea of local autonomy carried a double meaning right from the start: on the one hand, the assembly offered a basic unit of civil society where socioeconomic activities could develop relatively free from state intervention; on the other hand, allowing the local people to manage their own affairs would reinforce the bonds between individuals and the state, thus helping to find the "point of convergence" between the seemingly conflicting public and private interests (Kim 2005, 77).

Fukuzawa's writings on local autonomy significantly impacted the public discourse on the local administrative system. The two decades following the prefectural divisions witnessed a series of national regeneration programs, completely reshaping the state's structure. In 1878, *The County, City, Town, and*



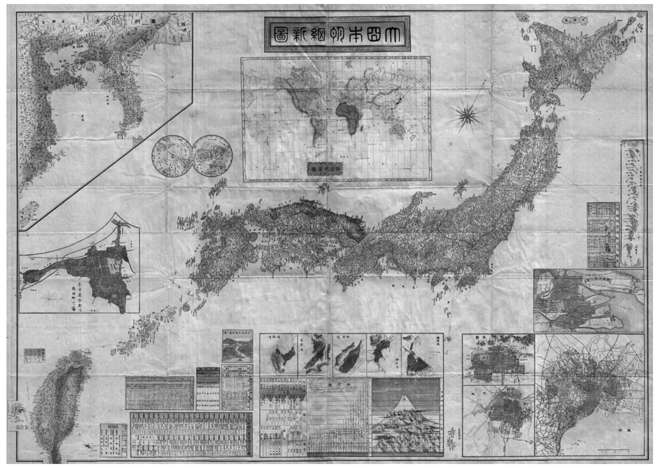


Figure 2 (left): Map of early Meiji Japan in 1875. Source: Wikimedia Commons.
Figure 3 (right): Map of Meiji Japan in 1895. Source: Wikimedia Commons.

Village Organization Law became official, abolishing the early-Meiji districts (*ku*) formalized about a decade ago (Kamiko 2010a). The law introduced counties and cities (*gun* and *ku*) as the units between prefectures (*fu* and *ken*) and towns and villages (*chou* and *son*), transforming the national territory into a three-tiered system. While local assemblies were not institutionalized this time, the 1878 law marked the beginning of the formal quest for modern local autonomy. In 1881, the central government announced its commitment to the promulgation of the constitution. Establishing a long-term local self-government system soon became one of the state's top priorities. Such an endeavor almost took a decade, culminating with the *City Law and the Town and Village Law* in 1888 (Kamiko 2010b). Cities, towns, and villages were finally designated as basic local administrative units, each with an elected assembly requested by law (Figure 3). For the lawmakers of the Meiji Constitution, the establishment of the city, town, and village system forms a stronger foundation of the state. It not only allows the local people to administer their own lives, but also helps cultivate their public spirit for the general needs of the state.

After the 1888 law, seeing the emerging struggles within the fledgling National Diet and the increasing international tensions between Japan and China, Fukuzawa published a few essays re-evaluating the local communities of traditional villages and towns in the pre-Meiji era (Kim 2005). As contended by Fukuzawa, the people of the Edo era, though unable to practice political power, had proved their potential to thrive via self-administration despite the turbulent conditions of civil warfare (Kim 2005). For Fukuzawa, it was the local communities and the individuals diligently working on their private pursuits that formed the bedrock of modern Japan. With the growing uncertainty of the internal and external circumstances, local self-government seemed to be the only way to keep most people out of the political turmoil. And it goes without saying that agriculture would play an indispensable role in this community-based local autonomy. In fact, as Carol Gluck reminded us, the agrarian texture within the spirit of local autonomy continued to grow toward the final years of the Meiji era (Gluck 1985). Faced with the financial crisis following the Russo-Japanese War, the local self-government system was increasingly called upon to fulfill its functions, such as social education, moral exhortation, the management of finance and infrastructures, and of course, the support of agricultural production. Officials of the central government started to make frequent references to Western agrarian projects, such as French *départements* and communes, and the Garden Cities of England (Gluck 1985). For the statesmen and many intellectuals of the late-Meiji period, local autonomy not only functioned as a key fiscal solution to the national difficulty, but also stood for an idealized agrarian model in the civil society.

As history tells us, this set of modern agrarian ideas was introduced to China by the turn of the twentieth century, and eventually developed into a major discourse on state regeneration. Many intellectuals contributed to this learning process. Huang Zunxian (1848–1905), who lived in Japan as a counselor of the Chinese embassy from 1877 to 1882, first introduced the term self-government (*zizhi*) to China (Kuhn 1975). Kang Youwei (1858–1927), a leading reformer advocating constitutional monarchy, was also a key figure popularizing such an idea. However, it was Liang Qichao (1873–1929) who was able to make a radical departure from Confucian morality, and brought the discourse on local self-government to the next level.

Liang's encounter with Western ideas started in the early 1890s. While initially very much a disciple of Kang Youwei, Liang quickly broadened his mind. By the time he started to publish essays making impacts across the country, Liang had developed professional relationships with Yan Fu and Huang Zunxian, both famous for their first-hand Western learning (Chang 1971). Liang's unique vision and experience made him one of the few who could break away from traditional Chinese thinking, and synthesize Western liberalism and Meiji Japan's success in a relatively coherent way. Drawing from Yan Fu, Liang attributed the power expansion of the West to the sheer energy unleashed from individual pursuits (Chang 1971). For him, the traditional Chinese society had long lacked the very energy needed for a national transformation. In contrast, as Liang argued, Meiji Japan witnessed groups of "dynamic activists" who unselfishly fought for the fate of the state. Liang called these people *zhishi* (gentlemen with great goals) (Wills 2012). For Liang, the Japanese success lay in its Westernized political system, which offered a dynamic framework where public and private interests could be achieved at the same time.

In an 1897 essay entitled *Shuo qun* (On Grouping), Liang delivered the term *qun* (grouping), which was to become a central concept in Liang's social-political thinking (Chang 1971). For Liang, the notion of *qun* is closely associated with local self-government. Central to it lies the issue of how to integrate the Chinese people into a cohesive community. This community, as Liang stressed, should never be confused with the kinship institute in Chinese tradition. It instead indicated a new social order grounded on democracy and "public-mindedness," an ideal where the common people would be granted rights of political participation (Chang 1971). Since most Chinese had not been sufficiently educated, as Liang contended, modern institutions such as journals and study societies would be necessary steps toward any truly self-governed locality. In particular, Liang saw the study society of the gentry-literati as the most crucial organization in the coming reform. It was out of this idea that Liang accepted an invitation from a reformist governor, and became the chief lecturer at the School of Current Affairs (*Shiwu xuetang*) in Hunan in 1897 (Chang 1971). With the support of the local gentry, Liang founded the famous Hunan Study Society (*Nan xuehui*), and designated "local self-government" as part of its motto (Zhang 2012). While his reform program in Hunan did not last long, Liang's radical teachings of popular rights and local self-government were disseminated throughout the country via an array of journals and newspapers.

After the Hundred Days' Reform of 1898, Liang fled to Japan, and spent most of his time in the Tokyo-Yokohama area until his return in 1912. The 14-year exile offered Liang profound first-hand experience of the Meiji reform. He quickly picked up the Japanese language, and soon was able to access various ideas of

Japanese thinkers and their interpretations of the Western world (Chang 1971). He founded a series of Chinese-language journals which circulated both in China and overseas. First, through the *Qing yi bao* (Journal of Disinterested Criticism) and later the *Xinmin congbao* (New Citizen Journal), Liang commented on current events and taught the general audience about new ideas from the West (Chang 1971). It was in this period that Liang was able to refine his thoughts in 1896–97, and became even more influential than in his earlier years in China. In his famous series *Xinmin shuo* (On the New Citizen) of 1902, Liang reinforced his earlier idea of *qun*, explicitly attached it to the concept of the nation-state, and developed a new ideal of citizenship (Chang 1971). For Liang, the essential morality of a modern citizen was public virtue. The only way to ward off Western imperialism, as Liang put it, was to develop a national community where every individual could participate in the state's public life. Central to this collective freedom was the idea of self-government with three folds: "individual self-mastery, local self-government, and national self-rule" (Chang 1971). As Liang argued, individual liberty and local autonomy not only did not impede "collective freedom," but they also formed the basis for a cohesive national community.

4. WAVES OF LOCAL SELF-GOVERNMENT AND ZHANG JIAN'S VILLAGE-ISM

The combined efforts of Yan Fu, Liang Qichao, and the like profoundly impacted the public discourse at the turn of the century. The last decade of the 19th century witnessed not only a growing trend of study abroad but also a few significant shifts within the group of international students. With the focus of Western learning switching from science and technologies to politics, Japan, blessed with cultural and geographical proximity, replaced the Western countries as the top destination for Chinese students. Within a couple of years, the number of students in Japan grew from several hundred to more than ten thousand, making Tokyo-Yokohama the center of the fledgling Chinese intelligentsia (Chang 1971). These changes, particularly coinciding with Liang's exile in Japan, reinforced the reformist influence that had already taken place. Japanese constitutionalism, especially the idea of local self-government (*difang zizhi*), became a central theme populated among the intellectuals at the turn of the century.

The Qing government, after the humiliating crisis in 1900, finally recognized the urgency of institutional reform. In 1901, the court issued an edict calling for complete reform over a wide range of issues (Wills 2012). It started to take proposals from high-ranking officials, many of whom held the same basic principles as liberal thinkers like Yan Fu and Liang Qichao. Between 1906 and 1907, the Qing court sent a group of commissioners traveling to Japan and the West to study various forms of constitutional government (Wills 2012). The Japanese constitutional monarchy and local self-government system became the primary model that the Qing rulers were to draw from in the final years of the dynasty. In 1908, the court officially announced a gradual installation of local assemblies (Kuhn 1975; Kuhn 1986). In the following year, the self-government regulations for cities (*cheng*), market towns (*zhen*), and rural townships (*xiang*) were promulgated, marking the official government's first commitment to local self-government (Kuhn 1986).

To be sure, as Philip Kuhn reminded us, these self-government programs formalized by the Qing court were in many ways "highly restrictive," and were hugely different from the liberal ideals envisaged by Liang Qichao and the like (Kuhn 1975; Kuhn 1986). For the Qing rulers, the local self-government system was completely supplementary with no substantially different functions than the rural gentry in the traditional society. The responsibilities of the local elites, who were to play a major role in the local autonomy, would be primarily limited to areas the county government was unable to cover, and would be strictly supervised by the regular bureaucracy. In contrast to the liberal reformers' enthusiasm for real public participation, the Qing court's programs were far from a genuine scheme of vibrant local communities. However, despite all its limitations, this constitutional experiment, with full support from the central government, significantly boosted the motivation of the local elites. According to Kuhn, before the fall of the Qing, local self-government entities such as deliberative assemblies (*yishihui*) and executive councils (*dongshihui*) had been put in place in many regions (Kuhn 1975).

It was against this background that Nantong, an erstwhile rural backwater in the Yangtze River Delta, became one of the most prominent self-governed localities in China. As we shall soon find out, not only was Nantong's transition influenced by the countrywide movement of the late Qing, but it also received direct impacts from Meiji Japan. Behind those Japanese experiences of local autonomy was a state-making ideal firmly grounded on interconnected agriculture and industries and a local populace well-equipped with public spirits. This line of thinking is fundamentally "agrarian." The story of Nantong vividly exemplifies how the Western ideal of the agrarian modern influenced China's rural-urban territory.

The modern transformation of Nantong cannot be separated from Zhang Jian (1853–1926), who famously received the highest degree in the imperial civil service examination, returned to his hometown, and ended up as the leading figure of Nantong's local elites (Shao 2003). The early development of Zhang's agrarian thinking dates back to the mid-1890s. In the wake of the humiliating defeat by Japan, Zhang determined to strengthen his country through "industry." To him, the concept of this industry was rather broad. Almost from the very beginning, Zhang was well aware of the central place of agriculture in Nantong's modernization (Wang 2005). From 1895, Zhang Jian and his associates built a series of factories, the Dasheng Cotton Mill being the most prominent (Shao 2003) (figure 4). In 1901, to meet the increasing demand for cotton, he established the Tonghai Land Reclamation Company, which turned out to be one of the first agricultural joint-stock companies in China (Wang 2005). The company's goal was to transform about 18,000 acres of salt land along the seacoast into cotton fields. The reclaimed land not only served as a reliable cotton-producing base for Zhang's factories, but also offered favorable conditions for pasture and grain cultivation for quite a long time (Wang 2005).In his 1901 Tonghai Land Reclamation Company IPO Prospectus (*Tonghai kenmu gongsi jigu zhangcheng qi*), Zhang explicitly referred to the Japanese Agricultural Society, and proposed building an agricultural school on the site of the land reclamation. While the school did not materialize for various reasons, the proposal revealed Zhang's early commitment to the agrarian modern, and the Japanese impacts way before local self-government became a nationwide movement.

In 1903, invited by the Japanese consul in Shanghai, Zhang Jian took a seventy-day trip to Japan, which tremendously shaped his vision of modernity (Shao 2003). He visited the Fifth Industrial and Agricultural Exposition in Osaka, and spent most of his time investigating factories, farms, schools, and libraries, among others. Shortly after his return, Zhang published the Diary of Travels East, in which he recorded what he had learned in remarkable detail (Shao 2003). For Zhang Jian, the trip to Japan offered him a glimpse of how a system of local self-government would work in a constitutional monarchy. As the call for an institutional change gradually took up the major discourse, Zhang joined the constitutional reformers, and became a full supporter of local self-government. From 1904, Zhang used his close relationships with high-ranking officials to push forward the Qing court's reform agenda (Shao 2003; Wang 2005). After the central government publicly endorsed the model of local assemblies, Zhang worked with the reformist elites, and formally requested permission from the

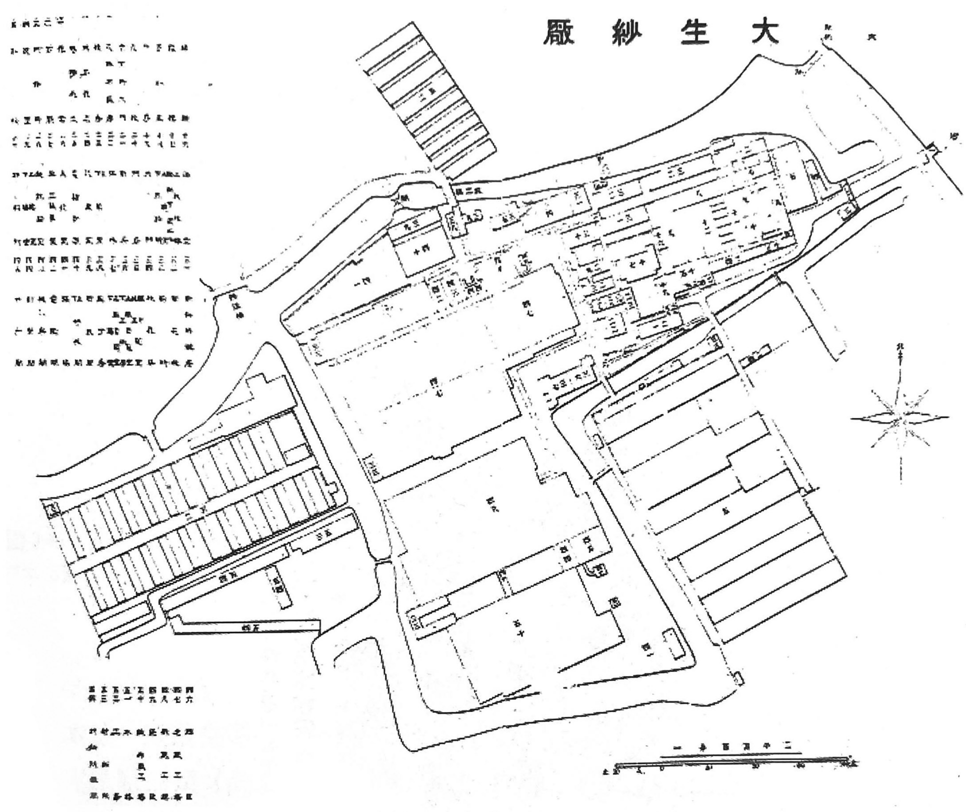


Figure 4: Plan of the Dasheng Cotton Mill. Source: Fan Kai, *Minguo Nantong xian tuzhi*, 1991.

Nantong administration to put local self-government into practice. In 1908, the Nantong local assembly and executive council were elected, with Zhang as head of the former (Shao 2003). Through the self-government bodies, the new elites—essentially consisting of merchants, industrialists, professionals, and scholars—were granted administrative authority over an array of local affairs. They took over the existing institutions, such as the educational association and the local chamber of commerce, and soon built a group of quasi-government agencies ranging from the Survey Bureau to the Agricultural Society. Such an institutional change significantly expanded the power of the new elites, enabling local people to manage virtually everything concerning the public interest.

As the local self-government reform began to take shape, the modern transformation of Nantong went into a new phase. Increasingly, local self-government became the single rubric under which new projects were organized. For Zhang Jian, local self-government was the centerpiece of the constitutional reform. It provided an effective system channeling energies at the lower level for the general welfare of the state. It also allowed a certain degree of local autonomy. In the scenario where the Qing should fall, the self-governed localities could even serve as what he would call "pure self-government" entities to keep the people away from the political turmoil (Shao 2003). For Zhang Jian, the crux of this model was finding the convergence point between national and local interests. Zhang often used "village-ism" (*cunluo zhuyi*) to describe his idea of local self-government. For him, not unlike the case of Meiji Japan, the village in China formed the basis of the

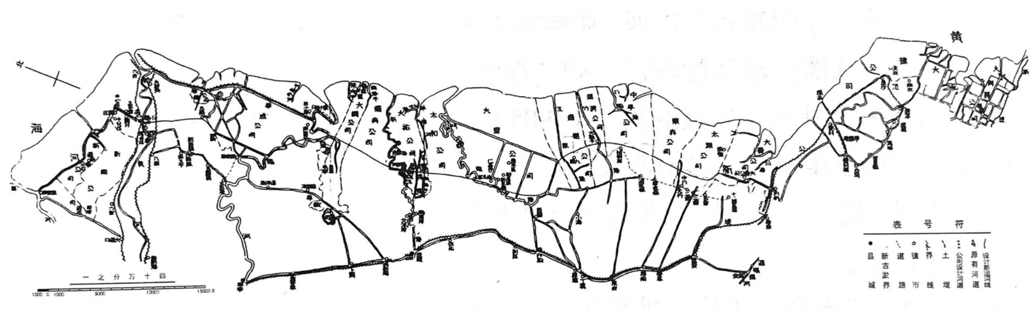


Figure 5: Masterplan of land reclamation companies in the region. Source: Wu Liangyong, Zhang Jian yu Nantong, 2006.

entire empire (Shao 2003). Drawing from the Japanese model of local autonomy, Zhang saw implementing a variety of initiatives from village to county as the key to sustaining Nantong's flexibility amid the growing domestic instability. To this end, for Zhang Jian, "village-ism" had a broader connotation beyond the traditional concept of village per se. It meant transforming the whole region of Nantong—an effort of modernization across the rural-urban continuum.

The two decades following Zhang Jian's trip to Japan witnessed an array of projects with such an ideal of "village-ism." Centered around the industrial system of the Dasheng mill, the new local elites founded dozens of factories and more than 20 land reclamation companies in the Nantong region (Wang 2005) (figure 5). These projects not only restructured the local economy, but also transformed the urban-rural territory. Salt marshes were converted into cotton fields. With a growing number of immigrants, new types of buildings, such as factory dormitories, office buildings, and warehouses started to emerge. Numerous towns arose directly out of the agro-industrial initiatives. In the case of Tangzha, an erstwhile tiny village five miles from the county seat was transformed into a prominent industrial center with more than a dozen factories. As more and more peasants chose to specialize in cotton growing, the town also became a grain trade center due to the increasing demand for grain imports (Shao 2003). Prompted by the immense need for fuel, machines, and raw materials, Tiansheng, the closest port to Tangzha, soon developed into a full-fledged town with ample facilities. Under Zhang Jian's leadership, a canal was created to ease the traffic between the port and the factory; new means of transportation, such as steamships that were introduced to connect Nantong to the outside world (Shao 2003). In 1912, the local elite leadership founded the Roadway Bureau and proposed a new highway system, further breaking down the geographical barriers between different parts of the region. All these efforts were charged by the regional self-government idea of village-ism. From the very beginning, the modernization of Nantong was on the track of an agrarian alternative, aiming for a self-governed community distinctive from the city-centered paradigm.

The fall of the Qing dynasty did not stop Nantong's modern exploration. On the contrary, the empire's collapse generated a power vacuum much more favorable for the new local elites. To be sure, the local self-government efforts had to adapt to the fledgling Republic, especially after 1914, when the central government officially cut off the support to all the self-governed initiatives (Kuhn 1975). It was against this background that Zhang Jian decided to enhance Nantong's self-government movement, and started to consciously build a "model city" potentially to be applied in other parts of the nation. Such an idea entailed a shift of focus from agriculture and manufacturing to cultural facilities and social welfare. To attract and accommodate the increasing number of visitors, Zhang

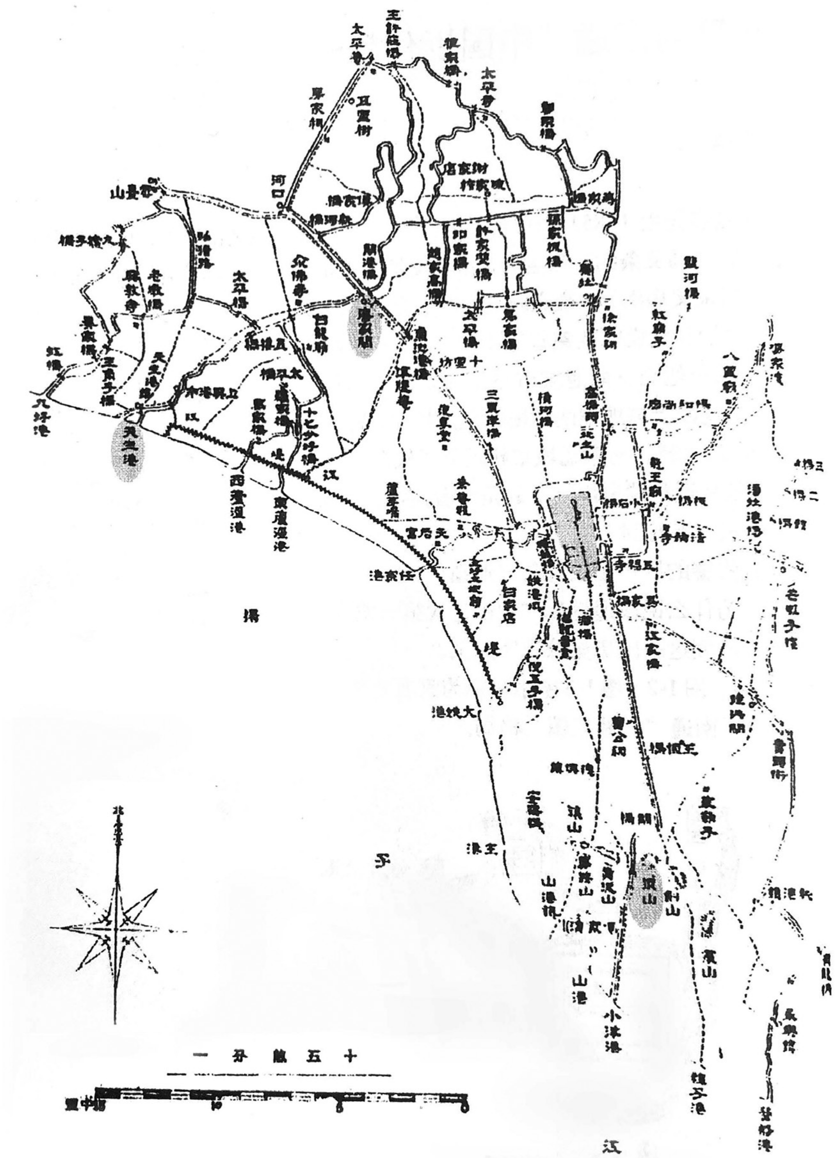


Figure 6: The "one city and three towns" in Nantong region. Source: Wu Liangyong, *Zhang Jian yu Nantong*, 2006.

Jian and other elites developed a new downtown outside the south gate of the old city, and created a recreational center consisting of five public parks. An equally ambitious plan was put forward in the mid-1910s to transform the Langshan area, a traditional religious and scenic spot several miles from the county seat, into a "model district" of cultural landscapes (Shao 2003). These efforts soon paid off. By 1918, Nantong as a "model county" received high recognition from both the domestic and foreign press. Tangzha, Tiansheng, and Langshan, together with the expanded downtown and numerous factories and townships in between, formed the famous regional structure of "one city and three towns" (Wu 2006) (figure 6).

Behind all these achievements was Zhang Jian's intellectual debt to the Japanese local self-government, which was deeply informed by the agrarian modern first developed during the Enlightenment. Recalling this origin is essential as it allows us to truly make sense of Nantong's transformation: the fact that Nantong was one of the first efforts to modernize the rural-urban continuum all at once is precisely the manifestation of its agrarian root. Wu Liangyong, a renowned Chinese urban planner, once compared Zhang Jian's Nantong model with Ebenezer Howard's Garden City (Wu 2006). As Wu argued, both projects appeared at the turn of the century, and both aspired to "promote urban development and improve citizens' lives." And yet, Wu went on, while Garden City was a response to the deteriorating living environment of modern cities, Zhang Jian initiated the Nantong model in a historical context where modernization had barely begun. Instead of following the mainstream mode of city-centered development, the self-government of Nantong embarked upon an alternative path to modernity. The urban development Zhang Jian aspired to achieve might be better understood as a rural-urban development, or—to completely lose the binary thinking—an experiment of the agrarian modern. This concept of the agrarian is closely attached to the global intellectual framework of modern agrarianism. By tracing the Western agrarian roots of Zhang Jian's ideal, not only can we compare the case of Nantong with Western reforms, but we can also examine their true intellectual connections.

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ON THE ‘INTEGRAL CANONS’ OF FRANK LLOYD WRIGHT IN ORNAMENTATION AMID THE MODERNIST EXPEDIENT

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Ornamentation, a jargon that has been relentlessly criticized and embraced during the Modernist movement of the twentieth century has, in substance, maintained its polemical occupation throughout architectural history. Being reckoned as a crime of wasting labor on practical objects by Adolf Loos (1870-1933), ornaments were, nevertheless, adopted by a rank of Beaux-Arts trainees, and notably by Louis Sullivan (1856-1924), among others. Despite endless debates on this topic, little attention has been given to the ‘integral ornament’ initiated by Frank Lloyd Wright (1867-1959) in his *Autobiography* of 1943. Free architecture, he insisted, must be characterized by integral fibers that are developed from within, as against the prevalent yet abusive formula of oversimplification. Different from the ornamental orders of classicism, he subtly analogized ornaments to the organic pattern of rational structure, which refers to the ornament integral to buildings as a poetic garment. In his yearning for a ‘third dimension’ of architecture, Wright not only synthesized Viollet-le-Duc’s faithful expression of the structure and Gottfried Semper’s three factors of formal beauty but also expanded his ‘integral canons’ into a sequence of ‘integral form’, ‘integral order’, ‘integral light’, ‘integral fireplace’ and ‘integral building’. Within this process of natural integration, Wright saw human life as an ornament integral to nature and architecture as an ornament integral to human life. However, this proposition was never always in place for Wright ever since his apprenticeship with Sullivan. It shifted throughout his career from the surface to the requisite refinement of the natural pattern of structure. Doubtless, his spiritual mentor Beethoven (1770-1827) and his codas contributed their indispensable parts. Although James Dennis and Lu Wenneker suggested in 1965 that three major epochs ought to be considered in interpreting Wright’s alteration to ornamentation from the attached to the integral, more thorough consideration is still needed in redistributing and reconstructing the epochs in collaboration with the case analysis of his organic designs across time. The scope of this research is aimed to reconsider the ‘integral ornament’ through retrospection of the ornamental history pivoting between ornament attached and ornament integral from Vitruvius to Wright, followed by a layout mapping the culture that preceded the ‘integral ornament’ and how Wright attained his maturation in ornamental integration after years of practice, to help redefine an ornamental culture within the context of an organic order appropriate for the present day.

Keywords: Integral ornament, third dimension, organic order, plasticity, continuity.

INTRODUCTION

The last decade of the nineteenth century saw academic unrest upon the cliché of ornament talk, within which a collection of big names was entangled. Being perceived as “a waste of labor and an abuse of material”[1] by Adolf Loos in his 1908 drafting of *Ornament and Crime*, the terminology of ornamentation, being cumbersome and obsolete, seemed to have been cast in doubt in all perspectives of the modern world, and ultimately saw its disappearance in the 1930s. Lingering amongst the prevailing victory of Walter Gropius, Marcel Breuer, Mies van der Rohe, and Le Corbusier in the impulse of Functionalism and Modernism, a “standard” architect would without hesitation dismiss the elusive concept of ornamentation except to satirize its vulgarity and coarseness, and thus drift along the mainstream of his contemporaries. Inevitably, the unexpected movement only imposed a catastrophic and nonreversible affliction on the operation of Ecole des Beaux-Arts. Albeit nobody at that very moment was exploring the strata beneath the crust compressed by their obsessive zeal, the seed of ornamentation had never been fundamentally unrooted.

Simultaneously across the Atlantic, Frank Lloyd Wright, as a trainee from Sullivan & Adler, stayed out of the crisis enjoying his obsession with the Prairie Houses in the 1890s. Years of training had nonetheless hinged his aversion against the over-ornamentation of the Beaux-Arts style, though it never propelled him towards the school of the Bauhaus. As an alternative, he embraced the proposition that "all architecture without ornament is modern" as "one abusive formula" (Wright 1974, 247). Instead, "free architecture," he insisted, "must develop from within—an integral" (Wright 1974, 242), from which a reconciled idea of 'integral ornament' was incubated and initially remarked in his *Autobiography* (Wright 1943, 346-47). Significantly impacted by Viollet-le-Duc and Gottfried Semper, Wright synthesized this concept with his organic interpretation of the 'third dimension,'[2] continuity and plasticity in an 'organic unit.' With the puzzle box being opened, he further expanded his 'integral canons' to the stories of form, order, light, fireplace, and building quite implicitly. To him, these 'integral canons' translated as an integral chain, where light integrates with order, order integrates with form, form integrates with building, building integrates with landscape, landscape integrates with cityscape.

Unfortunately, just before anyone could properly assess its rationality, the notion of 'integral ornament' was soon buried in the relentless and inconclusive marathon of debate stretching until the 60s after the pass-away of Wright. Unlike nowadays, those years have been so polemical and frantic that it was perhaps not a felicitous moment for a roundtable talk to put out the fire. Nonetheless, after decades of serenity, we seem to have arrived at a juncture to reforge the disjointed chain, especially amid the Neo-Postmodern culture in which we live.

1. ORNAMENTATION AS HISTORY

Born of the Greek term *Kosmos*, which was primarily embedded with a threefold meaning of "to order," "to adorn," and "to embellish," the word *ornament* took its shape from *ornamentum* in Latin and was gifted with its preliminary meaning as "apparatus, accoutrement, equipment, trappings," with the secondary "to embellish" (Coomaraswamy 1939, 380). In his book *The Nature of Ornament*, Kent Bloomer maintained that the word *Kosmos* can be apprehended in contrast to the word *Chaos*, which means out of "the profound order of the world and the totality of its natural phenomena" (Bloomer 2000, 16). The word *ornament* has conventionally proved to be generated from the intimate expectation for order and "the sense of completion" rather than "aesthetic reasons alone" (Coomaraswamy 1939, 381). The same case goes with the Sanskrit word *alamkāra* and the Chinese semantics of *Shih*, where ornament has been emblemized as a necessity to make the whole like the limbs of the body. Despite being created so, the rigid inheritance throughout history has gradually ceded its originality to the solely attached embellishment, with the phrasal explanation inclining towards something as concealing, covering, and pretending. Mirrored in the realm of architecture, Vitruvius in his *De Architectura,* initially proposed the notions that "mutules represent the projection of the principal rafters" and "dentils ... are an imitation of the projections of the common rafters" while they served the primitive structural functions no more (Vitruvius 1960, 108). After that the Western concept of ornamentation prevailed for its freedom of application as "an accessory to work" (Bloomer 2000, 29).

On the flip side, while "the urge to embellish and the love of ornamental effect" is among the habitual unconsciousness of our nature (Jensen and Conway 1982, 3), its functional essence has nonetheless come to its cessation even until the Renaissance. In contrast to Vitruvius, Alberti claimed in *De Re Aedificatoria* that ornamentation could benefit a building by protecting it from an enemy's attack via aesthetic attractions,[3] and serve as the manifesto of the owner's standing, wealth, and reputation (Alberti 1988, 156-57). He even recommended that the ornament ought to be "free of all that is unseemly" (Alberti 1988, 163) and "has the character of something attached or additional"[4] instead of inheriting (Alberti 1988, 156), within which the primitive concepts of order and completion were readily preserved. Nevertheless, it is obscured by his following claim that the column should, in its own substance, be "the principal ornament" to a building (Alberti 1988, 183), towards which Kent Bloomer explained that the column Alberti mentioned was "an added bearer of the virtue that originated in ancient architecture" as "an often-unnecessary means of structural support" (Bloomer 2000, 20). In other words, the column hereby could substantially be substituted by order, not in modern accents, but in classical orders, including *Doric, Ionic,* and *Corinthian*. Ornamentation, for Alberti, might be both practical and symbolic since it "fulfills an object in the direction of its proper operation or noticing of detail" (Benzel 1998, 250).

Not until the eighteenth and nineteenth century, the demand for thriving productivity and booming commodification has eventually encouraged architects and artists to engage more in the exploration of the authentic meaning of ornamentation. To the extent of Alberti's notion regarding 'character,' Nicolas Le Camus echoed that ornament "should make us think it had been made for the place" (Le Camus 1992, 89). Like what is currently acknowledged that every building has its character, every ornamentation, he suggested, possesses its character as well, and it must speak for the building where they cannot survive without each other. It was a high time when the variety of materials and material-related techniques became much handier to architects, which prompted the emergence of the abusive utility of material in ornamentation to make it 'new' and 'exciting.' For instance, wood, in some extreme cases, has been intentionally employed in constituting the Corinthian capital in substitution of marble due to its processibility. Against which Gottfried Semper argued that the material of the ornamentation was supposed to imitate its function as it is and be consistent with its form (Semper 1989, 216). In *the Grammar of Ornament*, Owen Jones offered propositions that read "Construction should be decorated. Decoration should never be purposely constructed" and "That which is beautiful is true; that which is true must be beautiful" (Jones 1986, 5). In considering colors as ornamentation, he further iterated that the color was applied "to distinguish objects or parts of objects one from another" (Jones 1986, 6), which accounts for another layer of ornamental ipseity as an identifier.[5] Ruskin, in *the Seven Lamps of Architecture,* further expounded that the ornament might be a 'thermometer' of the enjoyment of its carver, vividly assigning its ornamental personality (Ruskin 2000, 218). Established as more of a structural designer, Viollet-le-Duc bluntly argued that "the structure of the architectural features constitutes the ornamentation" (Viollet-le-Duc 1987, 182). Even if being capsulated in the contemporary ambiguity, probably no one could defy that ornamentation has screwed itself onto one of the most tremendous identifying signifiers. Every building, in accord with the democratic culture, must be politely granted its individuality in order for this building to be properly identified regardless of wherever it situates as Louis Sullivan insisted that a building "cannot be stripped of its system of ornament without destroying its individuality." The ornamentation should "be determined at the very beginnings of the design" (Sullivan 1979, 188). Substantially, ornamentation, regarded as "the only constituents of the art of architecture" by Sullivan (Menocal 1981, 44), fulfills its slot as identifying signifier in three distinctive approaches: self-identification, identification amongst the adjacent urban fabrications, and symbolic identification of its culture and history. If analogizing a building to human life, these three approaches strive to answer the essential questions of who we are, where we are now, and where we came from. Imagine what a nightmare it is when someone is trapped in a local community where all the buildings appear the same in orientation with the imitative form. Without the signifier of ornament, he could be lost forever.

Entangled in Modern skepticism, another voice arose when Adolf Loos harshly criticized the ornamentation cast a gigantic and wasteful burden on the national economy of mass production, human labor, money, and material. To be aware of, by interposing the analogical instances of the Papuan covering their skin with tattoos, Loos specifically proposed that modern people had no demand for ornament, and “all objects we call modern are without ornament” (Loos 1998, 185). His logic of modern might be censored via his notion that “to waste art on” practical objects would pessimistically lead to “a lack of culture” (Loos 1998, 186). “Ornamentation means added labor,” he insisted, thus unmodern (Loos 1998, 186). In conclusion, he asserted that there would be no other doom for ornamentation unless it disappears “of its own accord” as “a necessary consequence of human development” (Loos 1998, 186-87). Almost simultaneously, the Bauhaus Modernists adopted this utterance and exalted it without much hesitation. Much milder than Loos, Le Corbusier enunciated that “modern decorative art is not decorated” (Le Corbusier 1987, xxiii), and he termed it as a layer of ‘limb-objects.’ His ‘decorative art,’ nevertheless, entailed not the ornamentation as in Alberti’s sense but the surrounding mechanical system around us in the modern world, which he appreciated to be ‘artificial limbs’ as an extension of our physical body. Such remarkable discourses labeled a revolutionary moment when ornamentation was being reduced to the object in architecture, and the subtle borderline between architects and artisans, high arts and minor arts, creation and commodity blurred into each other and obscured (Payne 2012, 12). Substituting ornamentation, objects have consistently been “collected and consumed . . . detached and detachable, discrete and unrooted, transient, short-lived . . . close to the body and discardable”, therefore, becoming “an antithesis of architecture” (Payne 2012, 11). Albeit the Bauhaus Modernists have preoccupied with the dominance of architecture in the early twentieth century, debates about whether their works, in essence, accounted for engineering construction or architecture have never seemed to rest in peace. Jacques Tati, the eminent filmmaker active in Postwar France, mirrored such embarrassment of modernity in several of his sarcastic movies, as in *Mon Oncle* filmed in 1958. Substantially, the Modernist architects by then were not unaware of these controversies while they would, oftentimes, hastily resolve them with a collection of patches on their theorizations. On the one hand, for the work to be recognized as an ultimate art, ‘something special’ is required to be offered unconsciously; on the other hand, Modern theory ordered designers to consciously omit as much as they could for ‘pure simplicity.’ Being ambiguous towards the modern interpretation of ornamentation, one might want to radically refer to their works, i.e., the colorful translucent dinner plates designed by Raymond Loewy in order to allocate their identity, as proposed by Owen Jones; and the vertical I-beams attached to the exterior of the Seagram Building designed by Mies van der Rohe without specific function. In their book, Jensen and Conway denoted this ambiguity by stating that the zeal of these Modernists to subvert the system of ornamentation pertained to their ambitions to convert their buildings in serving the “legitimate social expectations and [becoming] a symbol for them” (Jensen and Conway 1982, 7-8).

2. ORNAMENTATION AS ‘THIRD DIMENSION’

Amid the polemics in 1943, when Frank Lloyd Wright released the revised version of his autobiography, he initiated the concept of ‘integral ornament’—“the nature-pattern of actual construction,” which refers to the “ornament integral to building as itself poetry” (Wright 1943, 346-47). Instead of refuting the substance of ornamentation, he further suggested that “ornament meaning not only surface qualified by human imagination but imagination giving natural pattern to structure” (Wright 1943, 347). Agreed with the organic architect Victor Horta, Wright embraced “a ‘poetic expression of structure’ similar in approach to that of Mackintosh or Gaudi” (Dennis and Wenneker 1965, 2).

Despite his unprecedented discourse, Wright never 'invented' this terminology from imagination. Dating back to the fifteenth century, Alberti indicated that "the roof also has its attractions and charms, in its trusses, vaulting, and outer skin exposed to the sky" (Alberti 1988, 179), while he never explicitly analogized the 'roof structure' to the 'integral ornament.' Not until the nineteenth century, this idea of "integral" took shape from the renovation of Viollet-le-Duc implicitly "curtailing ornament to integrate the contingent and the expressive" (Kelly 1998, 26). In his *Lectures on Architecture*, Viollet-le-Duc initially interrogated whether the ornamentation entailed "an integral part of edifice" or simply "a clothing more or less rich with which the edifice is covered when its shape has been determined" (Viollet-le-Duc 1987, 170). In truth, this question had been frequently asked but rarely answered. Induced by the assumption of the skeleton of ribs as supporting structures of the Gothic cathedrals (Reynolds 1992, 40), Viollet-le-Duc insisted the pattern of the structure ought to have its manifesto on the form of the whole building (Reynolds 1992, 96). Therefore, he denoted that the structure, if "carefully considered, proportioned, and shaped", can "assume a decorative shape", constituting itself "the principal decoration" (Viollet-le-Duc, 1987, 182). Considering the degree to which the 'integral' relates this 'decoration' to the edifice, he suggested that "the best architecture is that whose ornamentation cannot be divorced from the structure" (Viollet-le-Duc 1987, 200). This perception from the nineteenth century laid out a perfect precondition for Wright's notion of 'integral ornament.' Instead of "a subsidiary and remnant afterthought," Wright analogized ornaments to "rational structure" as did Viollet-le-Duc (Kelly 1998, 21). No wonder he made it a motto among his Taliesin apprentices that "the history of architecture is essentially a history of the development of structure" (Guggenheimer 1995, 26).

In an article written in 1925, Wright iterated that, in addition to 'order' and 'style', our modern architecture was in urgent need of a third dimension—an integral architecture (Wright 1992, 210), which would resurrect the building with "an expression of its nature" in a "sense of depth" (Wright 1992, 212). For its own justification, "a process of simplification" had to be operated initially in "a rejection of the old meaningless forms" and "laborious mess of detail" (Wright 1992, 211). The simplicity, he continued, should be attained in "a clean, direct expression of that essential quality of the thing which is in the nature of the thing itself" (Wright 1954, 187), an archetype of his organic architecture. Subsequently, the third dimension ordered architects to be aware of the consistency and truth in material and the 'plastic' ideal in form. By presenting the formal plasticity, Wright meant not the streamline; instead, he maintained that the formal "style" had to be "due to the way it was 'made'" (Wright 1992, 212) in challenging "the empty ornamentality of the old order" (Wright 1954, 30), namely, to stay true to the actual construction of the structure. The ornamentation, he argued, unless to "mean something" as "an integral feature of the whole," ought to be erased, from where his renowned quote "form and function made one" emerged (Wright 1954, 29-31). In his *Autobiography*, Wright further verified that "the idea of plasticity" was largely exemplified on the "element of continuity" of his own works (Wright 1943, 146). Aided by the malleability of steel, his concept of 'continuity' was attained via integrating various architectural elements, for instance, ceiling and walls, into each other, to constitute an organic whole. Edgar Kaufmann Jr. believed that Wright's "power of continuity" has shifted throughout his entire career from the surface to "the requisite refinement of the natural pattern of structure" (Kaufmann 1989, 123). In contrast to the contemporary 'Fold Theory,' Wright always "abstracted nature's essential forms" into geometries to be used in not only structures but also plans, furniture, and integral ornament in most of his latest works (Nemtin 2000, 12). Such a system of "grand dynamic continuity," based on Kaufmann, has denoted insight of Wright that "human life as one of

Figure 1 (left): Johnson Wax Research Tower, Racine, Wisconsin, c. 1944-50. Source: Ezra Stoller/Esto 1951.
Figure 2 (right): Johnson Wax Administration Building, Racine, Wisconsin, c. 1936-39. Source: Ezra Stoller/Esto 1951.

the processes of nature" and "architecture as a natural process of human life" (Kaufmann, 1989, 123). Therefore, the integration of nature, human beings, and architecture have been synthesized in composing the poetics of the 'third dimension.'

Another impact on the acquisition of 'integral ornament' was from Gottfried Semper, although Wright has never explicitly acknowledged it. Edgar Kaufmann Jr., one of the Taliesin apprentices, endeavored to clarify such influences in his commentary entitled *Frank Lloyd Wright and Gottfried Semper*. The "three factors of formal beauty" of Semper – "symmetry, proportion, and orientation",[6] he believed, all imposed remarkable expressions on Wright's organic architecture (Kaufmann 1989, 130; Semper 1989, 198). Inspired by the property of geode in nature, Semper discovered that symmetry reveals at any of its bodily cuts due to its regular crystal sequences, from which Wright developed his textile blocks in California to imitate "crystalline structures growing out of the earth" (Etlin 1994, 34). Widely acknowledged as common sense, trees have their diminishing tip branches in proportion to their height that is "directed upwards against the force of gravity" (Semper 1989, 207). In his Johnson Wax Research Tower of 1950 (Figure 1), Wright imported such a natural model inversely into a visual proportion to make each floor extend from the central core, as though branches outstretching from the tree trunk. Inspired by the kingdom of plants, Semper further commended buildings to be devised with their orientation directed towards certain environmental contextualization, such as light and wind. Entrusting that we human beings should be organically included as components of the circumstance, Wright in 1939 rendered the 'mushroom columns' in the design of the Johnson Wax Administration Building (Figure 2) to simulate forests outstretching towards the sky for light and air. The 'lily pad' on the top of the column meanwhile reserves a lovely shading for its inhabitants to fictionalize themselves in a hallucinatory forest. Despite the ambiguous debts Wright might intentionally refute from Semper, there is no doubt that the Semperian ideas were among the most accessible concepts prevalent within the most if not all the Chicago School when Wright was still an apprentice, and all of which above has substantially validated so.

Over the horizon of 'integral ornament,' Wright further expanded his 'integral canons' into other categories. In his *Autobiography*, Wright iterated that the integral form, being "nature-pattern," is always "organic in character" (Wright 1943, 380). Being collaborated with the structure, forms in their own justification ought to reflect the 'nature-abstraction'. Since a building has been structured wholesomely as an integral ornament and, in tune with Viollet-le-Duc, forms display as the external articulation of the structure, these forms will inevitably be integral as organic ornaments. During his Taliesin years, Wright reoriented his quest onto the scale of materials, where he practicalized the notion that "the textures, rhythms, and patterns of wood and brick were ornament enough" (Legler and Korab 1999, 40). Out of the 'classic,' eclectic chaos, he conceived beauty as an 'integral order' of material, an order that is "apprehended by reason, executed by science" as "the rhythm of consequent harmony" (Wright 1974, 233). Synthesizing with the 'integral form,' such an incessant affinity systematically facilitated a natural 'integrity of each in all and all in each,' which in Wright's own interpretation was "the parts themselves in order with the form" and "the materials and methods of work in order with both" (Wright 1974, 233). Adding to the enhancement of the integral order, Wright further maneuvered his talented instinct into the beautifier of architecture—light. By resembling "glass and light" as "two forms of the same thing", he rationalized the windows as "screens, a blind, or insertion of opaque glass" discharging "enough light being diffused to flood the interior dimly" in order for the light to be integrated more cheaply and beautifully (Wright 1987, 200-202). In the design of this 'painting with light itself'—stained glass, Wright reversed the approach taken by his mentor, Sullivan, who started with simple geometries and developed complex organic forms, while he geometricized the organic natural forms from daily life to produce a certain aesthetics of configurative art. In line with the coziness of his Prairie houses, Wright repudiated the cumbersome furniture-like fireplaces as ornamentation that was commonly installed. Instead, he advertised the integral fireplace that is large in size and "a place for a real fire" (Wright 1954, 37). Much like the tales of Vitruvius on the origin of architecture from the bonfire, Wright over his entire career, never neglected the superimposition of fireplaces as the hearth of a house, from where comforts will be circulated amid the families from their deeply embodied societal nature. After his trip to Japan in the 1920s, Wright seemed to reaffirm his organic dream and was determined to expand his perception of architecture into a harmonious unit, with furnishing and landscaping included. Motivated by Japanese architecture embracing its surrounding environment, he articulated his designs in the jargon of 'integral building,' videlicet, the engagement of the edifice "as much a part of . . . ground as the rocks and trees and hills there are" (Wright 1992, 325). In his organic grammar, all houses, favored by Mother Nature, must emerge as if to "grow from the earth through the regular courses of brick or horizontal wood siding" (Etlin 1994, 34). Insofar as for the organic integrity, all these integral canons could elaboratively characterize the Prairie projects in the sense of ornamentation, with 'dual functions.'

Literally speaking, every component in architecture is the potential, within Wright's perspective, to be integral as an ornament, to facilitate the wholesome of the organic body in rhythmic aesthetics, including the sculptures and electricity. In contrast to his contemporaries, modern architecture was conceded by Wright being "qualified by light, bred by native character to environment—married to the ground" (Wright 1974, 249).

3. ORNAMENTATION AS VENTURE

Bridging over Wright's deliberations of the ornamental "expression of inner rhythm of Form" (Wright 1943, 347), one could identifiably survey the chronicle


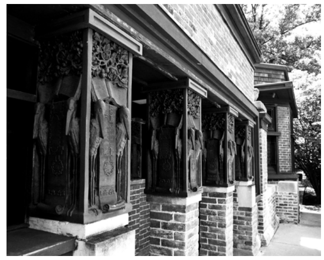


Figure 3 (left): Hillside Home School I, Wyoming, Wisconsin, c. 1887. Source: Columbia University 2016.
Figure 4 (middle): The exterior loggia of the Oak Park Studio, Oak Park, Illinois, c. 1889. Source: Mary F. Warren 2009.
Figure 5 (right): The "floated" ornament around the windows of the Winslow House, River Forest, Illinois, c. 1893-94. Source: Mary F. Warren 2018.

progression of his integral thinking via some of his works. Throughout his impressive career in practicing organic art, there beneath Wright's public legacies were numerous iconic impetuses that prompted a sequence of unexpected shifts from his youthhood to maturation in performing integral architecture.

Nevertheless, there were still things that remained unchanged until his last years. Amongst which, the music stood up as one of Wright's lasting interests ever since his boyhood, primarily due to his musician father William Cary Wright. During much of his Taliesin age, Wright always considered himself as a musical architect. His third wife, Olgivanna Lloyd Wright, even recalled, when she mourned her husband, that his belief, "in an inner sense," was "music and architecture are one" (Wright 1981, 25). In his *Autobiography*, Wright argued that "integral-ornament is founded upon the same organic simplicity as Beethoven's Fifth Symphony" (Wright 1943, 347-48). Wright has regularly referred to Beethoven as his spiritual mentor[7] not in classical elucidation but in "soul language never to be classified" (Wright 1943, 422). In his sentiment, Wright alleged that Beethoven must have seen buildings of "divine harmony alive in the human spirit" of whatever forms when composing his music, just like Wright himself designing the "constructed music" on his drafting board, merely different in material (Wright 1943, 422). "Beethoven's rhythms are integral like those of Nature," he enunciated, as though the integral ornament pertaining to "the simplest statement of the prime idea" upon which "the nature of materials" and "the beauty in tone and texture they possess" could be elaborately preserved (Wright 1943, 423). Regarding materiality, much like the "rejection of the symmetrical balance of the symphony in favor of codas that were often rich in thematic content" by Beethoven, Wright, as recalled by his apprentices, consistently refuted "the old symmetries of classical architecture" by repeating but also varying the gridded, simple modular forms in his drafting of the entire edifice (Friedland and Zellman 2006, 226). Carrying so in the pocket spanning all his decades, Wright often dedicated his works piously to Mother Nature as "an inner beat, an inner rhythm he listened to, the inner character that he transferred to paper without copying or imitating any form" (Wright 1981, 27).

If discerned as an ornamentalist, Wright must have had his works of ornamentation done in periodical progressions. In 1965, James Dennis and Lu Wenneker affirmatively implied that three major epochs ought to be constructed in comprehending Wright's system of ornamentation from the surface all the way to be adequately integral: the first from the late 1890s to approximately 1920, when "ornament remains applied or at least oriented to a surface"; the second briefly until the late 1920s, while "the ornament becomes more of a structural module"; and the last started at the early 1930s, in which "a total structure is often conceived as a full-scaled ornament in its own right" (Denis and Wenneker 1965, 4). This subtle deliberation seems to be readily persuasive, Anthony Alofsin,


Figure 6 (left): The vine-like capitals of the interior columns at the Winslow House. Source: Pamela Linn 2017.
Figure 7 (right): The entry foyer of the Winslow House. Source: Mark Hertzberg 2016.

nevertheless, ordered to reconsider the years of 1909-10 when Wright was on his trip to Europe (Alofsin 1993, 154). "Until 1910, Wright used geometric forms statically in symmetrical arrangements," Alofsin decoded, while after his trip back from Europe, he seemed to start experimenting with ornamentation with "a rich formal complexity" in incorporating "motifs using circles, square within squares, and triangles, that reinvigorated his use of geometry in addition to integrating sculpture more successfully into his architecture" (Alofsin 1993, 154). Beyond any doubt, it is verifiable to associate the chronic progression to the iconic incidents that occurred upon Wright, better in companion with his accommodative projects. In such a sense, our argument will trace Wright's venture of ornamentation in parallel to the timeline of his career to resolve the puzzle of his integral spirit.

As a junior apprentice first arriving in the dazzling Chicago of 1887 hungry for his ambitious future, Wright indeed bore none of the ornamental concepts from his purity. In his initial interior design of 'Uncle Jenkin's' Unity Chapel in 1886, collaborating with Joseph Silsbee and the Hillside Home School I designed for his aunt (Figure 3), ornamentation seemed still to be alien to his practices. At the golden age of Richardsonian Romanesque in Chicago, the Shingle-style was among the most accessible to young Wright. It is even more so if considering his apprenticeship with Silsbee. Literally speaking, not until early 1888 did this

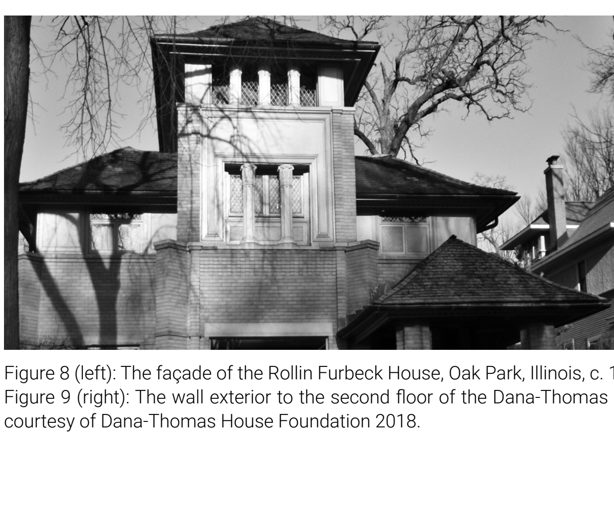
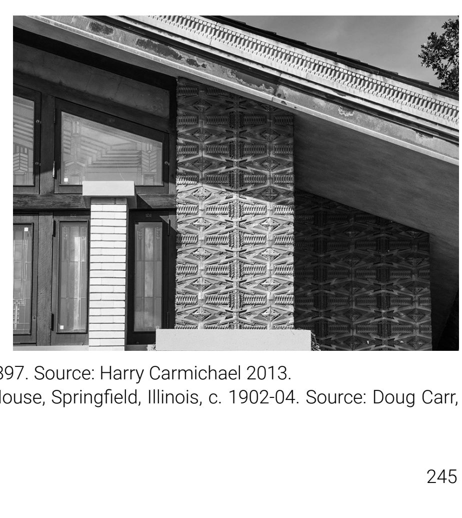

Figure 8 (left): The façade of the Rollin Furbeck House, Oak Park, Illinois, c. 1897. Source: Harry Carmichael 2013.
Figure 9 (right): The wall exterior to the second floor of the Dana-Thomas House, Springfield, Illinois, c. 1902-04. Source: Doug Carr, courtesy of Dana-Thomas House Foundation 2018.

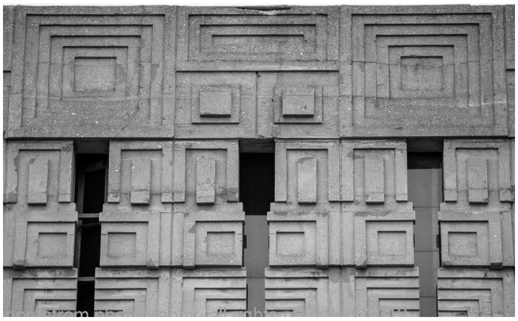

Figure 10 (left): The frieze exterior to the top floor of the A. D. German Warehouse, Richland Center, Wisconsin, c. 1917-21. Source: Eric J. Nordstrom 2019.
Figure 11 (right): The portico of the A. D. German Warehouse. Source: Eric J. Nordstrom 2019.

static cliché come to its end when the *Lieber Meister*[8] smashed this stagnancy for him. Shortly after his marriage with Catherine Lee Tobin, Wright schemed out the Oak Park Studio in 1889 using the thousands of dollars loaned from Master Sullivan. Despite the tight budget, he still strove to negotiate the stork capitals on the exterior loggia with Richard Bock (Figure 4), where the tree of life and the book of knowledge had been exquisitely emblemized, though cladded to the surface out of no structural or functional consideration. Albeit mildly, Wright indeed voiced out his kinship to ornamentation thanks to Sullivan. Such successions might be well censored on his debut of iconicity—the Winslow House accomplished in 1893 when the Columbia World Fair honored the last Beaux-Arts carnival at Jackson Park almost simultaneously. Shared Sullivan's frustration with the prevailing overwhelm of Classical Feudalism that "the damage wrought by the World's Fair will last for half a century from its date, if not longer" (Sullivan 1995, 325), Wright started to prepare for some shifts. On the exterior of the Winslow House, the ornamentation saw no change except for some formal manipulations (Figure 5). The highly ornamented terra-cotta friezes 'floated' around its windows, despite rhetorical, being easily peelable from the mass of the building. Rationally speaking, this marked a transitional era when Wright drew more of his attention to the formal manifestation rather than that of ornamentation, which echoes the notion of the early era by Dennis and Wenneker. In its interior, besides the vine-like capitals of the columns inspired by Sullivan (Figure 6), Wright inserted his very own trials – the recessing entry foyer for reception in consonance with the Japanese Ho-o-den[9] and the unessential but aesthetic addition of a seemingly-structural colonnade (Figure 7). Due to their slenderness, the colonnade was less structural than ornamental, though one could still read the struggles of young Wright against the applied ornamentation subtly. Uncoincidentally, it also marked the independence of his career from any aggressive or speculative 'mentors' to become ultimately established, when he could tranquilize himself into the meditation of his ornamental integrity.

This Sullivanian translation of ornamentation did abundantly dominate most of Wright's career in the late 1890s. Paradoxically, in a few instances of peculiarity, such as the Rollin Furbeck House, the classical grammar like neoclassical capitals and dentils reemerged abruptly, seeming to surge a revival as a response to his modern fatigue (Figure 8). Out of this modern disorientation, it correspondingly remarked a unique epoch for him to hibernate and simmer for a revolutionary leap. Not until the early 1900s, Wright, pioneering in the Arts and Crafts Movement, exploited the 'Prairie Style' in formalizing his petite dwellings, though still obsolete in ornamentation. In his designs by then, horizontality was dramatically embraced with geometrical configuration in place of the flowery

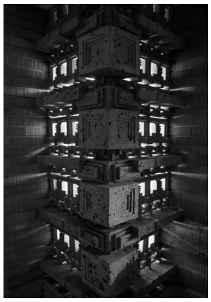

Figure 12 (left): The ornamental details of the Imperial Hotel, Tokyo (reconstructed), c. 1919-1923. Source: Kevin Earl 2016.
Figure 13 (middle): The interior of the Millard House, Pasadena, California, c. 1923. Source: Scott Mayoral with appreciation to Crosby Doe and architectureforsale.com 2013.
Figure 14 (right): The writing desk designed by Wright for S. H. Mori Gallery, c. 1915. Source: University of Illinois at Chicago Art Study Collection, Gift to the University from Mary Diamond Stein, 1969.

curvatures of Sullivan, albeit simple-symmetrically arranged. As a representative, the exterior walls on the entire second floor of the Dana-Thomas House were proliferatively embellished with emerald plaster friezes that borrowed the simple symmetrical geometries (Figure 9). Far beyond concoction, such symmetrical 'four-fold,' 'three-fold,' and 'two-fold' configurations might readily be credited to his childhood 'Froebel Blocks'[10]. Despite being distinguished enormously from his mentor in both Prairie forms and configurative ornamentations, Wright was yet unable to stay out from the 'comfort zone' of applied ornamentation "upon the surface as an addition to the structure, rather than functioning as an organic determinant to the whole" (Dennis and Wenneker 1965, 7-8). And unsurprisingly, it was well documented as a common struggle for his contemporaries amid the watershed between the nineteenth and twentieth century.

Such an unfruitful phase has not lingered for long before Wright himself felt "weary" and admitted that "I was losing grip on my work and even my interest in it" (Wright 1943, 162). Out of exhaustion, he ordered a trip to Europe in 1909, while advertising his 'Wasmuth folios' along the way. In Vienna, he immediately blended in and shared the formal vocabulary with Otto Wagner and the Secessionists, whose impact was explicitly showcased in his proceeding works after his return to the US (Alosfin 1993, 158). In place of the simple symmetrical ornamentations, Wright added remarkably to his ornamental complexity with the rotated square, the square within a square, the multiple frames, and the combination of various geometries in justifying his emblematic identity. As a felicitous instance, the A. D. German Warehouse devised by Wright in around 1915 fundamentally marked such a historic transition. Cladded with the ornamentation of multi-framed squares exterior to its top floor, the building could also exemplify Wright's absorption of native American art (Figure 10). Beyond any doubt, such novelty had never appeared in any of his precedent works until after his European experience. Fundamentally freed from the shadowy Sullivanian ornamentation, Wright reoriented his zeal onto the diversity and composition of geometries as showcased on the column capitals of the portico – the combination of triangles simulating steel trusses[11] despite at the surface-level (Figure 11). Soon such assiduities bloomed correspondingly with fruitful harvest in his celebrated landmark of the Imperial Hotel and Hollyhock House. The former one even survived the Great Kanto earthquake of 1923. Consanguineous to the A. D. German Warehouse, the Imperial Hotel that was preliminarily schemed by Wright in 1915 was substantially another commission resulting from the Secessionist influence, especially in ornamentations. Its wall decorations extended his addiction to multi-framed squares in developing not only patterns but also dimensions within



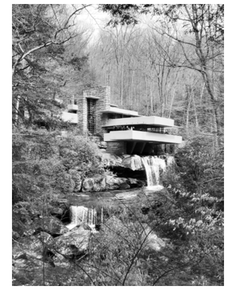

Figure 15 (left): The Herbert Jacobs House, Madison, Wisconsin, c. 1937**.** Source: David Heald 2009.
Figure 16 (middle): The living room of the Herbert Jacobs House. Source: James D. Steakley 2015.
Figure 17 (right): The Fallingwater, Mill Run, Pennsylvania, c. 1936-39. Source: Author 2019.

details (Figure 12). Much more than an ornamentalist, Wright seemed to have started approaching his modern ornamentation in a sculptural sense rather than relief. In other words, the forms he adopted began to be organically integrated into his architectural scheming instead of an afterthought. In comparison to the Secessionists who still “tended to pursue an art of surface” by then (Alofsin 1993, 223), Wright drew his attention radically onto the Far East, for an invigorating exaltation. Historically to say, this exotic exploration did not see its outcome “until his final return from Japan in 1922” (Alofsin 1993, 223).

As a matter of fact, the job as a professional Japanese-print dealer lent Wright enough exposure to Japanese art long before his sojourn there. Alternatively, the construction of the Imperial Hotel in Tokyo was an opportunity for him to substantiate the embodied experience of Japanese life, with which he reaffirmed his organic trajectory. Japanese art, he ascertained, “is a thoroughly structural art” (Wright 1992, 117). Presumably borrowed from the *Composition* of Arthur Wesley Dow,[12] the structure hereby in Wright’s discourse should be translated as “an organic form, an organization in a very definite manner of parts or elements into a larger unity – a vital whole” (Wright 1992, 117). Mentored by Hashiguchi Goyō, the celebrated Japanese printmaker, Wright mastered “the elimination of the insignificant, a process of simplification in art” (Wright 1943, 194), from where his ornament became revolutionarily structural, essential, and integral. Flipping over to say, this simplification of ‘all in one, and one in all’ might be rooted in Herbert Spencer’s theorization of ‘law of crystallization’—“a process of crystalline aggregation” “composed of simple geometric units at a fundamental level” (Nute 1993, 104). This also entailed a new page of Wright’s ‘integral order’ being opened. Beyond all disputes, the protocol between this Japanese structural appreciation and Wright’s geometrical configuration has attained a subtle yet brilliant peak of balance in his works of the early 1920s, especially in terms of ornamentation. Lingering within his delight of discoveries for so long, Wright hastened in conforming it with another of his innovations – the textile blocks upon his return from Japan via California. The Millard House constructed in 1923 as a monumental milestone refreshed his integral canons with an ingenious stroke. Each textile block as an organic cell conveyed tectonically the idea of ‘crystallization’ and the information of the entire organic construction,[13] without sacrificing the functionality of structure, ornament, and screening (Figure 13). Meanwhile, the screen fabricated by these blocks can filter the light to make it more integral to the space. Frankly, such an intriguing leap did enable Wright to effectively compromise his modern interpretation of ornament with the organic system of architecture without surrendering to the applied ornament or risking his design “comely in the nude” (Sullivan 1979, 187). Uncoincidentally, such quest has likewise been committed in Wright’s design of furniture, though earlier in 1915.

Figure 18 (left): The living room of the Fallingwater. Source: Allyson Scott 2015.
Figure 19 (right): The Pope-Leighey House, Falls Church, Virginia, c. 1941. Source: Paul Burk for the National Trust for Historic Preservation

In his writing desk (Figure 14) devised for S. H. Mori, his Chicago comrade of intimacy in the Japanese art collection, Wright homogenized "vaguely Chinese forms (spandrel, struts, and legs that terminate in outward-turning feet)" (Meech 2001, 126) in creating these stabilizing and elegant 'attachments,' unique yet functional. Amid this highly productive period, Wright claimed his maturation in ornamental integration naturally with architecture and its context while awaiting his heyday readily to come.

Unfortunately, the first guest was nothing but the Great Depression in 1929, when Wright was almost insulated from any projects for at least five years. To sustain his endangered career, he decisively perpetrated his architectural counterbalance – the affordable Usonian – to salvage his beloved American fellows. Beyond affordability amongst the middle class, these houses of "moderate cost," Wright commended, could instruct people on "how to live" "with style and not for *a style*" (Wright 1943, 489-90). Scheming modestly on the construction of the Herbert Jacobs House (Figure 15), Wright leniently compromised himself in omitting "all unnecessary complications in construction" including ornamentations in negotiating with the eliminated budget (Wright 1943, 490). In its exterior, the "horizontal-unit system" was intentionally featured in wood and brick constructions without painting "to simplify fabrication" (Wright 1943, 491). Nevertheless, Wright immediately smelled an opportunity of integrating the natural order of materials into his organic design since the material "best preserves itself" (Wright 1943, 491). Perhaps for the first time, he conceived the ornamentation not ornamented. Again, to simplify the interior (Figure 16), Wright further ordered that "furniture, pictures, and bric-a-brac are unnecessary because the walls can be made to include them or be them" (Wright 1943, 491), fireplace unexclusively. Relaxing in its handsome living room, one shall unconsciously perceive the natural ornament of "as much vista and garden coming in as we can afford" through the large pellucid windows (Wright 1943, 492). "A thing loving the ground with the new sense of space, light, and freedom," Wright continued, is "to which our U. S. A. is entitled" (Wright 1943, 493). To justify his mastership of integral ornament, Wright sincerely carved out his magnum opus – the Fallingwater, which indisputably ranked him a big name in the history of Modern American architecture. Its formal organization resembled stacking rocks on the cliff overseeing the creek gurgling, shadowed by the verdant forests (Figure 17), which itself is pleasing ornamentation, not ornamented. The contrast created by the roughness of layered rocks, the smoothness of concrete, the limpidness of windows, and the lushness of the trees, rendered an extreme organic delightfulness with no artificial touching. The greeting melody of the Bear

Run chorded on the “uneven surface” of “the living-room floor” (Figure 18), where “the irregular outline of their raised joints recreates the swirling movement of the stream as it rounds the bend before meeting the ledge” (Levine 2000, 63). Insofar as the organic integration of ornament, Wright seemed to have overthrown the shackle of decorated ornamentation. The integral ornament for Wright is to design, not to apply. Shortly after the economy recovered over the 1940s, some ‘outdated’ ornamentations reappeared in Wright’s design of the Pope-Leighey House despite being much simpler and more engaged (Figure 19). To avoid running out of budget, Wright dexterously synthesized the patterned ornaments into light screens to provoke diverting shadows. Despite being accused of being attached, these ornamentations were not merely embellishments. As in the Millard House, the Pope-Leighey House was also categorized with ‘integral light’, fashioning it as a preeminent archetype of Usonian houses. Most of Wright’s latest works were featured with the disappearance of perceptible ornamentation while their ornamental quality has never faded due to the charisma of his integral reinterpretation.

As a matter of fact, in his last years, Wright radically proposed another ambitious scheme—“large-scale ornaments spread out upon the landscape,” such as the Arizona State Capital “Oasis” in 1957 (Dennis and Wenneker 1965, 13). In line with his integral canons, these projects substantially materialized the ‘integral buildings.’ It also implicitly echoed Wright’s prior emphasis on the Broadacre City, while too much depiction seems to be redundant since it was still half-baked without systematical development, and it carried not so much structural value as done by the integral ornament. Alternatively, such landscape ornaments denoted Wright’s prospect of a future in architectonic ornamentation.

Overall, Wright’s insight on ornamentation could predominantly be redistributed into five determinant periods of progression from the Beaux-Arts accessory to the structural, formal, and functional integration spanning his entire career in architecture. Caught in the historic polemics when the word ornamentation was imperatively under suspicion and ‘the passing prejudice,’ it demanded far more guts for Wright to overthrow the critical oppression in propagating his ‘integral ornament’. Illustrations as such precisely rejuvenated Wright’s battle for modern ornamentation, while almost all his contemporaries outside Taliesin Fellowship unconditionally fashioned the Bauhaus oversimplification forsaking any ornamental spirit. Indeed, Wright was never unconcerned about it, especially towards the youths; he, who had been acquainted with Beaux-Arts conventions from Sullivan, maintained a clear mind about what mattered authentically to architecture, even amid the most ominous moment.

CONCLUSION

Insofar as his modern interpretation of ornament, Wright shared little in common with Bauhaus Modernism in his realm of architecture. Denouncing the ‘mediocre’ notion of ‘surface-and-mass’ proposed by the International Style, he tenaciously refuted “the ‘new’ architects use surface and mass” so much as their rejection of the “buildings using ornament” (Wright 1992, 327). In conforming the ‘surface-and-mass’ with “the ‘American Classic’ of New York City or Los Angeles Tudor-Spanish”, Wright asserted that the ‘third dimension’ should be our future of architecture (Wright 1992, 327). Instead of “the abuse of the thing taken for the thing” (Wright 1992, 327), this dimension of depth is aimed at the integration with natural order and beauty beyond any meaningless stylistic cliché that young Wright adopted in his apprenticeship with Sullivan. Conceivably, Wright’s yearning then did not draw enough attention until 1965 when Thomas Beeby emphasized the distinction between *structure ornamented* and *ornament constructed*[14] in his paper, quoted from the English architect Robert Kerr (Bloomer 2000, 210).

Answering this ‘novelty,’ Robert Venturi, in his *Complexity and Contradiction in Architecture,* propounded the terminology of “double-functioning structural form”, which entails the “correspondence between form and function, and form and structure” (Venturi 2007, 35). In response to decades of rejection, contemporary architecture witnessed an apparent renaissance of ornamentation, more engaged than attached, just like how Wright progressed his ornamental practice from surface to massing, while postmodern digital architecture has pushed too far.

In the year as early as 1929, Wright predictively warned the youth about the risk of neglecting the line between curiosity and the beautiful. In the 1920s, a surprising preponderance of young architects was merely instigated by their curiosity towards ‘new forms and fancy ornaments,’ under “demoralization of the beautiful in the name of the ugly and glorification of the ugly in the name of the beautiful,” ironically as its current today (Wright 1992, 330). As a result, more and more ‘oeuvres’ have been irrationally rolled out purely for sale and curiosity but not beauty, which deeply exacerbated the issue of public aesthetics and sanity. Derived from human nature, curiosity caters “to senses or instincts gone wrong” since it migrates towards “the wrong side of the line” (Wright 1992, 330). Mocked by Wright as nose and tail being inversely placed, the disorder of curiosity might elusively fantasize a smug of astonishment, or even fascination, from the ghastly mistakes. The integration of distortion and displacement has aggressively constituted the ornamental generality of our daily routine, hoaxing to be the protagonist of our architecture. As an alternative, the beautiful must be austerely defined by “integral Order or the expression of internal harmony” (Wright 1992, 332), which portrays the essence of Wright’s integral ornament. As dictated by Erich Fromm,[15] “beauty is not the opposite of the ugly, but of the false” (Pallasmaa 2005, 318). Our architectural education should have excluded everything but the responsibility of reshaping the ornamental culture into organic order before it slips into the swamp of eternal abstraction and confusion. The obvious epistemological approach is again the trace from which Wright progressively remedied his struggle with Modernism from the frivolous surface worship to the enlightening integration between form and function. What we need towards the status quo is not exoneration but rejuvenation. Taking “nothing for granted as appropriate in this sense” (Wright 1992, 332), Wright’s integral canons in ornamentation might be a remedy for our Modernist expedient.

ENDNOTES

1 Loos literally proclaimed that ornament is a crime only for a cultured man, and the “amoral” (the Papuan or the child) should be freed from any confinement. In his sense, our culture has no “organic connection” with ornament. See Adolf Loos, “Ornament and Crime,” in *Ornament and Crime: Selected Essays*, ed. Adolf Opel, trans. Michael Mitchell (Riverside: Ariadne Press, 1998), 167-76. (Original work published in 1929)

2 To be noticed, Wright’s idea of the “third dimension” took its flight much earlier than the “integral ornament,” named after the dimension of “orders” and “styles.” It somehow refers to the fact that Wright himself might have already been wedded with this concept even before the initial publishment of his *Autobiography* in 1932; however, the specific terminology was not grounded until 1943. See Frank Lloyd Wright, “In the Cause of Architecture: The Third Dimension,” in *Frank Lloyd Wright Collected Writings*, ed. Bruce Brooks Pfeiffer (New York: Rizzoli, 1992), 209-14. (Original work published in 1925)

3 Alberti argued that the enemies were more likely to help in protecting the building they captured due to its ornamental beauty. Not uncommonly, it could easily be exemplified by the case of China in the later 19th century, where the highly ornamented palaces and artifacts that were prolifically produced to indicate the majesty of the emperors survived as precious even after the military defeat.

4 Regarding his translation of *De Re Aedificatoria*, Joseph Rykwert later proclaimed that the ‘additional’ must have been mistranslated and should be substituted by ‘in accord’ or ‘agreeable’ in the senses of harmonious to fit in the context.

5 The idea of color being “one of the most effective means of ornamentation” was later reaffirmed by Eugène Emmanuel Viollet-le-Duc; however, it hardly can be determined whether Viollet-le-Duc borrowed such ideas from Own Jones since he innovatively pushed it towards the boundary of the structure. “Colour,” he asserted, “served to distinguish the architectural members, and to give the serval planes of the structure their due relief.” See Eugène Emmanuel Viollet-Le-Duc, *Lectures on Architecture (Vol II),* trans. Benjamin Bucknall (New York: Dover Publications, Inc., 1987), 176. (Originally published in 1872)

6 In Semper’s discourse, these three factors were also described as formal “authorities” that were enlisted as “eurythmic-symmetrical authority,” “proportional authority,” and “directional authority,” which he borrowed from Vitruvius in emphasizing “certain formal components of a phenomenon that stands out from the rest.” See Gottfried Semper, *The Four Elements of Architecture and Other Writings,* trans. Harry Francis Mallgrave and Wolfgang Herrmann (Cambridge: Cambridge University Press, 1989), 209. (Original work published 1851)

7 At Taliesin and Taliesin West, Wright would air Beethoven’s melodies publicly in loops for hours until Olgivanna or someone else urged him to cease. See Olgivanna Lloyd Wright, “My Husband…,” in *Writings on Wright: Selected Comment on Frank Lloyd Wright*, ed. H. Allen Brooks (Cambridge: The MIT Press, 1981), 25. (Original work published in 1966)

8 *Lieber Meister*, the honorific Wright typically used to refer to his mentor, Louis Sullivan, in his *Autobiography*.

9 Ho-o-den is the Japanese Pavilion at Columbia World’s Fair designed by Masamichi Kuru in 1893.

10 The ‘Froebel Blocks’ his mother Anna Lloyd Jones purchased for him dramatically enriched young Wright’s comprehension of geometry and form. In his later life as an architect, Wright repeatedly recalled his memory of childhood with the “optical illusions appear as the cube twirled rapidly on an axle-stick through each of the axes.” And he often claimed the credits from such special gifts in reshaping his architectural life even until his last years. See Jeanne S. Rubin, “The Froebel-Wright Kindergarten Connection: A New Perspective,” *Journal of the Society of Architectural Historians* 48, no.1 (1989): 24-37, https://doi.org/10.2307/990404.

11 Perhaps this structural intimation implied the dedication to his cherished but fugitive education as a part-time engineering student under Professor Allan D. Conover at the University of Wisconsin-Madison. Moreover, it was by then when young Wright set out on his architectural journey in seeking a handsome integration between structure and ornamentation in modern senses.

12 The book *Composition: A Series of Exercises in Art Structure for the Use of Students and Teachers* was originally composed in 1899 by Arthur Wesley Dow (1857-1922), who was an American painter and assistant curator of the Japanese collection at the Museum of Fine Arts in Boston. It demonstrated how the three elements of line, *Notan*, and color are structurally organized into an organic unit in Japanese prints. The term *Notan*, according to Dow, is a Japanese word that means “dark, light” and “refers to the quantity of light reflected, or the massing of tones of different values.” His artworks were tremendously influenced by Japanese woodblock prints, which made him known to Wright.

13 Instead of curvilinear or simple geometries, the pattern of each textile block has intentionally been integrated with the significance of its natural surroundings or the house itself (plan, elevation, or specific architectural component) without necessarily replicating their forms. Therefore, one could freely read the entire edifice through one block or appreciate the block as a minimal building by overlooking the whole, just like organic cells and the human body.

14 In Beeby’s discourse, the *structure ornamented* entails the ornamentation attached to the structure, while the *ornament constructed* denotes the plan and structure to be so arranged as a manifesto of ornamentation, similar to Wright’s integral ornament.

15 As Juhani Pallasmaa indicated in his essay, the quotation from Erich Fromm is unidentifiable. See Juhani Pallasmaa, “Melancholy and Time,” in *Encounters: Architectural Essays*, ed. Peter MacKeith (Helsinki: Rakennustieto Oy, 2005), 318. (Original work published in 1995)

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