Artisanship in a post-industrial present:

A physio-biological framework for restorative design artifacts

by
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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Architecture

Waterloo, Ontario, Canada, 2025
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Author's Declaration

I hereby declare that I am the sole author of this thesis.
This is a true copy of the thesis, including any required
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I understand that my thesis may be made electronically
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Abstract

Over billions of years, organisms have evolved from single cell organisms into the human species of today. That process shaped the physiology and psychology of the human species.[1] While each person is unique, a product of each individuals experiences and specific genetic endowments, there exists universal features that are innate in the biology of humans.[2] One aspect of this is our brain, a unique organ which has evolved through thousands of generations, and through countless interactions with our environments into a mechanism for our species survival.[3] This evolutionary process created a deep innate relationship between humanity and our natural environments.[4]

When modernism emerged at the turn of the 20th century, it fundamentally changed architecture.[5] The economics of mass production mingled with advancements in medical reasoning to produce an architecture of efficiency.[6] Architects such as Adolf Loos, Le Corbusier, and Alvar Alto translated the sterility and medical principles of the sanatorium into housing and beyond, producing an architecture founded on the principles of air and light as essential elements to health, while peeling architecture away from the "humid ground where disease breeds" as defined by Le Corbusier.[7] Large windows, rooftop terraces, and spotless interiors crafted light filled spaces and spotless environments, perfect for the air and sun cure against tuberculosis, but which increasingly separated individuals from the ground humans have evolved to thrive in.[8] Architecture shed the rich visual complexity, naturalistic illusions, and fluid interior exterior relationships of historic architectures, replacing it with a sterile incubator, targeted toward contemporary concepts of health.[9]

Modernist architectural advancements led to a sterility that has permeated modern architectures, producing a cognitive discord that is actively harmful to individuals.[10] Researchers in neuroscience and environmental psychology have sought to understand this discord, producing studies which seek to better identify the underlying cognitive mechanisms that inform these interactions.[11] Designers in turn have developed frameworks for applying this research to design for well-being.[12] This thesis proposes a framework for restorative design principles, and advocates the harnessing of digital fabrication technologies to produce restorative artifacts for well-being. Through the development of a framework specifically tailored to the production of digitally fabricated artifacts, this thesis proposes a methodology for generating restorative environments through informed design. The artifacts presented in this thesis demonstrate the application of restorative principles through digitally fabricated artifacts, advocating the adoption of a new architectural language for restorative, evolutionarily informed design.

Acknowledgments

I would like to express my gratitude to my supervisor Fiona Lim Tung for her unwavering support, encouragement, patience, and guidance through this journey. I am deeply grateful for your thoughtful insights, limitless curiosity, and unending encouragement. Thank you. I would like to thank my committee member Tara Bissett, whose limitless knowledge and curiosity drove me to keep reading, exploring ideas, and inspired. Tara, I truly valued our conversions, and can't thank you enough for the encouragement, belief, and generosity you have shown. I am deeply grateful for the time and care both of you have invested in supporting me.

A special thank you to my friends and family who have encouraged and supported me through this journey, it made all the difference.

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Introduction

Decades of research in environmental psychology has reinforced our understanding of the evolutionary connections between our environments and our psychological and physiological well-being.[13] This research has continuously shown that humans require complex environments rich in stimuli, colours, patterns, and have innate preferences for objects that mimic the qualities of nature.[14] These preferences are so fundamental that they appear in both neurotypical and non-neurotypical bodies, suggesting these connections are deeply ingrained into human physiology.[15]

Despite these innate preferences, modern architecture has adopted a sterility that is actively discordant to our physiological well-being, producing harmful and un-restorative environments.[16] Despite the majority of our time being spent indoors, and apartments being programmatically spaces for rest, there has been little consideration for our spaces to function as restorative environments.[17] This thesis explores how research in neuroscience and environmental psychology can inform design interventions which allow our domestic and urban spaces to better meet our physio-biological needs. Through the lens of a restorative framework, digital fabrication will be harnessed to produce artifacts which are aligned with our neurological and physiological needs, and present tools for designers to intentionally augment sterile domestic space and design intentionally for restoration.

This thesis posits that architecture's anthropocentric ethos has led to a sterile architecture which has created a form of sensory deprivation in our built environments. Despite a desire to produce healthier, better environments, we have produced environments that lack the necessary elements for neurological nourishment.[18] Architecture must adopt ecocentrism to produce environments that are physio-biologically nourishing and aligned with our evolutionarily defined needs. By accepting humans have been evolutionarily shaped by our ancestral environments, architecture can adopt a design philosophy which seeks to imbue our built environments with the same qualities as the natural

world. Through digital fabrication, designers now have the tools to produce rich and visually complex stimuli. By combining technological advancements with research in environmental psychology, designers have the ability to craft healthier restorative environments.

Health and Design

Modern architecture shares an intrinsic link to health. Its origins trace at least partially to the emergence of sanatoriums in the early 20th century, which saw the development of an entire design philosophy grounded in medical reasoning.[19] Prior to this, applications of restorative design principles were common in architecture.[20] Architectural forms depicting plant life and complex geometric patterns were common, and grottoes, both natural and artificial can be traced back thousands of years.[21] These principles transcend any particular culture, appearing across the world in decorative relief. Modernists such as Le Corbusier, Adolf Loos, and Richard Neutra believed that design could calm nerves, stamp out tuberculosis, and imbue health into buildings and people; however, they lacked the current medical knowledge we have access to today.[22] The classic elements of modernism, the sterile white walls, large glass windows, pilotis,and smooth surfaces have remained as remnants of outdated medical thought that surrounded design for well-being. These elements, while well intentioned, stripped architecture of visual complexity, and naturalistic forms and materials, producing a sensory sterility and separating us from our natural environments.

While these elements have remained steadfast in the commercial and domestic designs of today, they have not been without their criticism.[24] Writers like Mayer Spivack, Christopher Alexander, and Don Norman began writing and speculating on the importance of cognitive processing in design, challenging the sterility that had become widespread through the International Style. They advocated for a reconsideration of widespread sterility in design, re-igniting the initial spirit of modernism in looking to health and science for design innovation.

Environmental Psychology

In the midst of the 20th century, we witnessed the maturation of psychology as a new science.[25] Darwinian thought deeply influenced this research and led to the emergence of environmental psychology, a study concerned with how our environments have shaped and impacted the human psyche. These theories proposed an innate relationship between humans and their ancestral environments, questioning the role our surroundings play in our well-being.

From these Darwinian ideas emerged theories such as Biophilia, , and Stress Recovery Theory (SRT), Attention Restoration Theory (ART) all of which sought to explore how the human brain responds to our natural environments. These theories proposed intrinsic relationships between the natural world and our restorative neurological processes, identifying a discord between humans and their sensory deprived built environments. These researchers explored how the natural world may provide key restorative benefits that were increasingly missing from modern lifestyles. Today, research continues to evolve, with new studies in skin conductance, MRI scanning, and eye tracking allowing researchers to biologically measure our responses to the natural world revealing a deep bio-physiological connection. This body of research, while constantly evolving, provides insight into how humans have evolved over time, and how we may shape our environments to better align with our physiological and psychological systems to reduce strain and evoke restoration.[26]

Technological Advancements:

As research continues to push our understanding of how the human brain interacts with the world around us, technology is creating new tools for designers to augment and fabricate space.[27] Advancements such as CNC milling, 3D printing, and laser cutting are allowing designers to achieve new levels of complexity in their designs with increased efficiency.[28] In tandem, advancements in computing are allowing more powerful processing, which allows designers to generate increasing levels of complexity in their digital models.[29] These advancements have enabled designers such as Michael Hansmeyer and Benjamin Dillenburger to produce intensely detail rich environments. Critiques of these works have described them as evoking sensations of discomfort, estrangement, and alienation.[30] Characterized as displaying levels of “excessive resolution” the works demonstrate how technology can generate deeply complex visual stimuli, but without a connection to our natural environments, produces an almost uncanny effect.[31] This thesis proposes that by combining the advancements of digital fabrication technologies with research in environmental psychology, designers can craft interventions that mimic the inherent qualities of the natural world and create restorative spaces. Utilizing clay 3D printing and nature-derived data, this thesis will explore the fabrication of artifacts of various scales, to identify methods for translating data derived from nature into artifacts that evoke restorative function.

Methodology:

A framework for the production of restorative artifacts is proposed, informed by existing frameworks and research in environmental psychology and neuroscience. Existing frameworks which attempt to spatialize this restorative research are evaluated and consolidated into a newly proposed framework, specialized toward the digital fabrication of restorative artifacts.

For the purposes of this design research, several key components were selected for exploration, referred henceforth as the utilization of natural materials, integration of naturalistic forms, presence of colour, complexity and sense of time. These elements represent significant overlap within existing frameworks, and contain sufficient research to support their credibility as elements capable of inducing restorative responses. Each characteristic can be designed for and implemented through modern fabrication methods.[32] This framework is then utilized to produce design artifacts which select for these characteristics. Clay extrusion printing was selected in conjunction with photogrammetry modeling and LiDAR capturing as the primary tools for executing these artifacts. These technologies represent modern advancements that have facilitated the economic and technological advances needed to execute large scale adoption of restorative design principles.

LiDAR and photogrammetry data are streams of big data, that distinguish themselves in one key aspect: they are not information derived from complex digital simulations, but precisely measured models of the natural environment.[33] This information is valuable as it may bypass the de-humanizing impact of purely digitally generated stimuli. By manipulating this data into design artifacts, a visual complexity is maintained, which may theoretically retain the neurological processing efficiencies experienced between our visual processing systems and our natural environments.

Framework For Artifact Fabrication	
Metric	Description
Integration of Natural Materials	Relays the importance of utilizing materials with rich textures & patterning, that changes and patina's over time, and that contains natural geometries.
Evocation of Naturalistic Forms	Promotes the development of forms which evoke nature and advantageously draw on digital fabrication's ability to generate visually complex geometries.
Presence of Colour	Advocates the use of neutral tones with low saturation to provide restorative environments with low cognitive arousal.
Visual Complexity	Advocates for stimuli with high levels of visual complexity, and statistical similarity, producing artifacts which contain visual complexity similar to that found in natural environments
Sense of Time	Promotes for the use of materials and symbolism that evoke the dynamic forces of aging and changing.

Fig 0.1. Artifact fabrication framework diagram.
diagram by author

These ambitions specifically align to the complexity and integration of naturalistic forms found in the spatial framework, providing a stark contrast to the sterile environments they occupy. By allowing the forms to be directly translated from nature, the artifacts align with an evolutionary framework, producing artifacts that not only contain a high visual complexity, but contain the same naturalistic qualities as the stimuli it is derived from. Photogrammetry and LiDAR enable this data to translate the complexity of objects directly from nature, avoiding the hyperrealism, estrangement, and discomfort sometimes associated with digitally generated complexity.

Utilizing this framework, artifacts are produced which harness the proposed characteristics to produce varied experiences and attributes. Starting with the scale of a lighting sconce, this artifact demonstrates the potential of subtle interventions that evoke a sense of excitement and visual delight within a small scale intervention. A second lighting intervention, a large scale floor lamp, demonstrates the scalability of these techniques, engaging more directly by producing a large scale object that is more tactile in nature, more richly textured, and spatial in its application. A furniture scale intervention, in the form of a geologically inspired side-table, demonstrates a more subtle spatial intervention. Finally, a mural scaled tile assemblage, demonstrates the scalability of these design principles into large ceramic interventions. Capable of growing to the size of a wall, a room, or a façade, this application illustrates how a restorative framework can be interpreted into large scale interventions with maximal impact. These artifacts, executed across various scales, illustrate the potential of digital fabrication to realize the ambitions of restorative design, and provide functional design solutions that augment our sterile environments.

1 Terrain Sconce

2 Stalagmite Light

3 Geologic Table

4 Topographic Mural

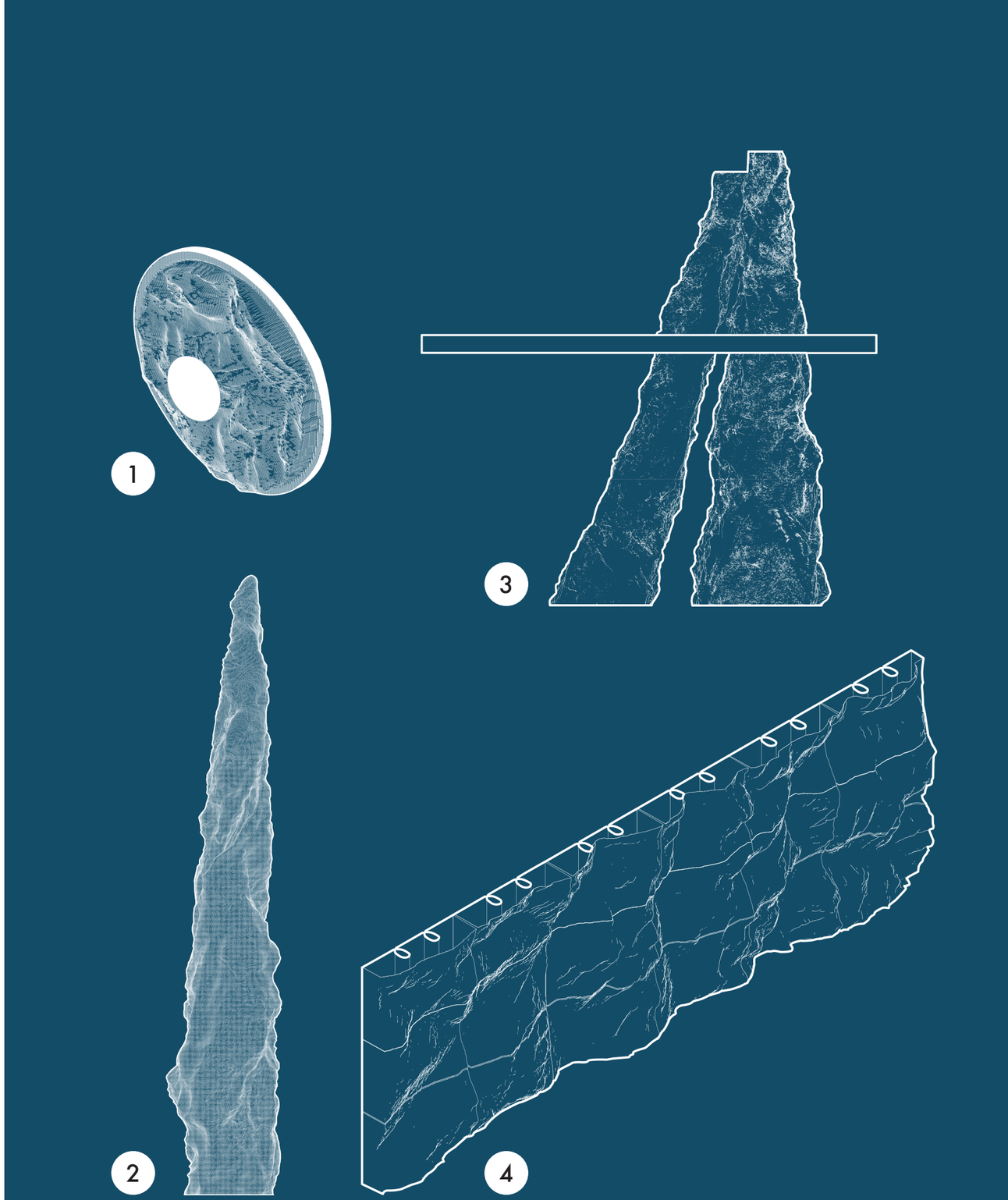


Fig 0.2. Illustrations of thesis artifacts. Illustration by author

While increasingly, Western architectures have sought to include greenery, there has been little attention paid to how surfaces and furnishings can equally contribute to producing more biophilic, and by extension, more restorative environments. As noted by Salingaros

"anxiety-inducing industrial forms, materials, and typologies remain firmly in place as the current architectural paradigm. Plants satisfy only one part of biophilia that depends upon proximity to nature but could obscure the need for healing geometries in the fabric of the building itself."[34]

This disconnection, between form and the presence of plants, have produced "schizophrenic" results, where "superficially the plants are biophilic, but the built structures are not."[35] While architecture may be far from adopting widespread restorative applications, these artifacts argue that designers have the tools and technology to generate restorative designs. Barry Wark has compared the sterility of our domestic spaces to a form of "sensory deprivation," a term that denotes just how discordant our human-built environments are to our biological functioning.[36] It is imperative today that designers take note of the plentiful research that exists in environmental psychology, to inform design philosophies which provide a restorative reprieve from discordant urban environments. With the tools of post-industrial technologies, the ability to generate fascination and restoration are widely available. The proposed framework and accompanying artifacts represent one interpretation of that design philosophy to inspire and present meaningful alternatives to sterile built environments.

1.0 Health and Design

1.1 How medical discourse shaped modernism

Modernism, perhaps more so than any architectural style, is intrinsically tied to concepts of health.[37] Emerging in the 20th century, its roots are based in the tuberculosis epidemic and the emerging fields of psychology and medical advancement.[38] Sanatoriums, luxury medical facilities catering to the upper classes suffering from tuberculosis and more minor maladies, became a testing ground for innovative architectural and design interventions that sought to improve the health of its occupants.[39] Alvar and Aino Aalto's Paimio Sanatorium emphasized these features, with everything from the furniture, fittings, and surfaces designed explicitly toward a contemporary understanding of health.[40] Surfaces were minimized to prevent dust accumulation, which reduced visual complexity and created sparse interiors. Chairs were designed to improve breathing, sinks were designed to reduce splashing, even the handles were designed to prevent catching doctor's white coats.[41] The entire building centered around the importance of air and sun as a form of therapy in the curing of tuberculosis.[42] This focus on sparse materials, stripped references to naturalistic forms *and* materials, reducing both the complexity and richness of colour found in contemporaneous styles such as Art Deco and Prairie Style. Siegfried Giedion argued that the Aalto's sanatorium represented one of the three foundational institutional buildings linked to the emergence of contemporary architecture.[43] Beatrix Colomina argued in *X-Ray Architecture* that "tuberculosis helped make modern architecture modern. It is not that modern architects made modern sanatoriums. Rather, sanatoriums modernized architects."[44]



Fig 1.1. Gustaf Welin, Top floor sun terrace in 1933, 1933. Photograph. Alvar Aalto Foundation



Fig 1.2. Gustaf Welin, Approach to the Paimio Sanatorium, 1930s. Photograph. Alvar Aalto Foundation.

The distillation of sanatorium design features into housing was rather direct. Aalto himself wrote extensively about how his experience designing the sanatorium imparted important lessons that he carried into "generic" houses.[45] Aalto noted:

"I was able to discover that special physical and psychological reactions by patients provide good pointers to ordinary housing. If we proceed from technical functionalism, we shall discover that a great many things in our present architecture are unfunctional from the point of view of psychology, or a combination of psychology and physiology.[46]"

Aalto's looked to psychology and physiology to inform architectural interventions that expanded the material palettes, functionalist principles, and design features associated with sanatoriums to commercial and domestic architectures.[47] Colomina argued that beyond Aalto, "many modern architects did a sanatorium at some point, and it often defined them. The sanitorium was the testing ground of new materials and techniques of construction."[48]

Some tendrils of the expansion outward from sanatoriums can be seen in the emergence of open-air schools, such as the Wald-Oberschule in Berlin which opened in 1904 for "pretubercular" children.[49] This school sought to adopt the principles of fresh air, and exposure to the sun as integral principles to health, with the reference to "pretubercular" children drawing a clear linear relationship between the growing list of sanatoriums.[50] The school situated itself in a forest, directly connected to natural elements, but the architecture itself adopted a material palette similar to Aalto's sterile walls and large windows, devoid of naturalistic forms, colour, or visual complexity.

Another example of this outward expansion can be seen in the 1929 publication of *Befreites Wohnen* (Liberated Dwelling) which was published with the subtitle "*Licht, Luft, Oeffnung* (Light, air, opening)."[51] Despite the title and objective of the book to describe modern dwellings, more than half of the illustrations depicted images of hospitals and sports, showcasing new attitudes toward dwelling as

a form of medical instrument.[52] Many characteristics of sanatoriums were present in the homes illustrated, including open air terraces, gyms, and lounge chairs associated with sanatoriums.[53]

Beyond the confines of the sanatorium, health appears as a repeated motif throughout treatises of modern architecture. In Le Corbusier's Vers une architecture (1923) he provides a "diagnosis" on the state of architecture.[54] He particularly, "condemns the traditional house for producing the debilitating effect of tuberculosis."[55] Both in *Vers Une Architecture* and *Urbanisme* he critiques architecture from a medical perspective, going as far to argue cities were "rotten old houses full of tuberculosis."[56] Through his writings Le Corbusier advocated for the characteristics rampant in sanatoriums to find widespread adoption in housing typologies.[57] Everything from pilotis, roof gardens, glass walls, and clean air are presented as not only architectural interventions, but medical devices.[58] In Le Corbusier's writings the line between domestic architecture and medicine blend together into a wholistic entity.

Colomina argued that the modernist puerility represented a type of anesthesia, relating the smooth surfaces of modern architecture to a tool to anesthetize bodily sensation in a form of sensorial suppression.[59] They supported this argument by pointing to the repeated instances of "calm" as an ideal in the writings of Le Corbusier, with architecture striving towards the purpose of stress reduction.[60] Colomina argued that "the elimination of ornament is not simply an aesthetic choice, but a neurological or even narcotic one."[61] This extension was grafted onto Adolf Loos's argument in *Ornament and Crime* where he described the "horror" he experienced upon viewing decorated animals in culinary displays and architectural ornament.[62] Colomina argued that instability of the 20th century led to a generation fractured by fragile psyche, where modern architecture became a protective incubator."[63]

The incubator metaphor is poignant in understanding the sterility that flowed from modernism. Design became reclusive, repeatedly disconnecting itself from the natural materials and the interconnectedness with nature found in vernacular and other contemporary architectures. In many ways, modernist architecture took on the role of a protective bubble that protected and sheltered, but that muted the senses from the outside world. The outside world became something to be experienced from afar, from balconies or rooftops, and the interiors became spotless, dustless refuges from the dirt, literally lifted from the ground and disconnecting itself from the diseases of the outside world. Modernism stripped architecture of natural materials, natural forms, and visual complexity, producing protective incubators that considered sun and light as the only beneficial elements of nature.

The rise of the sanatorium saw experimentation with architecture as a medical tool to produce healthier environments for healing and, in turn, inspired a generation of architects to reconsider how domestic housing impacted the people who lived within those spaces.[64] Architects began to craft intentionally disparate spaces, based on contemporary thoughts around health, which ultimately sheltered and removed individuals from the outside world. What began as a deep interconnection between the emergence of health innovations and architectural expression, proceeded into an almost pseudoscience. Richard Neutra's "health houses" presented a perfect example, where dwellings centralized around "theories about health, psychoanalysis, and nudism."[65] Neutra's Lovell Health House included sleeping porches, sunbathing opportunities "marathon showers," and built-in enemas, outdoor gyms, and kitchens specifically designed for a vegetarian diet.[66]

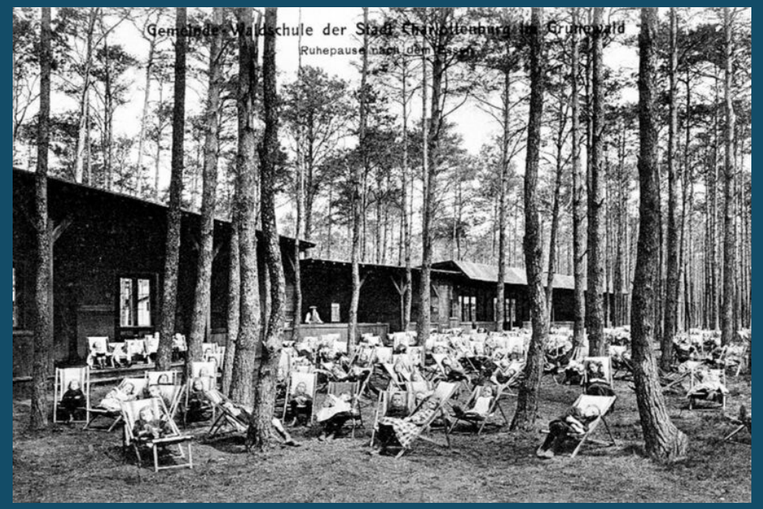


Fig 1.3. Ewald Schürmann, Wald-Oberschule in Berlin-Charlottenburg, postcard. https://siedlerverein-eichkamp.de/zum-ursprung-der-waldschule-als-freiluftschule/



Fig 1.4. Julius Shulman, Lovell Health House by Richard Neurtra, Photograph. Julius Shulman photography

Neutra viewed these innovations as holistic ways to improve the health of clients.[67] Adopting fringe health movements, his designs extended beyond concerns for tuberculosis, which at this point had become controlled with antibiotics in the Western world.[68] The newfound freedom allowed modernism to experiment with "new health" concepts. Colomina argued that Neutra's health houses represented a foundational shift, from architect as a "doctor to the idea of the architect as a kind of psychoanalyst.[69] The function of the house was to provide not just physical health, but also psychological well-being. [70]

These notions, while wrapped up in pseudo-scientific movements, represent how modernist design was shaped by ideas around health and well-being. Designers first adopted the newest technology to the needs of patients and later applied those principles to dwelling. The sterile white walls, sparse furnishings, and large glass windows of today trace their origin directly back to the fight against tuberculosis and a desire to produce healthier environments.[71] Despite the radical interventions and deeply well-meaning origins of these innovations, our understandings of health today have brought into question the merits of these principles. Just as scientific innovation proved the light, air, and sun treatment for tuberculosis was misguided, research today has exposed the minimalist sterility of Le Corbusier's search for "calm" to be neurologically harmful.[72] Essential elements of modernism, such as the large windows that allowed the penetration of light and air in the treatement of tuberculosis, high balconies, and pilotis that lifted buildings from the ground, all gradually removed architecture from natural elements. This severed architectures traditional relationships with nature and produced a womb-like incubation that severed the primordial relationship between humans and our natural environments. Critically, architecture of today needs to re-evaluate the assumptive health-conscious choices established over a century ago, against the knowledge accumulated within that gap. Perfectly summed up by Colomina in *X-Ray Architecture*:

"Every age has its signature afflictions," Byung-Chul Han writes in The Burnout Society. We can now add that each affliction has its architecture. The age of bacterial diseases – particularly tuberculosis – gave birth to modern architecture, to white buildings detached from the "humid ground where disease breeds" as Le Corbusier had put it, smooth surfaces, big windows, and terraces to facilitate taking the sun and fresh-air cure. When the discovery of antibiotics put an end to that age, in the postwar years, attention shifted to psychological problems. The same architects once concerned with the prevention of tuberculosis became obsessed with the psyche, with the house seen as not just a medical device for the prevention of disease, but as a way to provide psychological comfort, what Neutra called "nervous health," with the architect as psychologist.[73]"

Byung-Chul Han argued that the twenty-first century is the "age of neurological disorders: depression, ADHD, borderline personality disorders, and burnout syndrome."[74] This thesis proposes that to respond to these challenges, designers need to turn once again to science, to psychology, and to our environments. To meet contemporary needs, architecture needs to reevaluate the way we design, recontextualizing the sciences of today to advance architecture; and in doing so, reevaluate the relationship between humans and naturalistic environments.

1.2 The Emergence of Environmental Psychology

Environmental Psychology developed gradually as a formal discipline. Early innovators, such as Willy Hellpach, began exploring the "impact of different environmental stimuli, such as colour and form, the sun and the moon, and extreme environments on human activities."[75] This research was added to by progenitors such as Egon Brunswick and Kurt Lewin who, throughout the first half of the 20th century established founding elements of what would become environmental psychology.[76] Brunswick was one of the first to argue the equal importance of the study of environments in relation to the organism being studied and believed in the ability of environments to affect subconscious processes.[77] Lewin believed that the environment was a "key determinant of behavior" and advocated for research to adopt a non-reductionist, problem-focused approach to use research to address social problems.[78] This research developed gradually, and while difficult to formalize an exact date of the origin of Environmental Psychology, 1968 saw the establishment of the first Environmental Psychology doctoral program at the City University of New York.[79]

In tandem with the growth of Environmental Psychology, critical thought against modernism became more and more prevalent. In 1977, Christopher Alexander, Murray Silverstein, and Sara Ishikawa published *A Pattern Language*. While not scientific, their work advocated for a sense of connectivity and human-centeredness in design.[80] It critiqued modernism for its focus on form, and in doing so disconnected emotion and connectiveness from design.[81] Alexander advocated for a human centered design, and linked beauty to "the profound nature (notion or quality) of inner feeling, which we connect to unconsciously."[82] Alexander argued that "experience cannot exist detached from the human perceptual system, since the effect depends upon sensory connection."[83] While formally predating concepts of Stress Recovery Theory or Attention Restoration Theory, this notion drew similar conclusions by inferring the existence of an subconscious perceptual system which processed our environments. In a later book, *Nature and Order,* Alexander described the importance of biological processes in human centered design.[84] These ideas advocated the importance of utilizing an understanding of biology in design for well-being, while advocating for a return of visual complexity and representations of nature.

In Mayer Spivack's 1984 volume *Institutional Settings: an Environmental Design Approach*, he argued that institutional settings suffered from a sensory sterility.[85] He argued that humans are naturally a stimulus-hungry species, hypothesizing that neurologically barren environments would create feedback cycles that heightened anxieties and negatively affected patients mental health.[86] Their research referenced studies in sensory deprivation that found the removal of "opportunities to "fiddle"" caused individuals to shut down and focus inwardly, with many studies finding hallucinations were common in sense-deprivation experiments.[87] While Spivack's model was limited by the neurological research of the time, it represents a powerful moment where research and experiments in environmental psychology were used to question the established modernist canon. This work represents early critical thought on the neurological consequences of modernist design principles. While not stated explicitly, the critique of sterility inferred a need for greater visual complexity as a tool for well-being.

While at this time Spivack was far from the only critic of modernism, they were foundational in establishing the link between psychology, environmental research, and the built world. While modernism continued to export the International Style, writers like Spivack were questioning the architectural impacts of sterility and its inflexibility in adapting to new findings in psychology.

As designers continued to grapple with concepts of cognition and design, environmental psychology began to take on a renewed focus centered around developing understandings of the environmental crisis. This would become the second wave of environmental psychology and was deeply rooted in environmental issues.[88] This fostered a deep interdisciplinary connection that grew in the following decades as sustainable architecture became more prevalent.

More recently however, a third wave of environmental psychology is arising, particularly focused around the neurological impact of our environments. Theories such as Stress Recovery Theory, Attention Restoration Theory, and Biophilia, all which arose in the late 20th century, have created models that seek to describe the evolutionary connections between individuals and our environments. This research has more recently been bolstered by studies in neuroscience that have utilized tools such as eye tracking, heart rate monitoring, brain scanning, and skin conductance to measure how our bodies respond to the environments around us. This has led to the development of models such as the Fractal Fluency Model, which combines research in environmental psychology and neuroscience to propose innate neural mechanisms that unconsciously process our surroundings.[89] As this research progresses, designers today are being given new ways of understanding how design decisions impact the built environment, and in turn impact the people within it. Designers such as Wark have begun to integrate understandings of Darwinian evolutionary theory, restorative frameworks, and neuroscience into design explorations. In

his work *Nadarra*, Wark explores how digital fabrication can be used to generate neurologically stimulating objects through the design of evocative installations to realize complex patterns with high levels of visual complexity.[90]

Despite decades of research in environmental psychology, it has seen extremely limited integration into design teaching or practice. With the emergence of this proposed "third wave" of environmental psychology, this thesis argues that designers today have an ethical responsibility to learn about and implement research emerging from this field. By understanding how our brains and bodies react to our environments we can generate more thoughtful, compassionate, and nourishing design. While modernists pursued design for well-being, it quickly became institutionalized and rigid. The modern glass boxes of today, and the sterile white walls that penetrate from hospitals into dwelling units, and commercial spaces, all owe their existence to outdated medical thought. Modernist principles have removed us from our ancestral environments, and produced environments devoid of visual complexity, naturalistic forms and materials, and deeply limited in colour. Designers today need to extend beyond this limited scope, to explore how modern environmental psychology can inform healthier and better designed spaces.

2.0 Restorative Frameworks

2.1 Darwinism and Environmental Psychology

To understand how architecture effects our well-being, we must understand how humans and have been shaped by their environments overtime. To create environments that are supportive of human biological needs, designers must understand how we biologically respond to our surroundings.

This research is grounded in the theory of Darwinian evolution. By understanding the evolutionary processes that created the modern human, researchers can gain insights into how environments have shaped humanity, and how in turn, human cognition has developed to respond to the world at large. I am positioning myself in a field of study that believes that through a thorough understanding of human developmental past, designers can foster environments that are physiologically nourishing and generate restorative function. Through studying the body and understanding the multigenerational lineage that have shaped the modern human, designers can craft compassionate spaces for rest. This process of listening, while intimate in the individual sense, is derived from rigorous research and scientific reasoning. While Darwinian notions of evolution are often associated with a purist notion of survival of the fittest, this notion looks not to individual differences, but to instead focus on understanding the essential relationship between all humans and their environments. Studies have found that innate preferences for nature are equally strong in both neurotypical and non-neurotypical individuals.[91] By understanding this ingrained connection between humans and their surroundings, we can gain insight into compassionate universal design for all and draw on innate and universal cognitive qualities. Importantly, this research does not advocate for a model that promotes design for a "standard body" but advocates that current design practices are discordant to all bodies and require a reevaluation that better meets the needs of all.

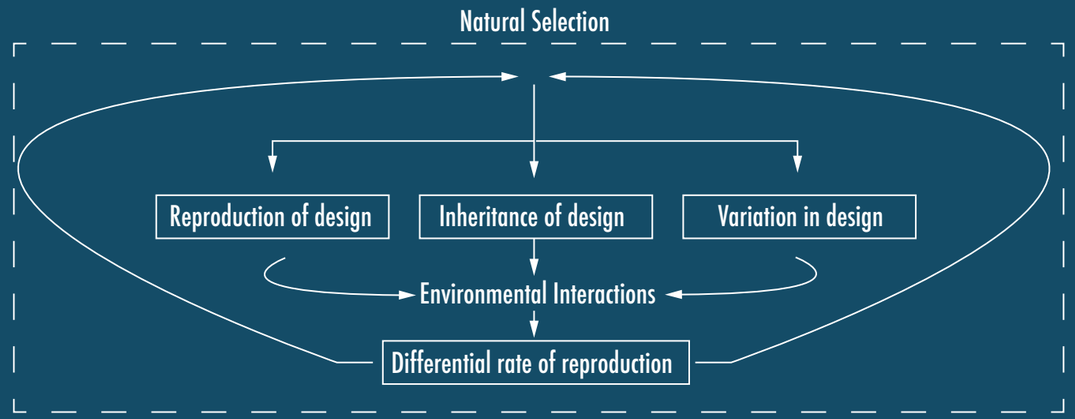


Fig 2.1.1. Natural Selection diagram. diagram by author

To understand how the environment has shaped the modern human, an understanding of Darwin's notion of evolution is required. Darwin's theory of evolution builds its logical core around the process of natural selection.[92] This process examines the role of the environment in the reproduction, inheritance, and variation of design characteristics in species, including humans.[93] This system created an outcome where individuals better suited to their environmental conditions thrived and informed the process of natural selection.[94] Through this process, humanity gradually developed in harmony with the environments it occupied.

This feedback loop, between design characteristics and environmental interactions, created a reproductive cycle that is known as natural selection.[95] These interactions led to the development of adaptations, which are a result of the coordination created by "selection as a feedback process."[96] Darwin argues that adaptations represent "evidence of special design" meaning "highly nonrandom coordination between recurring properties of the phenotype (individual organisms) and the ancestral environment."[97] The theory proposes that species and their environments share a deep link, where individuals who develop traits that help them succeed in their environments reproduce more successfuly and create a feedback loop that promotes adaptations.[98] Through this process a relationship developed that tied humanity to its surroundings, creating a relationship that shaped our cognitive processes to respond to naturalistic qualities.

Central to this thesis is understanding the role our ancestral environments played in the evolutionary adaptations that make up the human being. Natural selection as a force represents an intimate relationship between ancestral environments and the development of the modern human species.[99] For natural selection to occur, an interrelationship must be established between characteristics that

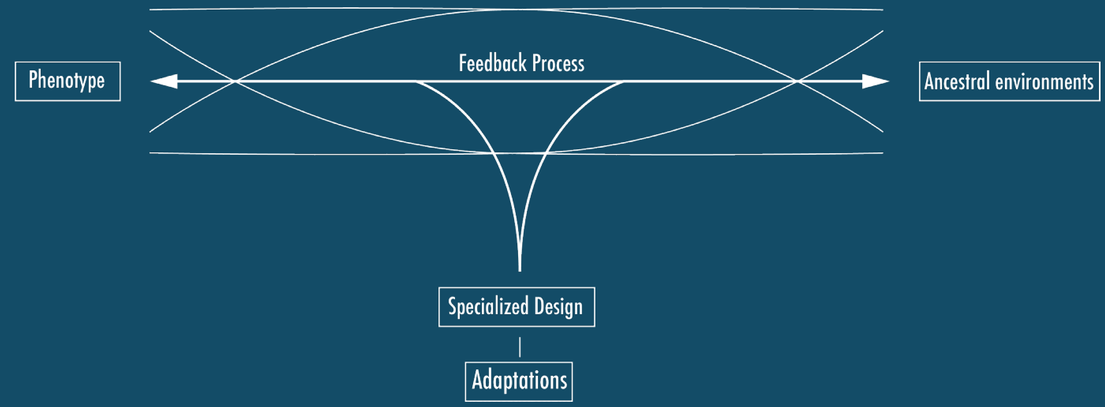


Fig 2.1.2. Adaptation diagram. diagram by author

appear cross generationally, and “stable and recurring environmental features.”[100] This interrelationship would have needed to produce a system that “systematically promoted the propagation of the genetic basis of the set of characteristics better than the alternative designs existing in the population during the period of selection.”[101]

To simplify, adaptations are the results of the interactions between members of human ancestors and their interactions with stable environments.[102] In understanding this developmental cycle, a foundational relationship can be established between environments and the development of the human species. This posits that by understanding this relationship, designers can identify what characteristics humans respond optimally to, with examples being visual complexity, specific colours, and naturalistic forms and naturalistic materials. These elements, all trace their origin back to our ancestral environments and conditions that humans evolved to respond well, and exist positively within.

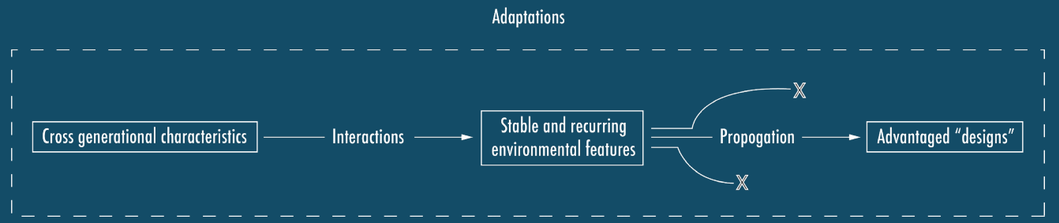


Fig 2.1.3. Adaptation process diagram. diagram by author



Fig 2.1.4. Adaptive problem diagram. diagram by author

2.2 Environments of Evolutionary Adaptation

The Environment of Evolutionary Adaptedness (EEA), first defined by John Bowlby is described as

"the ancestral environment to which a species is adapted. It is the set of selection pressures that shaped an adaptation. The EEA does not exist as a single geographical location during a discrete period of time during human evolution. Rather it is a set of selection pressures that formed a given adaptation."[103]

In essence, the EEA is a record of our ancestral environments combined into one statistical conglomerate.[104] It is the culmination of millennia of evolutionary environments which have shaped our development over deep time.[105] EEA has been criticized for its overreliance on a reference to a specific place, or typological habitat, and as a result failing to reflect the complexities of environmental variability.[106] However, this oversimplification fails to recognize that the EEA is a complex statistical composite of "structurally described contingencies of selection."[107] It is not a concept of a specific moment in evolution but alternatively represents the collective recording of all the stable environments encountered through our evolutionary processes.[108] For those reasons researchers do not look to specific plants, or particular stimuli that humans respond positively to, but instead look for trends in complexity and types of naturalistic stimuli that we may have developed particular cognitive relationships with.

As our evolutionary lineage, and indeed all organisms' lineages, date back billions of years, characterizing ancestral conditions "requires a time structured approach matching specific statistical environmental regularities against specific instances of evolutionary modification."[109] At its core, EEA, adaptations, and natural selection, require the establishment of historic equilibriums where stabilized selection could occur, and therefore establish as part of the EEA.[110]

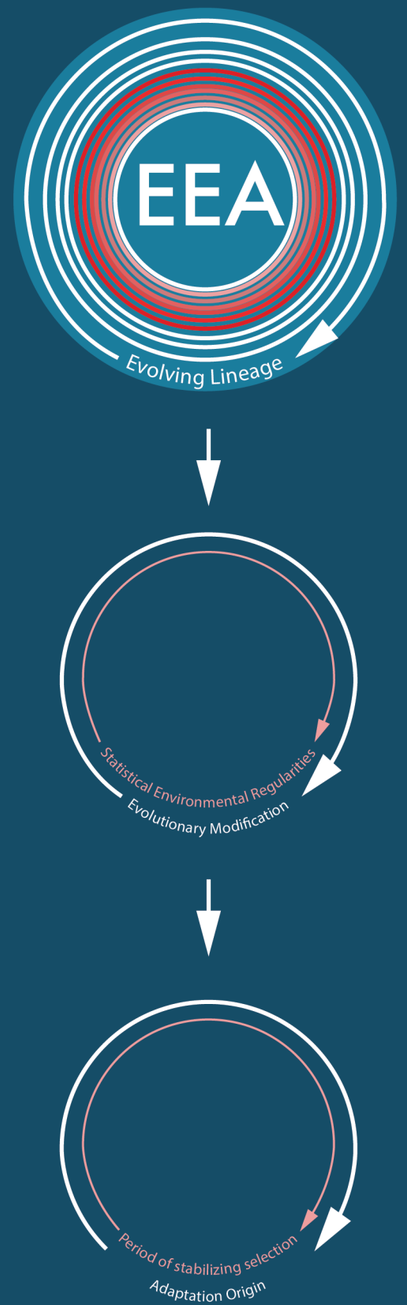


Fig 2.2.1. Environment of Evolutionary Adaptation diagram. diagram by author

It is important to establish that our current environments, if stable, represent only a single increment in the EEA of future adaptations.[111] Individuals represent a single organism which, fixed at conception, encounter our current environments (specific ontogenetic environment), and result in a set of inputs which influence future development.[112] These result in parametric inputs but do not contribute to our current evolutionary foundations.[113] It should be noted that while our current environments may not influence our genetic endowments, they do contribute to our neurological development. Studies have found individuals growing up in urban settings have an over responsiveness to stress.[114] A study by Simone Kuhn et al found that access to "enriched environments," which this study correlated to forests, led to healthier brain development than individuals who grow up in urban cities.[115] These studies support the notion that environments that overlap with periods of stability in our evolutionary past, and as such are part of the EEA, result in improved developmental outcomes, providing higher visual complexity, and naturalistic qualities.

2.3 Restorative Frameworks

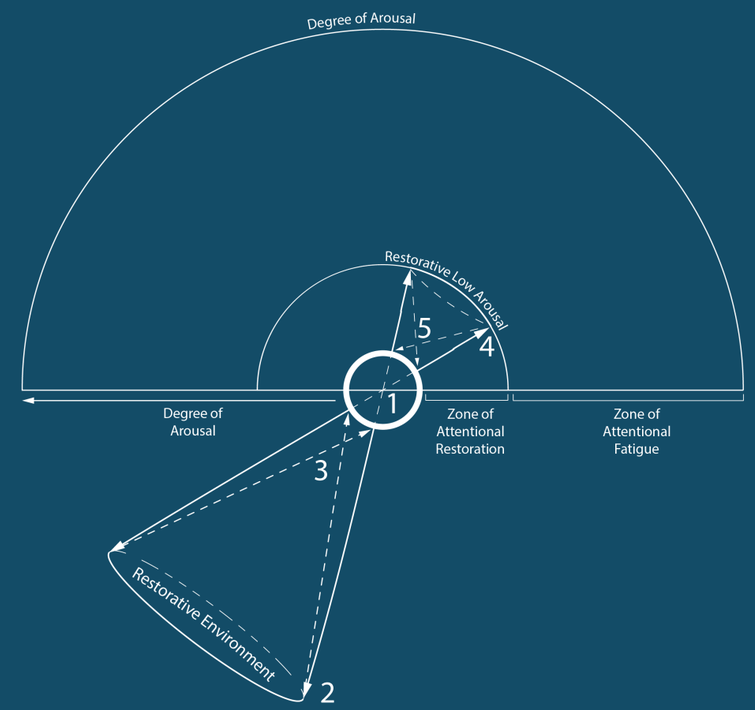
Environmental researchers have built upon Darwinian theory, proposing new psychological theories to better understand the relationships between our behaviour and our environments. Viewed through a lens of EEA, we can interpret these models as theories of cognitive adaptations that suited our ancestral environments. Biophilia was first described by Erich Fromm in *The Anatomy of Human Destructiveness* in 1973 where he defined biophilia as "the passionate love of life and of all that is alive."[116] It was later popularized by Edward O.Wilson in his 1984 publication *Biophilia* in which he described the Biophilia Hypothesis, "the idea that humans possess an innate tendency to seek connections with nature and other forms of life."[117] This broad overarching concept forms an umbrella for research focused on the connections between humans and nature. This notion has informed a series of subsequent research and has been supported by both anecdotal and qualitative evidence to demonstrate the existence of neural relationships between humans and nature. Repeatedly, research in biophilia has demonstrated faster recovery rates for patients, increased test scores, and report better improved physical and spiritual health.[118] This research has also helped to identify the key spatial contributors which impact and cause these neurological benefits, such as visual complexity and naturalistic forms and materials. Ultimately, this body of research suggested that natural environments have the potential "to restore humans in a physical and psychological manner, which is now referred to as the Stress Recovery Theory (SRT)."[119]

Stress Recovery Theory proposes that exposure to *natural stimuli* promotes "a psycho-physical well-being by activating responses at emotional, cognitive and physiological levels."[120] These activations are measured in the form of reduced heart rates, blood pressure, muscle tension, and skin conductivity."[121] These physiological responses support the notion that exposure to natural stimuli cause a direct and automatic reaction that produces a restorative effect in the body.

Ulrich argues that "evolutionary perspectives often contend that because humans evolved over a long period in natural environments, people are to some extent physiologically and perhaps psychologically adapted to natural, as opposed to urban, physical settings."[122] These physiological responses support this notion, demonstrating underlying and innate physiological responses to natural and not urban settings.

Predating SRT, Joachim F. Wohlwill suggested in 1983 that "natural content may be processed with relative ease and efficiency because the brain and sensory systems evolved in natural environments."[123] This argument synthesizes that "because this evolutionary tuning is lacking for urban or built environments, encounters with such settings place greater demands on processing resources."[124] Studies that examined "involuntary" attention, particularly in response to negative responses, such as to the presence of snakes or spiders, have shown that humans possess automatic attention or fascination responses to stressors. These responses suggest the existence of complex unconscious systems.[125] In 1990, Dimberg published a study which found exposure to positive and negative natural stimuli can measure responses in 400ms or less, suggesting rapid unconscious processing.[126]

Stress Recovery Theory: Responses to Unthreatening Environments



Stress Recovery Theory

SRT posits that environmental restoration is the result of interactions between organisms and unthreatening environments. These interactions cause low level neural arousal, which triggers innate restorative processing to increase or "restore" attentional resources.

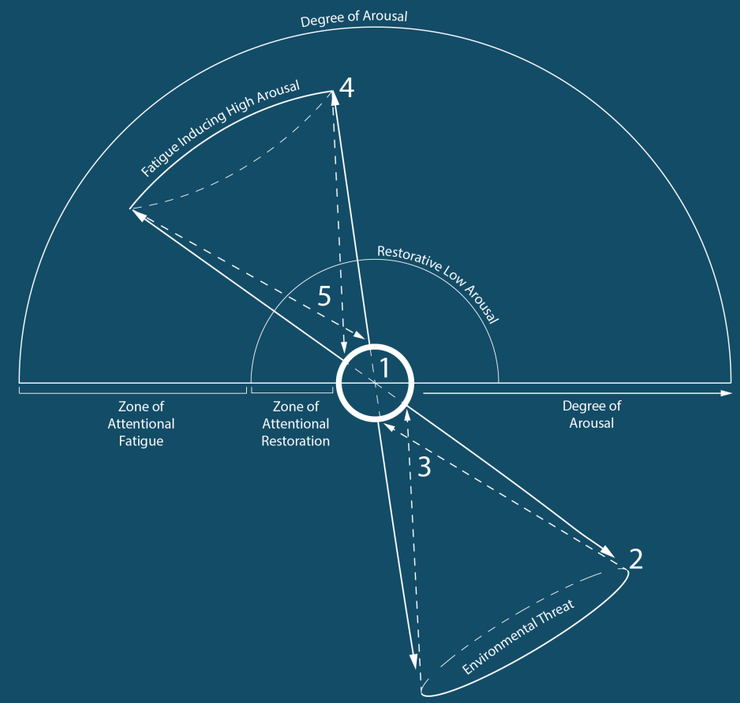
1. The ontogentic organism
2. The organism encounters an unthreatening environment
3. The brain triggers an innate unconscious immediate processing of the environmental stimuli
4. Low physiological arousal is the result of rapid environmental evaluation, such attention/interest evaluation, and positively tones emotional states, and feelings of liking
5. Low physiological arousal signals a restorative response, allowing rapid restoration

Fig 2.2.1. Stress Recovery Theory diagram depicting unthreatening environments. diagram by author

Stress Recovery Theory focuses not directly on the restorative influence of nature, but on identifying "patterns of aesthetic preference or judgments of visual quality."[127]

Built upon Ulrich's "psycho-evolutionary framework" Stress Recovery Theory "encompasses in addition to aesthetic preferences, a broad range of emotional and physiological arousal responses to natural configurations and content, including recovery and restoration."[128] SRT "postulates that immediate, unconsciously triggered and initiated emotional responses – not "controlled" cognitive responses – play a central role in the initial level of responding to nature."[129] Central to SRT is the notion that natural stimuli, whether positive or negative, illicit an immediate involuntary response.[130] This theory implies that restoration as a response to "unthreatening natural configurations" was massively beneficial as it allowed "rapid attenuation of stress responses following threatening encounters and fostering recharge of physical energy."[131] This theory then builds the logical argument that environments that contain unthreatening natural stimuli cause immediate restoration.[132] This research heavily implies that humans respond favorably to unthreatening natural environments, strongly suggesting that restoration through exposure to natural stimuli is deeply beneficial over sterile urban environments. As Darwin suggested that humans evolved to thrive in our natural surroundings, and that evolution is a long continuous process, SRT affirms that humans may beneficially access these psycho-physiological connections by surrounding themselves with stimuli that resembles their natural environment. By producing environments that more closely resemble the natural world we may trigger restorative mechanisms in our physiologically, allowing our spaces to induce rest.

Stress Recovery Theory: Responses to Environmental Threats



Stress Recovery Theory

SRT posits that environmental restoration is the result of interactions between organisms and unthreatening environments. These interactions cause low level neural arousal, which triggers innate restorative processing to increase or "restore" attentional resources. In contrast, environmental threats trigger innate responses, characterized by high levels of psychological arousal, inducing attentional fatigue.

1. The ontogentic organism
2. The organism encounters an environmental threat
3. The brain triggers an innate unconscious immediate processing of the environmental stimuli
4. High physiological arousal is the result of rapid environmental evaluation, such as triggering fear, dislike, and attention/interest evaluations.
5. High degree of arousal results in attentional fatigue

Fig 2.3.1. Stress Recovery Theory diagram depicting threatening environments. diagram by author

Attention Restoration Theory (ART) is built upon the Preference Matrix, which was introduced in 1989 by Kaplan & Kaplan. "The Preference matrix discussed how different visual aspects of an environment aim to predict preference toward a certain environment."[133] In essence, The Preference Matrix suggested that neurologically, our brains unconsciously scan our environments to determine their suitability for habitation.[134] This matrix defined four factors for predicting preference which include coherence, complexity, legibility, and mystery.[135] Attention Restoration theory, defined by Kaplan in 1995, and building upon the initial Preference Matrix, sought to propose that nature had the potential to be restorative.[136] ART described the existence of voluntary and involuntary attention. Voluntary, or directed attention, represents a limited resource which can be depleted through tasks that required active participation and concentration.[137] This depletion is referred to as attentional fatigue. Inversely, involuntary attention requires no effort.[138] This effortless stimulus is described as soft stimuli, which provides space for reflection, which theoretically provides a space to replenish attention.[139] Kaplan proposes clouds, sunsets, snow patterns, and motion in leaves as soft stimuli, all elements which contain a high visual complexity.[140] The primary differentiator between SRT and ART is the role of consciousness in restoration. While SRT focuses primarily on the underlying subconscious mechanisms, ART asserts that reflection, and conscious attention, plays a significant role in the replenishing characteristics of natural stimuli.

Attention Restoration Theory: Soft Stimuli Interactions

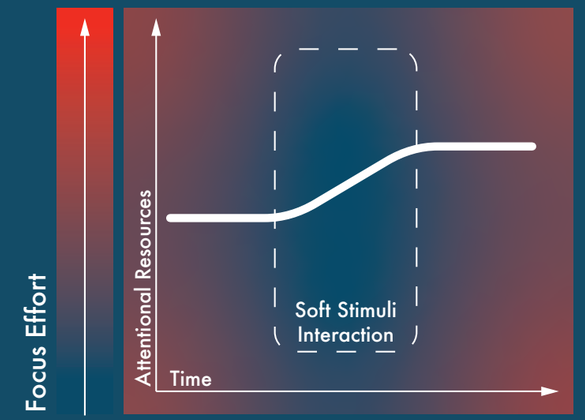


Fig 2.3.2. Attention Restoration Theory soft stimuli diagram. diagram by author

Attention Restoration Theory: Directed Attention Interactions

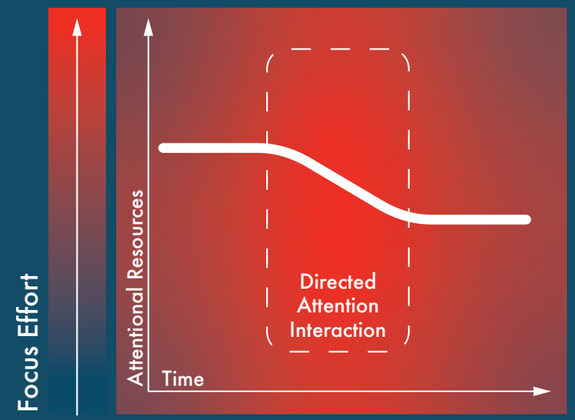
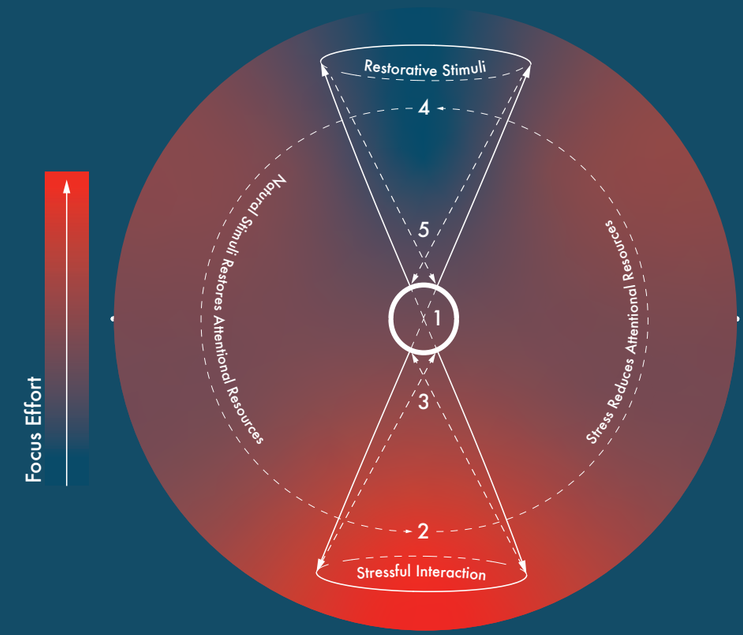


Fig 2.3.3. Attention Restoration Theory directed attention theory diagram. diagram by author

While ART and SRT disagree on the role attention plays in the restorative process, both present frameworks for nature providing a restorative function.[141] Lemmens argued for an integrated framework noting "an integrated framework shows that stress impacts attention by declining attentional performance and limits attentional resources, while reducing attentional resources create a response that could be interpreted as stress."[142] Lemmens added that "both theories explain a preference of humans for nature over urban scenes."[143]

Many studies have attempted to identify what characteristics present in nature correlate to positive preferences and restorative effect. Studies have found that a preference for perceived naturalness is an important component.[144] Higher naturalistic qualities were preferred over scenes which possessed a higher degree of artificial qualities. Additionally, organized complexity, which researchers such as Nikos A. Salingaros and Richard Taylor have begun to correlate to "fractal-like" patterns has been identified as having a strong automatic preference in humans.[145] The presence of fractal patterning producing higher levels of visual preference, as well as displaying measurable reductions of heart rate and body temperature, suggest an innate restorative effect.[146]

Integrated Framework for Restoration



Integrated Framework

1. The ontogentic organism
2. The organism encounters a "stressor"
3. The brain triggers an innate unconscious immediate processing of the environmental stimuli which expend attentional resources.
4. The organism encounters a restorative environments
5. The brain triggers innate unconscious processing of this stimuli, processing it effortlessly, and inducing a state conductive to attentional restoration.

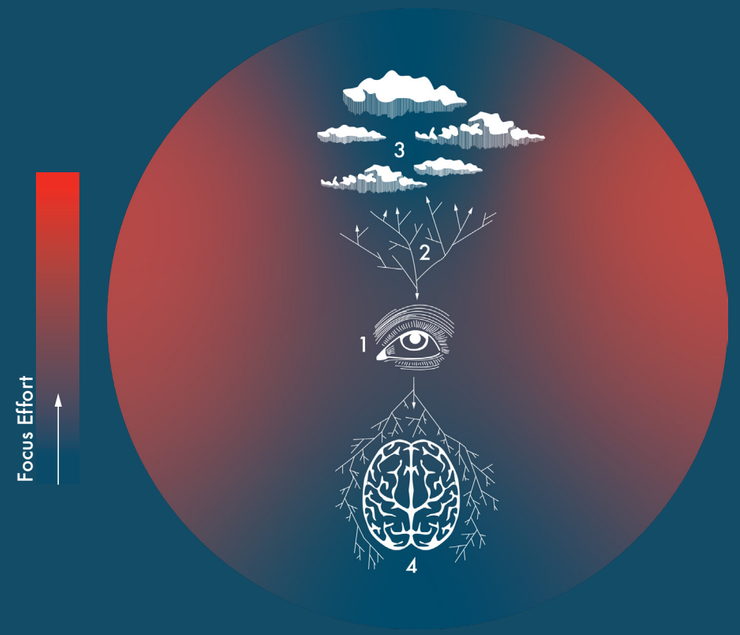
Fig 2.3.4. Integrated restorative framework diagram. diagram by author

Fractals, which are patterns in which each part follows the same statistical characteristics as the whole, contain recurring patterns which progressively repeat at smaller scales.[147] These patterns do not appear as perfect fractals in nature, but rather in the form of statistical similarity, in which features contain self-similar elements.[148] These fractal patterns are most common among trees, clouds, mountains, and geologic features, building a strong argument for the importance of naturalistic forms *and* materials.[149] Cumulative research has identified that humans tend to prefer mid-D fractals, or fractals containing a moderate level of complexity.[150]

The fractal fluency model "states that human vision has adapted to process these mid-range fractals with ease."[151] Studies have shown that these ingrained mechanisms generate aesthetic experience and physiological stress reduction.[152] Further evidence of the fractal fluency model can be seen in a NASA-funded study which measured the physiological signs of stress exhibited by participants in a mock-up space laboratory.[153] Participants alternated between periods of conducting stress inducing tasks and recovery periods, with research finding that participants who viewed mid-D fractals indicated a stress reduction of 60%.[154]

Eye motion studies have found that both neuro-typical and neuro-divergent individuals unconsciously traced fractal trajectories in a process defined as fractal gaze dynamics.[155] This suggests "fractal motion is intrinsic to eye-motion and is not modified by higher level processing in the visual system."[156] Taylor suggests that this system allows the eye to search through scenery to confirm fractal character.[157] This is theorized to evolutionarily support foraging behavior, in that it allows the identification of food and threat detection.[158] Further evidence of the fractal fluency model can be

Fractal Fluency Model: Interactions With Fractal Stimuli



Fractal Fluency Model

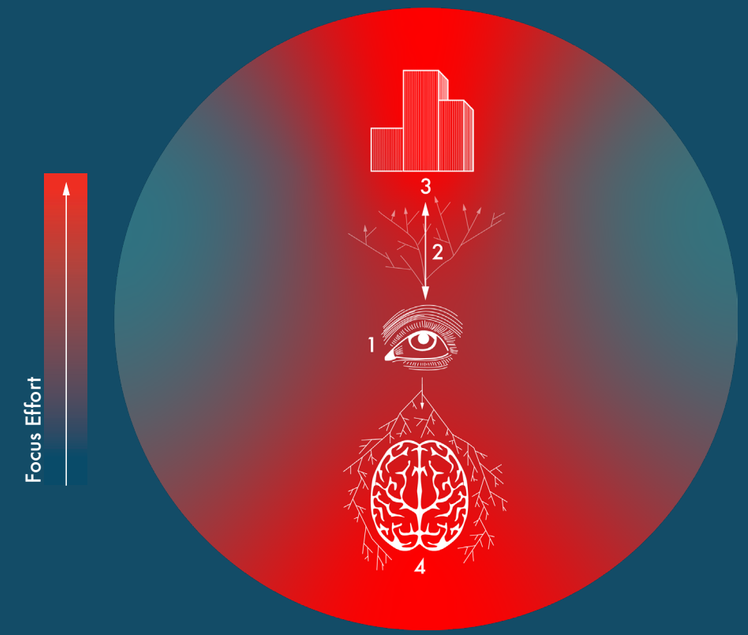
1. The human eye
2. The human eyes scans the environment through fractal motion known as fractal gaze dynamics.
3. Fractal environmental stimuli (such as trees, clouds, and mountains)
4. The brain receives signals from the eye, and processes it through the visual cortex. These "pathways" match the prominent complexity of fractals that dominate the environment. The information is fractally processed through simultaneous synthesis.

This process results in "effortless looking, which is effective for survival as it allows rapid identification of non-fractal forms such as animals, which switch to mechanisms of focused attention.

Fig 2.3.5. Fractal Fluency diagram depicting fractal interactions. diagram by author

seen in neurological processing in the visual cortex.[159] This area of the brain consists of a series of "virtual "pathways" that process scenic information."[160] The distribution of these pathways match the complexity values dominant in natural environments.[161] These pathways allow a "fractal processing that makes use of fractal images stored in our memories by utilizing simultaneous synthesis (an integration of current perceptual information with long-term memory)."[162] From an evolutionary perspective this model suggests the presence of an underlying unconscious physiological mechanism that processes fractal stimuli, enabling an "effortless looking."[163] This system however means that non-natural environments require conscious processing.[164] While evolutionarily advantageous, it has led to an overuse of focused attention in urban environments, which are largely devoid of fractal character or naturalistic qualities, and as a result increases attentional strain and risk of negative health outcomes.[165]

Fractal Fluency Model: Interactions With Urban Environments



Fractal Fluency Model

1. The human eye
2. The human eyes scans the environment through fractal motion known as fractal gaze dynamics, but encounters non-fractal stimuli, triggering mechanisms of focused attention.
3. Non-fractal stimuli, which evolutionarily consisted of animals and elements of environmental importance, is now also prominent in urban environments.
4. The brain receives signals from the eye, and processes it through the visual cortex. The detection of non-fractal stimuli activates focused attention and induces focused effort.

Fig 2.3.6. Fractal Fluency diagram depicting urban interactions. diagram by author

2.4 Spatial Frameworks for Well-being

The Biophilic Healing Index, first published in the *Journal of Biourbanism* in 2019, by Nikos A. Salingaros, seeks to predict what characteristics in our urban environment provide positive effects to our well-being. Based on decades of research, the index provides a methodology for applying research in environmental psychology to design for our built environments.[166] The goal of this index was to provide a framework for predicting the positive healing effects of spaces and structures before construction.[167] Importantly, the biophilic healing index identifies positive effects as being derived from both "close proximity and visual contact with plants, animals, and other people," and "positive response to artificial creation that follow geometrical rules for the structure of organisms."[168] This index argues that "the complex geometry of the environment is responsible for the biophilic effect."[169] In quantifying these features, ten components are listed including sunlight, colour, gravity, fractals, curves, detail, water, life, representations of nature, and organized complexity.[170] Each element references a characteristic found in nature and presents simple elements that can be intentionally designed for and implemented. Regarding the goal of artificial design, Salingaros expounds that

"the intended effect duplicates the positive healing feedback that a user experiences from living matter. Designers create shapes that trigger the same sensation as biological forms, but without necessarily mimicking them."[171]

Evidence for the positive effect of introducing *visual complexity* can be found in studies focused on "organized-complexity."[172] Studies have found that "enriched environments" produce enhanced brain development in animals, and has been supported by studies indicating "healthy brain development of children living near green spaces."[173] Notably, these studies found a high degree of correlation among children living near forests but not urban green space, the

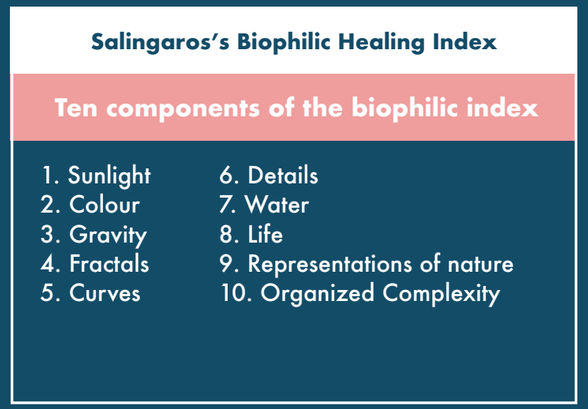


Fig 2.4.1. Biophilic Healing Index component diagram. diagram by author adapted from Salingaros, Nikos A. The Biophilic Index Predicts Healing Effects of the Built Environment. 8, no. 1 (2019).

key differentiation being the lack of organized-complexity in urban parks, which contained primarily green lawn with isolated foliage.[174] While this Index focuses more on a holistic building approach with characteristics such as ensuring natural light enters from at least two sides of a room, the presence of curves in the architectural form, and the presence of water, it also addresses the importance of minutia in the design of biophilic spaces.[175] Specifically, the index focuses on the importance of colour on mood alteration, the presence of fractals, and details (such as natural materials like wood, limestone, and coloured marble). Representations of nature are highlighted as being important to activating subconscious neural mechanisms.[176] Salingaros acknowledged that the index is not an irreducible set of biophilic qualities, but offers a "useful checklist that architects can use for improving their designs before implementation."[177] This framework provides a well-rounded summary of biophilic research and presents a logical framework for restorative design characteristics that reflect research in neural-architectures.

Kellert's Experiences and Attributes of Biophilic Design presents an alternate framework for well-being design. Built upon the same foundational theories as the Biophilic Healing Index, it presents twenty four elements associated with the application of biophilic design.[178] These elements are divided between three categories, direct experience of nature, indirect experience of nature, and experience of space and place.[179] Direct experience of nature references physical contact with "natural elements" such as "natural light, air, plants, animals, water, landscapes, fire, and weather."[180] While abstract, they highlight the importance of architecture's responsibility to integrate, exist among, and foster environmental relations, rather than erase ecology.[181] Indirect experiences of nature in contrast, focus on methods which evoke a sense of nature, such as "images of nature, natural materials, natural colours, simulating natural light and air, naturalistic shapes and forms, evoking nature, information richness, age, change and patina of time, natural geometries, and biomimicry.[182] These evoke methods of making and materiality, which describe the importance of our built environments reflecting qualities of nature, rather than contrasting our natural environments. Experience of space and place is much more esoteric in space making but refers to architectural characteristics such as a sense of prospect and refuge, wayfinding, and cultural and ecological attachment to place.[183] These twenty four elements define ways in which architecture can engage with biophilic design, and offer a robust window into the characteristics of biophilic incorporated design. Essential to this framework is the belief that

"aesthetically attractive nature particularly arouses our interest, curiosity, imagination, and creativity. By contrast, when we lack visual contact with the natural world, such as a windowless and featureless space, we frequently experience boredom, fatigue, and in extreme cases physical and psychological abnormality."[184]

Kellert's Experiences and Attributes of Biophilic Design

Direct Expereiences of Nature	Indirect Experiences of Nature	Experiences of Space and Place
01. Light 02. Air 03. Water 04. Plants 05. Animals 06. Weather 07. Natural Landscapes and Ecosystems 08. Fire	09. Images of Nature 10. Natural Materials 11. Natural Colours 12. Simulating Natural Light and Air 13. Naturalistic Shapes and Forms 14. Evoking Nature 15. Informational Richness 16. Age, Change, and Patina of Time 17. Natural Geometries	19. Prospect and Refuge 20. Organized Complexity 21. Integration of Parts to Wholes 22. Transitional Spaces 23. Mobility and Wayfinding 24. Cultural Ecological Attachment to Place

Fig 2.4.2. Experiences and Attributes of biophilic design attributed diagram. diagram by author adapted from Kellert, Stephen R, and Elizabeth F Calabrese. "The practice of biophilic design," 2015.

This framework, while acknowledging a vast number of influential characteristics, contains a striking overlap with Salingaros's Biophilic Healing Index. Representations of nature are clearly highlighted, the importance of colour is reinforced once again, though distinctly focused on the importance of "earth" tones characteristic of "soil, rock, and plants."[185] Natural materials are highlighted for their ability to be visually stimulating and evoke tactile responses.[186] Naturalistic shapes and forms as well as evoking nature, encompass the importance of patterns which mimic and resemble the natural world. Information richness, while not heavily expanded, suggests an overlap to the fractal qualities of the Biophilic Healing index. Finally, natural geometries and biomimicry draw direct connections to the natural world.[187] While organized complexity is referenced in both models, Kellert's model focuses on the importance of balancing coherence and variability and diversity.[188] This framework ultimately exists as a tool to advocate "ecologically interrelated design solutions at multiple scales from distinct interior spaces, the building as a whole, the surrounding landscape, to the urban and bio-regional scale."[189] While it exists as a practical methodological tool, the authors focus on the need for a "new consciousness toward nature as much as implementing a new design technique."[190] This focus highlights the importance of a foundational architectural shift away from the anthropocentric sterility of modernism, toward an ecologically conscious integrated ecocentrism.

Terrapin Bright Green is an "environmental consulting and strategic planning firm" that has developed its own internal model known as the 14 Patterns of Biophilic Design.[191] The paper defines its patterns as deriving from "over 500 publications on biophilic responses" which were "mined to uncover patterns useful to designers of the built environment."[192] Similar to Kellert's model, the 14 patterns are organized into three categories, Nature in the Space Patterns, Natural Analogues Patterns, and Nature of the Space Patterns.[193] Nature in the Space "addresses the direct, physical, and ephemeral presence of nature in a space or place."[194] Nature in the Space Patterns includes, visual connection with nature, non-visual connection with nature, non-rhythmic sensory stimuli, thermal & airflow variability, presence of water, dynamic & diffuse light, and connection with natural systems.[195] While its list differs from Kellert's exact descriptions, It closely resembles the direct experiences of nature model. More experiential in description, the elements describe the importance of physical connection to the actual natural world.[196] Natural Analogues in contrast refers to "organic, non-living, and indirect evocations of nature."[197] Natural analogues patterns include biomorphic forms & patterns, material connection with nature, and complexity & order.[198] These elements reflect Kellert's indirect experiences of nature and refer to man-made artifacts that evoke a sense of nature through intentional design decisions. Terrapin's model specifically references the importance of furniture, décor, and textiles in the built environment.[199] Nature of the Space "addresses spatial configurations in nature."[200] This model discusses the importance of integrating spatial concerns and draws largely from Prospect Refuge Theory.[201] Nature of the Space patterns includes prospect, refuge, mystery, and risk/peril.[202] These elements present another robust system, drawing complex characteristics into simple systems for integration. Unlike the other two systems, Terrapin's model references specific studies for each element and summarizes evidence for each model. Perhaps the most robust model, it synthesizes numerous studies into simple referenceable sheets with simple implementation plans.

Terrapin's 14 Patterns of Biophilic Design

Nature in the Space Patterns	Natural Analogues Patterns	Nature of the Space
1. Visual Connection with Nature 2. Non-Visual Connection with Nature 3. Non-Rhythmic Seonsory Stimuli 4. Thermal & Airflow Variability 5. Presence of Water 6. Dynamic & Diffuse Light 7. Connection with Natural Systems	8. Biomorphic Forms & Patterns 9. Material Connection with Nature 10. Complexity & Order	11. Prospect 12. Refuge 13. Mystery 14. Risk/Peril

Fig 2.4.3 Terrapin's 14 Patterns of Biophilic Design components diagram. diagram by author adapted from Browning, William, Catherine Ryan, and Joseph Clancy. "14 Patterns of Biophilic Design: Improving Health & Well-Being in the Built Environment." Terrapin Bright Green LLC., 2014.

2.5 Proposed Framework for Restorative Design

While each framework explored in the previous sections represents different interpretations of research in biophilic design, significant overlap exists between each model. While direct experiences of nature are deeply important, this thesis refines its scope to a focus on spatial interventions that work within existing interior spaces, so will be largely unrepresented in the proposed design model. Of particular interest is understanding how advancements in digital fabrication can inform and enable design which better aligns to these models, generating stimuli that has potential for stress reduction. As a result, a new framework must filter for characteristics which have direct interior application. Fig 2.5.1 below illustrates how overlapping characteristics have been filtered and categorized. These characteristics were organized into distinct elements which inform design interventions into interior spaces. From these exercises a series of metrics have been described, which inform all artifacts created in this thesis. These characteristics are listed as integration of natural materials, evocation of naturalistic forms, presence of colour, visual complexity and sense of time. This model differentiates itself by refining its scope to the production of design interventions which augment sterile interior spaces. This model particularly focuses on what characteristics designed artifacts should embody to produce restorative environments.

Framework For Artifact Fabrication

Proposed Metric	Salingaros	Kellert	Terrapin
Integration of Natural Material	N/A	Natural Materials	Material Connections with Nature
Evocation of Naturalistic Forms	Representations of nature + curves + fractals	Natural geometries + shapes and forms + Evoking Nature	Biomorphic Forms and Patterns
Presence of Colour	Colour	Colour	Material Connections with Nature
Visual Complexity	Organized Complexity	Informational Richness	Organized Complexity + Complexity and Order
Sense of Time	N/A or Life?	Age, Change and Patina of Time	Connection With Natural Systems

Fig 2.5.1. Artifact framework. diagram by author

Integration of natural materials:

This combines Kellert's characteristics of Natural Materials with Terrapin's Material Connection with Nature. These materials carry associations with additional characteristics such as Biomorphic Forms & Patterns, Notions of Complexity and Order, Sense of Age, Change, Patina of Time, and Natural Geometries. While wide encompassing, this characteristic relays the importance of utilizing materials that have natural characteristics and trigger low arousal neural stimulation. Equally this characteristic advocates the avoidance of flat, texture-less materials that cause a neurological discord. Evidence for the importance of natural materials can be found in studies by Tsunetsugu, Miyazaki and Sato, which identified that natural materials result in decreased diastolic blood pressure and increased comfort.[203] The study tested occupants physiological signs of restoration in rooms of 0%, 45% and 90% wood coverage.[204] While the room with 0 wood coverage indicated no blood pressure change, the other two conditions showed significant reductions in blood pressure.[205] The room with 90% wood coverage was reported as providing too much information and reduced cerebral activities. This research suggests that a balanced use of natural material is beneficial to restorative function.[206] Two additional studies by Tsunetsugu, Miyazaki, and Sato found that direct exposure to forests resulted in reductions in pulse rate, diastolic blood pressure, and showed that the prefrontal region of the brain is calmer in forest environments in comparison to city environments. [207] This research ultimately supports the notion that natural materials cause a restorative response, reducing physiological signs of stress and improving comfort.

Integration of Natural Materials

Framework	Salingaros	Kellert	Terrapin	Supported Research
Primary Characteristics	N/A	Natural Materials	Material Connections with Nature	Tsunetsugu, Yuko, Yoshifumi Miyazaki, and Hiroshi Sato. "Physiological Effects in Humans Induced by the Visual Stimulation of Room Interiors with Different Wood Quantities." Journal of Wood Science 53, no. 1 (February 2007): 11–16. https://doi.org/10.1007/s10086-006-0812-5. Tsunetsugu, Yuko, and Yoshifumi Miyazaki. "Measurement of Absolute Hemoglobin Concentrations of Prefrontal Region by Near-Infrared Time-Resolved Spectroscopy: Examples of Experiments and Prospects." Journal of PHYSIOLOGICAL ANTHROPOLOGY and Applied Human Science 24, no. 4 (2005): 469–72. https://doi.org/10.2114/jpa.24.469.
Secondary Characteristics	Organized complexity + Detail + Life	Organized complexity, Age, change, and patina of time, natural geometries	Biomorphic forms and patterns + Complexity and Order	

Fig 2.5.2. Integration of Natural Materials diagram. diagram by author

Evocation of Naturalistics forms:

This catagory was informed by Terrapin's characteristic of Biomorphic Forms Patterns, Kellert's Naturalistic Shapes and Forms, Evoking Nature, and Natural Geometries, and Salingaros's Representations of Nature, Curves, and Fractals. This catagory attempts to combine these into a clean definition, of developing forms which evoke nature and advantageously draw on digital fabrication's ability to generate visually complex geometries.

In 1983, Roger Ulrich proposed that modernist environments may trigger negatively toned feelings and cause associated stress-related endocrinal reactions.[208] Russ Parsons later in 1991 argued that these negative responses, while unnoticed due to regular habitation in these environments, may have cause long term stress reactions with severe health affects.[209] This potential long term health effect is supported by increased rates of stress related illness seen in urban populations, as well as a study by Kuhn et. al which found humans who live in urban environments possess an over responsiveness to stress.[210] Cumulatively, these studies have built a strong argument that urban environments cause adverse health effects, specifically related to physiological stress responses.

In a paper published in 1982 by Thomas R. Herzog, Stephen Kaplan & Rachel Kaplan, they found that empirical evidence supported that a presence of balanced application of complexity and coherence contributed to aesthetic qualities of built settings.[211] A study in 2004 by Hagnerhall, Purcell, & Taylor found that preferences for natural settings are predictive based on geometrical characteristics.[212] This informed the notion that abstractions from nature can infer the same associated positive effects as natural geometries. These studies were important in helping to understand the role of complexity in neural processing.

EVOCATION OF NATURALISTIC FORMS

Framework	Salingaros	Kellert	Terrapin	Supported Research
Primary Characteristics	Representations of nature + curves + fractals	Natural geometries + shapes and forms + Evoking Nature	Biomorphic Forms and Patterns	Kühn, Simone, Sandra Düzel, Peter Eibich, Christian Krekel, Henry Wüstemann, Jens Kolbe, Johan Martensson, et al. "In Search of Features That Constitute an 'Enriched Environment' in Humans: Associations between Geographical Properties and Brain Structure." Scientific Reports 7, no. 1 (September 20, 2017): 11920. https://doi.org/10.1038/s41598-017-12046-7. Herzog, Thomas R., Stephen Kaplan, and Rachel Kaplan. "The Prediction of Preference for Unfamiliar Urban Places." Population and Environment 5, no. 1 (March 1982): 43–59. https://doi.org/10.1007/BF01359051. Brown, Daniel K, Jo L Barton, and Valerie F Gladwell. "Viewing Nature Scenes Positively Affects Recovery of Autonomic Function Following Acute-Mental Stress." Environmental Science, n.d. Chatterjee, Anjan, Alex Coburn, and Adam Weinberger. "The Neuroaesthetics of Architectural Spaces." Cognitive Processing 22, no. 1 (August 27, 2021): 115–20. https://doi.org/10.1007/s10339-021-01043-4.

Fig 2.5.3. Evocation of Naturalistic Forms diagram.
diagram by author

A study in 2013 by Brown, Barton, and Gladwell, found that even images of nature illicit physiobiological signs of stress reduction.[213] This research was extended by a study in 2019 that found "nature-like patterns explained most of the variance in preference ratings of both architectural facades and interior scenes, even after controlling for the amount of actual vegetation visible in each scene." This suggests that "implicit naturalness" in architectural environments plays an equally important role to "explicit natural elements."[214] Collectively, this research built a strong foundation to affirm that naturalistic forms provide positive benefit over more traditional urban environments.

Another emerging concept in perceived naturalness is the notion of fractal complexity. Clearest in the fractal fluency model, this model suggests that naturalistic forms with fractal qualities are responsible for the majority of biophilic restorative response.[215] In a 2012 publication in the *Journal of Biourbanism* Salingaros argued that "human beings seem naturally attuned to a visual signal of fractal character and particular fractal dimension. The brain is constantly computing characteristics of our environment, evaluating features that are essential for our survival, so this resonance has deep meaning."[216] In line with the Darwinian model of evolution, studies in environmental psychology and neuroscience have found significant evidence to support that fractal stimuli activate psychophysiological mechanisms that trigger restorative effect.

Studies in neuroscience have identified both that our visual system is proficient at "grouping together repeated elements and processing fractals automatically and fluently."[217] Additionally, under MRI Tsunetsugu and Miyazaki documented neurons in the primary visual cortex displaying preferential responses to fractal stimuli.[218] This research ultimately supports the notion that the symbolic and literal presence of naturalistic forms can activate restorative mechanisms in our bodies.

Presence of Colour:

Studies by Jacobs and Hustmyer in 1974, and Kurt and Osueke in 2014 found many bright intense colours positively affect mood.[219] A research review by Rikard Kuller and Byron Mikellides concluded that our bodies exhibit automatic responses to color stimulation, such as a change in blood pressure, skin conductance, or respiration rate, all of which align with theories of Darwinian models of evolutionary adaptations.[220] Current colour research is limited, but several key takeaways influence design. The colour red has been found to activate high levels of psychological arousal, the primary theory being that red is "by far the most common color signal in nature."[221] As red commonly appears in nature in both positive and negative contexts, examples being edible berries, poisonous animals, and blood, the colour itself does not necesarily contain an evaluation of the stimuli.[222] This means that while red may not naturally be associated with being positive or negative, it does active an immediate hieghtened arousal.[223] Saturation in general has been found to increase arousal, so more saturated hues will increase arousal.[224] While not well understood, a study by Lichtenfeld et.al. found that the colour green "facilitates creative performance but has no influence on analytical performance."[225] Another study found that humans can distinguish more variations in the color green than any other color.[226] Cumulatively, these studies support an evolutionary connection to colour, where evidence for automatic processing suggests we are well attuned to distinguish greens, the most common natural colour, and to search for saturation and specific colours for sustenance and survival. These elements, while not fully understood, support the use of natural tones to avoid high arousal and support passive, non-directed visual processing.

Presence of Colour

Framework	Salingaros	Kellert	Terrapin	Supported Research
Primary Characteristics	Colour	Colour	Material Connections with Nature	Jacobs, Keith W., and Frank E. Hustmyer. "Effects of Four Psychological Primary Colors on GSR, Heart Rate and Respiration Rate." Perceptual and Motor Skills 38, no. 3 (June 1974): 763–66. https://doi.org/10.2466/pms.1974.38.3.763 Küller, Rikard, Byron Mikellides, and Jan Janssens. "Color, Arousal, and Performance–A Comparison of Three Experiments." Color Research & Application 34, no. 2 (April 2009): 141–52. https://doi.org/10.1002/col.20476. Lichtenfeld, Stephanie, Andrew J. Elliot, Markus A. Maier, and Reinhard Pekrun. "Fertile Green: Green Facilitates Creative Performance." Personality and Social Psychology Bulletin 38, no. 6 (June 2012): 784–97. https://doi.org/10.1177/0146167212436611.

Fig 2.5.4. Presence of Colour diagram. diagram by author

Visual Complexity:

This element draws together Salingaros's organized complexity, Kellert's informational richness, and Terrapin's organized complexity and Complexity and Order elements. While the field is somewhat ill-defined, Salingaros argues that results from a 2019 study by Coburn et al. supports Christopher Alexander's research in naturalness being a high predictor of visual preference. Salingaros argued that this research could be applied to support organized-complexity as a requirement for perceived naturalness.[227] Another study in 2012 by Mehaffy and Salingaros found that "enriched environments" led to enhanced animal brain development, elaborating the research could likely apply to humans.[228] A study done by Kuhn et al. in 2017 found that children who lived near forests (environments with a high degree of organized complexity) exhibited healthier brain development.[229] While the correlation was strong among those living near forests, the correlation was weak in children surrounded by urban green areas, which exhibit low degrees of organized-complexity.[230] When extrapolated, this study is perhaps the strongest indicator that complexity plays a significant role in neurological development.

Visual Complexity

Framework	Salingaros	Kellert	Terrapin	Supported Research
Primary Characteristics	Organized Complexity	Informational Richness	Organized Complexity + Complexity and Order	Chatterjee, Anjan, Alex Coburn, and Adam Weinberger. "The Neuroaesthetics of Architectural Spaces." Cognitive Processing 22, no. 1 (August 27, 2021): 115–20. https://doi.org/10.1007/s10339-021-01043-4. Kühn, Simone, Sandra Düzel, Peter Eibich, Christian Krekel, Henry Wüstemann, Jens Kolbe, Johan Martensson, et al. "In Search of Features That Constitute an 'Enriched Environment' in Humans: Associations between Geographical Properties and Brain Structure." Scientific Reports 7, no. 1 (September 20, 2017): 11920. https://doi.org/10.1038/s41598-017-12046-7. Taylor, Richard. "The Potential of Biophilic Fractal Designs to Promote Health and Performance: A Review of Experiments and Applications." Sustainability 13, no. 2 (2021). https://doi.org/10.3390/su13020823

Fig 2.5.5. Visual Complexity diagram. diagram by author

Sense of Time:

This characteristic is only explicitly identified in Kellert's *Experience and Attributes of Biophilic design* model in the form of "Age, change, and the patina of time."[231] This attribute specifically advocates for the use of materials and symbolism that evoke the dynamic forces of aging and changing.[232] Examples include the use of naturally aging materials, weathering, or textures and symbols that create a sense of time.[233] While not explicitly present in Salingaros's or Terrapin's model, both present parallels. For example, Salingaros compares his characteristic *life* to being comparative with Terrapin's visual and non visual connections with nature characteristics, which age, change and patina of time is one element within the category.[234] Life, while wide encompassing, draws on a notion of providing living stimuli and engagement with spaces and stimuli that change over time and throughout the day.[235] Unfortunately, little empirical evidence supports the integration of allusions to changes in time, however, Kellert, Salingaros, and Terrapin's models all relate a sense of changing time as contributing to biophilic effect. While not currently well understood, *sense of time* is included in this framework as an additional call to action to evoke forces of nature, and connect with natural elements. Due to the static nature of the artifacts produced, sense of time was largely explored through symbolism in the generated stimuli.

Taken together, each element forms an essential piece of the proposed framework, drawing together and synthesizing research into tangible design decisions. Through better understanding the origins of these design philosophies, and by rigorously evaluating the contemporary research in restorative design, this framework proposes a series of key characteristics that influence restorative design. By adopting the same rigour of early modernists, but with a renewed understanding of research in psychology and physiology, we can transform the characteristic interiors of today into nourishing enriching and compassionate spaces.

Sense of Time			
Framework	Salingaros	Kellert	Terrapin
Primary Characteristics	Life	Age, change, and the patina of time	Material Connections with Nature (extrapolated)

Fig 2.5.6. Sense of time diagram. diagram by author

3.0 Methodology

3.1 Restorative Aesthetics

When confronting the question of defining the form of restorative aesthetics, several key elements influenced the design of the artifacts proposed. The first, is an acknowledgment of a deep historical lineage in the utilization of naturalistic forms in architectural history. Transcending any particular culture, architectures were rife with depictions of nature. These depictions vary greatly from direct depictions of nature, to complex geometries such as Celtic knots Middle Eastern mishriyabas, and Mediterranean foliated scrolls. These practices all present a lineage that can be re-adopted, re-interpreted, or transformed with new technological tools and methods. Nature inspired geometries remained an almost architectural constant until modernism, as illustrated by fig 3.1.1 depicting column capitals through time.[236]

As technology has continued to evolve, digital fabrication and big data gathering have allowed the fabrication of complex geometries to become continuously more economically viable.[237] While not yet at widescale adoption, the promise of additive manufacturing envisions a technological future where complexity is no longer an economic factor in fabrication. As we move toward that world, designers must grapple with the question of what naturalistic design looks like today. For the purposes of this thesis, that question is answered through a technological approach. The tools utilized to generate visual complexity are taken directly from nature, in the form of LiDAR data collection, and photogrammetry tools. These tools allow the translation of naturalistic form, not from abstraction, but from the translation of natural stimuli directly to form through various filtered processes. These resolution filters naturally change the initial data, and through digital and physical fabrication processes lend a distinct visual fingerprint to the final artifacts. These layers informed the rest of the design process, which work within the limitations of the fabrication process to produce evocative artifacts. For the purposes of these artifacts, they adopt a philosophy much closer to the Renaissance



Egyptian Temple of Edfu: 237-57 BCE



Roman Pantheon: 118-128 AD



Southwell Minster Foliated Captial: 13th century



Southwell Minster Foliated Captial: 13th century

Fig 3.1.1. Column capital illustration. Illustration by author

grotto, than that of the foliated scroll, choosing to mimic a direct translation of nature, aligning more closely with goals of translating naturalistic forms, rather than operating within abstractions. While some research has suggested the same neurological benefits can be accomplished through patterns that possess similar qualities to naturalistic patterns, other studies have identified perceived naturalness as being important in the stimuli itself. From this perspective, these artifacts contend that maximum benefit is achieved through mimicking both the underlying patterns and the naturalistic visual forms of the artifacts themselves.

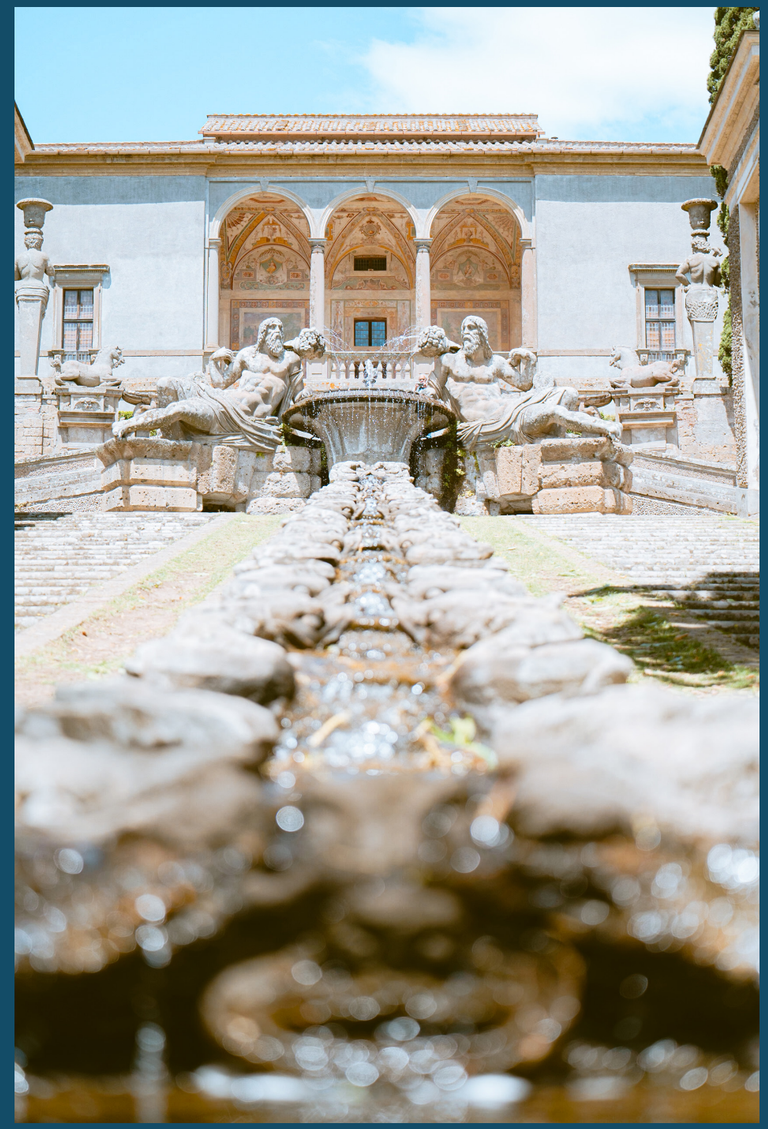


Fig 3.1.2. Catena d'acqua con delfini at the Villa Farnese. photograph by author

3.2 Applying a Restorative Framework

I developed the framework specifically with digital fabrication in mind. New technologies have enabled levels of detail and richness that were previously prohibitively costly and time intensive. Additionally, new informational capturing technologies have enabled designers to borrow from natural environments in new and innovative ways. The purpose of this thesis was not to present a rigid inflexible model for applying restorative design principles for spatial impact, but rather to illustrate examples of how this methodology could be applied in a variety of contexts and scales. Each artifact was given a typology; lighting, furniture, or mural, and had the framework utilized centrally in the design process. Each artifact underwent a series of experimentation and prototyping to identify useful tools that could be utilized and showcased in the design of these artifacts.

3.3 Post Industrial Technologies/Tools

To execute these design artifacts, I selected clay extrusion printing due to the abundance of clay as a non-renewable but massively available material, its status as a naturally occurring material, cost effectiveness, ability to achieve scale, and availability for experimentation. As a natural and abundant material, clay provides a sustainable material, enables zero waste prototyping, and has minimal environmental impact when operated on a green energy grid.[238] Its inherent malleability allows it to express complex forms while introducing elements of randomness which add to the fractal nature of the designs. The natural material makeup of clay in its hardened fired form makes it ideal as a durable, water impervious material that is well suited to the demands of interior spaces. Notably, clay as a natural material aligns to the ambitions of the framework, as well as allowing for rich colour variation depending on the clay body used, or glaze application. In relation to the proposed framework, it offered a natural material base, could express rich detail and form, and allowed design freedom for colour decisions.

The desire to explore new methods of generating naturalistic forms was paramount to the ambitions of this thesis. Creating environmental stimuli that mimic the patterns and complexity of the natural world is essential to creating restorative and cognitively aligned environments. While artificial methods could be utilized to generate visually complex and patterned stimuli, these methods have so far produced artifacts which have been criticized for evoking sensations of discomfort, estrangement, and alienation.[239] Examples of these artificial methods include Benjamin Dillenburger's and Michael Hansmeyer's Digital Grotesques, and Pavlos Fereos, Kilian Bauer, and Eftychios-Nicolaos Efthimious's additive hyper-ornamental prototypes trilogy. This effect, sometimes referred to as digital hyperrealism, has been described as "the richness and figural sumptuosity of highly detailed digital artifacts produced through big data methods."[240]

Author Mario Carpo of the *Second Digital Turn* has argued that this distancing effect is caused by the outward "excessive resolution" being a sign of the inward and invisible excess of data that humans may master and unleash, but can neither replicate, emulate, or simply comprehend with our mind."[241] I posit that through utilizing big data that is derived directly from the natural world, through LiDAR and photogrammetry, we can bypass the distancing effects of big data and generate familiar fractal qualities that are nourishing rather than estranging. Through this lens computer generated complexity lacks a sense of familiarity, perhaps evolutionary, and may cause some form of uncanny valley effect, which at present, designers and researchers lack the understanding to fully circumvent. By borrowing stimuli directly from the natural world, I hoped to generate artifacts that retain a level of familiarity that may be more closely in tune with our biological systems.

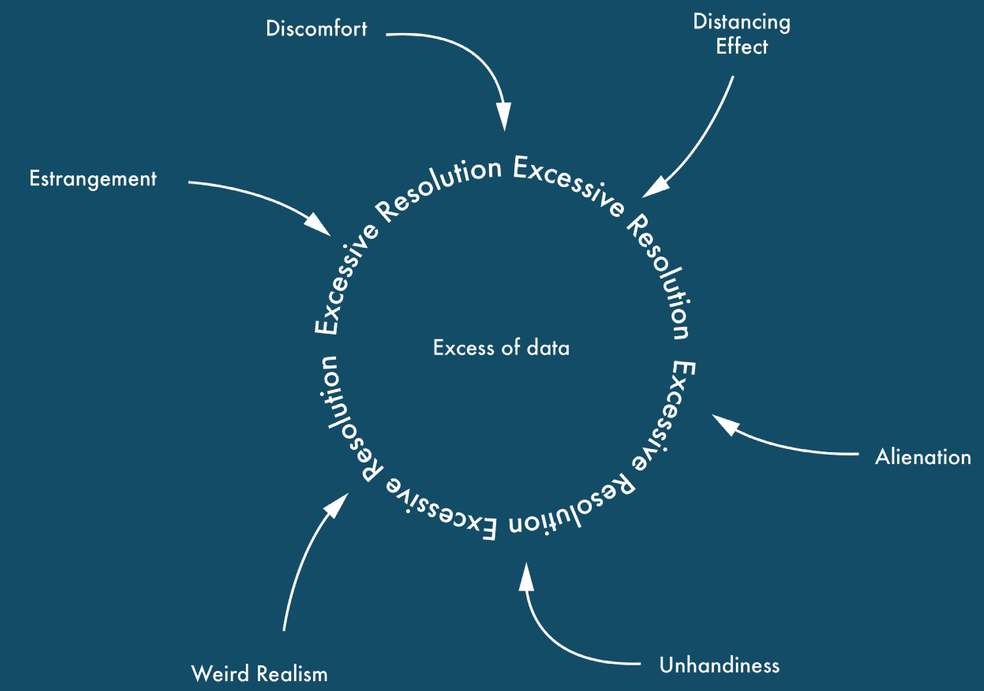


Fig 3.2.1. Excessive resolution diagram. diagram by author

The greatest limitation of this process is the layers of resolution filters that the data must pass through before fabrication. Using currently available technology, the initial data is captured at a limited resolution, which is itself processed into a file size that is manageable using currently available technologies. These initial processes transform the input into an already reduced set of information. After this initial processing, the data must undergo a series of transformations to generate the final design artifacts. These transformations include clipping, re-meshing, reducing, and re-generation of material outputs which dilute the purity of the gathered data. Once digitally transformed into artifacts, the data is generated into an output code that is executed by a printer with limited nozzle size, further reducing the material resolution. This process ultimately results in the dilution of the natural input. While these resolution filters ultimately dilute the initial input, the intent is to retain as much information as possible in generating visually complex, nourishing stimuli.

I chose LiDAR and photogrammetry as the initial data sourcing methods as they represented both widely available forms of data gathering from the natural world, and highly detailed methods of data gathering. Importantly, both methods retained the visual complexity, and three-dimensional information gathered.

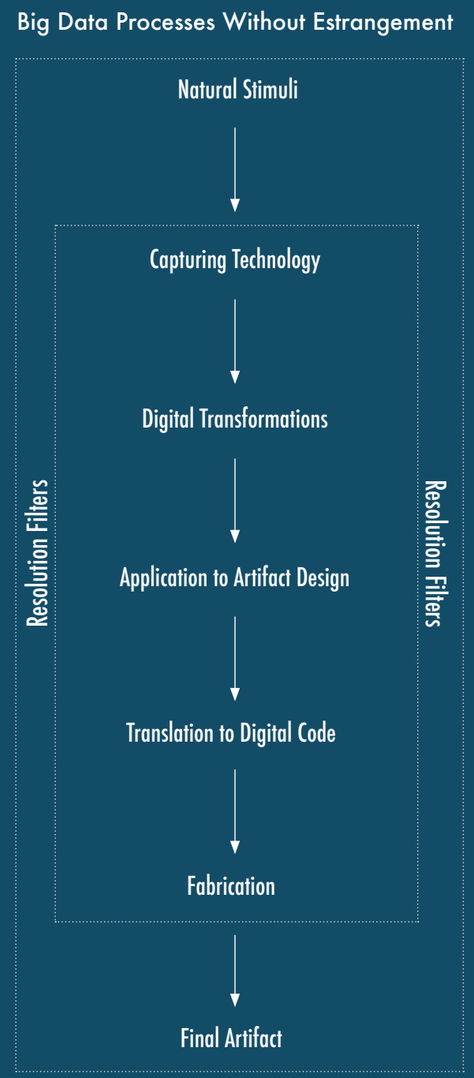


Fig 3.2.2. Big data translation diagram. diagram by author

LiDAR, or light detection and ranging, is a method for creating precise digital scans of the natural world. Through a pulsing laser, the instrument measures variable distances and constructs a precise three-dimensional scan of the environment.[242] I chose to work with topographic LiDAR, which is traditionally mounted to an aircraft and utilized to scan large areas.[243] This unit bounces light signals from the aircraft to the surface of the earth below, and back to measure precise data.[244] My information was sourced from LiDAR BC, as it offered publicly available access to detailed maps of British Colombia's topography. I specifically chose to work with the topography of British Columbia as its geography includes a large portion of the Coast Mountains, an area with high topographic relief and visually complex landscape that seemed ideal for the gathering of highly detailed fractal information. This data was processed through GIS software into slope maps which could be generated into complex image maps for the purposes of creating meshes with fractal relief.



Fig 3.3.1. LiDAR diagram. diagram by author

Photogrammetry, a process of creating digital approximations of the real world, was also utilized as it allowed more sculptural control than LiDAR sources. Photogrammetry works by stitching together a series of two-dimensional images to create a 3D model of the captured imagery.[245] This stitching references the different positions from which the photos were taken and analyzes the overlap to create an accurate and detailed point cloud of three-dimensional information.[246] For my explorations I utilized Blender's open-source photogrammetry brushes, which utilize scans of natural rocks to generate complex three dimensional information. These brushes can be layered onto meshes to imbue surfaces with textures found in the natural world. This process allowed the application of detailed textural information from geology to be imparted onto digitally fabricable meshes. These processes allowed an almost digital artisanship, allowing the imbuing of natural textures onto digital designs.

By utilizing big data capturing technologies we create an opportunity to translate information directly from the natural world into artifacts that are suitable for our demestic settings. While currently limited by a myriad of resolution filters, this information retains a level of detail far beyond the typical white walls and sterile environments currently characteristic of modern dwellings and environments. The development of affordable big data capturing, and large-scale additive manufacturing are imperative, as they have generated methods for creating intensely detailed stimuli in an economically viable way.[247] While many barriers still exist to widespread adoption, the promise of additive manufacturing and big data technology is immense. Additive manufacturing works at a voxel volume-based cost, meaning that cost of manufacturing is not determined by complexity, but simply by the volume of material required to produce the artifact.[248] This allows, perhaps revolutionarily, ornament, detail, and expression, to exist no longer as a superfluous cost, but rather be ingrained as an integral part of form.[249]

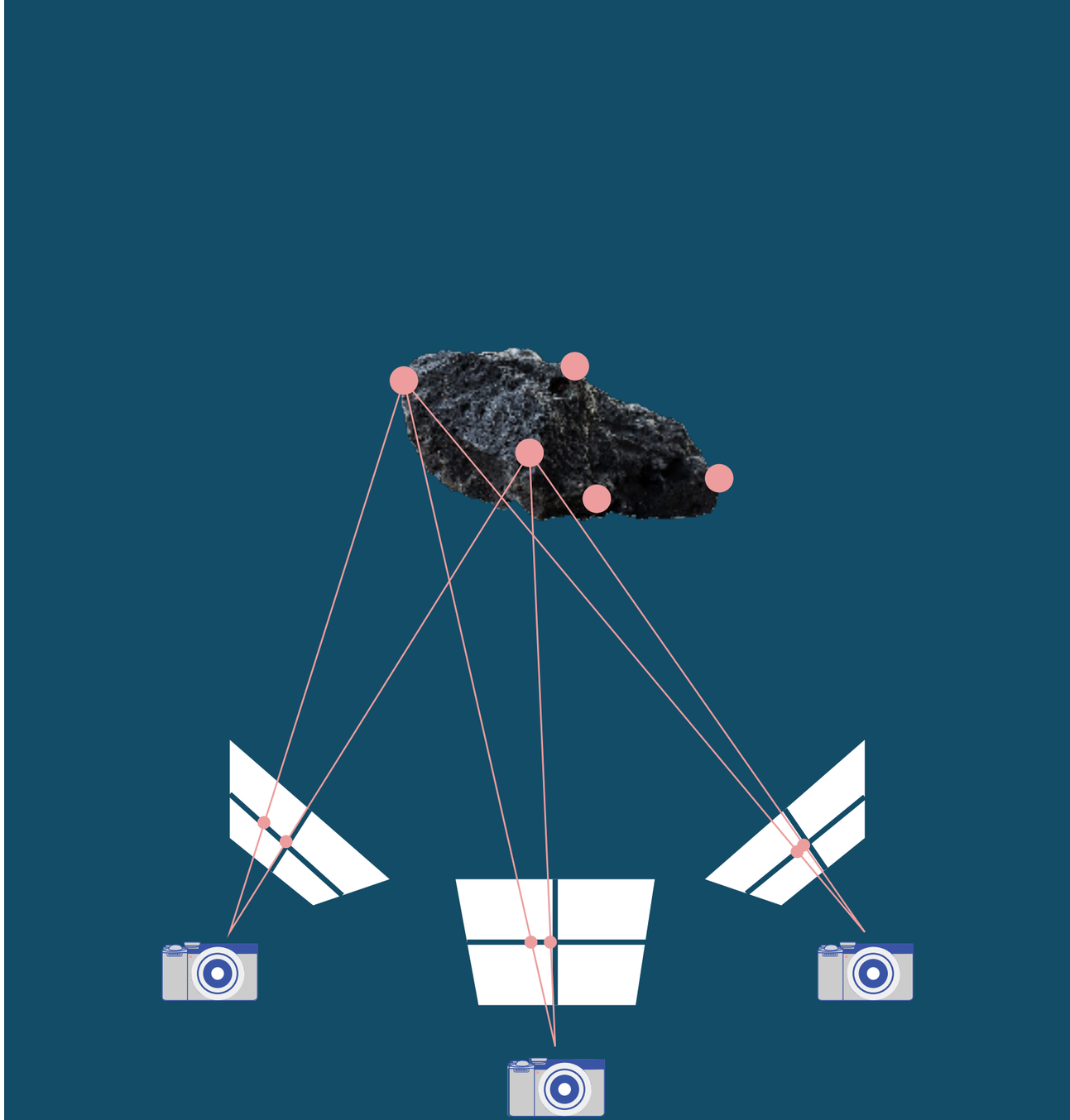


Fig 3.3.2. Photogrammetry diagram. diagram by author

Big data allows for the generation of visually complex stimuli that would be prohibitively expensive, and time consuming to fabricate by hand or conceptualize and draw. This tool allows for the generation of forms that would be almost inconceivable through traditional methods. Through the combination of these tools, designers today have the ability to translate visually complex stimuli found in the natural world into physical artifacts in an efficient way. While technological hurdles still limit the resolution of these filters, these technologies present a direct way of translating the research happening in environmental psychology and neuroscience into tangible design interventions. The following artifacts represent examples and explorations in how these technologies can be utilized, and how this data can be translated into artifacts fit for domestic use.

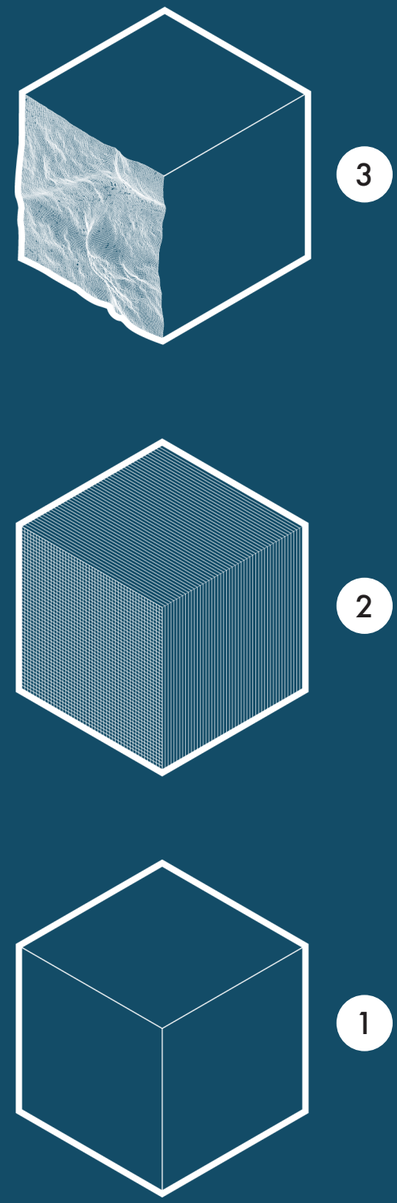


Fig 3.3.3. Photogrammetry brush diagram.
diagram by author

3.4 Fractal Texture Prototyping

I conducted a series of explorations to to identify methods of imbueing fractal character to design artifacts. These included the utilization of aerial photography as image maps onto meshes, the generation of patterns, translation of LiDAR mapping to image maps, and photogrammetry. Ultimately LiDAR and photogrammetry were chosen as they allowed the most direct translation of information derived from the natural world to digital processes, and in turn into physical artifacts. In addition to identifying the most succesful tools for crafting nature derived data, this process helped refine key learnings in working with clay extrusion in the generation of complex stimuli. A key lesson was the importance of fine print lines to add resolution and reduce distracting elements in the form. This created a trade-off, requiring longer print times and more heavy artifacts, but allowed greater detail and more three dimensional relief through additional material support. These tests informed future artifact creation through testing the limitations of relief and overhangs, various layer heights, print sizes, and resolution limitations. While I ultimately abandoned many of these processes, they represent early iterations in translating visual complexity and naturalistic qualities to design artifacts.



Glacial river aerial photography image map table

Illustration image map side table

Grand canyon LiDAR image map vase

Layered illustration details

patterned image map vase

Layered illustration vase

Fig 3.4.1 fractal prototyping diagram. diagram by author

3.5 Processing workflows

Each artifact is produced through a series of data transformations, that while individual in their specific elements, follow an identifiable workflow. These data transformations seek to translate natural stimuli into physical artifacts. The starting data comes already processed from the natural world, already subject to resolution filters that are a result of the capturing technology. How that data is transformed however, is crafted as a balance between resolution filters (additional steps), and technical considerations for translating raw information into design artifacts. These steps fall broadly into three phases: data processing, artifact generation, and artifact fabrication. Each phase further reduces the resolution of the data set, but allows the fabrication of design artifacts into physical form. These phases can be expanded upon, but broadly define the steps which data must be translated through to reach final realization. This process varies slightly between LiDAR and photogrammetry in that LiDAR data is largely translated into different forms before being applied to a design, whereas photogrammetry processes start with a design where photogrammetry is applied additively to, and allowed to transform. Each artifact explores different filters for translating artifacts to production, but are colour coded into these categories to allow a clearer understanding of the filters that occur in the design process.

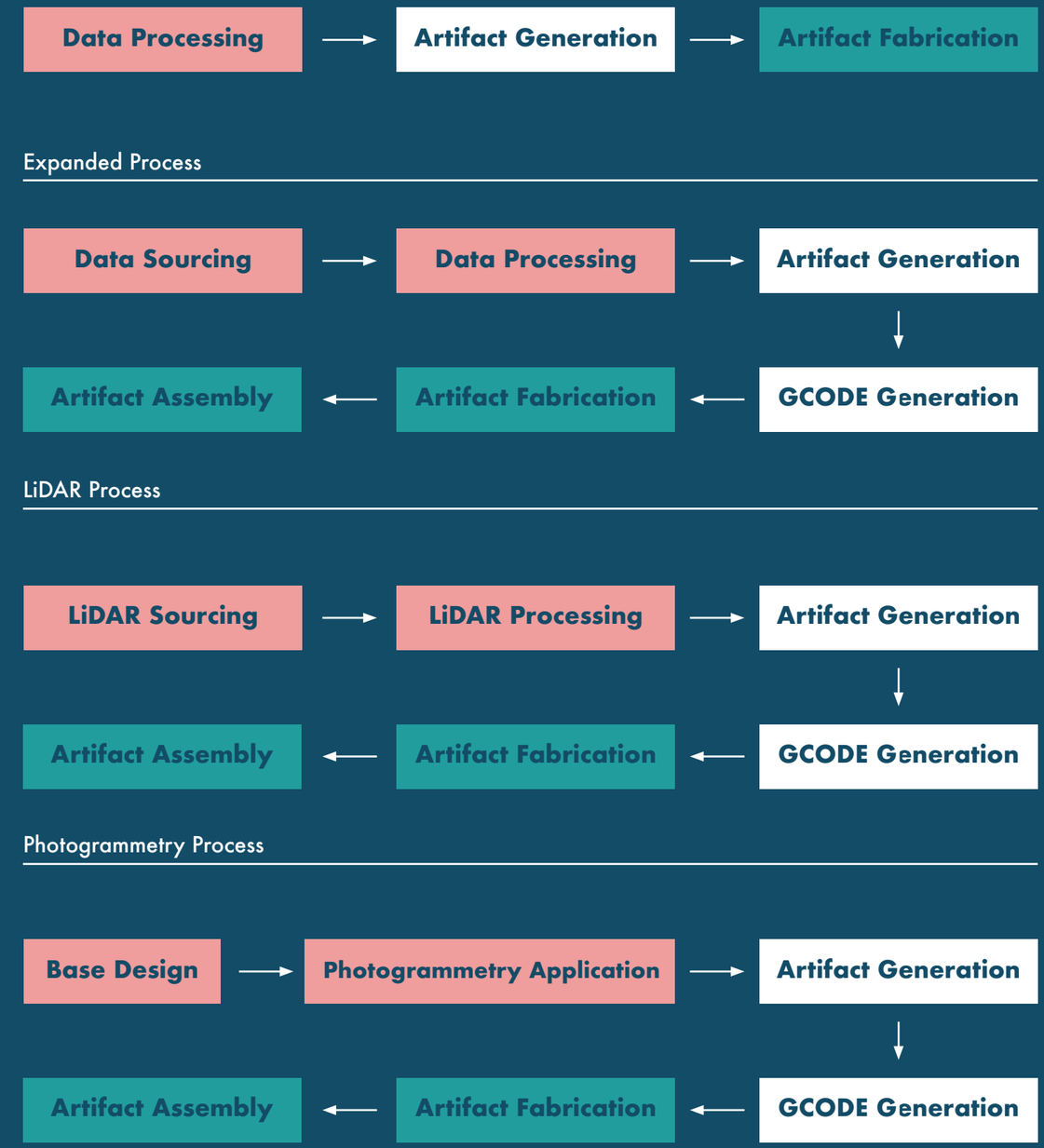


Fig 3.5.1 Processing workflows diagram by author

3.6 Code Development

To execute the design ambitions of the thesis, several custom codes were developed to facilitate the translation of complex meshes to GCODE. These codes will be briefly described below.

GCODE generation:

Select artifacts utilized a simple code written in Grasshopper to generate GCODE. These were ideal for situations where the complexities of the mesh made it difficult to slice in traditional softwares, and added an extra level of control. This code translated various inputs into a text box that could be copied and saved as a GCODE file to be read by the Scara extrusion printer. The code translated meshes into a single polyline, and fed that polyline into an organization node that consolidated information including the desired extrusion rate, print speed, and printer's standard start up and end protocols, into a set of instructions readable by the printer. This script while simple, required the division of the input mesh into a single print line which could be fed into the script and turned into a series of movements for the printer to execute.

Image map generation:

Image maps were utilized in Grasshopper to apply LiDAR derived data to a base surface. This required a script which could reference a simple surface, break that surface down into a series of points, and rearrange those points based on black and white values provided through the image map. This allowed greyscale maps which communicated topographic information through gradient change, to be fed into this code and be applied to a set number of points. These points would be pushed or pulled in space based on the associated gradient values. This code would then utilize those points to reassemble a new polysurface based on the LiDAR derived image map. These polysurfaces would then be transformed into meshes.

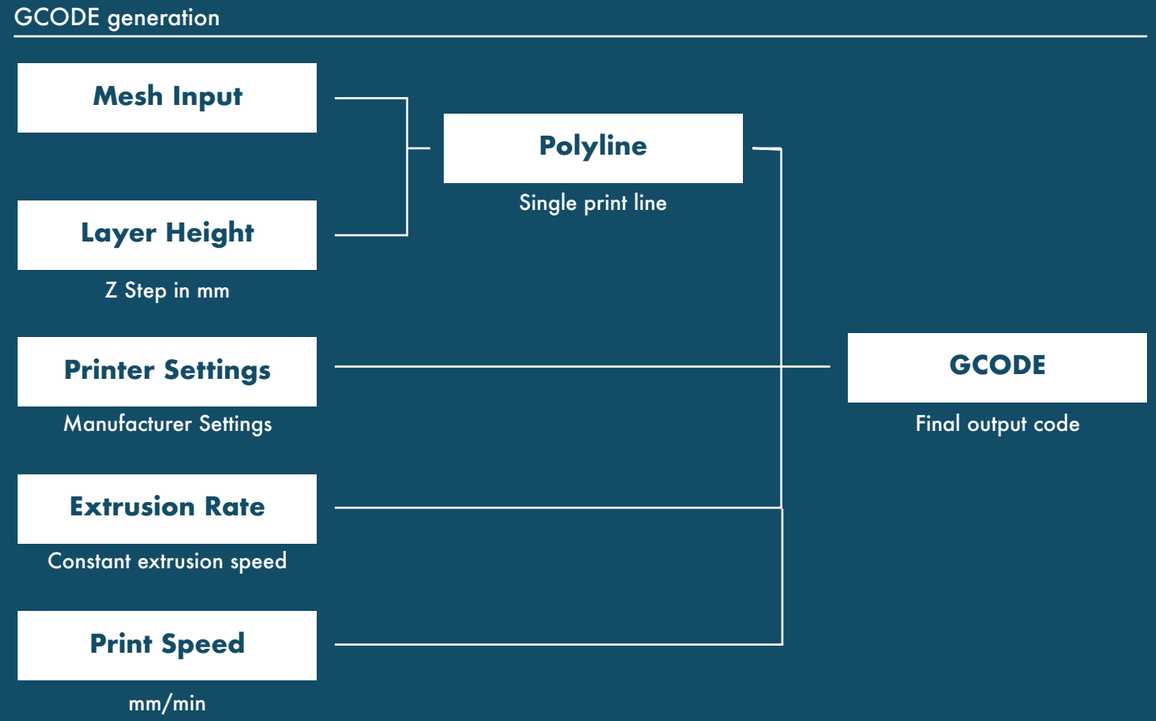


Fig 3.6.1 GCODE generation diagram by author

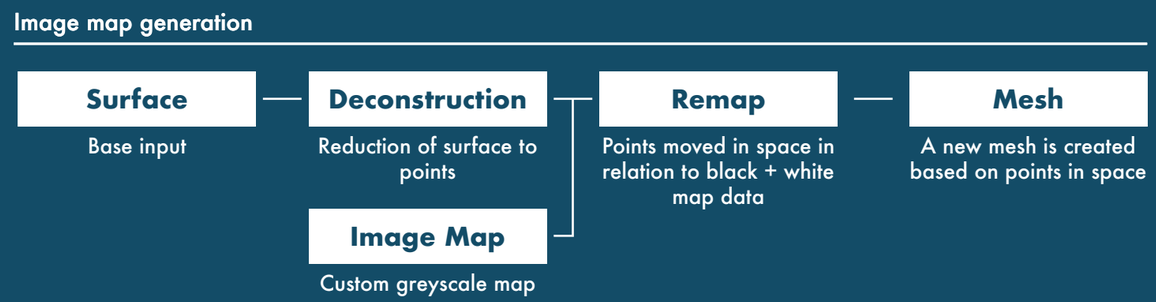
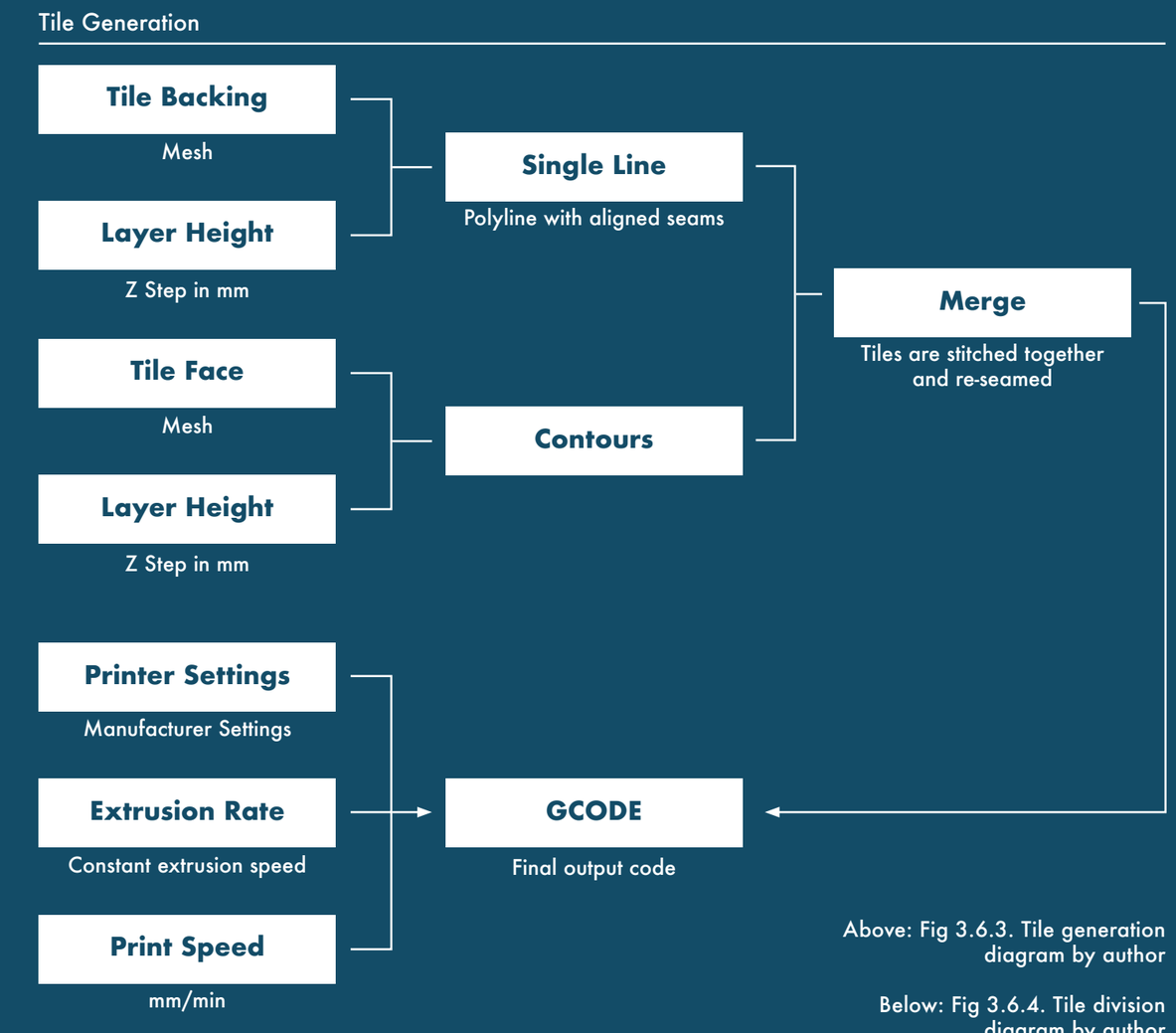


Fig 3.6.2 Image map generation diagram by author

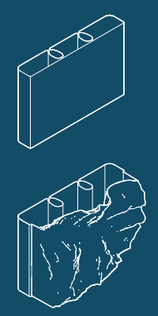
Tile Generation

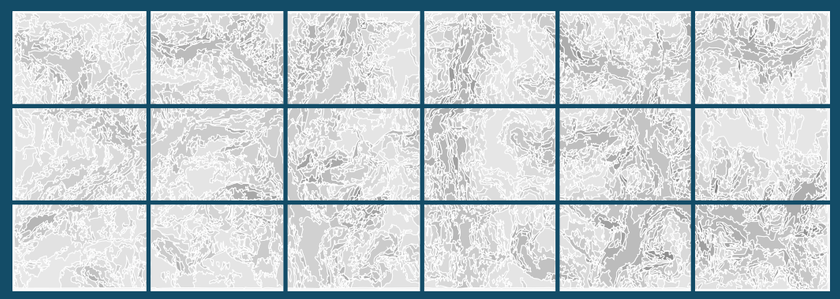
This code was developed for the topographic mural to allow all 18 tiles to be generated from 1 base tile backing and tile face surface. Each tile face was first run through the image map generation code, where a simple 2D surface was transformed into a polysurface, and then into a mesh. Each mesh was then referenced in this code, where it was stitched together with the tile backing to create a singular polyline. This polyline was then fed into a slicer interface that combined the GCODE parameters into one copyable text file for export. This code worked to align seams, simplify print lines, and generate a code directly for fabrication.



Above: Fig 3.6.3. Tile generation diagram by author

Below: Fig 3.6.4. Tile division diagram by author





The mural is divided into 18 image maps as shown, each image map is applied to the same base tile.

4.0 Design Artifacts



Fig 4.1.1. Artifact collage. collage by author

4.1 Terrain Sconce

Goals:

This lighting artifact exemplifies the ambition of producing restorative design interventions with practical application in contemporary spaces. The production of this piece illustrates how LiDAR information can be successfully translated and fabricated through clay extrusion printing. This artifact explores the limitations of nozzle sizes, fabrication challenges, and material limitations in the production of LiDAR informed forms. Through the production of a sconce, this lighting piece demonstrates how the adoption of LiDAR derived data and digital fabrication can produce visually complex artifacts with practical implications. This piece explores a visual relationship, meant to produce a subtle spatial impact. The piece is modest in scale and can be easily integrated into existing furnishings, but is flexible in its wide spread application.

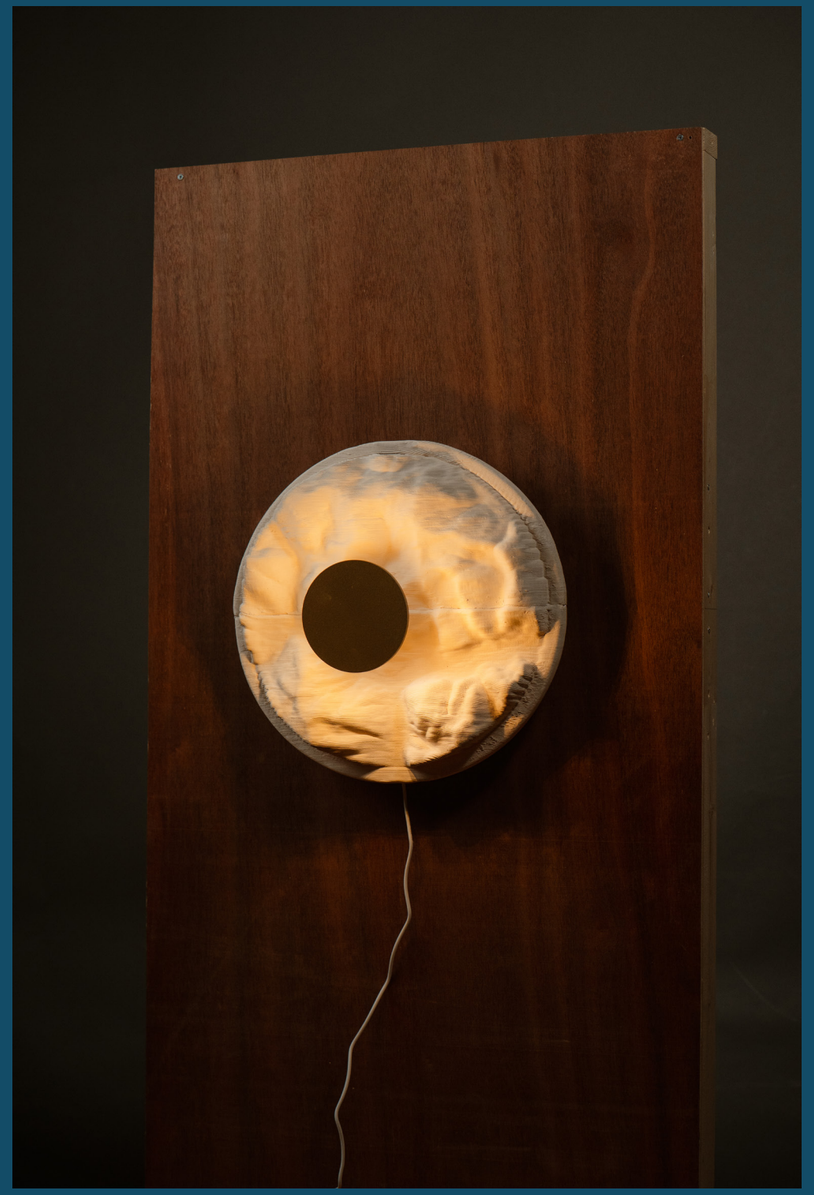


Fig 4.1.2. Terrain sconce photograph. photograph by author

Framework alignment:

The form is derived from LiDAR scans of British Columbia's Coast Mountain range. This geologic area was chosen as it represented mountainous terrain with high degrees of fractal complexity and vertical relief aligning with the visual complexity characteristic. This allowed a strong evocation of naturalistic forms, through recognizable and complex stimuli, with steep elevation ideal for a strong relief, but which maintained a recognizable form. To achieve the form, clay extrusion printing was used, which allowed clay to make up the primary material of the piece, with minimal metallic accents. This allowed a strong alignment with the characteristic of integration of natural materials. A raw clay body was used to allow a neutral soft white, aligning with the neutral earth tones as described in the presence of colour characteristic. The mountainous terrain provided both visual characteristics and allows the symbolic representation of deep time geologic forces, evoking a sense of time.

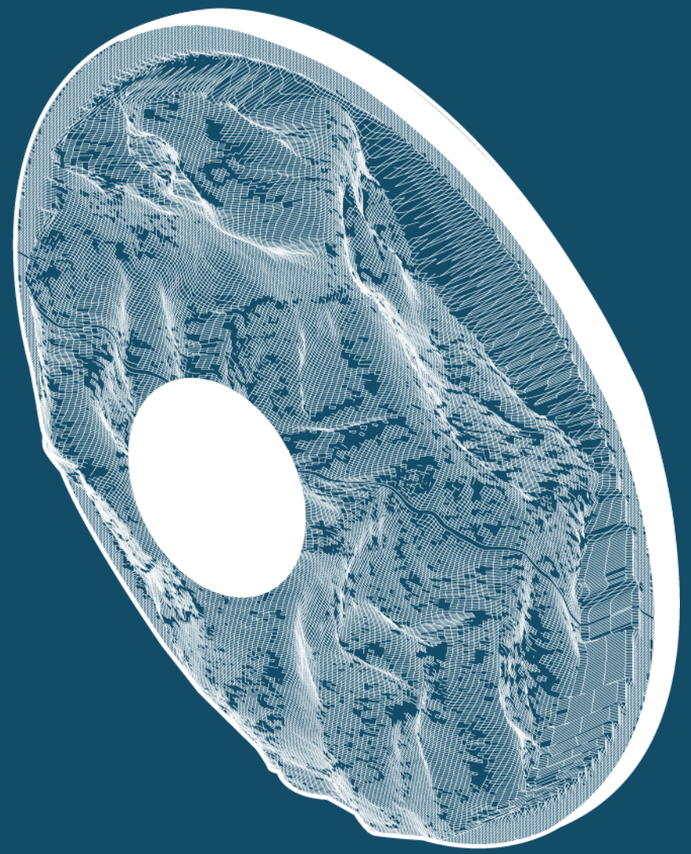
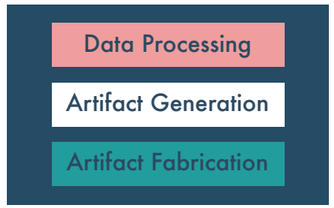


Fig 4.1.3. Terrain sconce axonometric. drawing by author

Terrain Sconce Workflow:

The greatest challenge with the sconce was to solve production limitations with translating raw LiDAR data into a circular form. Early attempts to export LiDAR directly to an STL three-dimensional file proved promising, however attempts to trim, shape, and transform this data into a design object proved unfeasible due to the messy nature of the mesh created, and limited computing power. An alternative strategy was employed which allowed the translation of three dimensional data into a two-dimensional map, which communicated the elevation data of the raw LiDAR. This greyscale map was used to create an image map that could transform a flat plane into a three dimensional relief of the LiDAR originated data. This allowed the creation of a much more controlled mesh, which could then be trimmed and transformed into a design ready for fabrication. Careful consideration was paid to overhangs and production strategies to allow a clean print without failure. A printing nozzle of 4mm was ultimately chosen as it allowed a balance between structural rigidity, allowing a stiff back for the piece, while retaining resolution. 3mm nozzles were tested but resulted in the backing buckling without providing significant improvements to resolution. The final assembly is a mix of off the shelf and custom fabricated components to allow a translation of the final vision.



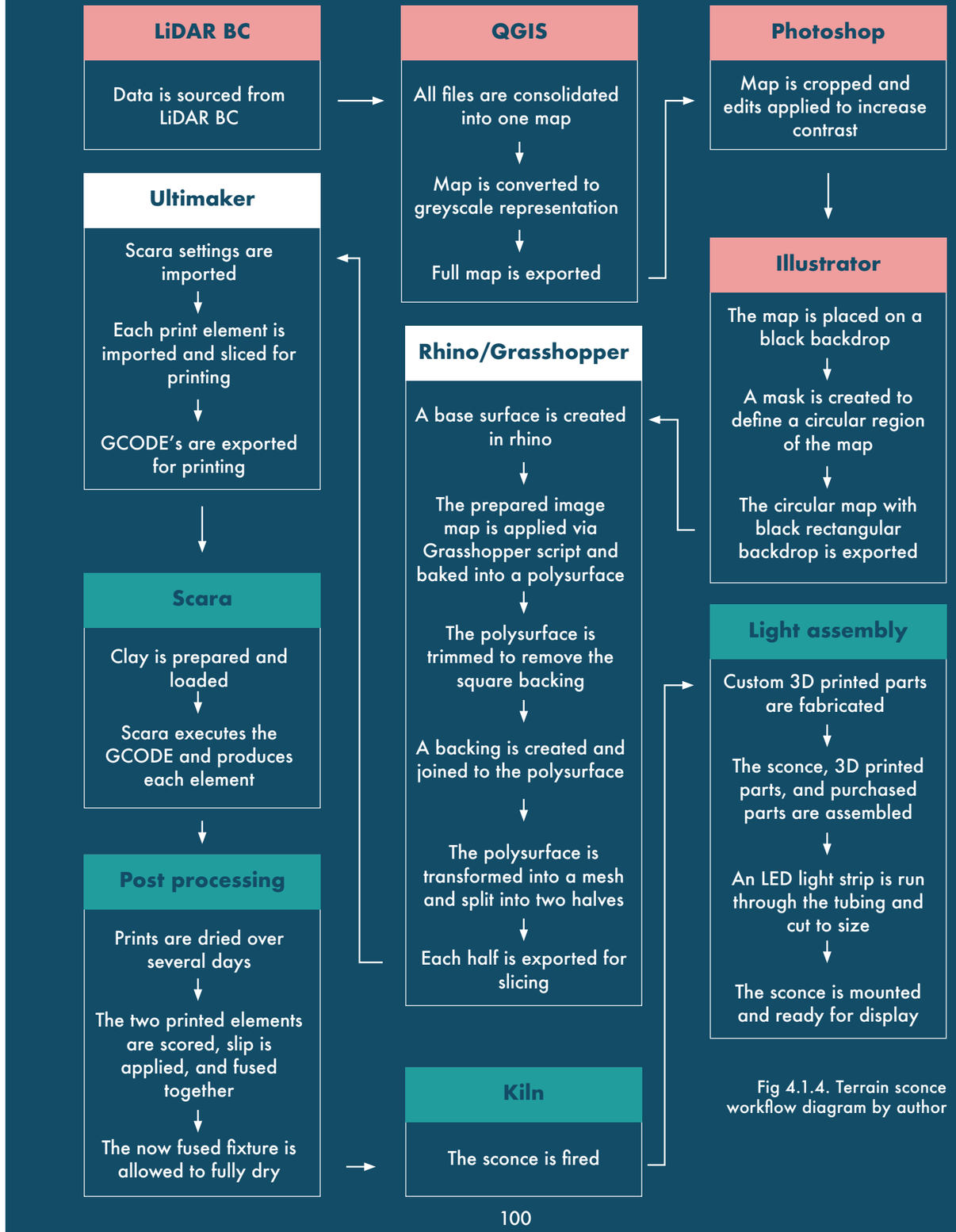


Fig 4.1.4. Terrain sconce workflow diagram by author

LiDAR Integration:

LiDAR integration in this piece slowly developed through a series of prototypes. Ultimately, LiDAR information was sourced from BC LiDAR and imported into QGIS where the data was translated into a slope map. This information was then translated to a greyscale map before being exported. In Photoshop a mask was used to select a portion of this map and placed on a black backdrop to be used as an image map. The final image map was exported and applied to a square surface. This polysurface was then trimmed to remove the rectangular surface, and a backing was merged onto the polysurface. This surface was then turned into a mesh and split. Once split the two halves were printed and re-joined physically once sufficiently dried. At this time holes were made in the print for lighting hardware. Once dried the pieces were fired and assembled for display. These processes, while transformative of the initial data, allowed a clear and flexible design path to emerge.

1. LiDAR derived slope map
2. LiDAR derived greyscale map
3. Image map with black backdrop for surface application



Fig 4.1.5. Image map generation diagram. diagram by author adapted from BC LiDAR. *LiDAR DSM Index 1:20,000. DSM. August 8th, https://lidar.gov.bc.ca/pages/download-discovery*

Design Methodology/Fabrication:

Design:

1. A rectangular surface is created
2. A pre-prepared image map, processed from LiDAR data and imaged masked into a circular form is applied to the surface
3. The surface is then trimmed to retain only the circular input
4. The circular surface is then split and a backing applied
5. The two pieces are then rotated and exported for processing. Each component is then imported into a slicing software and processed for the Scara printer. A 4mm nozzle was ultimately selected as 3mm caused the back to collapse, and offered minimal additional resolution

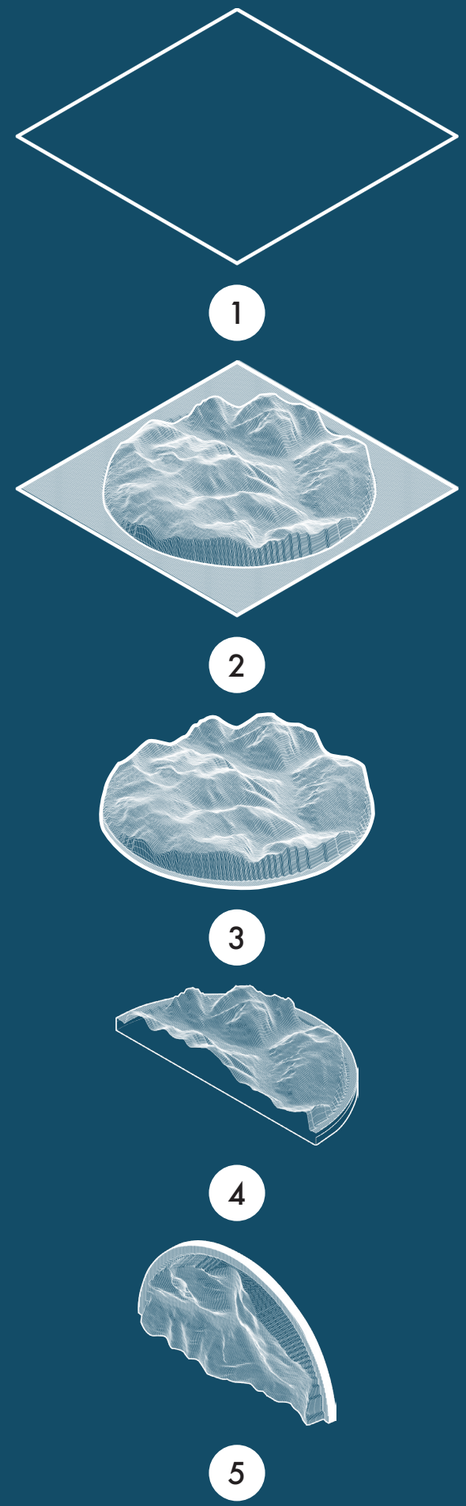


Fig 4.1.6 Sconce digital model generation diagram. diagram by author

Design Methodology/Fabrication:

Assembly

1. The printed piece is allowed to slowly dry

2. Once sufficiently dried the two halves are manually joined together through hand-building techniques. The seam is scored and covered in slip before pressure joining the two pieces. Once joined, holes are made for the hardware

3. The now joined piece is allowed to fully dry to bone dry before under going a bisque firing

4. The final piece is then fired to cone 6 before assembling the lighting components for display

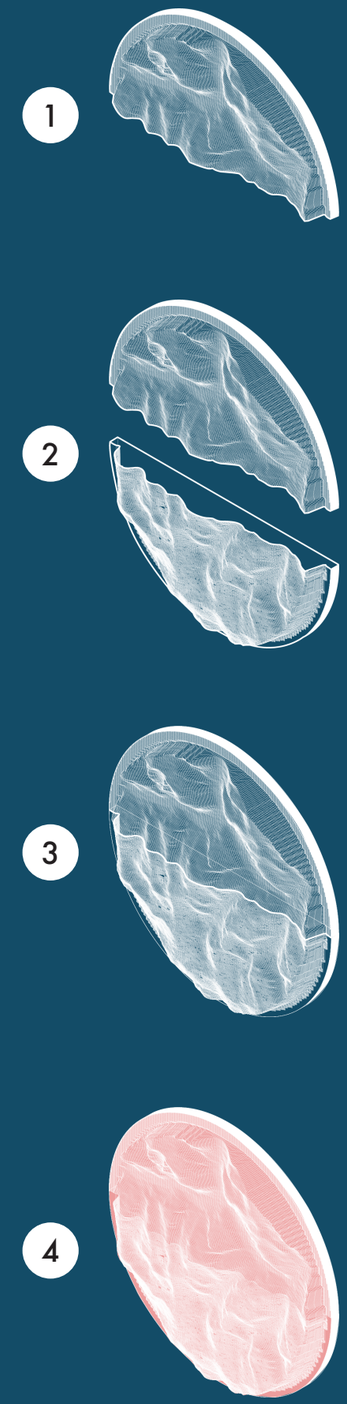


Fig 4.1.7. Sconce fabrication diagram. diagram by author

Design Fabrication: Lighting components

Lighting components

1. Custom 3D printed face plate + LED strip holder
2. Custom 3D printed housing to connect face plate and flange
3. Brass flange
4. Brass canopy with cross bar and 4 inch brass pipe

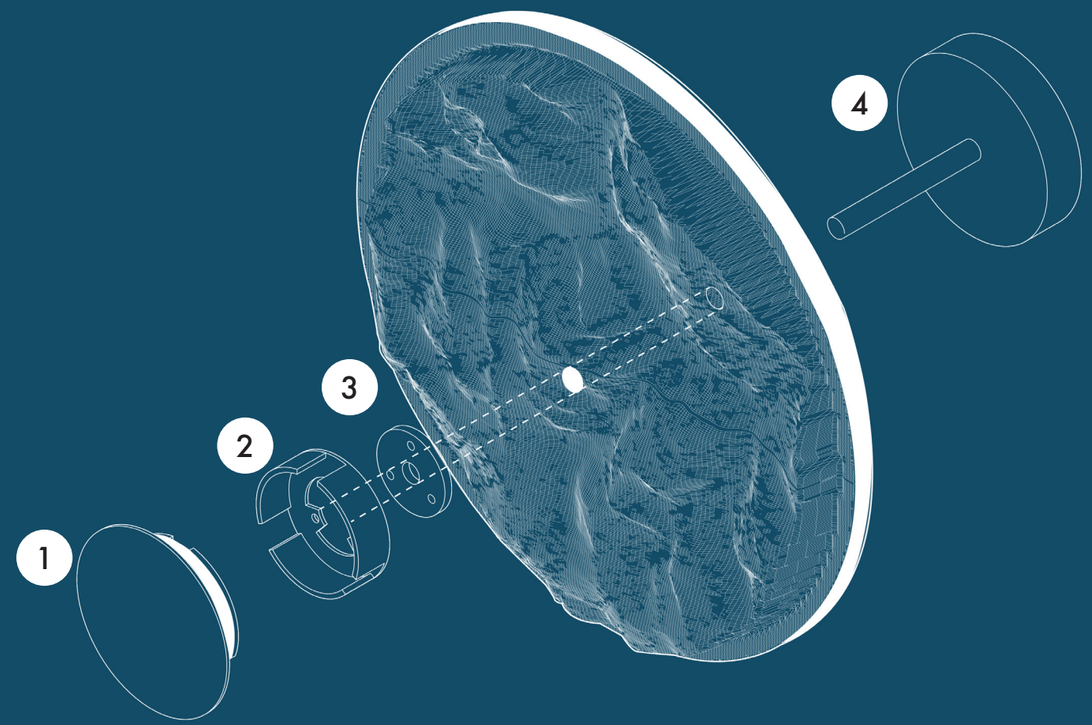


Fig 4.1.8. Terrain sconce lighting component diagram. diagram by author

Process Documentation:

Images of the terrain sconce elements post printing, post print fusion, and drying.



Fig 4.1.9. Process documentation collage - sconce. collage by author

Gallery:

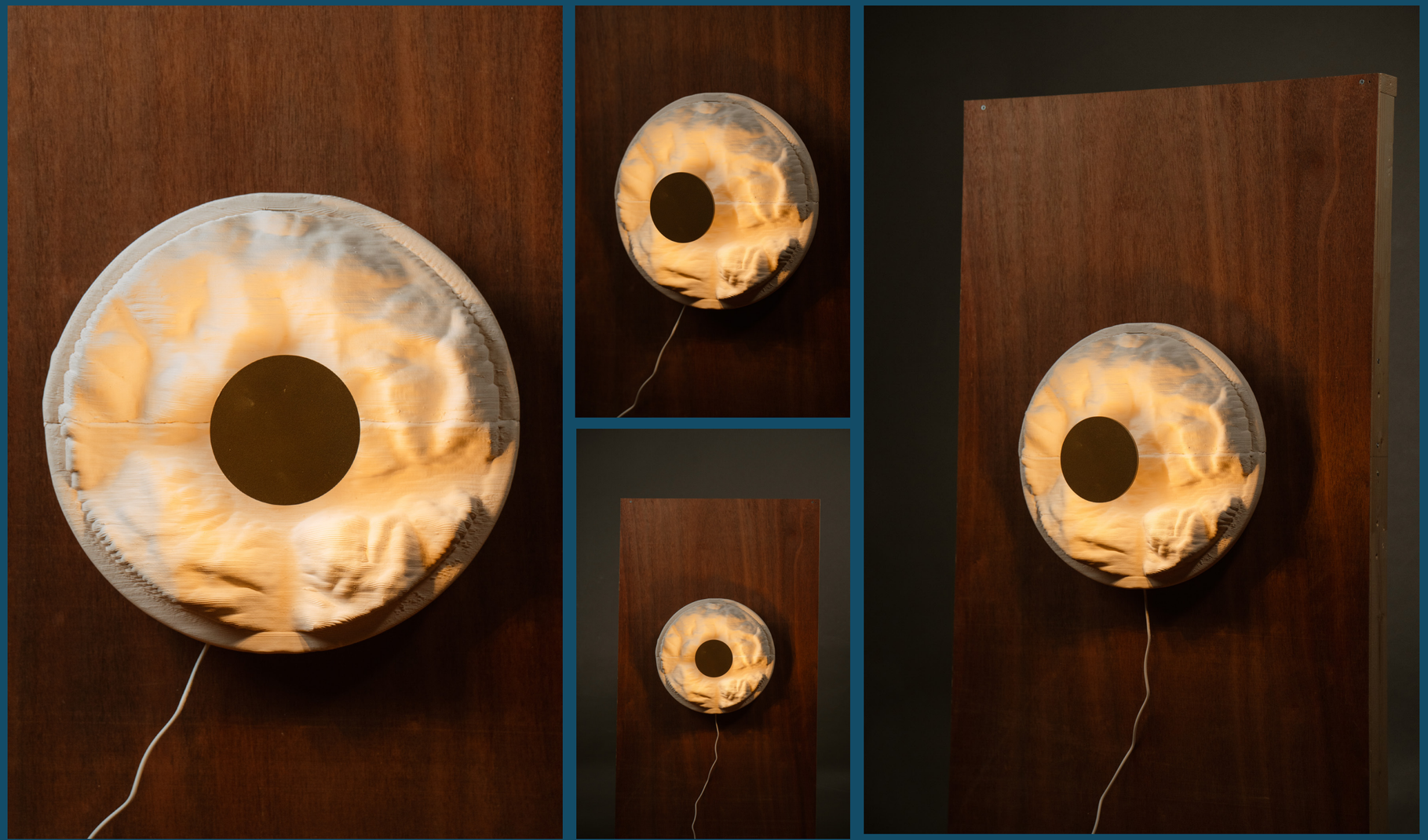


Fig 4.1.10. Final image collage - sconce. collage by author

Reflection:

This artifact identified key challenges to working with LiDAR, particularly the translation of meshes to workable print files. Attempting to translate LiDAR directly to meshes proved feasible, but repairing the mesh, trimming, and shaping it into a final form that could be exported to a print file, proved unmanageable. As a result, an alternative method was developed where LiDAR data was translated to an image map that could be applied to a base mesh. This process allowed more direct control over the final form but added additional resolution layers.

Fabrication experimentation led to several key revelations, most notably in fabrication resolution. Nozzle sizes of 3mm, 4mm, and 5mm were tested, with 3mm allowing the highest resolution but leading to print failure due to structural instability in the long uninterrupted straight line across the back of the print. Rather than adding reinforcing, a 4mm nozzle was chosen as it offered similar resolution without compromising the initial form. Post processing the prints produced unique challenges, including unseasonably high humidity leading to some unexpected warping, and fusing prints together requiring careful seam alignment and slip usage. This proved an iterative process that was improved with time.

This methodology proved highly successful in producing visually complex stimuli that remains recognizable in form. While small in scale, its visual impact is immediate and produces a highly successful print.

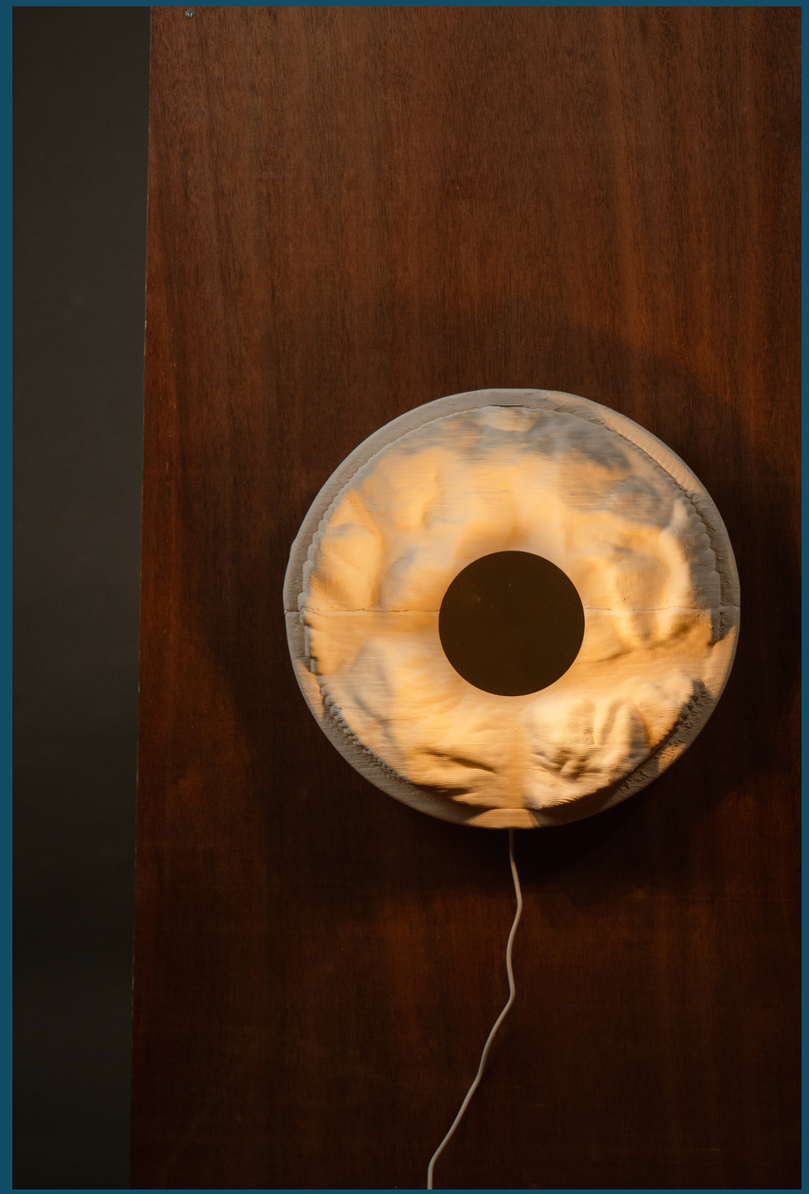


Fig 4.1.11. Terrain sconce detail. photograph by author

4.2 Stalagmite Light

Goals:

This artifact sought to explore how photogrammetry could be scaled to produce an impactful object at large scale. More sculptural in nature than the terrian sconce exploration, it utilized photogrammetry modeling to produce a large centerpiece with visual impact and experiential character. The three dimensional potential of clay extrusion printing was fully advantaged to produce a piece that expressed detail and visual complexity from every angle. The lighting integration sought to produce a soft mood glow rather than functional lighting, allowing the form to prioritize visual expression and retain the ambitions of utilizing digital fabrication for restorative mood alteration rather than task lighting or more functionalist purposes. The snaking crack-like appearance of the light, added a visual interest and invited a sense of delight and curiosity to the piece, embodying an invitation to move around and engage with the light. This piece exemplifies the potential impact of large three-dimensional interventions in domestic and commercial space, forming a deeper relationship through the production of highly tactile and experiential artifacts.

The form is inspired by cave stalagmites and pillar like structures found in high alpine environments caused by high degrees of erosion. Its obelisk like nature plays on the duality of nature to produce both restorative stimuli, but in forms that may produce or culturally signal unease.



Fig 4.2.1. Stalagmite light photograph. photograph by author

Framework Alignment:

Geologic photogrammetry brushes were utilized to produce visually complex stimuli with recognizably geologic character, aligning with both the evocation of naturalistic forms *and* visual complexity characteristics of the proposed framework. This process allowed an exploration of the direct translation of naturalistic texture to digital, and in turn physical artifacts, producing an almost one for one sculptural relationship. This process allowed intentional digital sculpting to produce an artifact with naturalistic characteristics, but with formal design control. Through the utilization of a granite grey clay body, with black speckle, the form could both integrate natural clay bodies, aligning with the integration of naturalistic forms characteristics, but also utilize a naturalistic earth texture, allowing a distinct presence of colour.

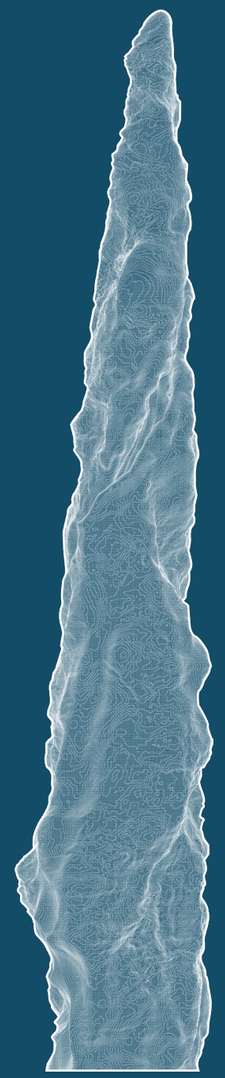


Fig 4.2.2. Stalagmite light elevation. drawing by author

The overall form borrows from stalagmites and tall jagged pillars reminiscent of high alpine environments. These forms appear in nature as a result of erosive forces over long periods of time. Additionally, the deep crack or fissure in the piece that is highlighted by illumination evokes a sense of time and the immense forces that break apart and carve geologic features.

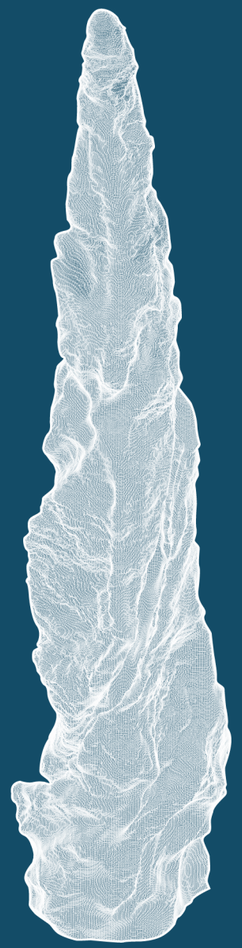
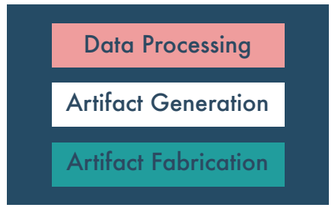


Fig 4.2.3. Stalagmite light axonometric. drawing by author

Stalagmite Light Workflow:

Working with photogrammetry required an almost sculptors-esque approach. The application of photogrammetry through Blender brushes was chosen for its user friendliness and open-source software availability. This tool allowed photogrammetry geologic texture to be added through simple brushes which applied three-dimensional texture on top of existing meshes. This process allowed a responsive design approach, where a rough mesh could be formed, then transformed through additive and subtractive layers to gradually create a final form. This allowed an organic design approach, permitting the design to reveal itself across multiple iterations and layers. This process created a rich textural mesh full of variation and geologic expression. Once fully formed, the mesh could be exported and split into manageable pieces, printable using the maximum height and clay capacity of the Scara printer. Once finalized, these pieces were sliced through UltiMaker's slicing software and fabricated. Once printed, they were allowed to dry then joined together into three large components. This allowed the final piece to be assembled from fewer elements and minimized visible seams. These elements were allowed to fully dry and were fully fired to cone 5, assembled and ready for display.



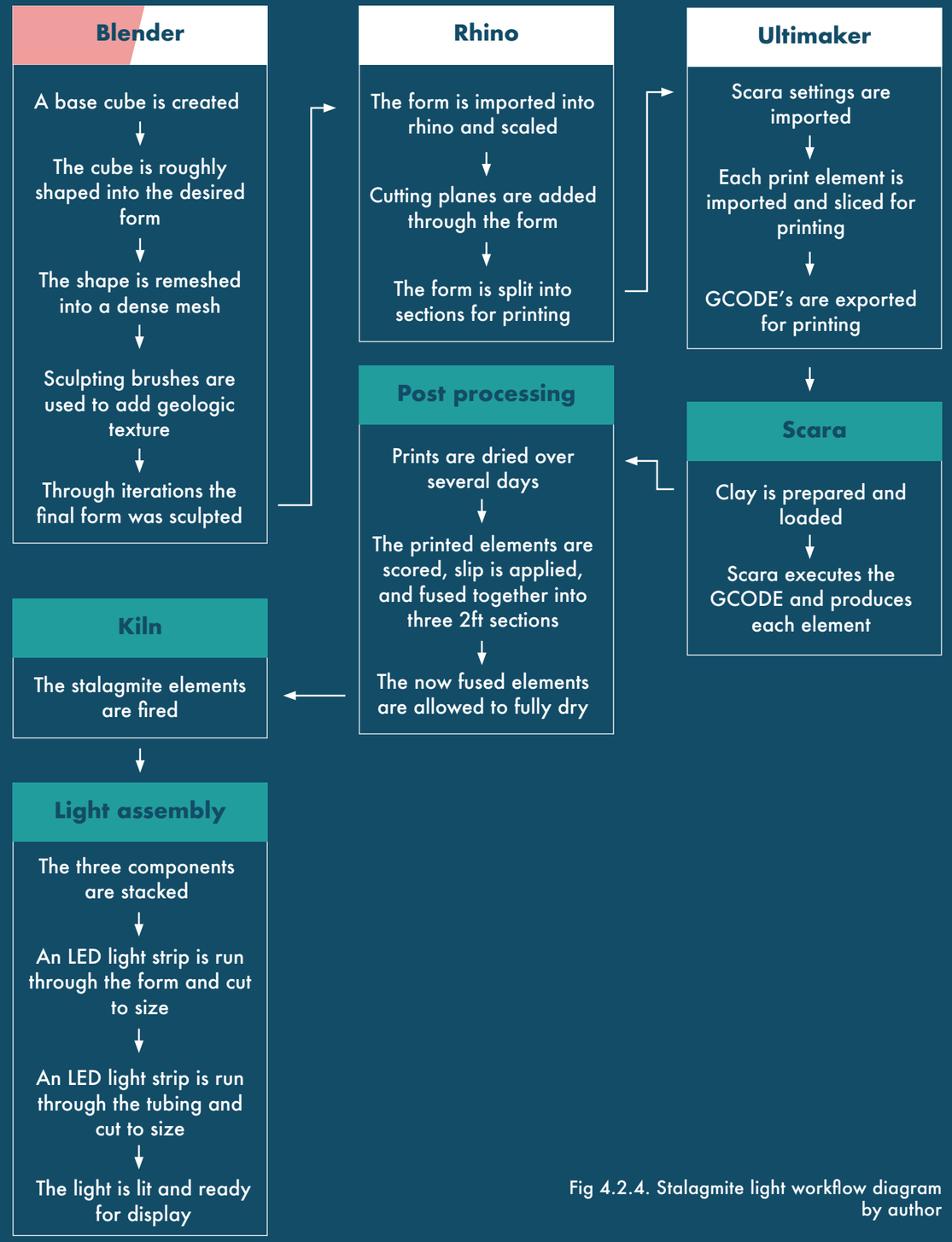


Fig 4.2.4. Stalagmite light workflow diagram by author

Photogrammetry:

The design started with a simple cube, shaped into a tall pyramidal form. This form was then re-meshed to allow complex manipulation. Gradually, the mesh was shaped, with photogrammetry rock textures added in layers. For this design I utilized a sculptural approach, with the form slowly carved or added too, layered upon, and textured. The fissure was roughly carved from the form, smoothed, and shaped through subsequent iterations. Overtime, the design took shape through sculpting and additive layers of geologic texture. This process was highly sculptural, a result of hours of manipulation and digital carving techniques, inspired by traditional sculpting methods.

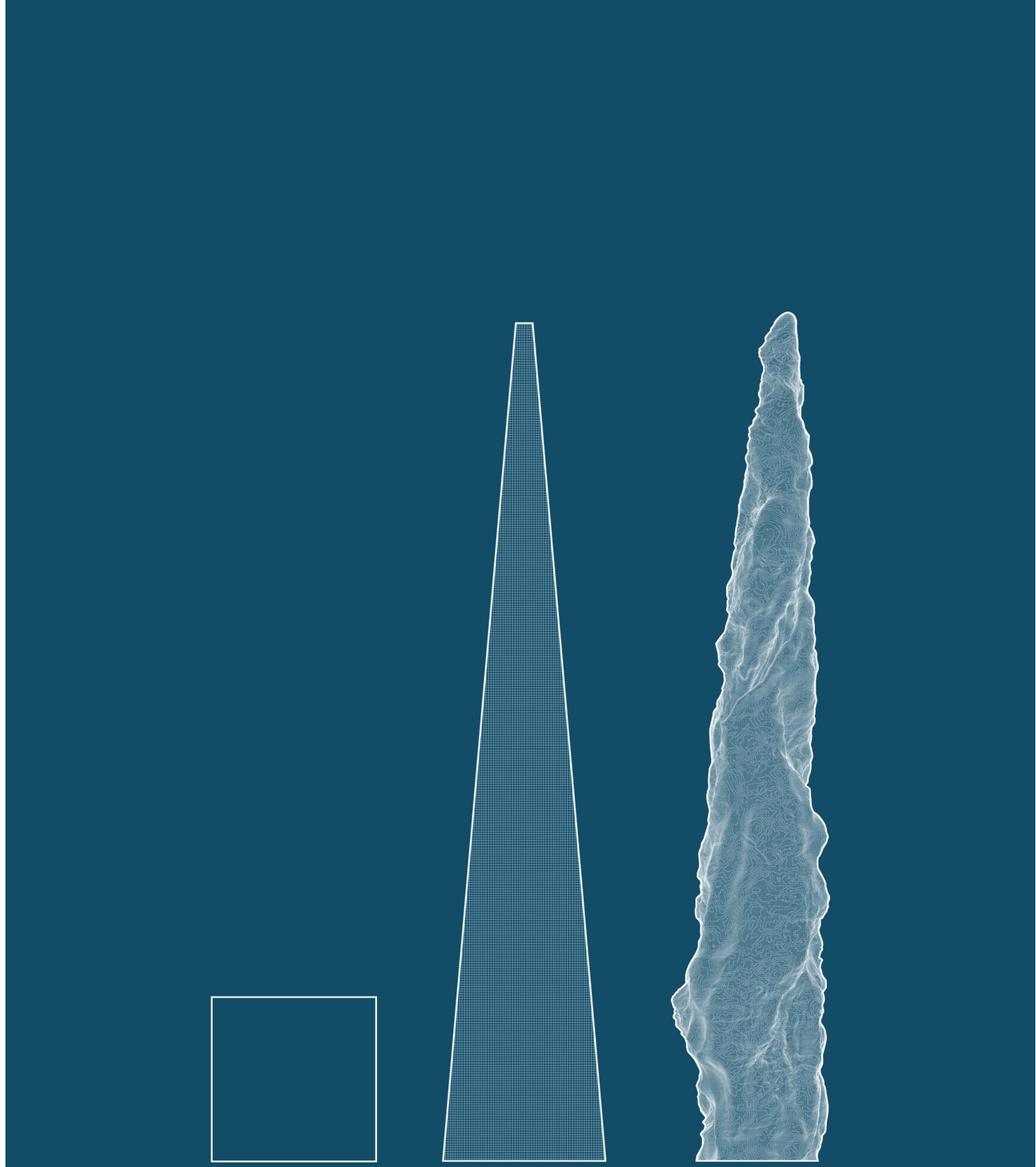


Fig 4.2.5. Mesh generation diagram. diagram by author

Design Methodology/Fabrication:

Design:

Once shaped, the form is imported into Rhinocerous 8 where it is split into a series of fragments for fabrication. Each fragment was then processed into GCODE through UltiMaker. Each piece is then printed and allowed to partially dry before several fragments were joined together and smoothed to reduce the total number of seams in the final piece. At this time, accommodation for lighting elements are made during the drying process.

These now consolidated fragments are then fired and stacked to assemble the final piece. These pieces are placed onto a base, lighting is run through the form, and assembled for final display.

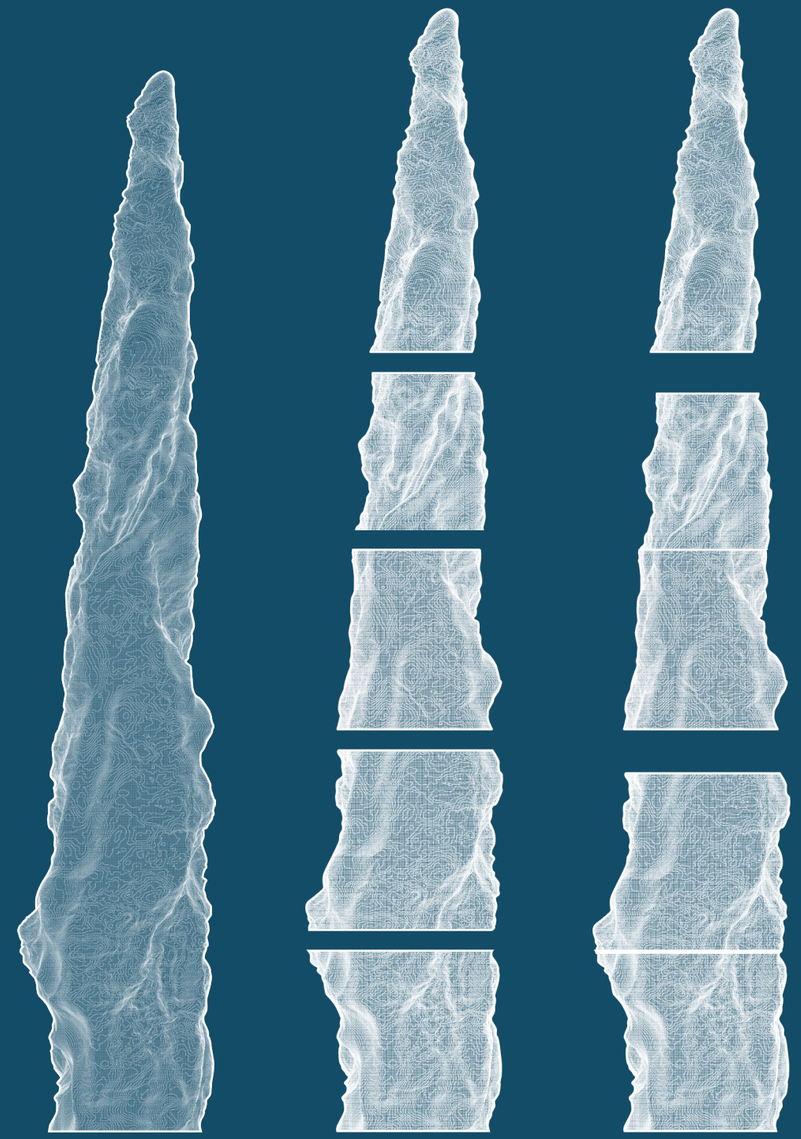


Fig 4.2.6. Mesh fabrication diagram. diagram by author

Process Documentation:

Images of stalagmite light elements during printing, drying, and post fusion into larger elements.



Fig 4.2.7. Process documentation collage - stalagmite light. collage by author

Gallery:



Fig 4.2.8. Final gallery collage - stalagmite light. collage by author

Reflection:

The fabrication process for this artifact required overcoming several key challenges in large scale production. The first was working within the maximum printable height of the printer, which proved to be approximately 445mm as currently assembled. This limitation required each artifact to be fabricated in sections, which were then slow dried, and fused together. This process proved highly effective, however led to the creation of three large two foot sections that required careful drying and moving to reach the kiln. In order to maximize strength of the pieces, they were slowly dried over the course of a month, a sizable time investment in this process. A significant challenge came with firing, which resulted in warping which prevented clean alignment between the three components. This could be reduced in the future through either creating spacers in the seams during drying, or modeling carefully to avoid less robust, or more narrow, elements which experience larger degrees of warping. Future research on establishing better component connections would be highly valuable.

Smaller tests also established that glazing ceramics of this scale would be prohibitively costly, as the large surface area created by highly textural relief led to a high volume requirement for glaze. The final piece, while imperfect, achieved a high degree of textural relief, and highly successful translation of geologic stimuli to physical form. Future research should be focused on crafting more successful connections between fired pieces, and reducing warping in clay extrusion printing. Despite challenges, the final piece represents a highly successful translation of the framework, and specifically geologic scans, into a physical artifact.



Fig 4.2.9. stalagmite light. photograph by author

4.3 Geologic Table

Goals:

The ambition of this artifact was to explore how clay fabrication printing could be used to generate furniture scale interventions which contained practical spatial characteristics. Central to the concept was the introduction of fractal stimuli in everyday furniture typologies to produce provocative pieces which maintained a familiarity in contemporary spaces. Key aspects to be explored in this process were how natural forms could inform massing, how photogrammetry could be translated to physical artifacts, and to identify technological and production challenges in the adoption of technologically produced nature derived stimuli. This piece sought to scale up the tactile nature of the artifact, allowing a more direct and inviting connection through touch and interaction.

The form was inspired by a variety of influences, primarily Japanese rock gardens and high alpine landscapes. The forms rise sharply and dance together in similar arrangements as can be seen at the Enko-Ji garden in Kyoto. These dueling planes provide a playfulness and evocative sense of movement in the stoic geologic forms. The cantilever helps enforce the geologic connection, inferring a heavy and immovable form. These elements combine to create a sense of a geologic forces playing against gravity to create a playful and expressive artifact.



Fig 4.3.1. Geologic table image. photograph by author

Framework Alignment:

As with the Stalagmite Light, photogrammetry techniques were utilized to produce geologic forms in alignment with the evocation of naturalistic forms and visual complexity characteristics found in the framework. The piece largely differentiates itself through the intended spatial relationship of the piece, taking the role of a furniture object fully integrated into interior planning, rather than forming a three dimensional centrepiece to be circulated around and experienced. This differention allows a more direct tactile integration. The introduction of a stained oak top allowed further experimentation with the integration of natural materials. Colour was embraced through both the integration of a granite clay body, mimicing the natural variation of stone, and amplified through the stained wood top, adding rich textural and visual variation.

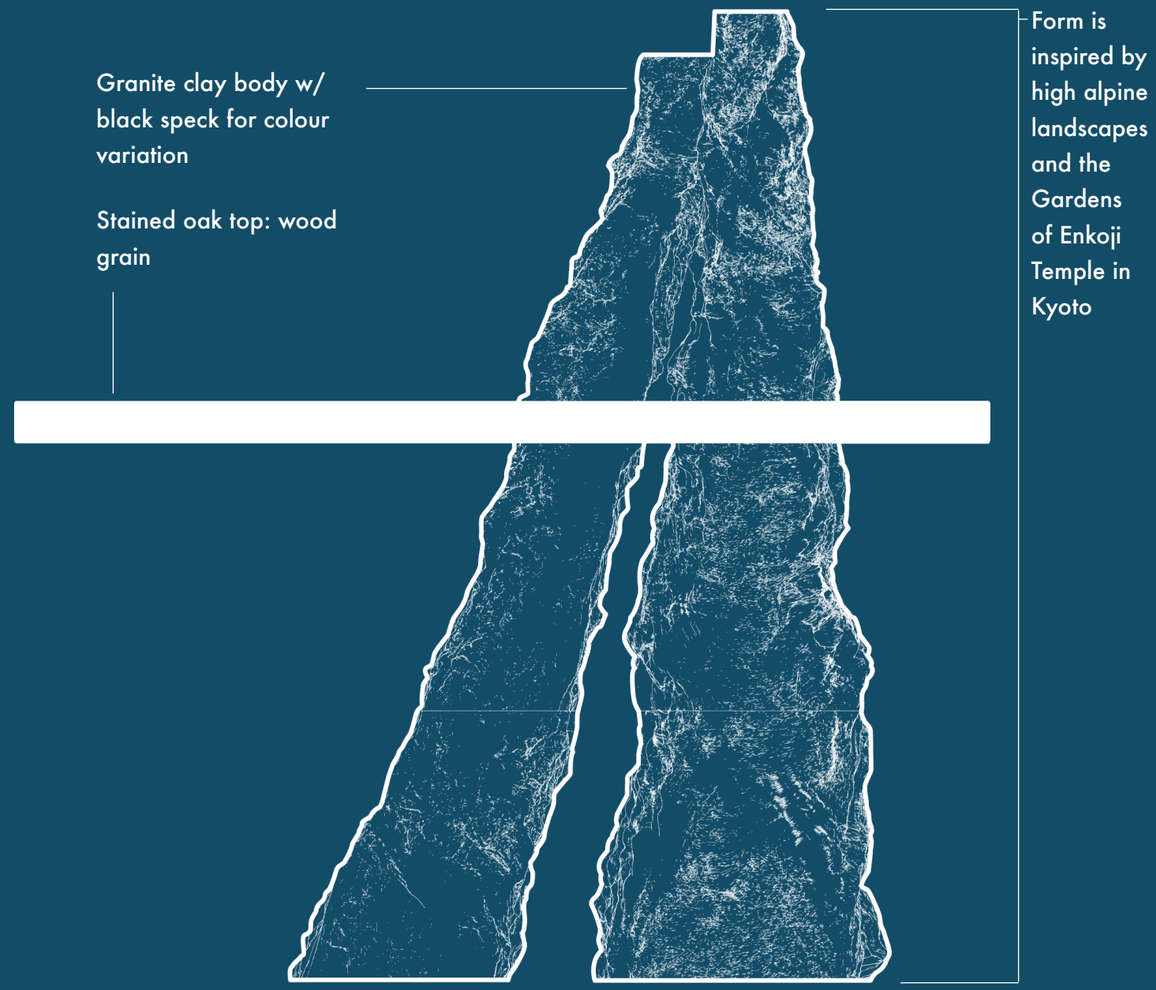


Fig 4.3.2. Geologic table elevation - framework alignment diagram A. diagram by author

This piece experimented with over-extrusion to allow deeper visual complexity than the Stalagmite lighting fixture through the addition of randomness in the print. The embedding of the wood in the clay body is reminiscent of how objects become trapped within stone and wood over time as erosion or geologic events trap objects or trees grow, or decay, around objects allowing a sense of time.

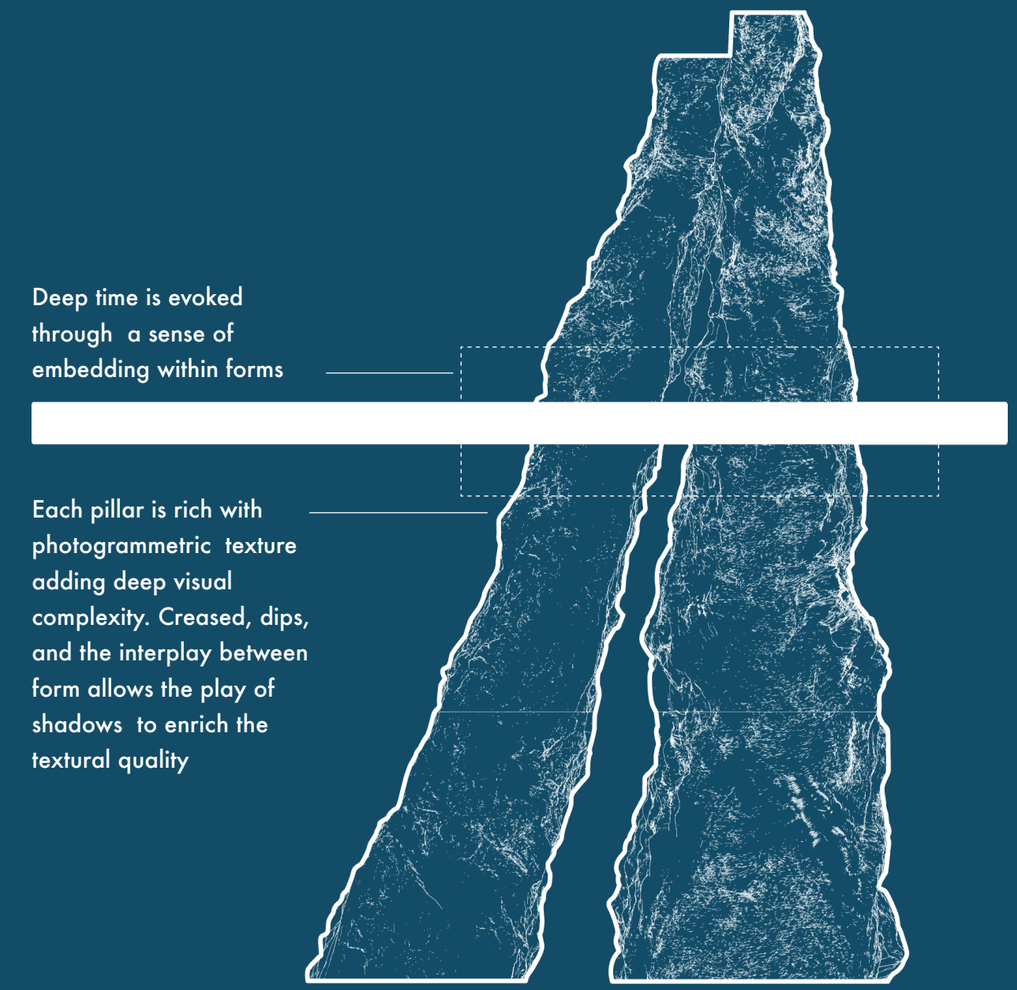
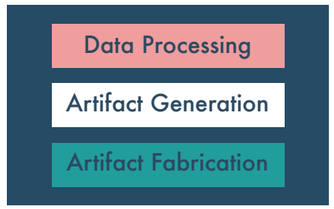


Fig 4.3.3. Geologic table elevation - framework alignment diagram B.
drawing by author

Geologic Table Workflow:

The geologic table sought to further explore the photogrammetry process through the addition of custom written code and more complex assembly methods. The design was produced in alignment with the stalagmite light, sculpting the form through layers of iterative addition and subtraction. Once split and processed into manageable pieces, each component was fed through a code which converted the base mesh to a printable GCODE. This code required iterative experimentation to produce a script capable of managing the immense and complex meshes generated by blender. Once a working code was established, each component was fabricated via a Scara 3D printer, dried, and fired before undergoing a more rigorous assembly process that included the fusing of pieces via tile grout, and the pouring of a concrete base with embedded steel rod to counterbalance the wood table top. This engaged process allowed the permanent fusing of tile elements and allowed hollow clay forms to be used to conceal structural elements in the piece.



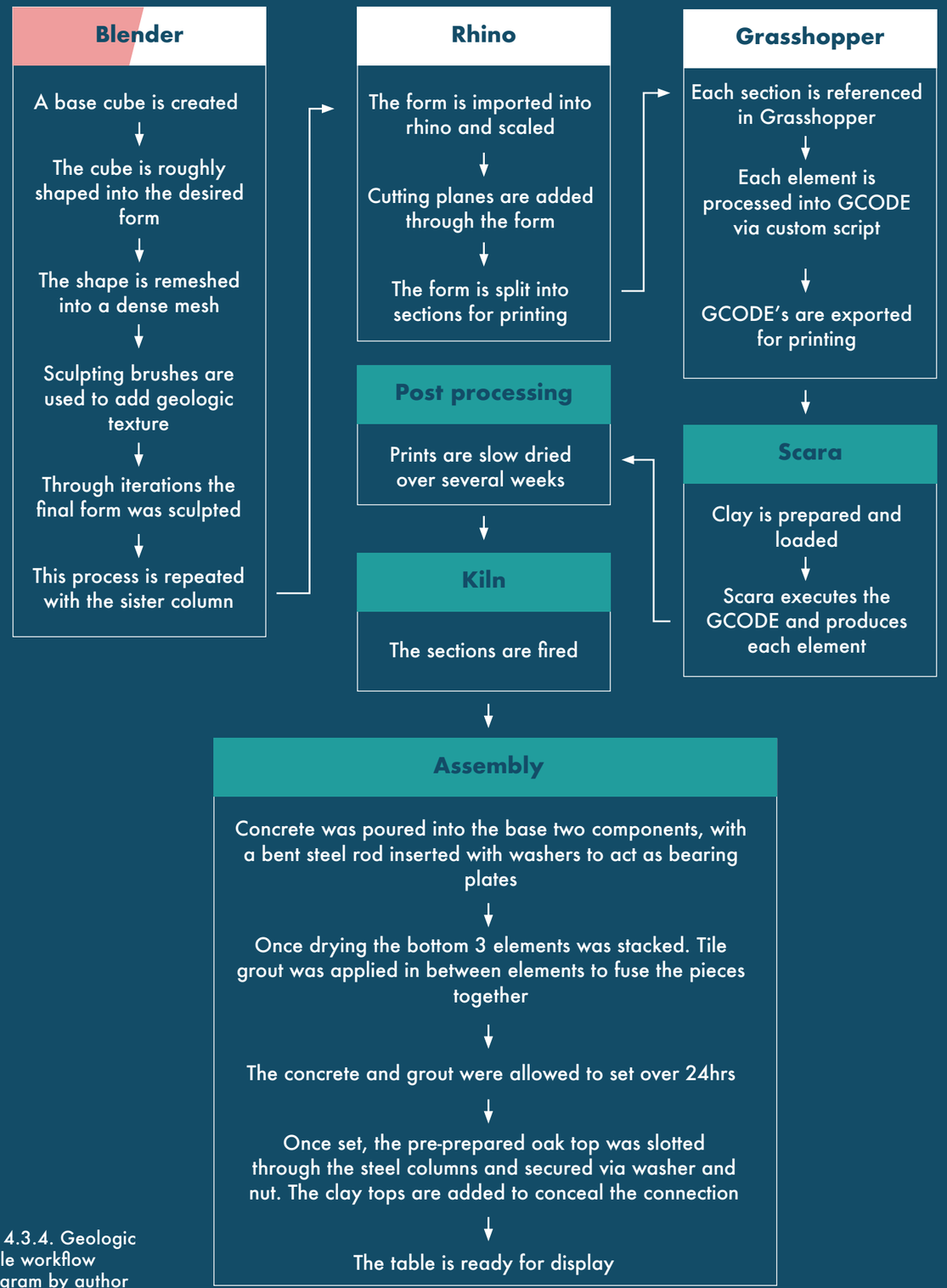


Fig 4.3.4. Geologic table workflow diagram by author

Photogrammetry integration

The design process starts with the creation of a base mesh which is roughly shaped into the desired form. This form is then re-meshed to produce a highly detailed surface. Photogrammetry brushes were then used to add layers of texture and three-dimensional relief based upon scans of real world geologic features. The mesh is then iterated through phases of sculpting and re-applying brushes to arrive at the desired form. The intensity of the brushes are adjusted to increased or decrease amount of desired relief, and the shape is adjusted to accommodate printing limitations. Once shaped, the mesh is exported into Rhinoceros 8 where it is split into printable sections and processed via a custom GCODE. This code was written to allow the processing of complex meshes into printable code. The pieces were then printed and allowed to slowly dry before being fired directly to cone 6.



Fig 4.3.5. Photogrammetry integration illustration A. drawing by author

Design Methodology/Fabrication:

Design:

1. A base mesh is created in blender by manipulating a cube.

2. The base mesh is then re-meshed to create a very fine mesh for manipulation

3. The mesh is then shaped using blenders sculpting brushes and photogrammetry brushes to create a the final form.

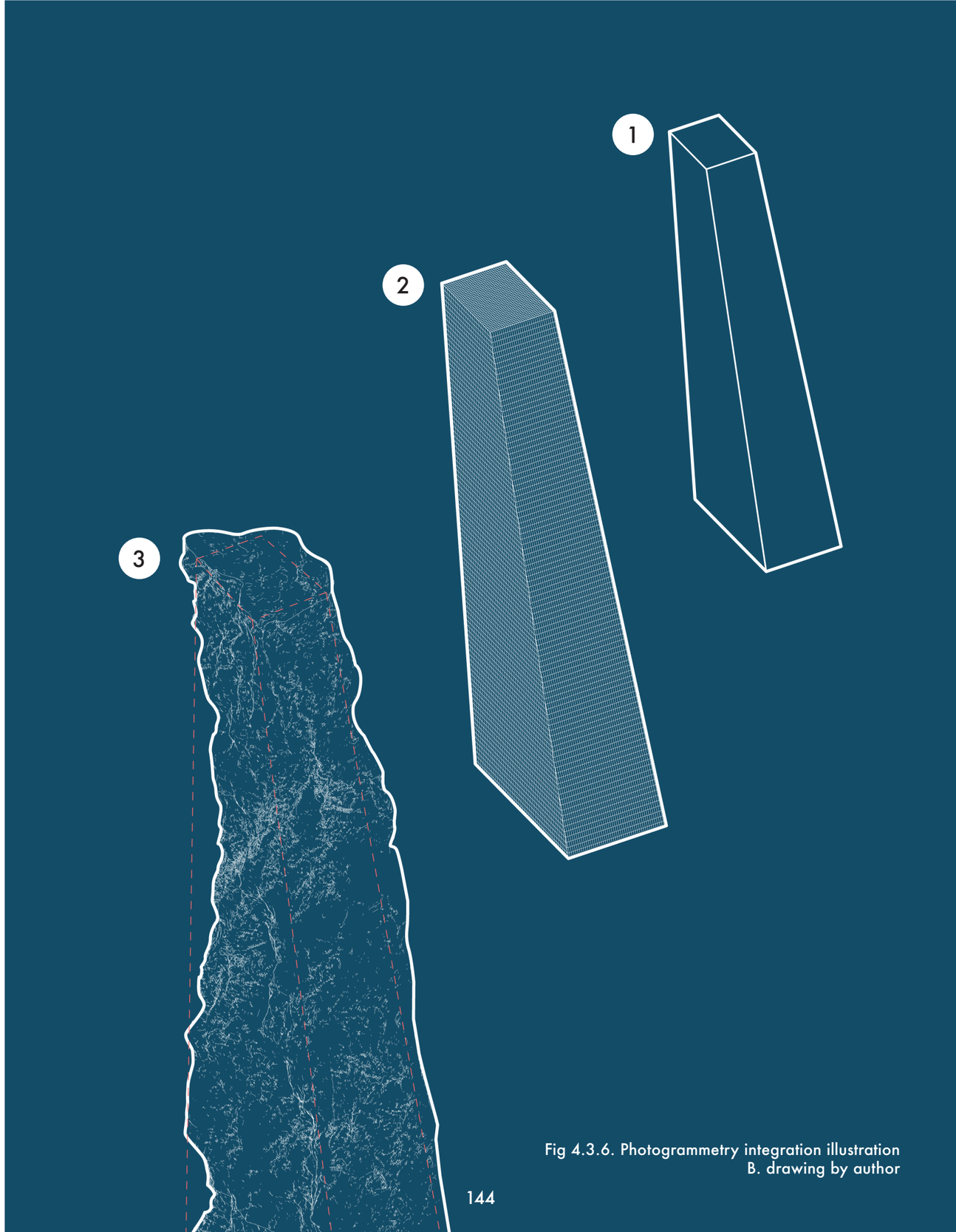


Fig 4.3.6. Photogrammetry integration illustration
B. drawing by author

Design Methodology/Fabrication:

Design:

1. In Blender the process starts with a basic cube.
2. The cube is roughly shaped into the desired dimensions and form.
3. Sculpting tools are used to add general form, mimicking erosion and degradation
4. Photogrammetry tools are used to add texture, re-shape, and sculpt the form. This process is sculptural in essence and based on feel, allowing the form to develop organically and respond to the added texture and elements.
5. The process is repeated with the second pillar, allowing them to be designed in unison, responding to one another.
6. Once designed the pillars are exported to Rhinoceros 8, the wood top was then placed into the design.
7. The clay pieces are then split into fragments based on the clay capacity of the clay extrusion printer.
8. Each piece once split is processed via a custom grasshopper script into GCODE.

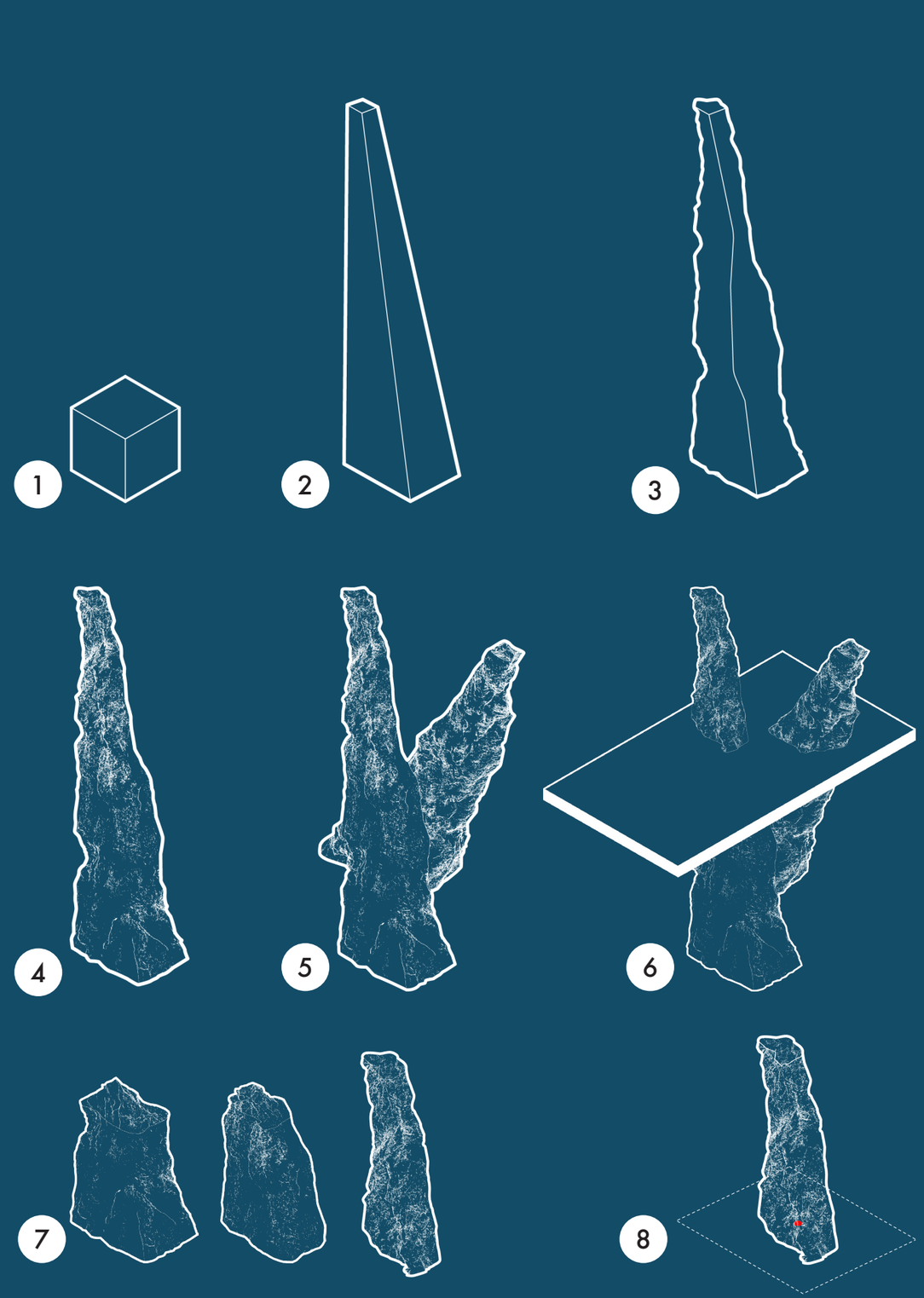


Fig 4.3.7. Geologic table assembly fabrication diagram. diagram by author

Design Methodology/Fabrication:

Assembly:

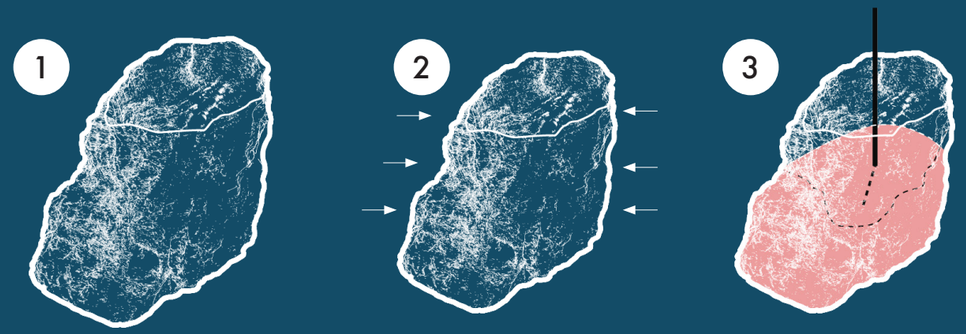
1 Fragments are printed and slow dried over a period of one to two weeks. Each print took between three and four hours to print. This print time was extended due to low layer height to obscure print lines, intentional over extrusion for textural quality, and the unexpected time added by converting extremely large meshes to code, which created very small segments in print lines.

2 All prints were able to fit into a single kiln firing. The elements were fired directly to cone 5 achieving full hardness. During the firing time each fragment shrunk by approximately 12-15%.

3 Once fired the bottom element was placed on a board and clay was used to seal the edges of the print. Fast setting concrete was then poured and a bent steel rod was inserted with a washer and nut at the base acting as a bearing plate.

4 While concrete dried, the fragments were cleaned, tile grout was added in between the bottom two fragments, and pieces were stacked allowing the artifacts to harden together.

5 Twenty-four hours later the joint pillars were now moved to a worktable where the custom made wood top was placed on top of the bottom pillars, feeding the steel rods through the two pre-drilled holes. The top was secured via washers and nuts before the top two clay fragments were placed on top. These elements act both to hide the structural elements but also to provide the illusion of the wood intersecting the table.



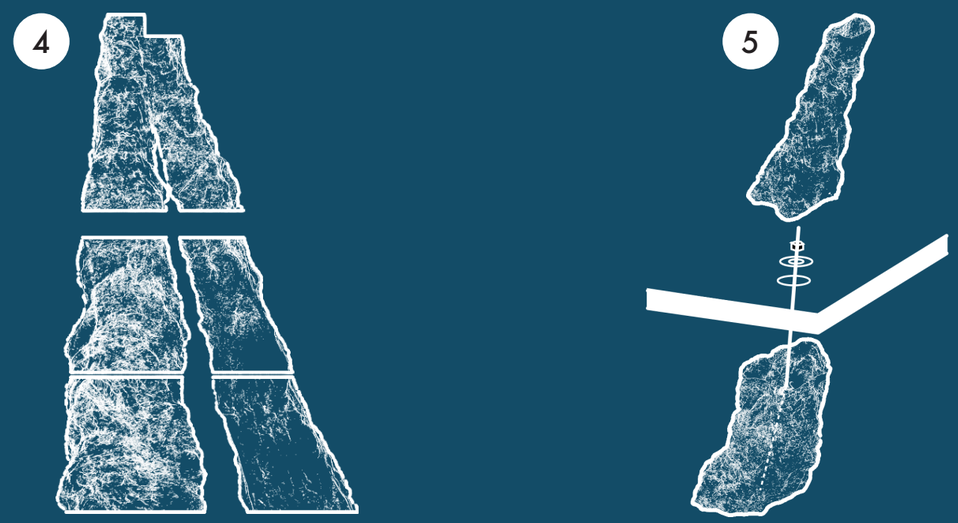


Fig 4.3.8. Geologic table fabrication diagram. diagram by author

Process Documentation:

Images of the geologic table elements during drying, assembly, and test fitting for assembly.



Fig 4.3.9. Process documentation collage - geologic table collage. collage by author

Gallery





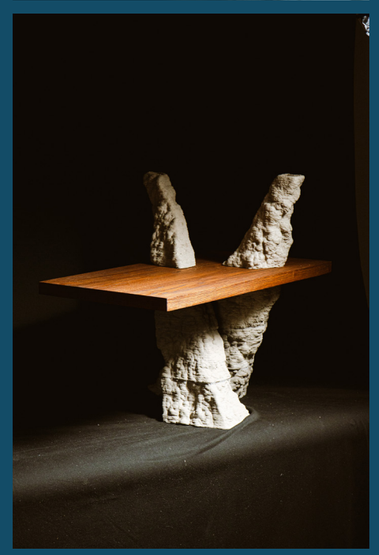




Fig 4.3.10. Final image collage - geologic table.
collage by author

Reflection:

Several key challenges were identified which will need to be overcome in future research. The generating of script from complex meshes created through photogrammetry resulted in large print times that limit its viability. If this corresponding script can be simplified, and print times decreased, fabrication viability will be greatly improved. Some minor warping did occur which was the result of ambitiously angled geometry which could be resolved via counterweighting methods (adding clay in key areas while drying) or reshaping the geometry. While some limitations certainly create challenges for widespread use, photogrammetry tools proved successful in generating deeply rich visual stimuli with naturalistic qualities. The final artifact illustrates a successful translation of big data and additive manufacturing into a design object that contain the desired qualities selected for through the design process.

The smaller scale of this piece, comparative to the lighting fixture, meant that the photogrammetry achieved a lower resolution and expression, which was notable for appearing less naturalistic than the larger counterpart. While successful, a higher resolution print, or more pronounced photogrammetry application may have produced greater results. The integration with a wood top and furniture component however, proved highly successful in creating an evocative and unified object for daily use.



Fig 4.4.11. Geologic table photograph. photograph by author.

4.4 Topographic Mural

Goals:

This artifact attempts to illustrate the potential of digitally fabricated large scale murals for restorative effect. Through clay extrusion, this intervention demonstrates the potential for a high degree of three-dimensional relief in digitally fabricated tiles. This allows a more intense visual connection, producing a highly evocative relief with the opportunity to produce an engaging feature, experienced through direct visual connection. By applying a surface application, it allows a scalable, and dominating artifact to be produced.

To demonstrate the potential of large scale ceramic murals, mountainous terrain was chosen as it allowed deep three-dimensional relief across recognizable form. Building from the sconce, mountainous relief presented an opportunity to test the limitations of the achievable relief and to test the ability of the clay printer to produce strong durable components while retaining a high degree of relief. This stimuli also presented an opportunity to test how current technological limitations impacted the translation of the LiDAR imagery to printed relief. In order to execute the project, a large area containing deep visual relief was required to increase visual complexity. This specific area of LiDAR was chosen as it represented the largest swatch of continuous visually complex topography that could be located.

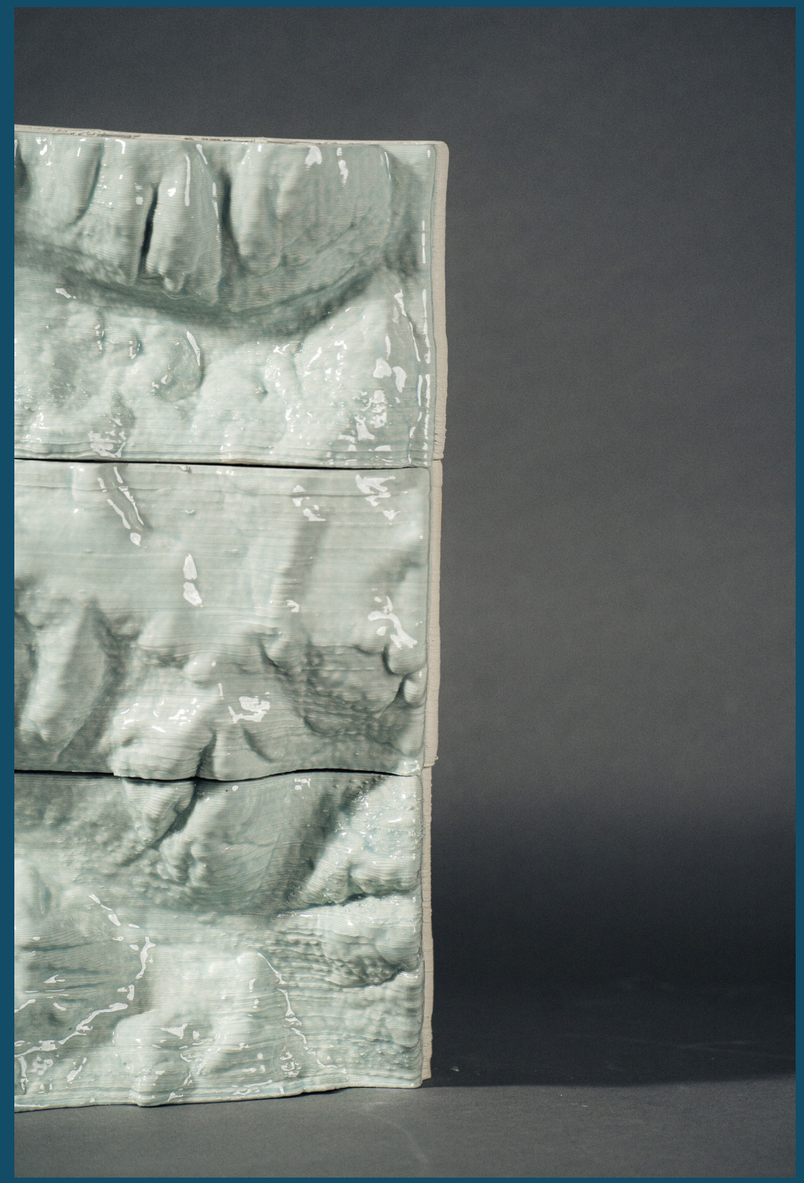


Fig 4.4.1. Topographic mural detail photo. photograph by author

Framework Alignment:

LiDAR of British Columbia's mountain ranges were used as they represent areas of high visual complexity and three-dimensional relief. The high degree of relief allowed greater expression and play of shadows in the final pieces, which contributed to increased visual complexity. The section of LiDAR used was specifically chosen as it represented a largest patch available to source, which meant a higher degree of complexity within each tile. Mountainous terrain presented an immediately recognizable stimuli, drawing on a clear and instantaneously recognizable evocation of naturalistic forms.

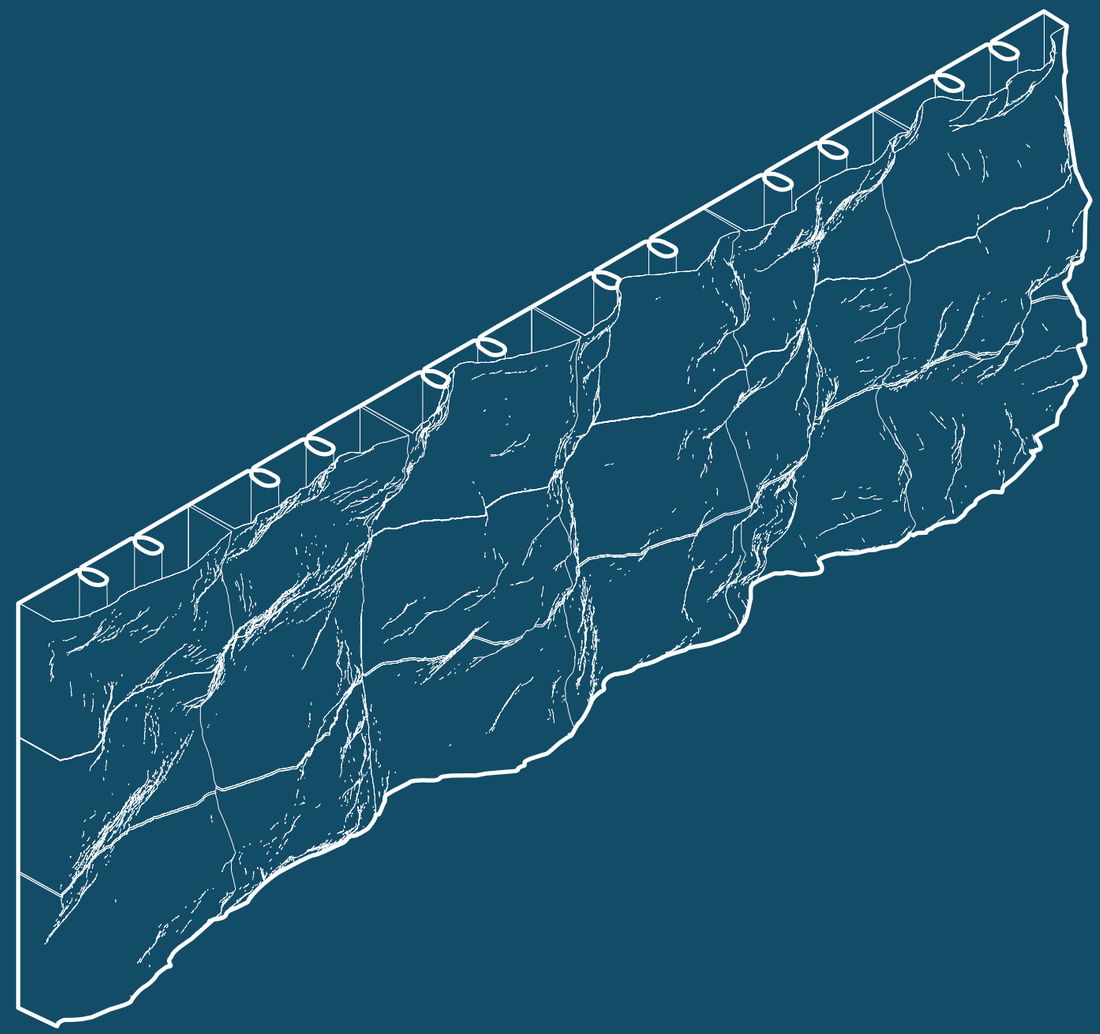


Fig 4.4.2. Topographic mural axonometric. drawing by author

Colour was a central interest of exploration in this piece, ultimately utilizing a glacial blue that evoked the natural landscapes of mountainous regions. Mountainous regions represent visual reminders of the complex earth shaping forces of time, with the glacial blue evoking both the glacial waters of mountainous regions and reflected light of snow off snow-covered mountains, a constant seasonal flux in these regions, creating an evocative symbolic representation of a sense of time.

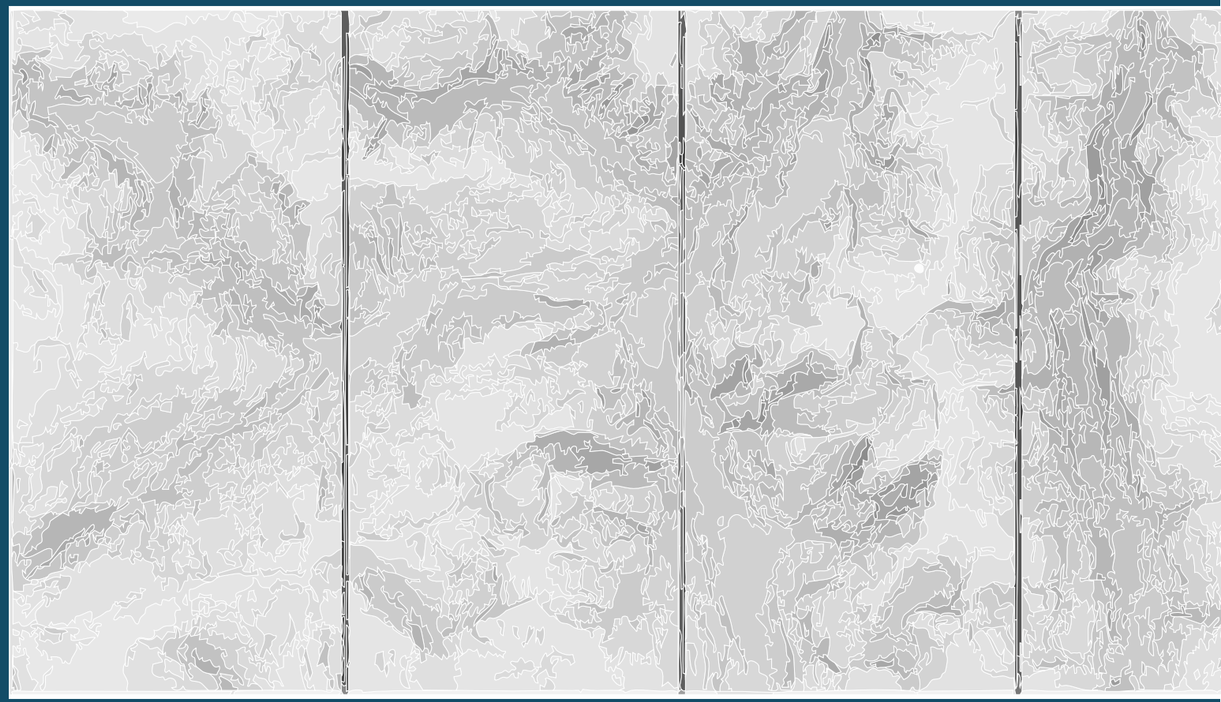
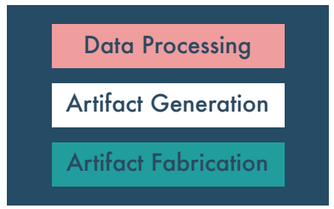


Fig 4.4.3. Topographic mural illustration close up. drawing by author

Topographic Mural Workflow:

The creation of a larger scaled architectural mural required the addition of several intermediary steps. Once a sufficiently large region of data was gathered and exported from QGIS as a greyscale map, the large scale jpeg was imported into Photoshop and contrast was increased to allow greater three dimensional relief. This file was then imported into InDesign where it could be tiled into 18 pieces to facilitate a production plan. This was then exported to Illustrator where it could be split into 18 individual image maps. This was then run through two custom scripts, which first allowed the image map to be applied to a base surface, forming the tile face. The second script then fused the tile face and backing together to create a single polyline that was converted into a series of printing instructions. This process was highly successful in generating a series of tiles. One major limitation was the challenge of fusing the image mapped surface back to the base tile. This required a clean point to stitch the two meshes together. While this was doable, it created a condition that exaggerated the seam between each tile. Additionally, warping was a concern in the kiln, so additional bracing was manually added to each tile. Once printed, dried, and bisque fired, each tile was glazed and fired to cone 6. Once fully fired, the tiles were assembled and stacked.



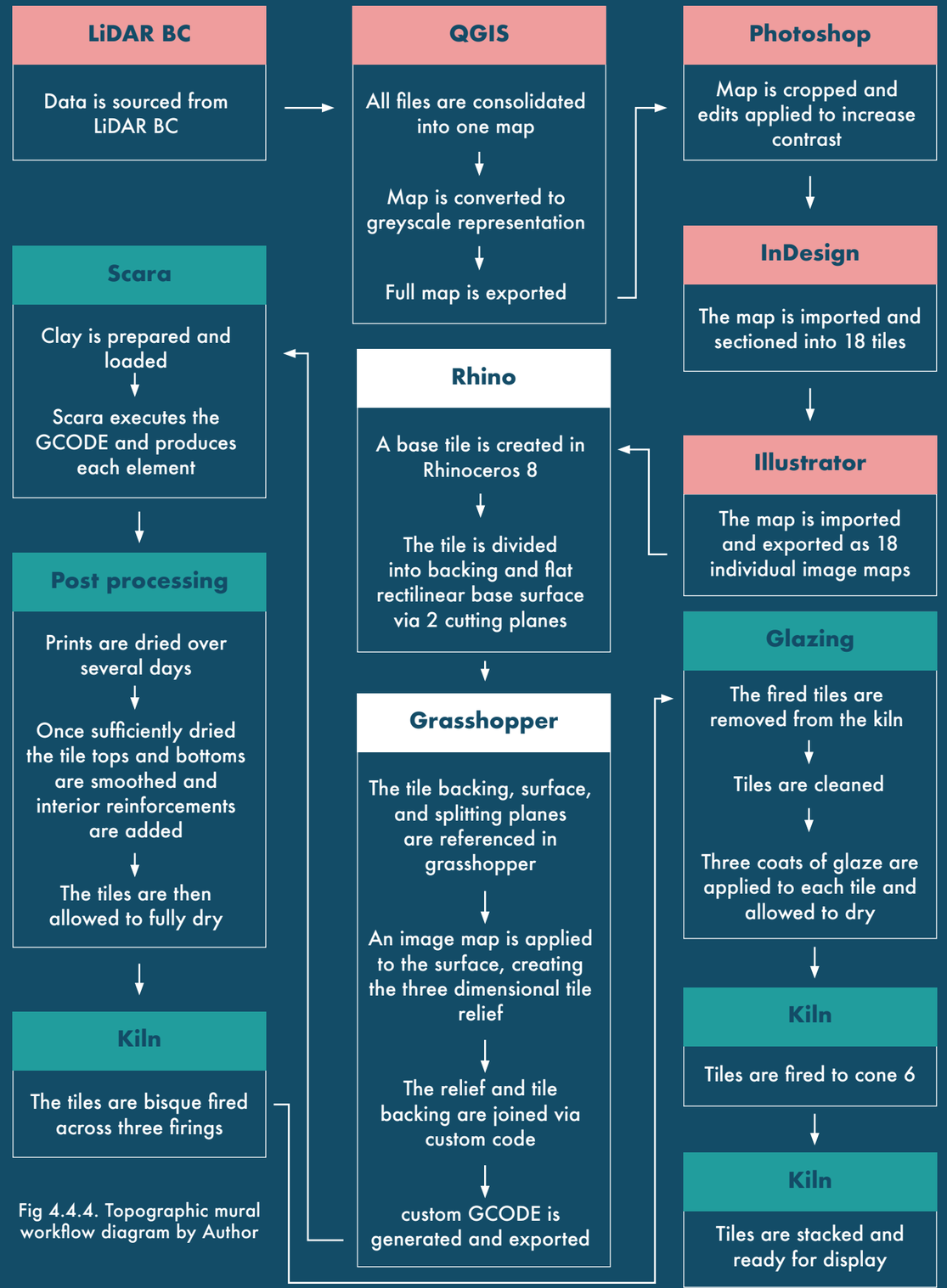


Fig 4.4.4. Topographic mural workflow diagram by Author

Fabrication:

LiDAR information was sourced from LidarBC a government repository for LiDAR information. This LiDAR was generated into a map utilizing GQIS and exported as a large resolution PNG. This information was used to generate image maps.

Image maps were utilized to generate digital meshes through a custom Grasshoppper code and then joined with a digital tile backing via Grasshopper script. These tiles were then prototyped and refined to minimize warping, maximize expression, and minimize seam appearance. Several glazes were then tested before the final artifact was fabricated.

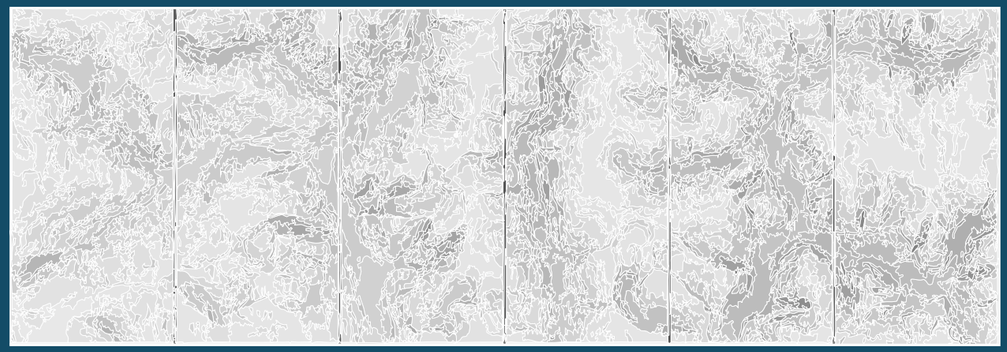


Fig 4.4.5. Topographic mural illustration elevation. drawing by author

LiDAR Integration:

A large swatch of LiDAR was downloaded and compiled into one map. Once assembled this data was processed into a slope map, then grey-toned map before being exported as a large scale JPG. This file was then cropped into a rectilinear frame, before being sectioned into printable tiles. These tiles were then individually exported as image maps. The image map was then applied to a surface with pre-made tile backing. The tile was generated, digitally stitched together, and exported into GCODE via a custom made code. Each tile was then individually fabricated, smoothed, dried, fired, glazed, and assembled into the final configuration.

1. BC Coastal Mountains slope map
2. BC Coastal Mountains grey-toned map
3. BC Coastal Mountains grey-toned map with section divisions for image mapping tiles

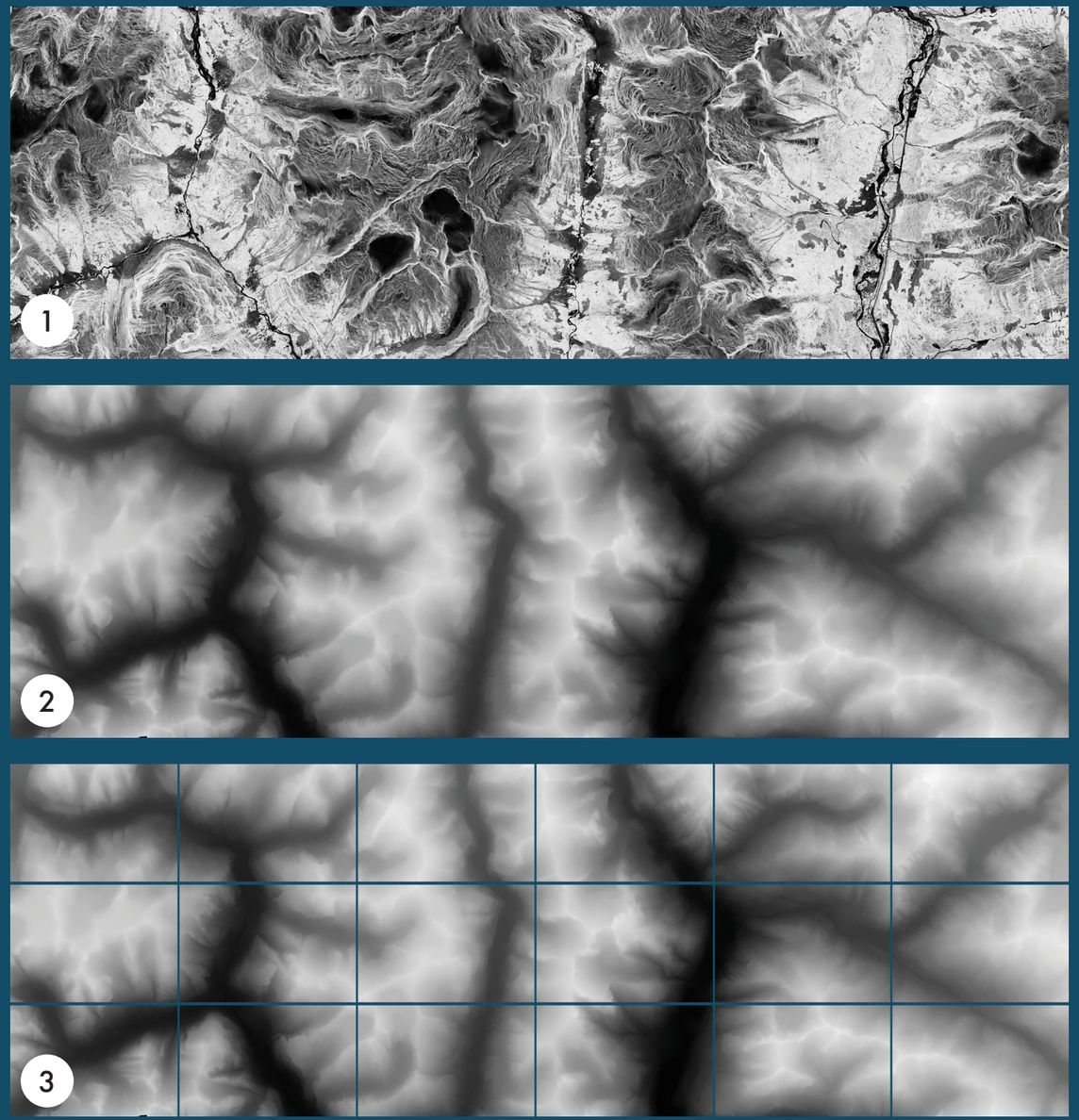


Fig 4.4.6. Topographic mural LiDAR integration diagram. diagram by author adapted from BC LiDAR. *LiDAR DSM Index 1:20,000. DSM. August 8th, https://lidar.gov.bc.ca/pages/download-discovery*

Design Methodology/Fabrication:

Design:

1. A base tile was created in Rhinoceros 8

2. Cutting planes are introduced to allow splitting of the tile in Grasshopper.

3. The tile is split in Grasshopper to create a base surface that can be manipulated.

4. The surface is then ran through an image map whose information is derived from the pre-sectioned LiDAR image.

5. This surface then undergoes a series of manipulations that merge the new surface to the tile backing and generate a code for production. This allows the generation of a GCODE instruction for the clay printer.

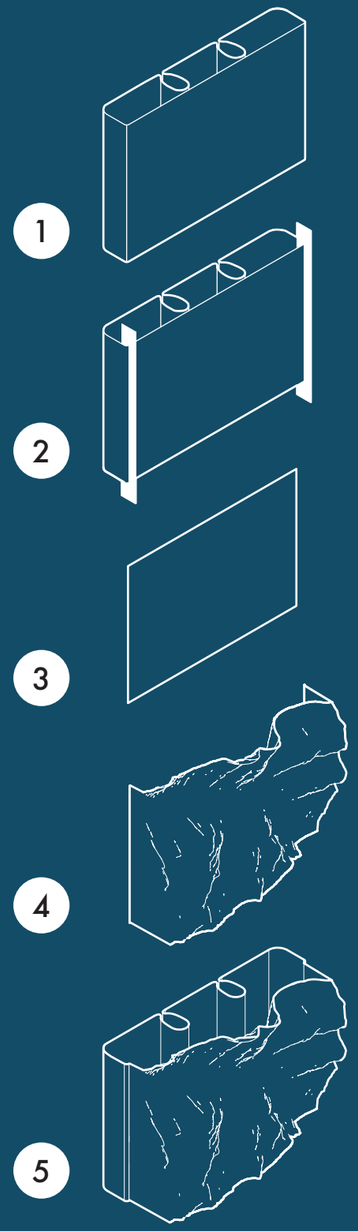


Fig 4.4.7. Topographic mural tile generation diagram. diagram by author

Design Methodology/Fabrication:

Design:

1. Post printing each tile is slow dried and smoothed to allow joints to align more cleanly. Once dried the tiles are batch fired to cone 06.

2. Once fired each tile is glazed. Glaze is applied only to the face of each tile to conserve cost and allow the tile to lay on its back for final firing without fear of sticking to the kiln shelf.

3. Once glazed, each tile is fired to cone 6.

4. Once each tile has been fired the assemblage is stacked together and prepared for display.

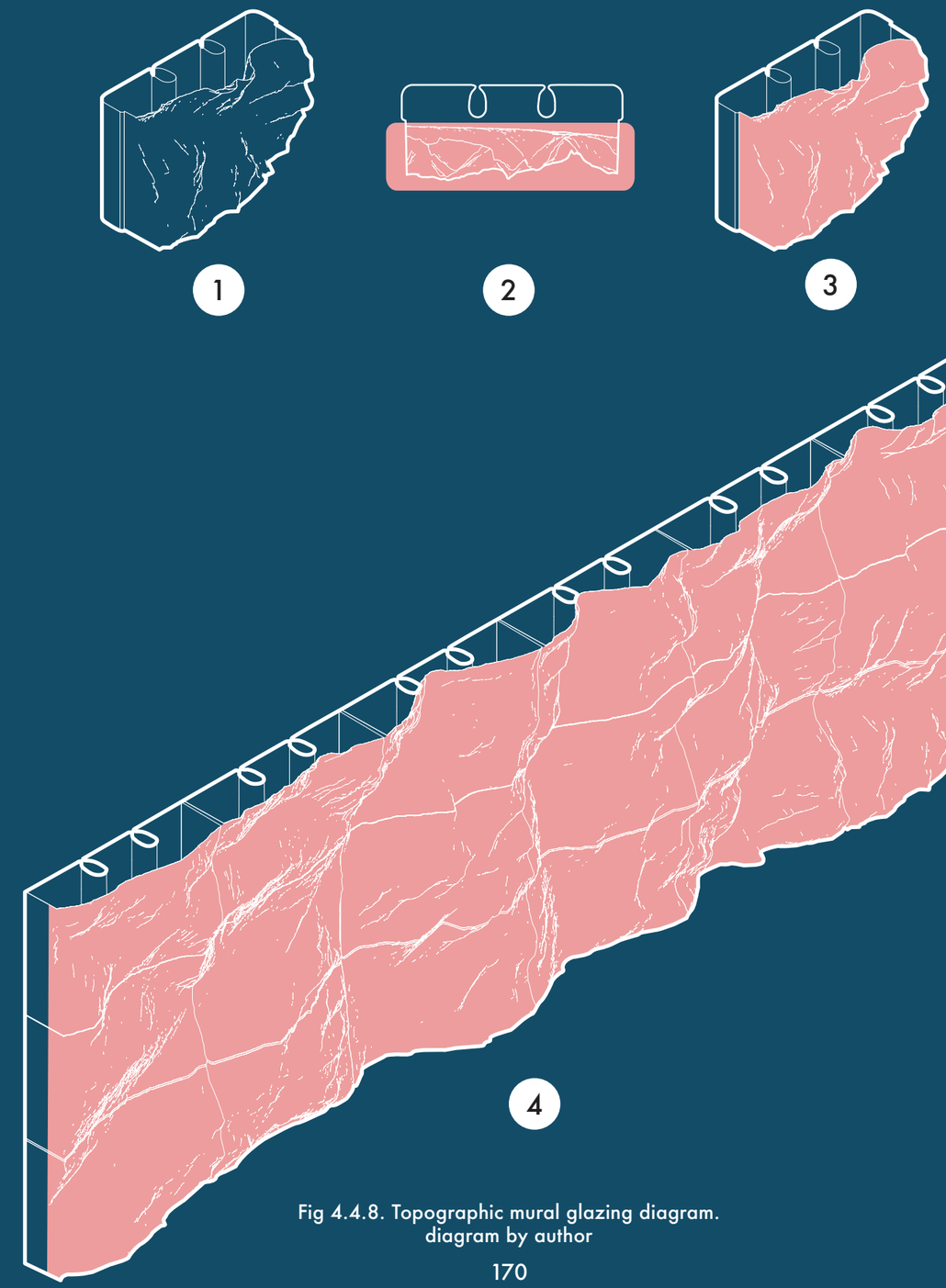


Fig 4.4.8. Topographic mural glazing diagram.
diagram by author

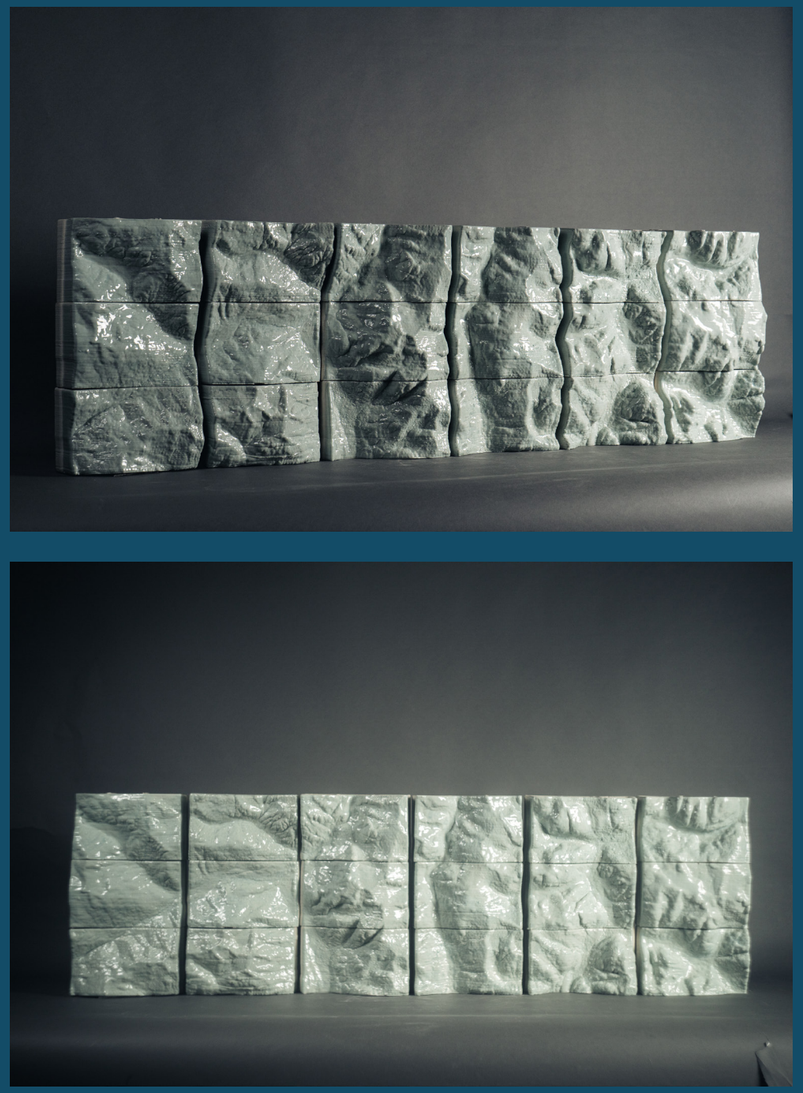
Process Documentation:

Images of individual tiles being printed, dried, and test fit for assembly after bisque firing.



Fig 4.3.9. Process documentation collage - topographic mural. collage by author

Gallery:





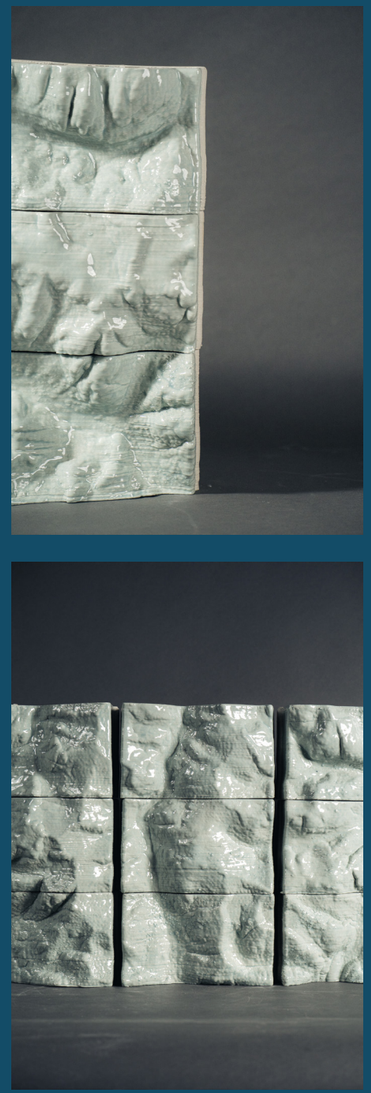


Fig 4.3.10. Final image collage - topographic mural.
collage by author

Reflection:

The realization of a large scale mural required careful consideration and coordination. LiDAR methods that were established through the topographic sconce were carried into large scale fabrication, with several small tweaks. The production of large tiles required support additions to prevent kiln warping, this was accomplished through a combination of initial supporting arms in the fabrication process, and additional hand built support. This was quickly added and was an effective solution to avoid more complex coding. However, these supports warped during the final firings and needed to be occasionally manually removed. This process could be streamlined through more effective coding practices.

Glazing required several tests, with a matte finish assumed to provide the best results. Ultimately, a glossy glacial blue was chosen, both for its design characteristics and qualities. The reflective glaze allowed a pooling of glaze into richly detailed areas which allowed an almost superimposition of shadow that allowed a better reading of details than matte finishes, or even a raw finish. This revealed that glaze qualities play an imperative role in the success of this type of stimuli, and that glazes which pool and crack around detail are highly advantaged in their ability to further strengthen the inherent geometries of the piece itself.

Future iterations should focus on developing better connections between LiDAR generated meshes (IE tiles), as this practice required a sizable gap that could feasibly be reduced with further testing.

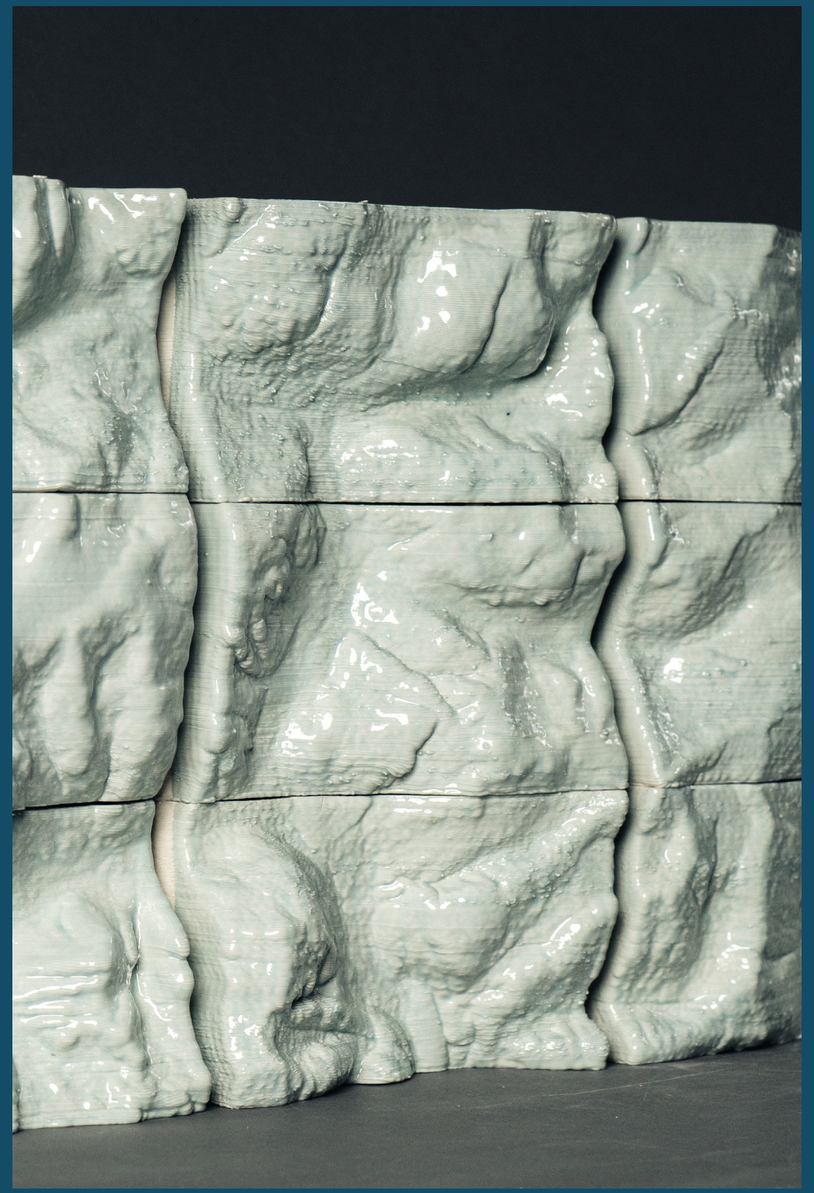


Fig 4.3.11. topographic mural photo. photograph by author

5.0 Conclusion

The pursuit of a refined restorative framework proved both ambitious and enlightening. While each framework supported their evidence in various ways, it revealed a web of research that drew from a number of studies with varying levels of support. Areas such as complexity, the importance of visual representations of nature, and more recently fractal fluency, were well supported by rigorous research. In contrast, colour theory remains somewhat understudied, with strong conclusions difficult to resolutely prove. Notions of time and a sense of gravity were supported by limited research but failed to form a cohesive argument and consensus. With this in mind this framework remains a starting point, to draw together convincing studies and shape an approach to architecture that is compassionate and reasoned. In its application each tool selected proved successful but with limitations. LiDAR proved a valuable starting point, containing large data sets with rich and detailed information. The translation of LiDAR to final form proved to have limitations, with complex meshes often difficult to work with, and resolution being lost through various manipulations. While the translation of LiDAR to image maps was greatly useful in the realization of printed artifacts, the direct translation of LiDAR to complex mesh, to print, would arguably allow for less loss of resolution. This process would make valuable future research. Photogrammetry initially produced somewhat disappointing results, as the final artifacts lacked the desired resolution. However, refinements in modeling techniques improved this process and allowed more successful prints to be developed. Both processes allowed for the generation of artifacts that stayed true to the ambitions of the framework and were notably successful in these ambitions.

Clay extrusion printing proved challenging for the translation of restoratively driven artifacts to physical form. While the material achieved the sustainability and material goals of the thesis, and well aligned to the integration of natural materials component of the framework, limitations in current clay extrusion technology proved difficult to balance. While high resolution is possible, it required

extremely long print times utilizing the available extrusion printers. This proved impossible for the purposes of this thesis. Additionally, small nozzle sizes require design limitations, such as reduced depth to the prints, and careful consideration of the structural stability of the print. To accomplish the large scale of the prints, a larger printer was needed with larger nozzle sizes. Ultimately a larger nozzle, often 4-5mm, was required to produce a stable print with high offset. This limited the material resolution, creating a difficult to balance design limitation. The works of artists such as Barry Wark, Michael Hansmeyer, and Benjamin Dillenburger utilized sand 3D printing which appears capable of much higher degrees of detail. In this way, clay extrusion, while capable of producing successful prints, is more resolution limited than alternative print methods. Additionally, many challenges were encountered in the generation of clay artifacts, including the joining of multiple pieces, post smoothing challenges, and overcoming warping challenges as prints produced by clay extrusion warp somewhat less predictably than those hand thrown. The durability of these prints, and suitability for both interior and exterior surfaces do however, present a strong argument for clay extrusion as a successful tool for implementing restorative design artifacts into physical space.

On the implementation of restorative design into sterile domestic and commercial space, this thesis has demonstrated that digitally fabricated clay artifacts do have feasible application as restorative interventions. Tsunetsugu, Miyazaki, and Sato's study found a positive response to wood elements in interior spaces.[250] Further research is needed to identify whether these interventions could produce similar results. To that end however, Fig 5.0.1 serves as an example of how these design interventions could be scaled, to produce spaces with relatively small interventions, to entirely encompassing proposals, such as adopting clay extrusion printing as a full skin to the augmentation of space.

While these artifacts by no means represent an exhaustive exploration of the application of restorative design implementation, they represent a tangible physical realization of the implementation and translation of restorative design principles into physical artifacts. Both methods, LiDAR and photogrammetry, proved feasible potential design tools for designers to sculpt and develop visually complex stimuli with potential restorative effect. While clay extrusion printing is subject to material and technological limitations, it ultimately presents a useful tool for the generation of large scale complex geometries, efficiently, and with affordable material elements. The final artifacts, while inevitably flawed prototypes, showcase a wide variety of potential applications, scales, and strengths, in the pursuit of restorative design.

Early modernism ultimately heralded the disappearance of rich textural interiors, drawing on contemporary notions of health to re-imagine how spaces could better serve their occupants.[251] Through these interventions, architecture gradually lost connection with our ancestral environments, and developed a language of sterility that permeates modern architecture. Now, over a hundred years later these spatial shifts remain resolute parts of contemporary interiors. In the intervening decades a rich landscape or research has emerged, inspired by Darwinian notions of evolution which helped reveal the intimate connections humans have to our ancestral environments. Models such as Stress Recovery Theory, Attention Restoration Theory, and the more recent Fractal Fluency Model has developed to make sense of these evolutionary mechanisms and provide insight into how space can be better attuned to our physio-biological needs. These systems have revealed a preference for rich textural landscapes, which offer opportunities for reprieve and restoration. The demands of contemporary living have made the need for restorative space ever more imperative.

Advancements in technology have begun to create opportunities to re-introduce a visual complexity and richness into today's architectures. This framework and associated artifacts present one possible future, where enriched vibrant interiors can provide restorative space for recovery and relaxation. With access to new technologies designers have the tools to craft and imagine more restorative environments. As early modernists looked to science and technology, architects of today have the same opportunity to update their methods to better reflect our physio-biological needs.

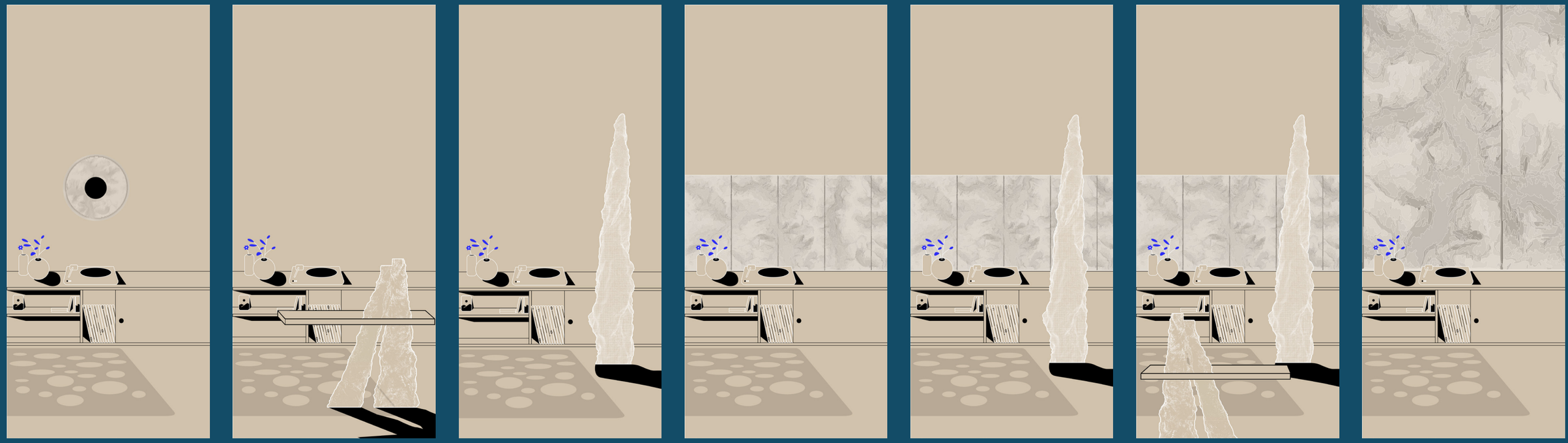


Fig 5.0.1. Restorative artifact scale of intervention illustration. drawing by author

Left to right illustrates increasing levels of intervention through increased scale and density of artifacts.

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