Modulating Visual Connectivity Through 3D-Printed Ceramic Light Screens

by
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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 final revisions, as accepted by my examiners.

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ABSTRACT

This thesis investigates an iterative modeling and fabrication process for customizable building components through the design of a high-performance light screen. Light screens, mostly implemented as physical boundaries for modulating light and providing visual accessibility between the exterior and interior spaces, are considered as highly ornamental elements in the building. One of the most common methods for constructing these screens is casting which provides a high level of flexibility for making pieces with complex geometries. However, casting technique requires making a new mold for every different piece. As a result, designers' capability to experiment with more complex designs through these trade-off techniques has been limited by the amount of time and cost required to go beyond one-off prototypes. To avoid making new molds, this research uses clay 3D printing as it creates a direct link between the material and the digital model and results in making the pieces without needing a mediator element. Having the opportunity to apply real-time changes to the design parameters, this study evaluates the performance qualities of the screen by regulating the major influential parameters on its functionality: Form, material, light penetration, and position of the viewer. The 3D-printed components are tested with iterative physical prototyping, computational modeling, and digital simulation to demonstrate the created visual and light qualities in different applications. This framework can significantly change the process of design and fabrication of functional building components towards a more affordable and customizable approach.

ACKNOWLEDGMENTS

I would like to express my gratitude to my supervisor, David Correa for your devoted support and mentorship in pursuing a unique research topic. Thank you for your constructive feedback and continuous encouragements. Your wisdom and enthusiasm were crucial for achieving this success and inspired me beyond this project.

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TABLE OF CONTENTS

Chapter One: Introduction

Chapter Two: Context

Chapter Three: Methodology

Chapter Four: Design and Fabrication

Chapter Five: Discussion and Research Outlook

LIST OF FIGURES

CHAPTER ONE

Introduction

“From now on, we are no longer designing the form that will ultimately be produced, but the production process itself. Design and execution are no longer phases in a temporal sequence design sketches do not need to be converted into execution drawings anymore. The design incorporates the idea and knowledge of its production already at its moment of conception.”

Fabio Gramazio, Digital Materiality in Architecture (Baden, Switzerland: Lars Muller Publishers, 2008), 8.

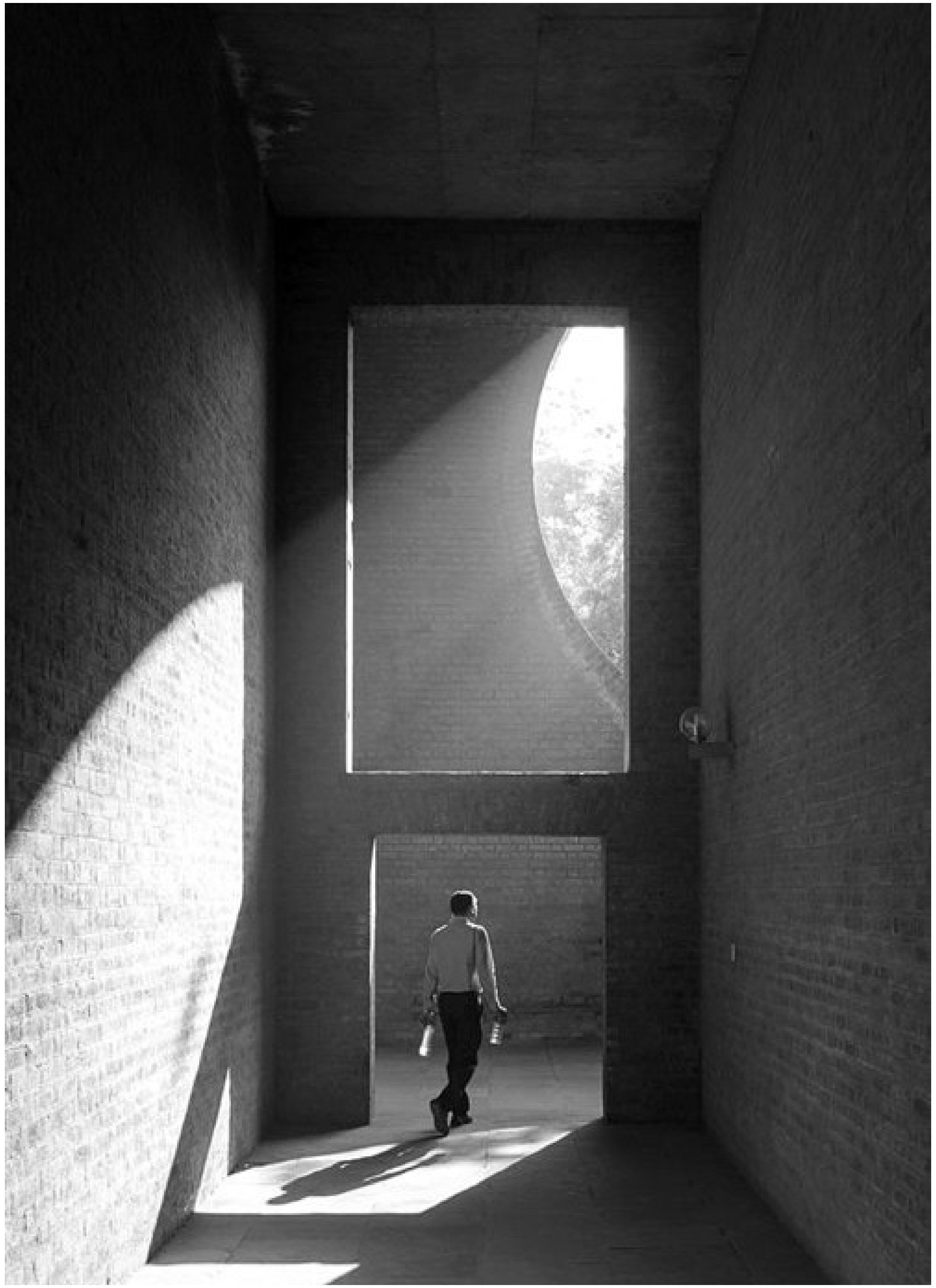

Figure 1.01. The Salk Institute by Louis Kahn, 1957.

1.1. Aim

Masonry light screens, known as physical boundaries separating the interior and exterior environment of the buildings, can significantly heighten one's perception of the space by controlling the observer's visual connectivity. These screens are rooted in the architectural history of many nations and are still implemented in buildings for different purposes. Among numerous architectural applications of light screens, these structures are mainly used for modulating light and controlling visual connectivity between spaces in buildings. Designers' ability to improve these qualities is tailored to the components' level of customizability in changing the design attributes.[1] Maintaining the customizability of these building components must be kept central along with the provision of an affordable budget so the designers can carry out further explorations. However, these requirements are often at odds due to the limitations of the current construction methods. In this thesis, new techniques are tested by adapting clay 3D printing and computational design, applied to the design of a customizable and affordable light screen. Computational modeling, digital simulation, and physical prototyping are used to design and evaluate the functional qualities of the screens. The output of this research is a physical ceramic light screen at the scale of 1:1. The performance qualities of the structure are demonstrated through digital modeling and simulation of the screen in different spaces. In parallel to the central technological investigation, this thesis investigates the role of computational modeling optimizations in the conceptual development of mass-customization of complex designs which results in the improvement of individuals' accessibility to high-performance components.

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[1] Naboni, Paoletti, *Advanced customization in architectural design and construction.*

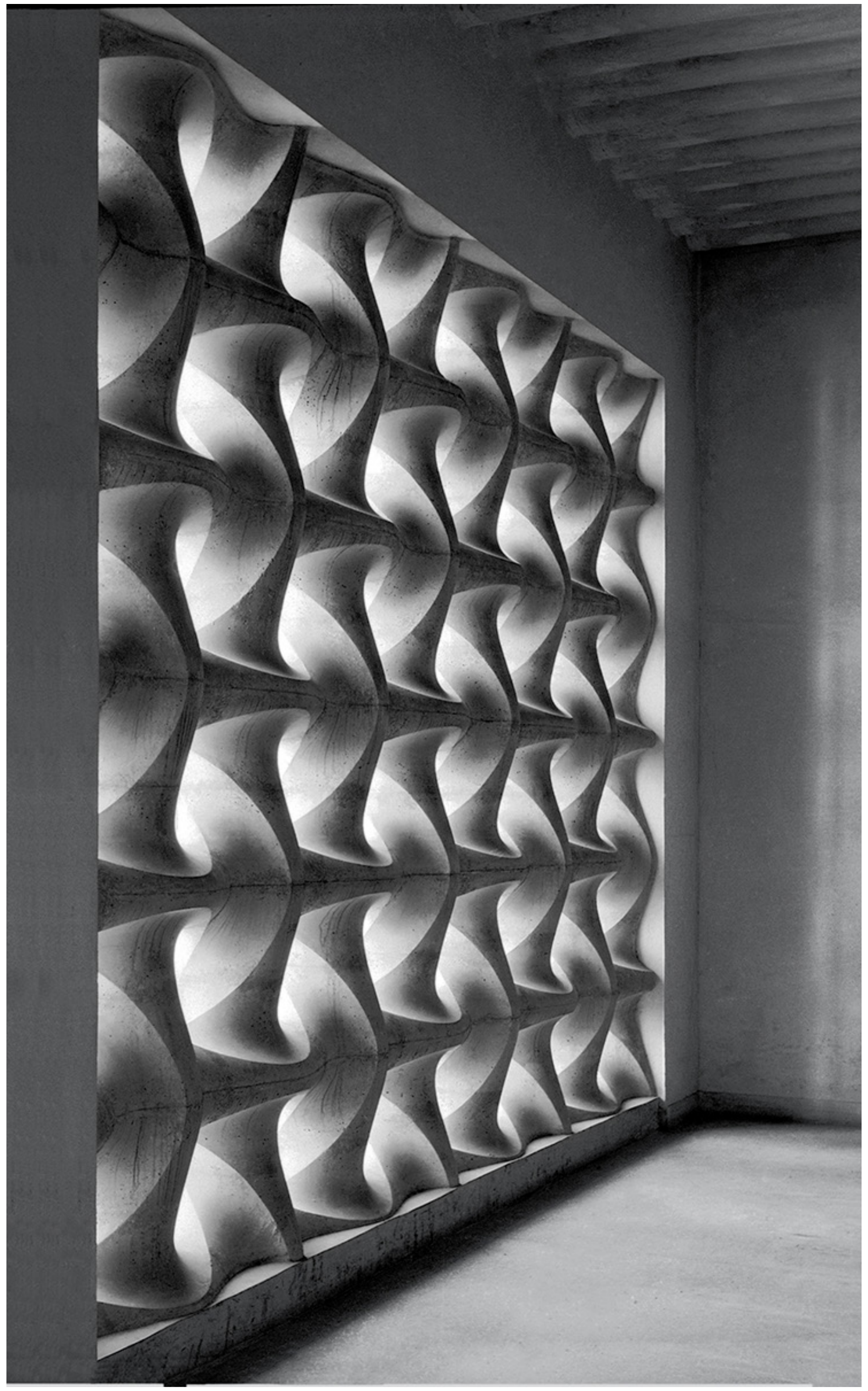
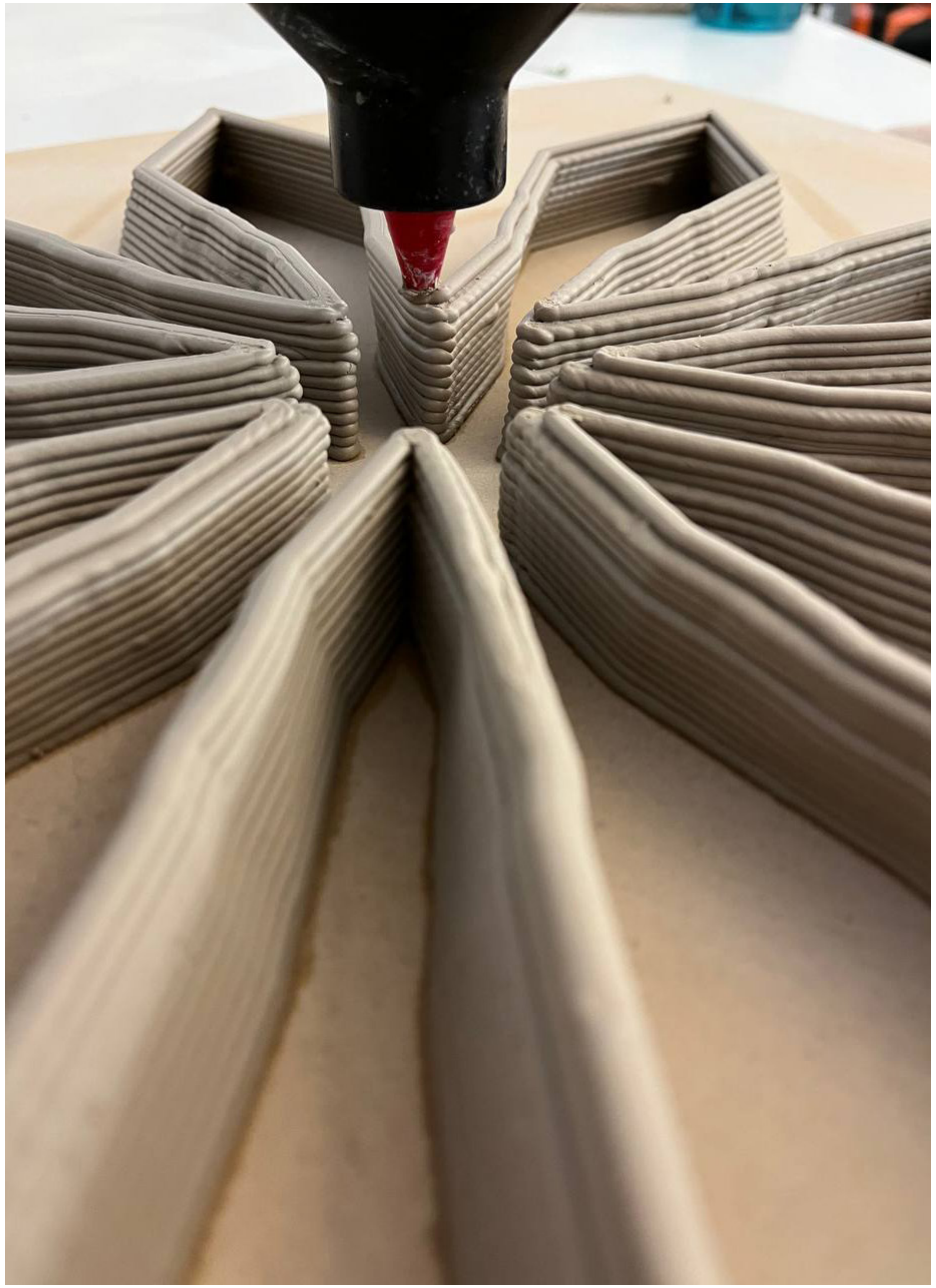


Figure 1.02. Continua Screen. Vienna's Pfarre Liesing church by Erwin Hauer, 1954.

1.2. Relevance

The pursuit of customizability in the design and fabrication of building products is present, whether hand-made or machine-made. The design of a masonry light screen is no exception. Light screens are frequently implemented for regulating visual accessibility to the space as well as modulating light in the built environment. One of the most common methods used for constructing these components is casting. For constructing the pieces in this technique, formative manufacturing employs casts or molds to shape the material and for every different piece in the structure, a unique mold needs to be made. Therefore, the process of prototyping to explore more opportunities is limited due to the time and cost required for making additional molds, ending up narrowing down the possibilities for designers to investigate more complex designs. However, additive manufacturing (AM) can be used as an efficient alternative for casting techniques to improve the customizability and affordability of such building components. AM and 3D printing bridge the material computation to digital data[2], allowing to shape and print the pieces without needing mediator elements like molds. Through the connection of computational modeling, digital simulation, and 3D printing, it is possible to apply real-time changes to design throughout the process. This results in giving architects the ability to improve the performance qualities of the building components at no additional cost. Fast prototyping, affordability, and customizability of the components provided in this approach are the criteria required for the mass-customization of complex designs which lead to enhancing individuals' accessibility to high-performance products.

Figure 1.03. 3D printing with clay.



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[2] Reichert, Menges, Correa, *Meteorosensitive architecture*, 50-69.

1.3. Scope

Having the opportunity to create new visual qualities between spaces through a digitized method, designers and architects can enhance an individual's spatial experience in the built environment. One of the most important factors affecting the atmospheric qualities of a space is the visual connectivity and light modulation between interior and exterior spaces. This thesis aims to improve the observer's visual connectivity through a customizable 3D-printed screen. Considering this goal, four major parameters on the extension of view have been defined in the body of this research, including form, material, light, and position of the viewer. To control and evaluate the design based on these parameters, 3D printing technology, computational design, and digital simulation are combined to redefine the existing methods toward a customizable and affordable approach.

1.3.1. The Main Focus of a Digitized Architecture

There is an argument that architects' misperception of the notion of digital lies in the concept of digital production and its process. CNC machines were mostly considered tools that could produce thousands of equal and diverse components with similar costs.[3] In addition, comparing differentiation to Ford's assembly line which is all about consecutive iterations supports this discussion.[4] The economical aspect of digital manufacturing needs to be redefined here. The use of CNC machines was

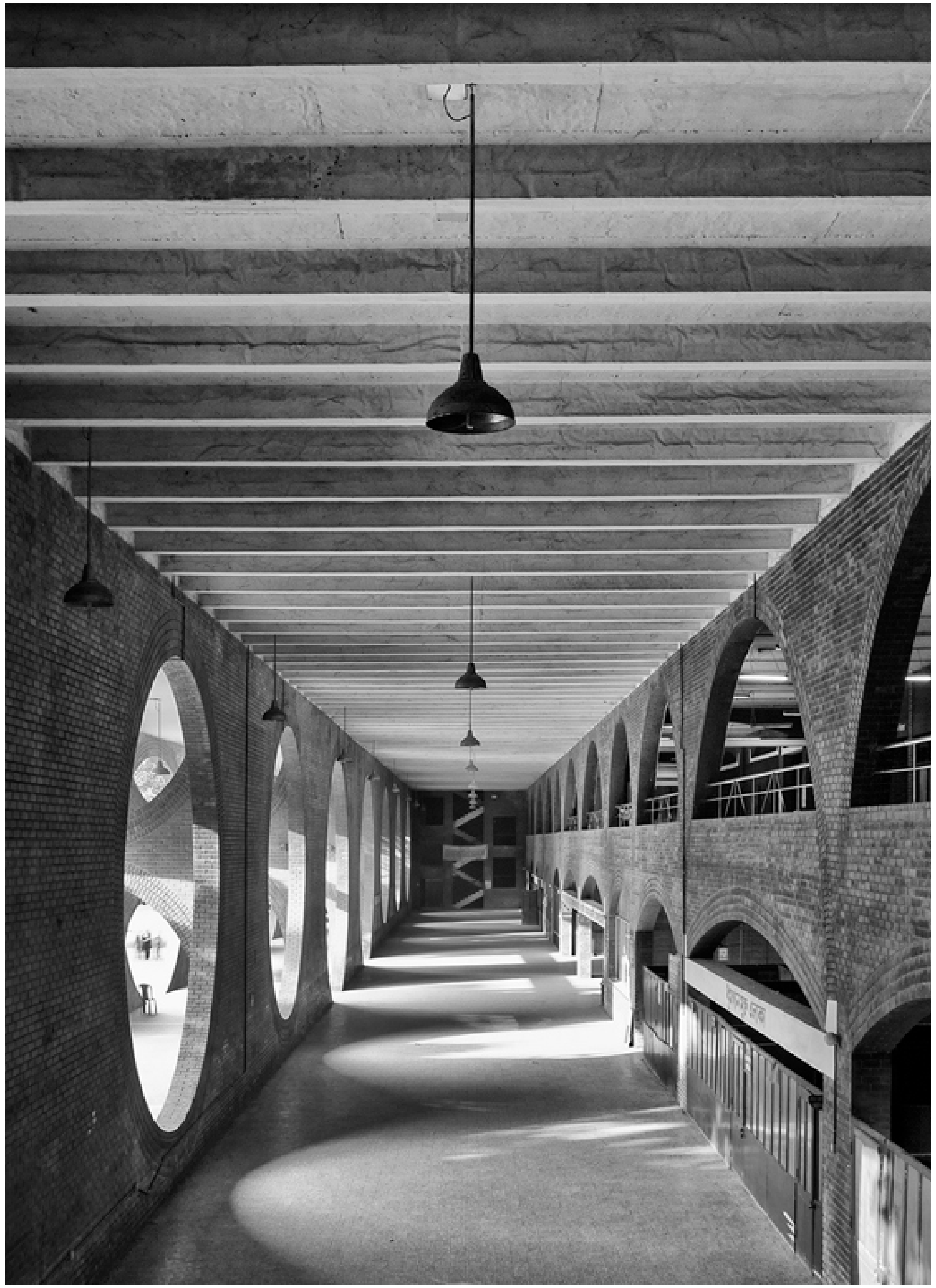

Figure 1.04. Ayub National Hospital by Louis Kahn. Bangladesh, 1962.

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[3] Retsin. *Discrete and Digital,* 82-96.

[4] Ibid

first established as they could precisely repeat a task; Not their potential for creating different components.[5] Like CNCs, a robot arm also provides iteration and accuracy. Architects' misunderstanding of differentiation was closely chained to mass customization, a famous concept in the nineties, which was assumed to be the process of creating different forms; while the actual purpose was to develop and improve the manufacturing process.[6] The real goal of digital fabrication is not only about creating pieces and components with different forms but about making the production process shorter and more convenient for distribution.[7]

Therefore, to be able to develop architectural ideas through a digital process, it is important to first define a sensible notion regarding the project's approach to it. The result of this thesis goes beyond the form of the structure and investigates the customizability, affordability, and accessibility of the building components.

Figure 1.05. The origins of CNC machine by John Parsons. MIT lab, 1952.

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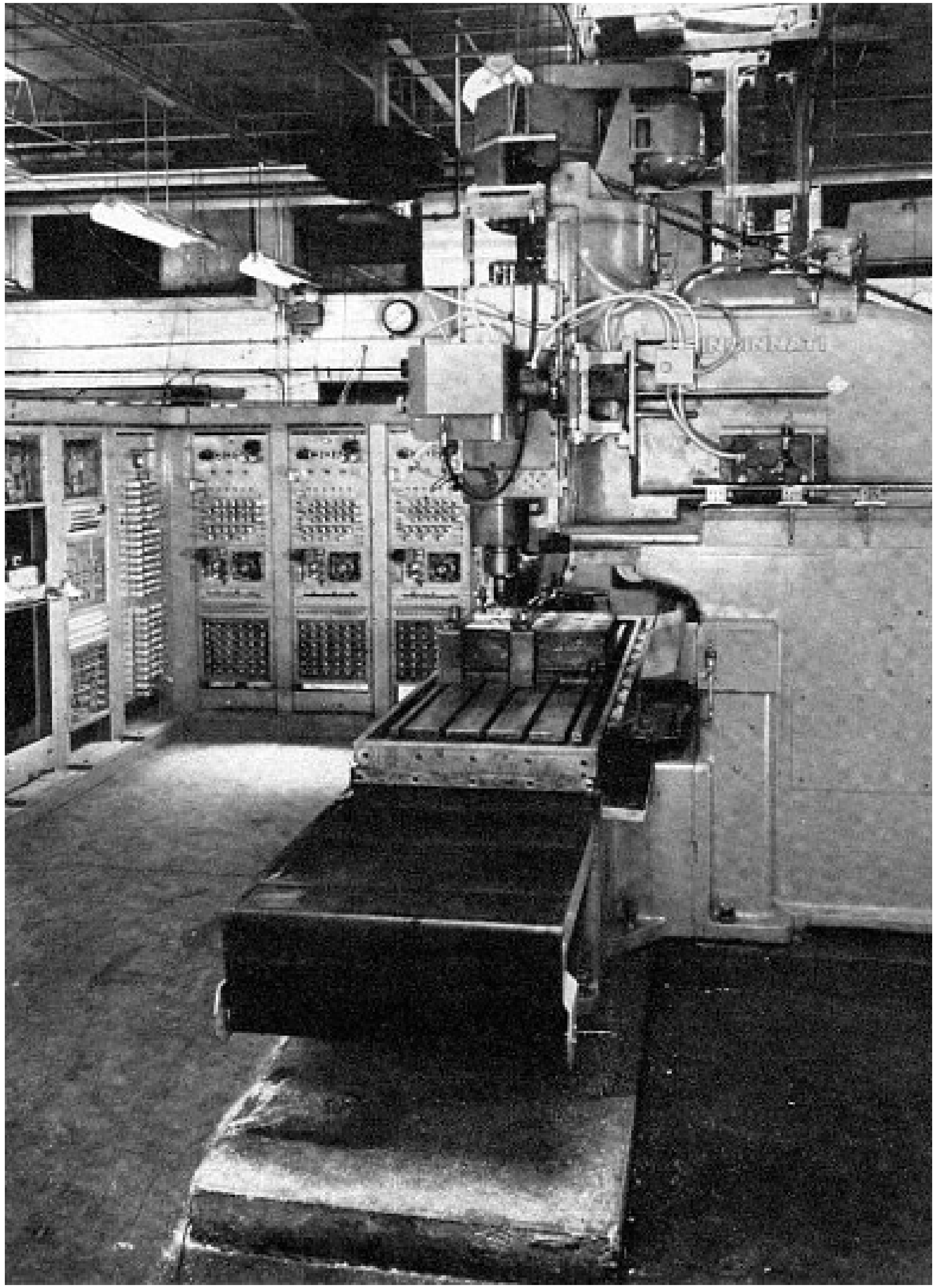
[5] Retsin. Discrete and Digital, 82-96.

[6] Ibid

[7] Ibid



CHAPTER TWO

Context

2.1. *The History of Light Screens*

The screen is historically recognized as a divider[1], a shield[2], or a filter[3]. The implementation of masonry screens has a long history in many nations, forming part of their locally grounded architecture. Depending on geographical conditions and cultural values, these screens are known for their spatial, environmental, and optical functions.[4] The desired level of perforation was commonly created by organizing bricks, as the basic construction units. Likewise, perforated walls constructed with varied block units and patterns appeared in built works for multiple purposes.

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[1] From the Dutch word *scheidingslijn,* an architectural partition used to hide something or divide a space.

[2] From the German word *skirm*, meaning a "shield".

[3] The sense of something which by standing in between, acts as a "filter" or a protective membrane. This meaning originates from the word *scherma* or *escrime* that means fencing in Italian and French.

[4] Casetti, *What is a screen nowadays?*, 16-40.

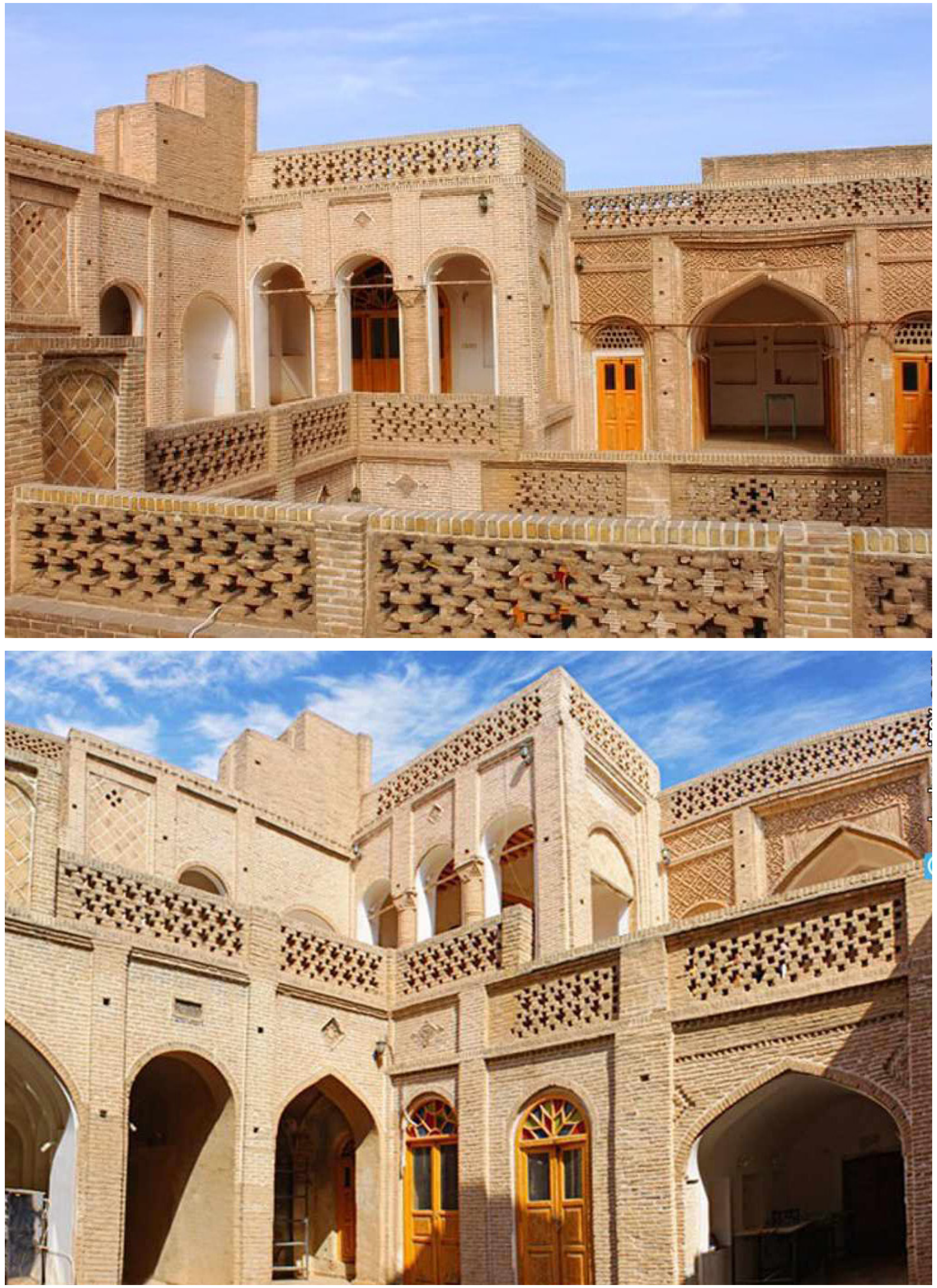

Figure 2.01. Golchin House located in Dezful, Iran.

2.2. Light Screen's Performance

2.2.1. Climatic conditions

In hot and humid regions of Iran in the south, Taremi - a perforated screen commonly made of clay - was used in porticoes and on roofs to minimize the obstacles that block airflow.[5] These screens are considered a regional solution, a vernacular passive strategy to achieve thermal comfort by filtering sunlight and allowing for natural ventilation. Mashrabiya was also commonly used in Egypt to enhance air ventilation, increase humidity, and reduce the temperature balance in buildings.[6] Similar examples can be seen in other areas such as Latin America, where a series of shading walls appeared in the 1920s, known as Cobogos.[7] These screens acted as efficient protective skins in buildings for passive cooling and heating strategies.[8] However, the performance of light screens goes beyond the optimization of climatic attributes to regulating visual connectivity between spaces and light modulation.

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5 Najafabadi, Daneshvar, Pakseresht, Pooryousefzadeh, *Role of wind in vernacular architecture of hot and humid region of Iran.*

6 Ashour, *Isla`ctural heritage*, 245-253.

7 Vazquez, Duarte, Poerschke, *Masonry screen walls,* 262–274.

8 Zárate, Piel poros. Biomimética en clave cerámica. 36-47

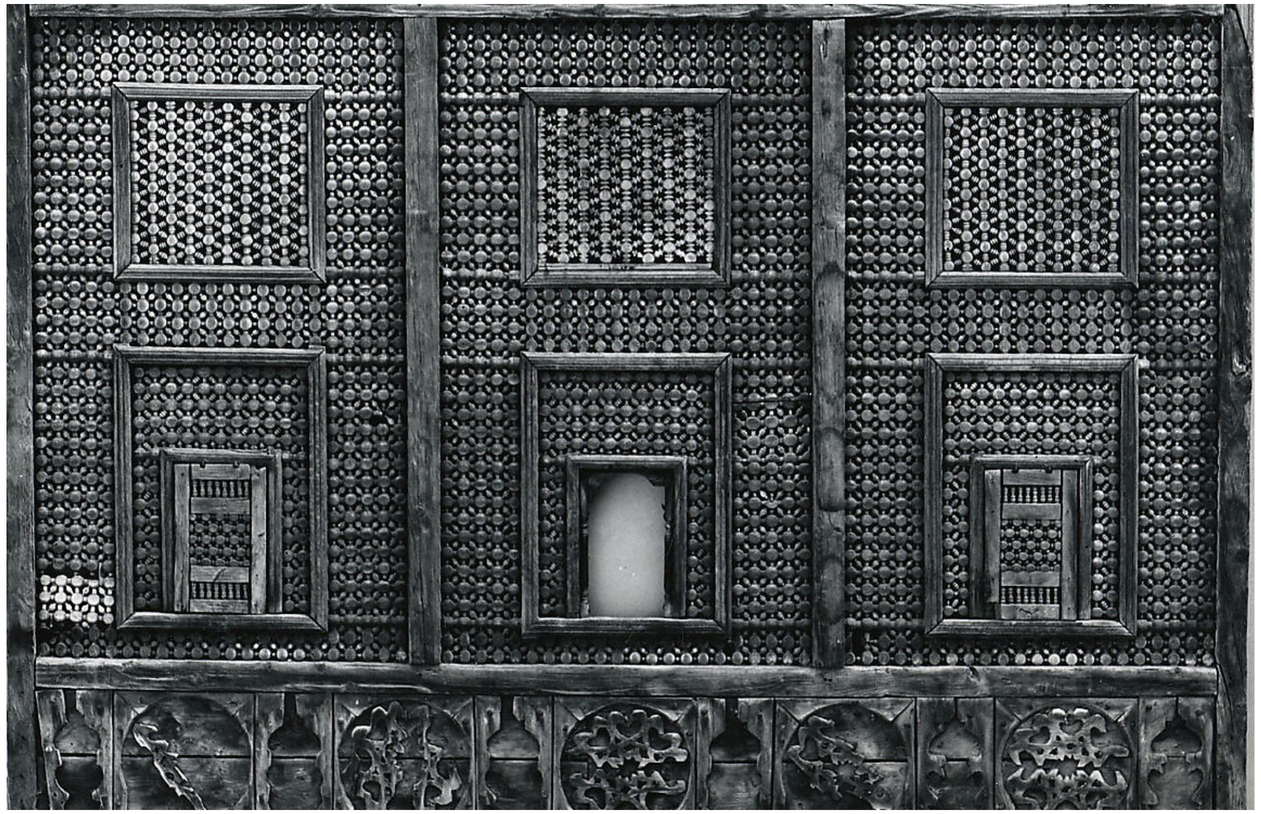

Figure 2.02. Exterior Mashrabiya in Cairo, Egypt 1865.

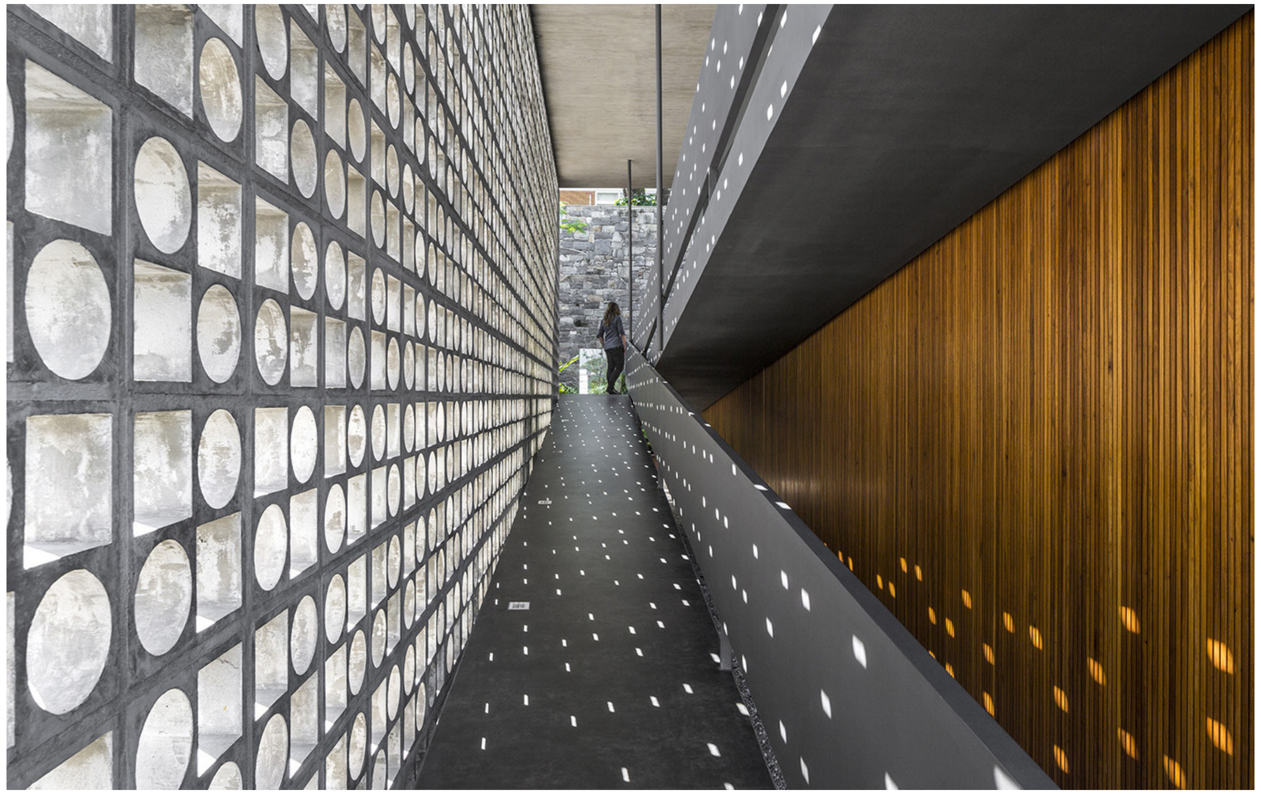

Figure 2.03. Hollowed-out concrete screen designed for B+B House, By Marcio Kogan. Brazil. 2014.

2.2.2. Visual Connectivity and Light Modulation

The depth of humans' perception of space is established by the level of their sensorial engagement with it. The most important human sense affecting spatial perception is sight. We mostly understand our environment through what we see. Therefore, the more visually engaging the spaces are, the better we understand their context and experience a deeper connection with them.[9] Visual Connectivity and the way it affects one's spatial perception can be investigated through two different aspects: visual access and visual exposure.[10] Visual access is the potential for monitoring an individual's immediate physical environment by sight. The extension of visual accessibility determines one's capability to understand the spatial qualities created in the space. On the other hand, visual exposure is defined as the possibility that individuals' own overt behavior can be detected from their immediate physical surroundings by sight.[11] This allows one's existence to be noticed immediately by others occupying the space. The level of individuals' visual accessibility and exposure to the space affects their spatial knowledge in many ways and defines new characteristics and qualities in the space.[12]

Cobogos, for instance, are known as strong identical elements that shape the architectural language of Brazil and regulate visual permeability between spaces, in addition to their performance as

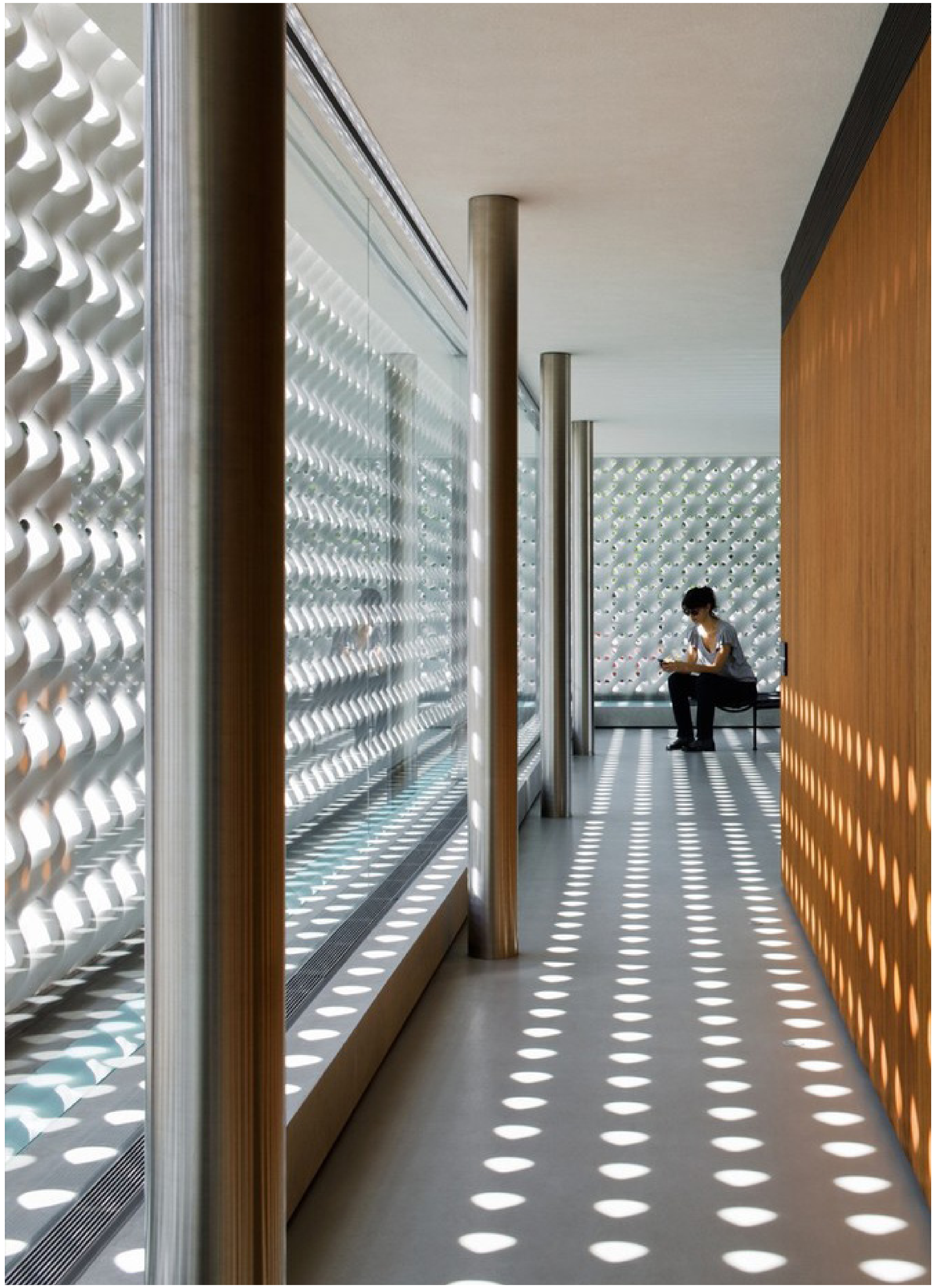

Figure 2.04. Light modulation through Erwin Hauer's screen. Cobogo house by Marcio Kogan, 2011.

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[9] Crosby, *The measure of reality.*

[10] Archea, *Visual access and exposure.*

[11] Ibid

[12] Ibid

a climatic strategy.[13] Based on the defined pattern as well as the degree of porosity, these screens provided privacy and intimacy for the occupants without losing the possibility of connections to the outside.[14] Like Cobogo, Mashrabiya was also used as a solution to the privacy requirements for women in Egypt's Islamic community.[15] Through this screen, it was possible to control women's visual accessibility and exposure to gaze outside while being unseen. Therefore, visual accessibility/exposure through the screens determines individuals' privacy in the space, establishing their social circle; Whether by improving solitude[16] or by fostering social interactions within the public domain.[17] Other than the provision of visual privacy, architects continued to explore the potential qualities of the screen walls in different applications.

Around thirty years after the innovation of Cobogos, in 1950, Erwin Hauer adopted casting methods for fabricating unique construction units to build screen walls.[18] He investigated the modularity of light and shadow created through geometrical opportunities and explored the relationship between the human body, shape, and space. This investigation results in the creation of architectural qualities that heightens an individual's spatial perception.[19]

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[13] del Real, Gyger, *Latin American modern architectures.*

[14] Ibid

[15] Ashour, *Isla`ctural heritage*, 245-253.

[16] Zimring, *The built environment as a source of psychological stress.*

[17] Zeisel, *Inquiry by design.*

[18] Hauer, *Erwin Hauer: Continua-Architectural Walls and Screens.*

[19] Hauer, *Erwin Hauer.*

Figure 2.05. Shayk Sadat's house, Ciro, 1875. Painting by Frank Dillon.

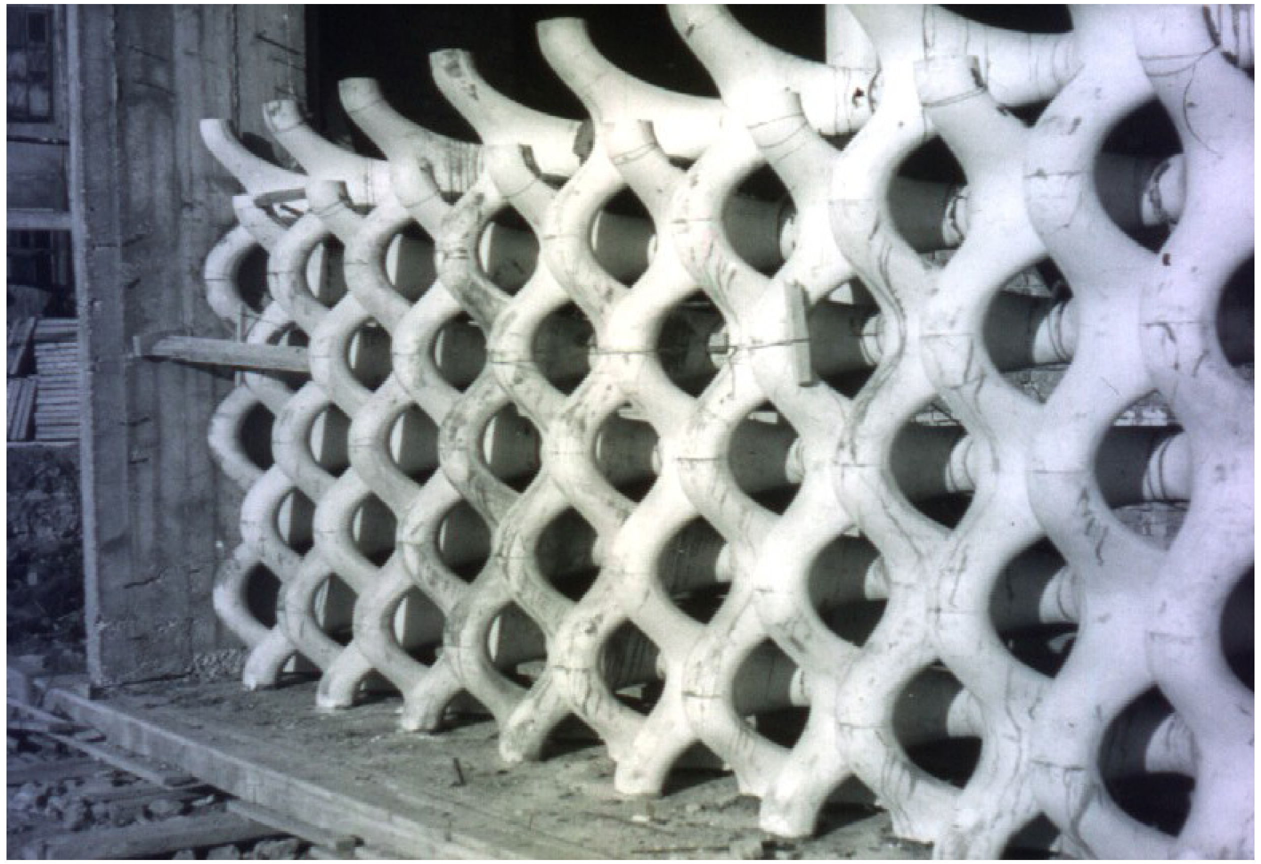

Figure 2.06. Top-left. Continua screen's fabrication process. Pfarre Liesing Church, by Erwin Hauer. Vienna, 1954.

Figure 2.07. Bottom-left. Continua screen. Pfarre Liesing Church, by Erwin Hauer. Vienna, 1952.

Figure 2.08. Right. Playing with shadow and light, Continua screen, by Erwin Hauer. Design 1. New York city, 1954.

2.3. Light Screens in Contemporary Architecture

Following this tradition, light screens have increasingly found their place in contemporary architecture, characterized by the innovative use of building units and the use of traditional fabrication techniques. Peter zumthor - a Swiss architect - designed the Kolumba Museum's facade using screen walls. Articulated with perforations, the brickwork allows diffused light to fill specific spaces of the museum, creating a mottled pattern of light and shadow.[20] The exploration of light qualities and controlling visual permeability are also noticeable in the hollowed-out concrete screen designed for B+B House[21] or the masonry screen wall in Jardin house that visually connects the kitchen to the backyard.

The method that was commonly used for most of these projects is casting. Following this approach minimizes the possible opportunities to investigate more complex architectural ideas and limits the customizability and affordability of the screens. Having the opportunity to adopt new digital methods and computational design, architects have started to evolve their design ideas through new approaches.

Figure 2.09. Top- Modulating light through brick screens. Kolumba Museum, by Peter Zumthor. Koln, Germany. 2007.

Figure 2.10. Bottom- The brick screens in Kolumba Museum by Peter Zumthor. Koln, Germany. 2007.

Figure 2.11. Next page- Left. The glazed light screen. Jardin House by CR2 Arquitetura. Sao Paulo, Brazil. 2013.

Figure 2.12. Next page- Right. Hollowed-out concrete screen for controlling visual privacy and modulating light. B+B House by Marcio kogan. Brazil, 2014.

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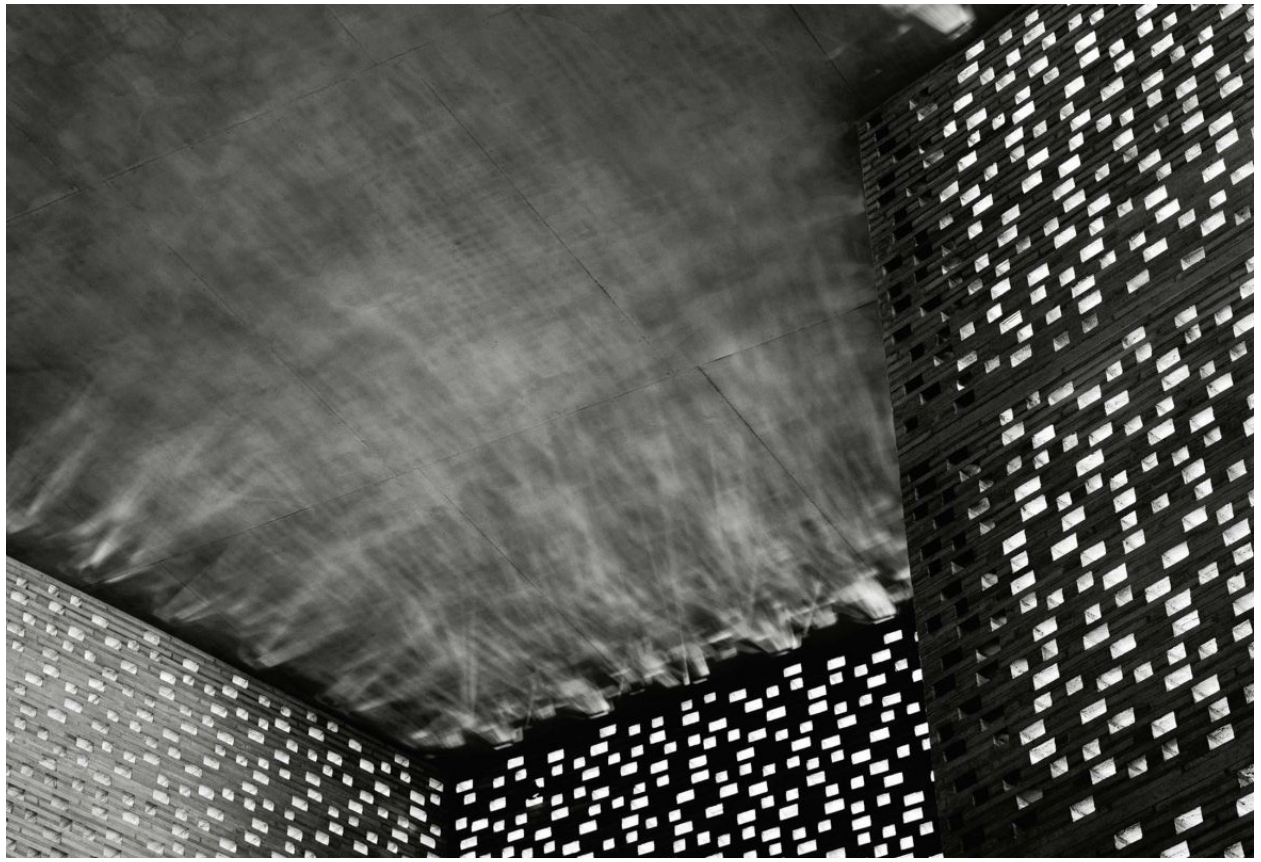
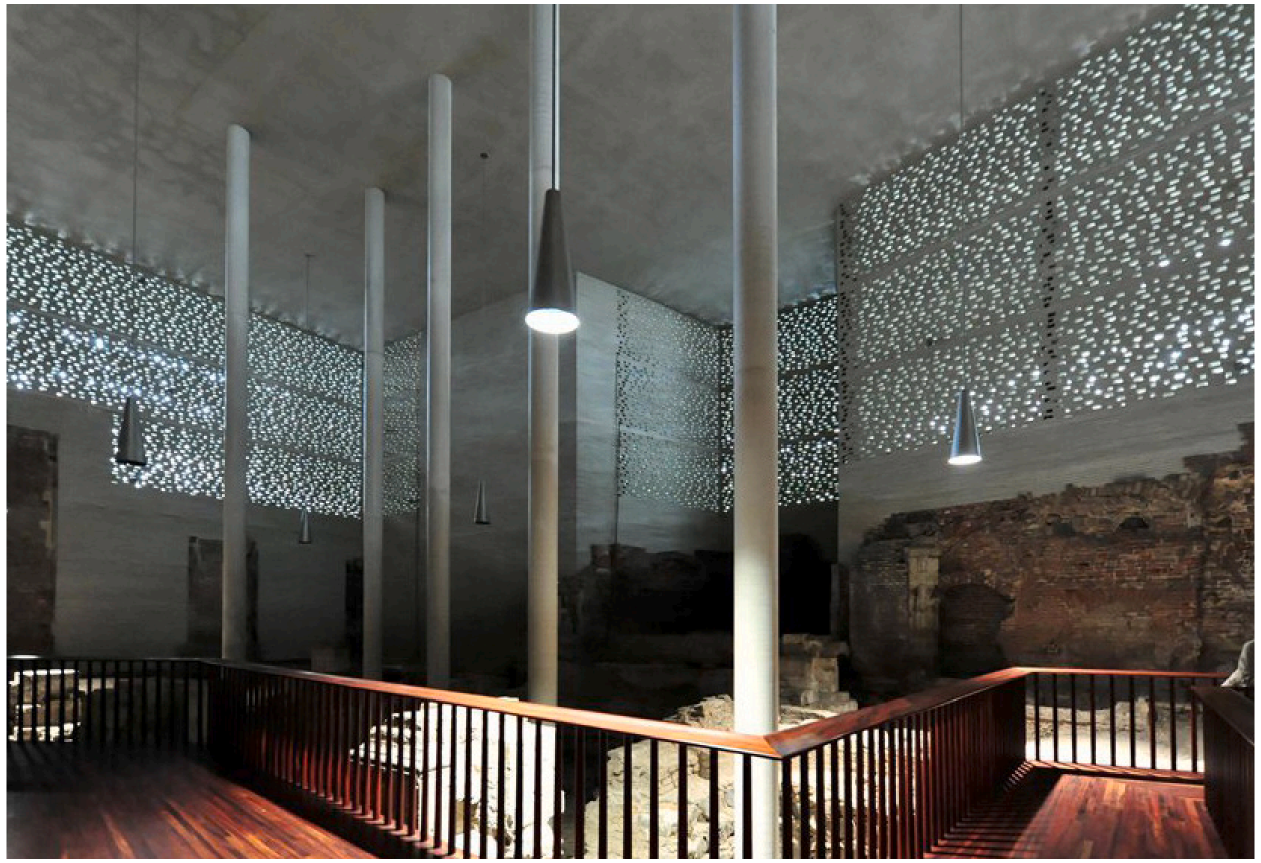
[20] Platt, Spier, *Seeking the real,* 30-42.

[21] Koudlai, *In and Out of Control.*





2.4. *Toward a Digital Architecture*

The significant shift from traditional industrial production to digital fabrication started in the early 1990s and the production of architecture is no exception.[22] The concept of mass customization was introduced in Future Perfect[23] by Stanley Davis in 1987, where he explores and redefines the process of producing single products based on the approaches used in mass production. He explains that single building blocks can be generated as economically as mass-produced products.[24] Contrary to the industrial age, when the focus was on standardizing methods and products, today, the driving force is to generate unique pieces.[25]

In Gramazio's opinion, one of the pioneers in the intersection of architecture and robotics, robots are capable of handling more than one task at a time. Like personal computers, they can be optimized to execute multiple tasks in different applications including data analysis and physical operations. By programming the robotic arm and defining its movements, we are introducing it to a new task and method. The arm is taught to monitor its surroundings through sensors and to manipulate the environment based on the restored data.[26]

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[22] Bonwetsch, *Robotically assembled brickwork.*

[23] Davis, *Future perfect,* 18-28.

[24] Ibid

[25] Gramazio, Kohler, Willmann, *The robotic touch.*

[26] Ibid

Through this process, the world of "Digital Reality"[27] is connected to "Physical reality"[28]. The integration of machines and robots that are digitally controllable with digital design tools, has provided the opportunity to create a link to transmit design information to the fabrication procedure, integrating the processes of design and making. Additive manufacturing is one of the methods that create the link between the two worlds of digital and physical material.[29]

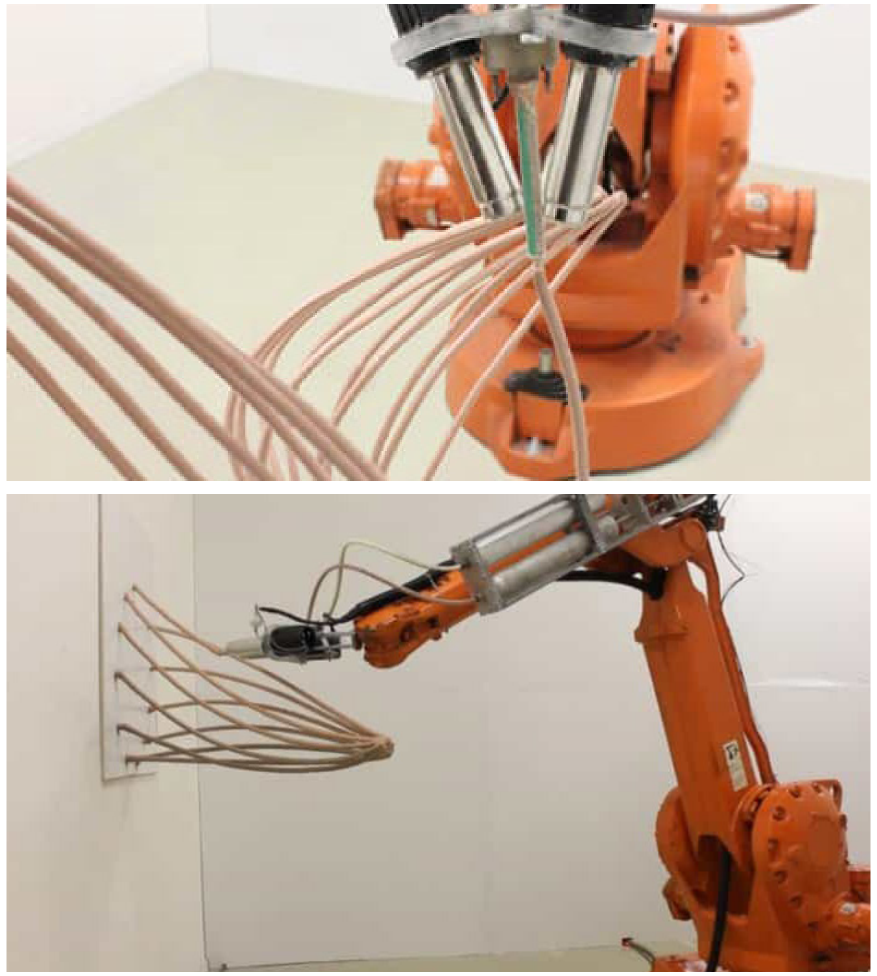

Figure 2.13. Anti-gravity 3D printing on non-horizontal surfaces.
Anti-gravity object modeling, Maraerial, IAAC, & Joris Laarman Lab. Barcelona. 2018.

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[27] Gramazio, Kohler, Willmann, *The robotic touch.*

[28] Ibid

[29] Ibid

2.5. *Additive Manufacturing and 3D printing*

Additive manufacturing (AM) in architecture has provided lots of opportunities and new strategies in the construction process toward an integrative, material-based, and computational design approach.[30] It provides the opportunity to achieve a great deal of complexity and variation by creating links among geometry, virtual design model, and physical reality.[31] Based on these new improvements in computer-aided design (CAD) technologies and computational design processes, it is possible to model, analyze, and simulate complex data-driven designs. Therefore, today this technology is known as an inseparable part of the construction process in the industry, mentioned as "transformational technology in architecture".[32]
Additive manufacturing methods, firstly used for rapid prototyping, are today used for producing functional components in different fields of industry.[33] The application of this technology in architecture has been proven to be significantly beneficial regarding the possibilities provided by FDM. The logic of 3D printing is based on the principles of stacking a layer of a given fluid material upon another with a controllable height, usually thermoplastic, deposited through a numeric-based mechanism.[34]

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[30] Correa, Krieg, Menges, Reichert, Rinderspacher, *Hygroskin.* 33-42.

[31] Naboni, Paoletti, *Advanced customization in architectural design and construction.*

[32] Wit, et al, *Artificial intelligence and robotics in architecture,* 245-247.

[33] Sass, Oxman, *Materializing design*, 325-355.

[34] Kulkarni, Marsan, Dutta, *A review of process planning techniques in layered manufacturing.*

Figure 2.14. Different stages of 3D printing Tecla house, by Mario Cucinella. Massa Lombarda, Italy. 2021.

FDM systems typically function through exerting pressure to extrude a fused fluid material and subsequent vitrification followed by the addition of separate surfaces with a continuous tool path and each tool path contains concentrated coordinates and electromagnetic commands G-Code to demonstrate an approximate geometry of the 3D model by the extruded layers.[35] The process of translating the 3D model design to a geometry that is made of stacked layers of the tool path is called 'Slicing'.[36] To provide rigidity and stability for the geometry, the interior side of the model is filled with a constant formal pattern. The latest attempts in the intersection of additive manufacturing and architecture are toward 3D printing full-scale functional building components along with adaptation to the standards of 3D printing fabrication technology. Automating the process of construction with a high level of complexity and accuracy is possible through AM. The possibility of optimizing the design and infill provided by the slicing technique represents an opportunity for engineering the internal structure of the building components. Integrating digital simulation and robotic manufacturing methods into the architectural workflow allows for improvement in the functionality of building materials at the scale of the material structure itself.[37] By translating design parameters to digital data, it is possible to apply real-time changes to the model and directly translate the data for the 3D printers.

Figure 2.15. Investigating the scalability of 3D Printed Components. Pylos by Iaac, Barcelona, Spain. 2018.

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35 Kulkarni, Marsan, Dutta, *A review of process planning techniques in layered manufacturing.*

36 Cline, LaFlam, Smith, Nowicki, Ku, *Additive Manufacturing With Ceramics.*

37 Idib

2.6. Customizing Visual Connectivity

Having the opportunity to connect the digital and physical worlds using 3D printing technology, it is possible to control the design and fabrication attributes in different stages of the process. In this thesis, the design of the light screens is driven by the major parameters of visual connectivity and light modulation. Therefore, this study investigates how to regulate these factors to improve the screens' functionality in different applications. The process of designing and making the screen is driven by four major parameters affecting visual connectivity through the screen, including light, form, material, and position of the viewer. This section discusses these parameters and explains the way each affects the screen's performance.

Figure 2.16. Perforated concrete facade system. Binh Thanh house, by Nishizawaarchitetcs, 2013.

2.7. Influential Parameters on Visual Connectivity

2.7.1. Light

In this quotation, Le Corbusier famously described architecture as a composition of forms ‘brought together in light’. The purpose of this composition can be both aesthetic and functional. He implicitly acknowledges that the primary contribution of architectural forms in the daytime is actually to obstruct and modify the sunlight.[38] The existence of light is the most vital condition to grasp space, form, and structure. It is not possible to define humans’ capability to see their surroundings without light. Therefore, an individual’s visual accessibility and exposure are directly tied to the way the space is exposed to light. In the design of perforated screen walls, light and form can work together to enhance observers’ spatial perception and establish the level of their visual engagement with the space.[39] Whether natural or artificial, the location of the light source relative to the screen is important as it determines the way the space is exposed to light. The position of the light source can be investigated in three different conditions: inside, behind, or in front of the light screen. Although, the location of the light source is not separated from the light’s intensity or if the screen is exposed to direct or indirect light. Based on each one of these factors, the extension of observers’ view and the space’s visibility on two sides of the screen can be increased, or entirely blocked.

“Architecture is the masterly, correct, and magnificent play of mass brought together in light. Our eyes are made to see forms in light; light and shade reveal these forms.”

Le Corbusier – Vers Une Architecture, 1923. (Trans. Etchell – Towards a New Architecture, 1927.)

Figure 2.17. Light modulation in Persian architecture. Photograph by Jay Maisel. Iran, 1971.

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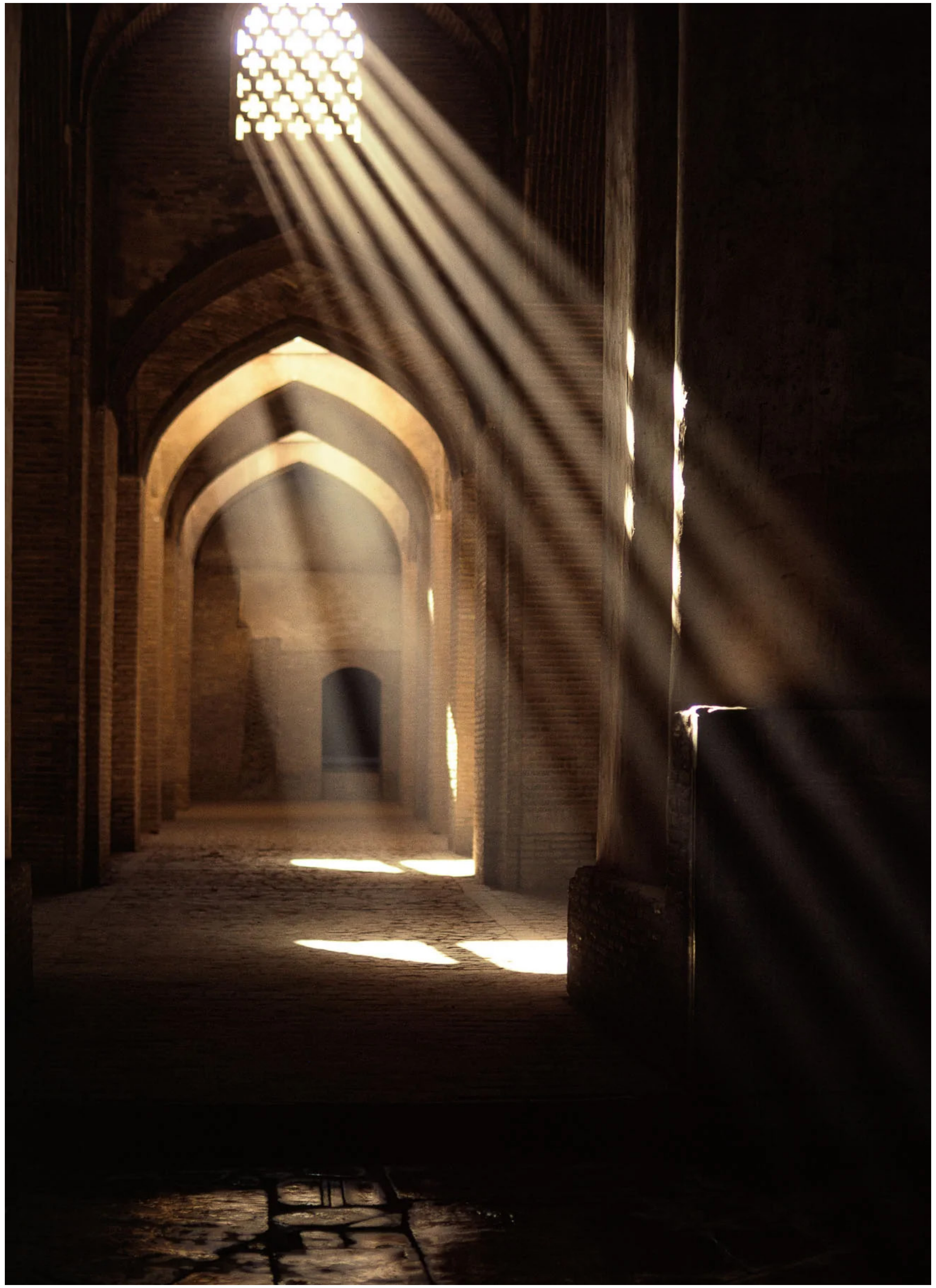
[38] Unwin, *Shadow.*

[39] Ertaş, D. & Sirel, A. *The Importance of Light in Steven Holl’s Perception of Form,* 49-61.

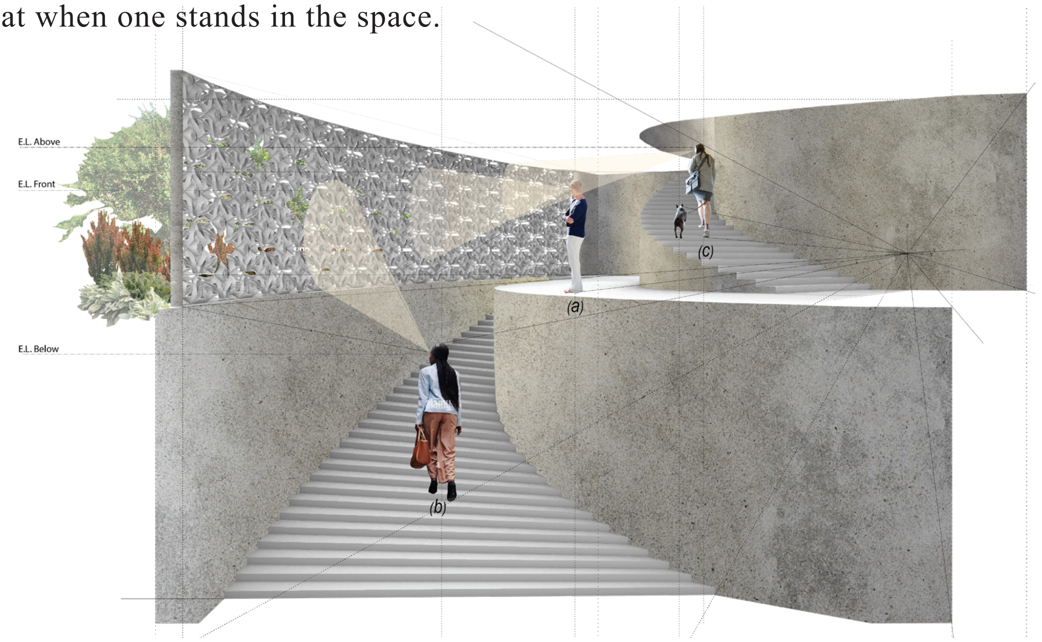


2.7.2. Position of the viewer

Where individuals stand in the room in relation to the light screen determines how they can evaluate the attributes in the environment and perceive the space on the other side of the screen. This perception is created through two factors that are related to one's specific location: eye level and field of view. Depending on these two factors, each person comprehends the space differently and experiences a certain level of visual connectivity. For instance, in figure 2.18, observer (a) whose eye level is positioned at the top 1/3rd of the screen, can visually communicate better with the exterior environment compared to observer (b) whose eye level is below the base of the screen. It is important to note that this factor corresponds directly with the orientation and depth of the pieces, as these attributes are defined in relation to one another in the space. Also noteworthy in this context is to consider individuals' motion, as walking in the room creates a whole different spatial knowledge compared to that when one stands in the space.

Figure 2.18. Position of the observer relative to the screen.

This factor affects the visual permeability through the observer's eye level as well as their field of view.



2.7.3. Form

"Architectural form is the point of contact between mass and space ... Architectural forms, textures, materials, modulation of light and shade, color, all combine to inject a quality or spirit that articulates space. The quality of the architecture will be determined by the skill of the designer in using and relating these elements, both in the interior spaces and in the spaces around buildings."

Edmund N. Bacon, The Design of Cities, 1974.

As discussed in the previous sections, form is an inseparable factor from light and the position of the viewer, establishing the level of visual accessibility and exposure to the space. Ching believes that in architecture, the term form is often used to establish the structure of a design; In other words, it is the manner of organizing the elements of a composition to achieve a specific purpose.[40]

Figure 2.19. Top, Inter(b)locks Screen. 3D printed terra-cotta blocks. By Brian Peters. Pittsburgh, PA. 2021

Figure 2.20. Bottom, Polsky Screen 3. 3D printed ceramic blocks by Brian Peters. Pittsburgh, PA. 2021

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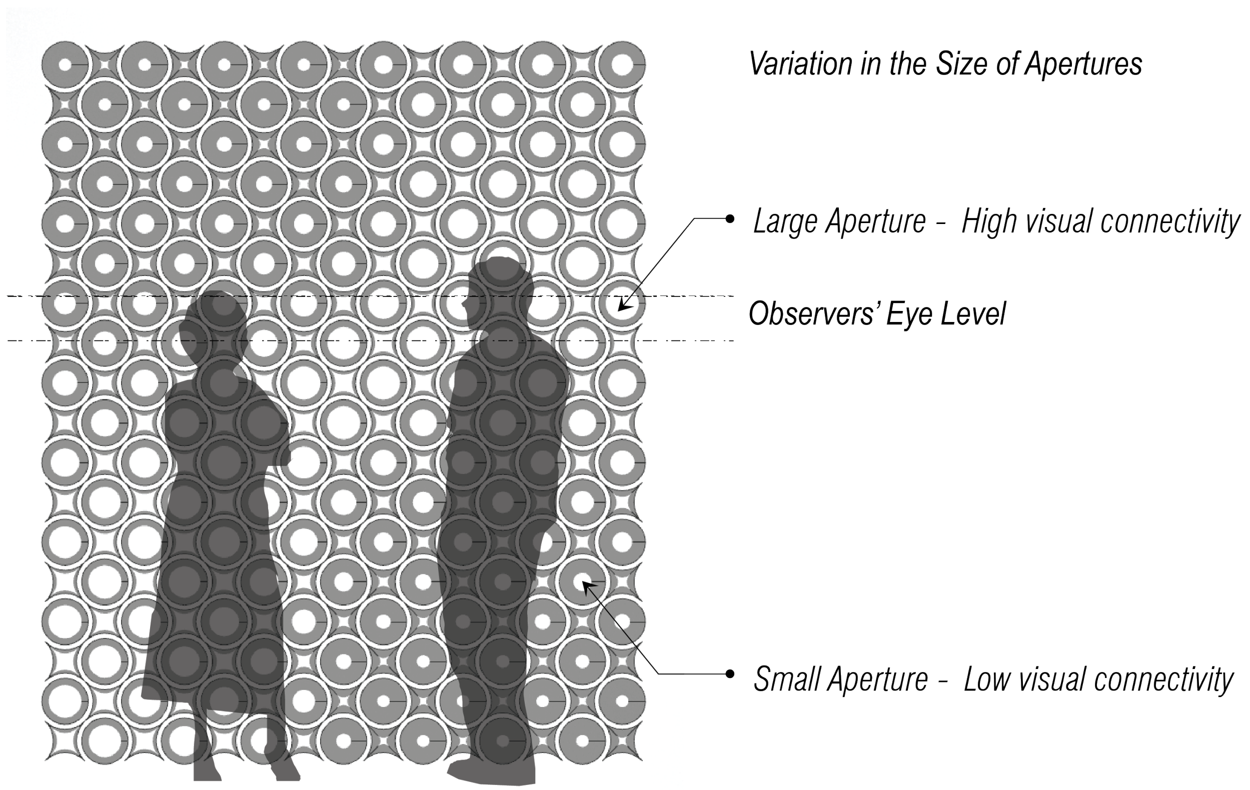
[40] Ching, *Architecture: Form, space, and order.*

a. Variation in Apertures

The form can contribute to the design and evaluation of the light screen in different ways. The variation in the size of apertures in different parts of the screen is one of the strategies affecting visual permeability. This alteration can be controlled based on the required level of visual accessibility and exposure for various spaces in the building. The pattern that defines the size of apertures is determined by the observers' eye level. For instance, in figure 2.21 the apertures are more open at the eye level of the viewers as the designer's goal is to provide visual connectivity between spaces in this part of the assembly.

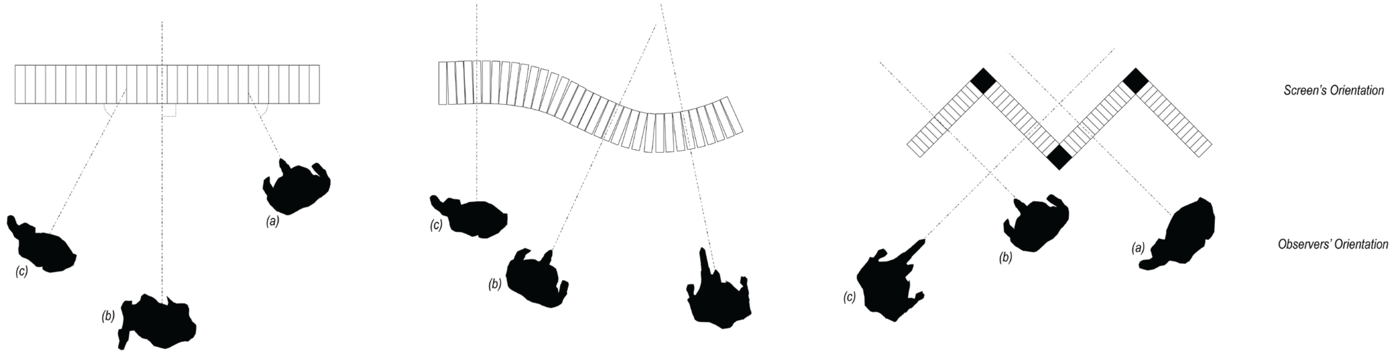
Figure 2.21. Alteration in the size of apertures.



b. Orientation of the Screen

In addition to the apertures' size, the orientation of each piece relative to the space and the viewer changes the level of visual continuity. As illustrated in figure 2.22 the bricks can be assembled in different directions, limiting or improving the observer's view. Based on the design's purpose, the 3D-printed wall can be aligned with various shapes and paths. The Changes in the configuration of the wall can modulate the type of visual connection and light diffusion between spaces in different architectural applications. This factor is closely related to the position and orientation of the viewer relative to the screen.

Figure 2.22. The impact of the screen and the observer's orientation on visual connectivity.



- In diagram 1 (Left), as the orientation of the viewers in relation to the screen changes from 90 degrees (a and c) they might not be able to see the other side of the screen as their view is confined by the bricks. To extend the observer's view it is possible to change the orientation of each piece. Therefore, the screen provides visual permeability for observers who are oriented in different directions, as illustrated in diagram 2 (Middle). Another alternative can be seen in diagram 3 (right) where visual permeability is controlled through a zigzag shape. Observers can see through the screen from only one side in front of them, while their view is limited in the vertical direction.

c. Depth

The depth of the pieces can affect visual connectivity in two separate ways. Firstly, depending on how deep different pieces are, the amount of light penetration - as one of the influential parameters on visual permeability- changes. Secondly, this factor alters the level of visual connectivity for an observer whose viewing angle relative to the screen is less than 90 degrees. The deeper the pieces are, the less visual permeability is provided for the viewer. For example, in figure 2.23 the view for observers (b) and (c) to the other side of the screen is less extended compared to the observer (a). However, while the viewing angle of the observer (d) is not perpendicular to the screen, visual connectivity is provided as the depth of the pieces in that section of the assembly is relatively low.

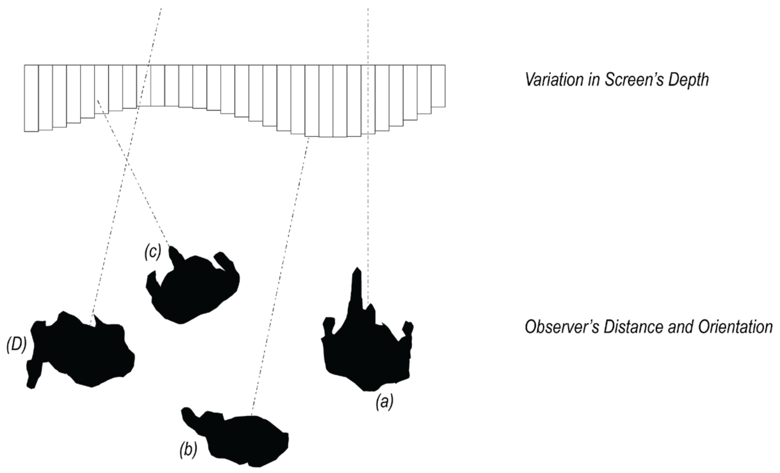


Figure 2.23. Variation in the depth of the screen and its impact on visual connectivity.

2.7.4. Material

Clay is known as an ancient construction material with a long history in many cultures. It can be collected at a low cost and therefore is an economical alternative for prototyping large-scale components. Moreover, because of its plastic deformation potential, clay is considered a mouldable material and can be shaped through its properties for different purposes. Lastly, after firing a ceramic piece, it can maintain a permanent form to be used as a building component in a stable structure. This study attempts to use clay through a digitized process for producing functional light screens; To do so, it is important to understand the concept of digital material.

In 2006, Gramazio and Kohler revealed the Gantenbein Vineyard facade which illustrated the shift from the manually repetitive to a digitized differentiated robotic manufacturing process, as the first architectural application of robots. This transition to a complex materialization method is only possible through computational and digitized design methods, instead of conventional design approaches. These novel processes which seemed impossible to be adopted before robots were introduced to architecture, provided the basis for the emergence of a new concept, described as 'digital materiality' by Gramazio and Kohler.[41]

Figure 2.24. Mud Frontier. By Rael San Fratello. San Luis Valley, Colorado, 2019.

The aim of the project is to promote a more sustainable and accessible construction method through material computation and 3D printing.

---

[41] Gramazio, Kohler, Willmann, *The robotic touch.*

> *"The synthesis of data and material, which decisively failed to develop in the early digital age, is being realized – enticingly, playfully, and sensually – in today's architecture. This becomes apparent in various medial, spatial, and structural manifestations, whereby one premise persists: At the moment in which two seemingly separate worlds meet through the interaction between digital and material processes, data and material can no longer be interpreted as a mere complement but rather as an inherent condition and thus an essential expression of architecture in the digital age. A digital materiality is emerging, where the interplay between data and material is seen then, in a new light, as an interdependent structuring of architecture and its material manifestations."*
>
> *Jan Willmann, Fabio Gramazio, Matthias Kohler, Silke Langenberg.*

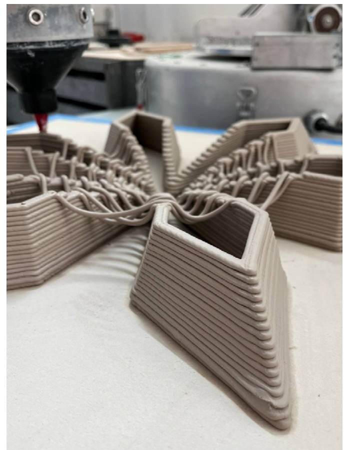
3D printer robots synthesize digital data with the materials' inherent qualities, enabling architects to benefit from these features and expand their architectural ideas. This connection can lead to a new architectural language and materials' expression.[42] Based on their specific characteristics, materials maintain a certain form and characteristics after being printed which results in the creation of different qualities.

Figure 2.25. Top. 3D printing prototypes, Screen 1.

The printer creates bridges in order to move from one arm to another in the piece.

Figure 2.26. Bottom. 3D printing prototypes, Screen 2.

Investigating material's weight distribution in the whole piece.



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[42] Gramazio, Kohler, *Digital materiality in architecture,* 179-199.

Considering the required level of visual permeability in the building, each one of these parameters can be considered for the design and fabrication of the light screens in different applications. Through the combination of 3D printing, computational design, and digital simulation, it is possible to define a framework where the defined parameters can be customized to achieve the desired spatial qualities. Having this opportunity, designers and architects have contributed to adopting 3D printing for enhancing their architectural ideas in designing light screens. The following section discusses the state-of-the-art projects that are designed and built through a cross-disciplinary approach.

2.8. State of the Art

This section investigates the state-of-the-art projects that explore 3D printing and visual continuity. In the next step, the aim, design strategies, driving parameters, as well as key impacts of each project are discussed. Two projects of TOVA and HIVE are investigated in detail. Both projects use clay 3D printing while considering visual connectivity as a performance goal in the design and making process. The Nest-ling project is positioned as my first experiment with clay 3d printing.

2.8.1. TOVA

Year: 2022
Location: Barcelona, Spain

TOVA is one of the first 3D-printed projects in Spain, built to answer the existing social and environmental challenges in housing. Designed and built in Barcelona, this research project connects the vernacular earthen architecture to 3D printing technology on a large scale. The geometry of the walls follows a network of cavities, creating a perforated screen wall to modulate the sunlight during the day. This feature also provides thermal insulation to prevent heat loss in the cold seasons and protect the structure from solar radiation in the summer. Although the provided porosity in the walls was mostly considered as a strategy to regulate the climatic attributes, it also improves visual permeability for the occupants.[43] Creating variation in the size of the screen's apertures is considered to create different levels of visual connectivity between the interior and exterior spaces. However, the screen's depth and orientation remain consistent along the wall.

The designers believe that the construction process of this structure is one of the most sustainable and environmentally friendly methods that can be used in today's existing technology. Throughout the process, zero material waste is produced as the robot extrudes material only where it's needed. Another reason for this is that the material is locally collected and sourced within a 50-meter radius around the site. The material used for this structure is local earth combined with additives and enzymes to guarantee the structural stability and material elasticity needed for 3D printing.[44]

Figure 2.27. Top left. Details, TOVA by Iaac. Barcelona, Spain. 2022.

Figure 2.28. Top right. Physical prototype. TOVA by Iaac. Barcelona, Spain. 2022.

Figure 2.29. Bottom. The implementation of TOVA in large scale by Iaac. Barcelona, Spain. 2022.

---

43 Alice, *IAAC builds TOVA.*

44 Ibid

Credits:

Design & Development:

Iaac Team:

Edouard Cabay, Alexandre Dubor, Lili Tayefi, Vincent Huyghe, Ashkan Foroughi, Eduardo Chamorro Martin, Elisabetta Carnevale, Guillem Baraut, Gloria Font basté, Nikol Kirova, Francesco Polvi, Bruno Ganem Coutinho, Marielena Papandreou and David Skaroupka.

Project Partners:

Colette, WASP, UN-Habitat, BAC Engineering, LaSalle, SmartCitizen, Scuares and Living Prototypes Research Innovation.

Researchers:

Adel Alatassi, Aslinur Taskin, Charles Musyoki, Deena El-Mahdy, Eugene Marais, Hendrik Benz, Juliana Rodriguez Torres, Leonardo Bin, Mariam Arwa, Al-Hachami, Marwa Abdelrahim, Mehdi Harrak, Michelle Bezik, Michelle Antonietta Isoldi Campinho, Mouad Laalou, Nareh, Khaloian Sarnaghi, Nawaal Saksouk, Orestis Pavlidis and Seni Boni Dara.

2.8.2. HIVE

Year: 2021
Location: Toronto, Canada

HIVE is a 3D-printed masonry screen designed and fabricated through the combination of traditional casting techniques, robotics, and computational design. This ceramic work contains 175 unique pieces assembled to shape a geometry as a honeycomb. The gradual variation in the size of the apertures in the screen's pattern results in different levels of privacy and light penetration along the wall. To design and fabricate the screen – as a wall or as separate units - designers adopted a highly iterative process, moving back and forth between analogue and digital modeling.[45] Material computation is central to this research and was investigated on two different scales. The modulation of visual connectivity was manipulated through the variation in the size of apertures, and like TOVA, the depth and orientation of the screen are consistent all along the assembly.[46]

Learning from state-of-the-art projects such as TOVA and HIVE, my experiments with clay 3D printing started with the design and fabrication of the Nest-ling project.

Figure 2.30. Top Left. Assembling the 3D printed pieces in an office. HIVE by Cho. Y, She. J, Taylor. am, Correa. D, Clarke-Hicks. J, Ochoa, I. Toronto, Canada. 2021.

Figure 2.31. Top Right. Assembling the 3D printed pieces. HIVE by Cho. Y, She. J, Taylor. am, Correa. D, Clarke-Hicks. J, Ochoa, I. Waterloo, Canada. 2021.

Figure 2.32. Bottom. Defining undulating texture for the 3D printed pieces. HIVE by Cho. Y, She. J, Taylor. am, Correa. D, Clarke-Hicks. J, Ochoa, I. Waterloo, Canada. 2021.

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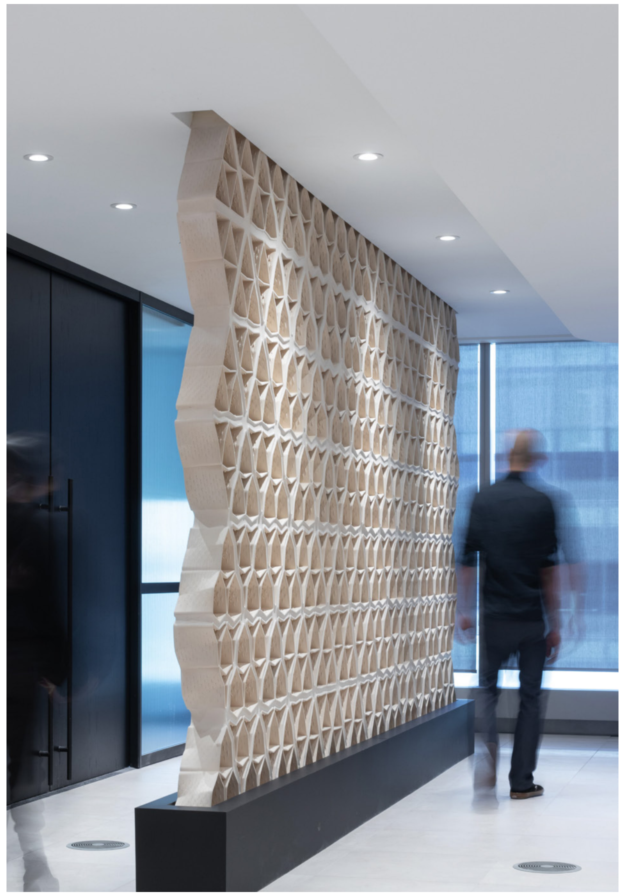
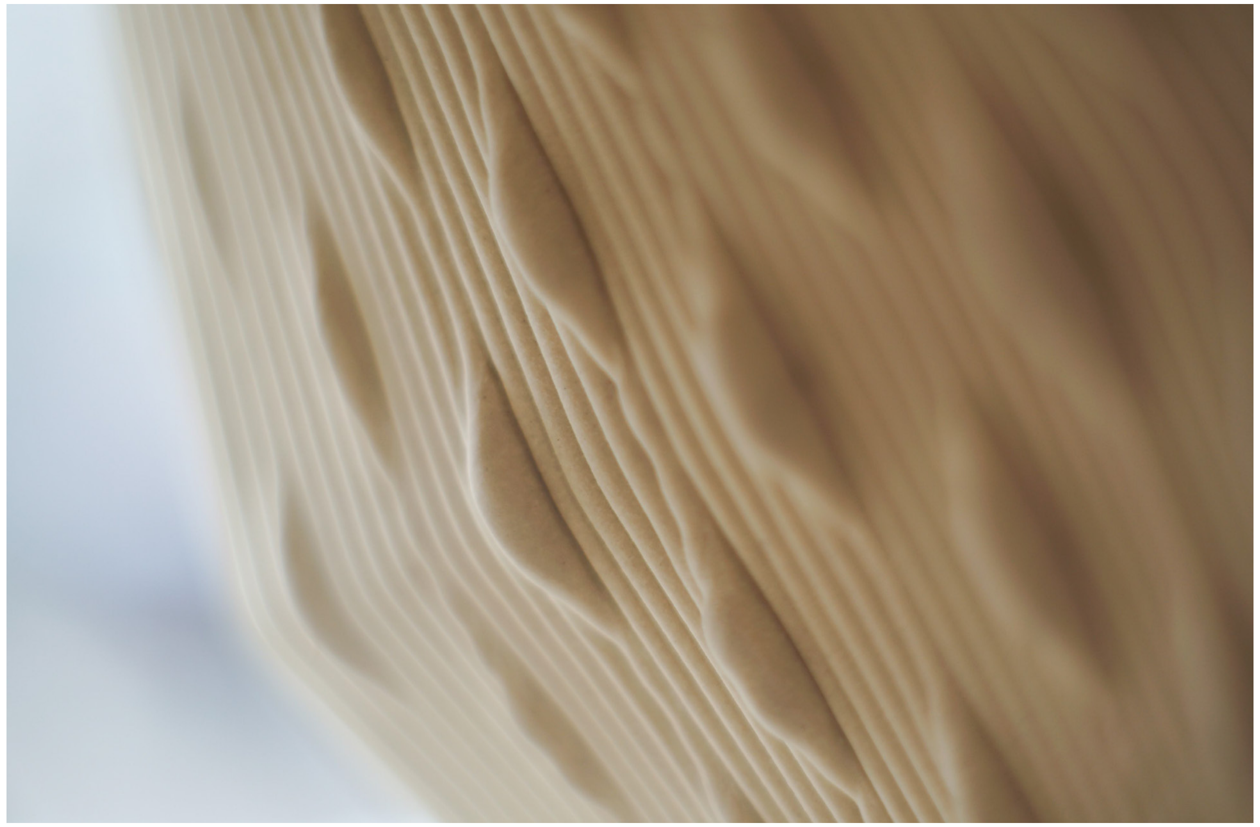
[45] Taylor, Cho, Shi, Correa, D. *Embracing Errors,* 18-19.

[46] Shi, Cho, Taylor, Correa, *Guiding Instability*, 477-484.





Credits:

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Ye Sul E. Cho (Project Lead, Alumna, Waterloo Architecture)
Ji Shi (Sci.Development Lead, Alumnus, Waterloo Architecture)
Meghan Taylor (Alumna, Waterloo Architecture)
David Correa (PI, Assistant Professor, Waterloo Architecture)
James Clarke-Hicks (Graduate Researcher, Waterloo Architecture)
Isabel Ochoa (Graduate Researcher, Waterloo Architecture)

Technical Support:

Heinz Koller (Shop Manager, WaterlooArchitecture)
Mychael Syms (Shop Technician, Waterloo Architecture)
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Interior Design:

SDI Design, Joanne Chan, Bruce Freeman

Project Management:

Cresa Toronto, Michael Wasyliw

Industry partners:

Masonry Works Council of Ontario, Andrew Payne Quikrete/Spec Mix., Dean Garbutt

Installation:

PAGE Flooring & Concrete Solutions, Tony Natali

Project Commission:

Investment Management Corporation of Ontario

Image credits:

Correa_hive : David Correa
Hunsberger_hive: Fred Hunsberger
Khokhar_hive: Shabaan Khokhar

2.8.3. Nest-ling

Year: 2022
Location: Waterloo, Canada

Nestling is a transformation of the rectilinear brick into a parametric form that provides habitats for birds, insects, and plants. Unique ceramic 3D-printed pieces are designed and printed to be dynamically integrated within masonry walls while providing various-sized openings for different species' habitats. The assembly is designed to attract smaller birds native to the region like chickadees and the red-breasted nuthatch, while allowing seeds and plants to grow on the lower edges, integrating living organisms and human habitats. As an assembly that will house living organisms, such as plants and birds, management of water collection and distribution is required. Designed drainage holes are strategically placed to lead the water toward the bottom units that are designed as planters. Since the size of the pieces is based on a generic masonry unit, the design team considered two different applications for assembling the bricks; A self-standing facade system that connects indoor and outdoor spaces or as installed pieces incorporated within an existing double masonry wall. Habitat biodiversity is enhanced through the integration of living organisms into the daily lifestyles of humans by bringing inert homes and facades to life.

Figure 2.33. Top. Variation in the size of openings for inhabiting different organisms. Nest-ling, Alnabelseya. S, Shehab. H, Varshosaz. P, Florence. Waterloo, Canada, 2022.

Figure 2.34. Bottom. Investigating undulating textures in the bricks. Nest-ling, Alnabelseya. S, Shehab. H, Varshosaz. P, Florence. Waterloo, Canada, 2022.

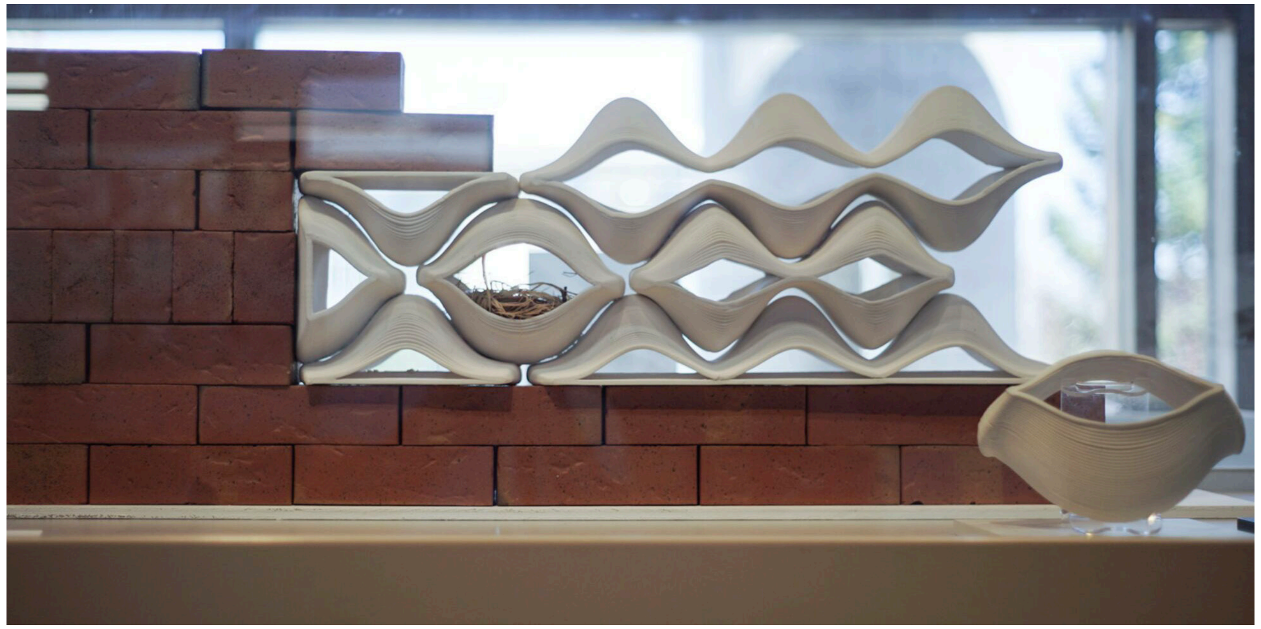

Figure 2.35. Multi-Organism design connects to modular elegance. Nestling, Alnabelseya. S, Shehab. H, Varshosaz. P, Florence. Waterloo, Canada, 2022.

Overall, the framework of this project provides customizability, compatibility, and sustainability in the existing design and fabrication system. The design offered for this screen is customizable as it allows the designer to change the size of the apertures, bricks, and dimension ratios. Therefore, it can be compatible with different architectural systems and applications. Also, the material used for fabrication is clay which can be recycled after physical prototyping and making the final pieces. Limiting the amount of material waste throughout the process makes this method environmentally friendly, compared to the existing construction systems.[47]

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[47] Alnabelseya, Shehab, Varshosaz, Wilson, Nest-ling.

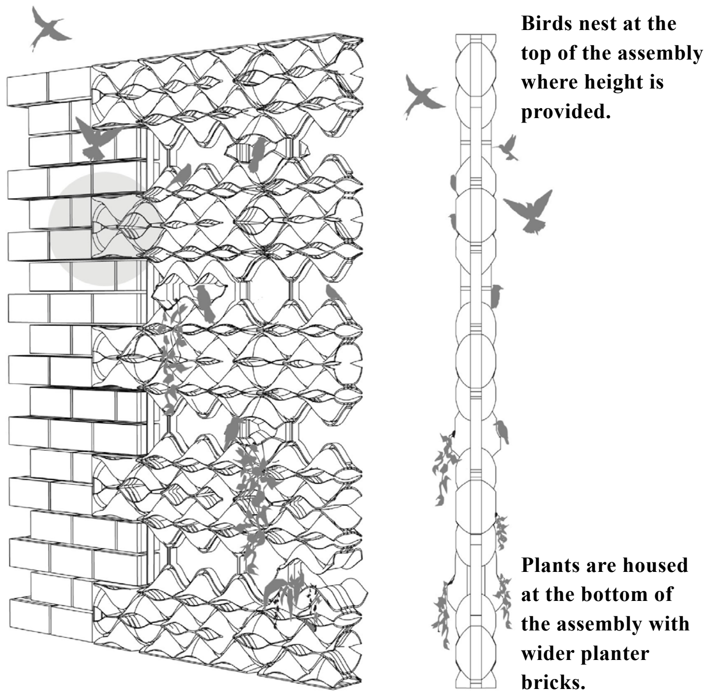


Figure 2.36. Top. Providing habitats for living organisms, including birds, plants, and squirrels at different heights.

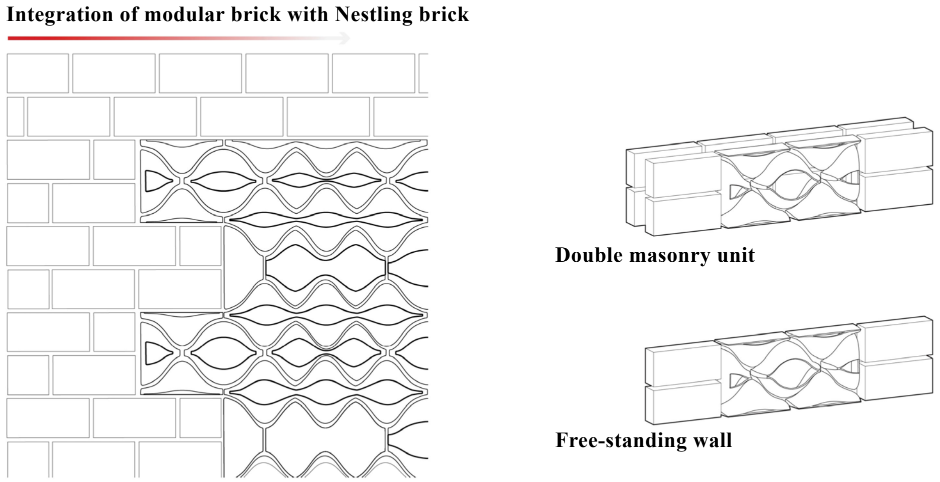


Figure 2.37. Middle. Two alternatives for the fabrication of the assembly.

- Two options are provided for the fabrication of the assembly: 1. double-sided free-standing wall, or 2. embedded in a double masonry wall. Also, the design offers two edging conditions: 1. smoothly integrating into the brick wall's pattern, 2. matching the rectangular shape of the bricks

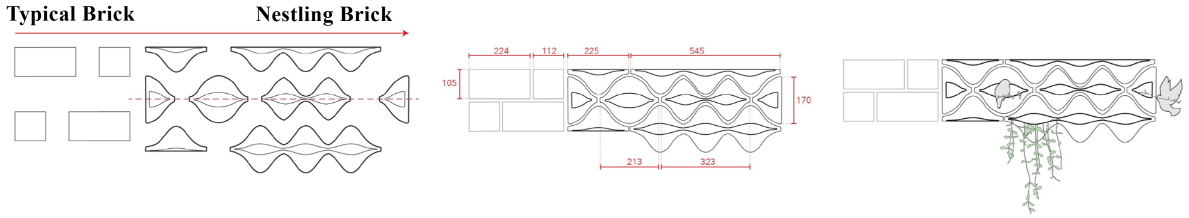
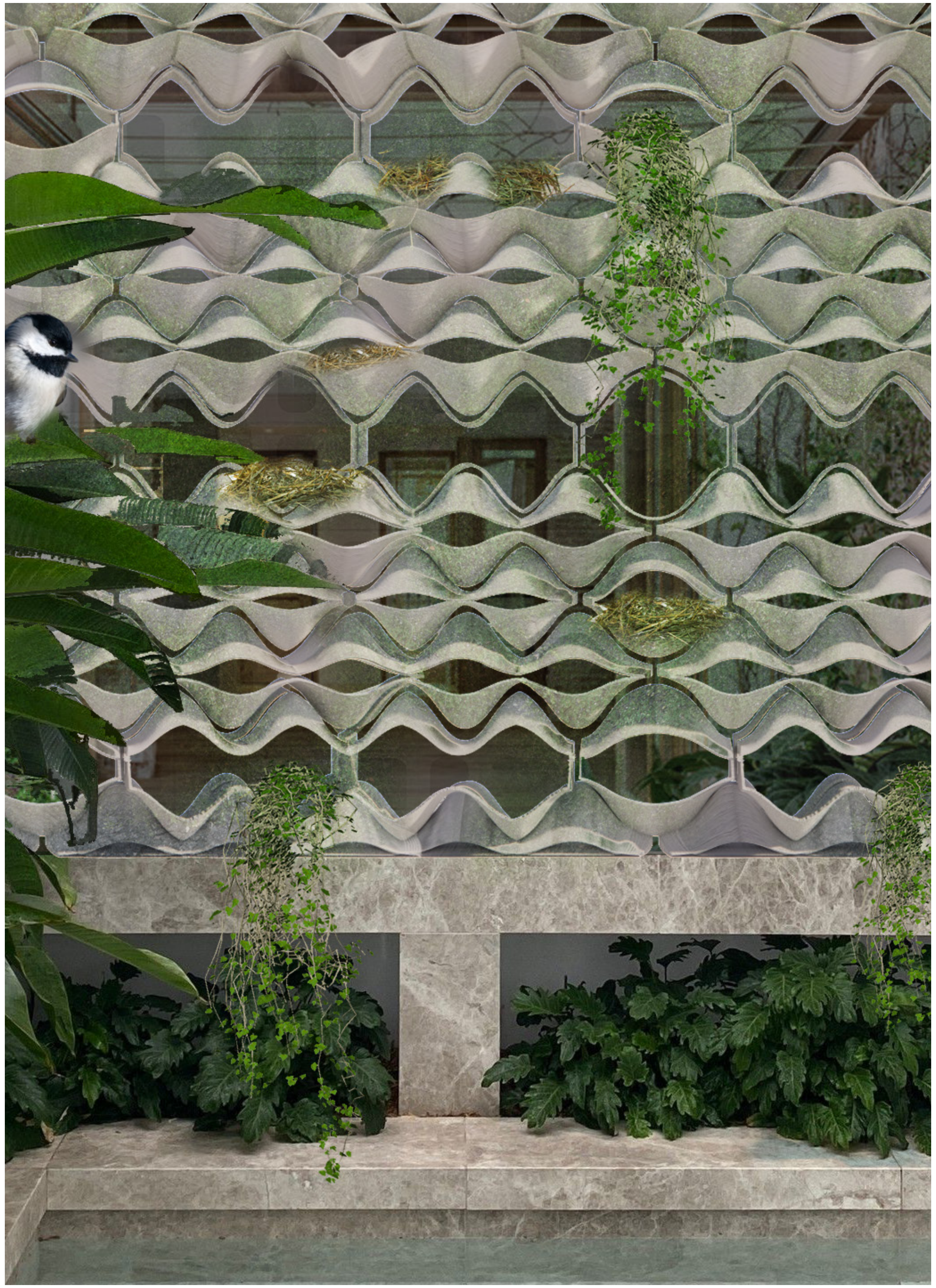


Figure 2.38. Bottom. Dimensions of the assembly and pieces.

Figure 2.39. Next page. Assembled 3D printed pieces.



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Hania Shehab (MArch Student, Waterloo Architecture)
Parastoo Varshosaz (MArch Student, Waterloo Architecture)
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Course:
Material Syntax

Course instructor:
David Correa (Assistant Professor, Waterloo Architecture)

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David Correa.

CHAPTER THREE

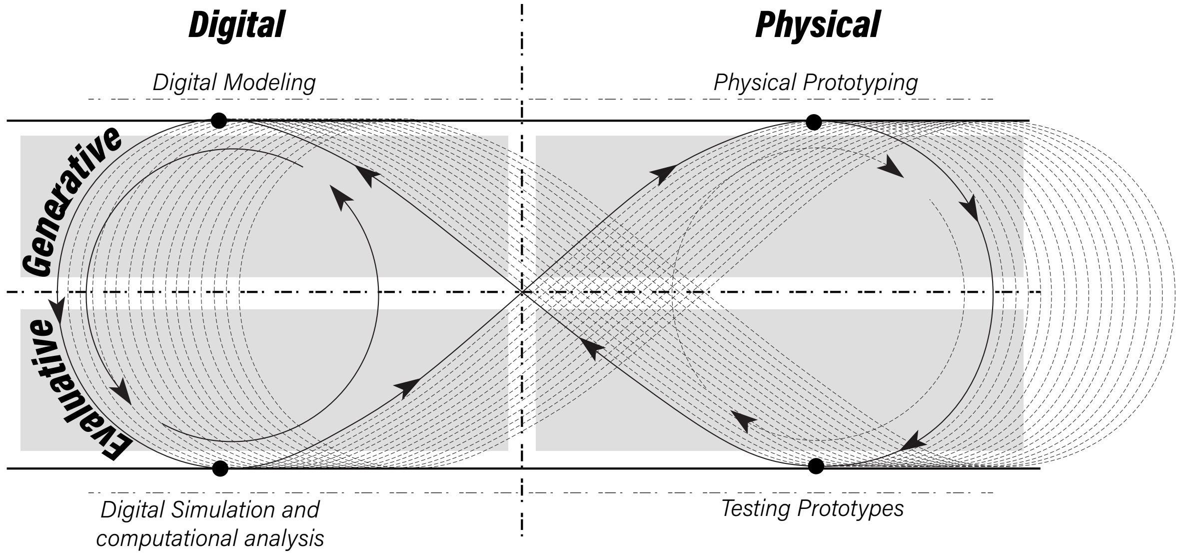
Methodology

3.1. A Reciprocal Method

The methodology taken for this investigation is generally defined in two sections, each separated into two parts: physical vs digital and generative vs evaluative modeling (Figure 3.01). Going through these four domains in a cyclic manner provides a significant opportunity to investigate the thesis question and achieve multi-dimensional solutions.[1] The process starts with digitally modeling the pieces and continues with translating them to physical prototypes using 3D printers. Moving toward the evaluative section, the physical models are tested and digitally simulated to be evaluated based on the target performance goals. This process allows for understanding the possibilities, potentials, and weaknesses of the design and assists to improve them. The following section discusses every step of the design and fabrication process in detail.

Figure 3.01. Thesis framework.

- This diagram illustrates the two sections of physical prototyping and Digital modeling that are in the generative domain, along with testing prototypes and analytical digital simulation that belong to the evaluative part. Through a reciprocal manner, the designer moves back and forth between these four sections until achieving the desired result.



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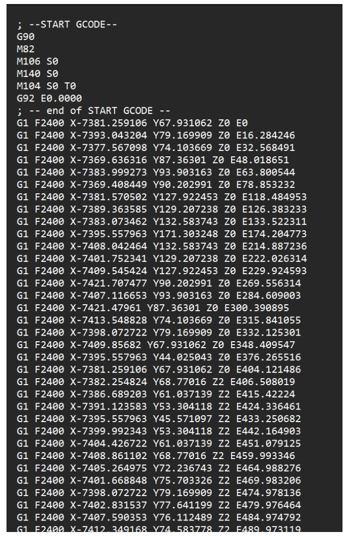
[1] Croll, *Hybrid Bivouac.*

3.2. From Digital to Physical Modeling

After establishing the major parameters that influence visual connectivity, the design is digitally modeled and optimized in Rhinoceros and Grasshopper. However, the resulting digital data in 3D modeling software are not directly readable by 3D printers. Most of the CNC machines and 3D printers including the one used in this research, work based on a scripting language known as G-Code.[2]

Figure 3.02. The G-Code script.



```
; --START GCODE--
G90
M82
M106 S0
M140 S0
M104 S0 T0
G92 E0.0000
; -- end of START GCODE --
G1 F2400 X-7381.259106 Y67.931062 Z0 E0
G1 F2400 X-7393.043204 Y79.169909 Z0 E16.284246
G1 F2400 X-7377.567098 Y74.103669 Z0 E32.568491
G1 F2400 X-7369.636316 Y87.36301 Z0 E48.018651
G1 F2400 X-7383.999273 Y93.903163 Z0 E63.800544
G1 F2400 X-7369.408449 Y90.202991 Z0 E78.853232
G1 F2400 X-7381.570502 Y127.922453 Z0 E118.484953
G1 F2400 X-7389.363585 Y129.207238 Z0 E126.383233
G1 F2400 X-7383.073462 Y132.583743 Z0 E133.522311
G1 F2400 X-7395.557963 Y171.303248 Z0 E174.204773
G1 F2400 X-7408.042464 Y132.583743 Z0 E214.887236
G1 F2400 X-7401.752341 Y129.207238 Z0 E222.026314
G1 F2400 X-7409.545424 Y127.922453 Z0 E229.924593
G1 F2400 X-7421.707477 Y90.202991 Z0 E269.556314
G1 F2400 X-7407.116653 Y93.903163 Z0 E284.609003
G1 F2400 X-7421.47961 Y87.36301 Z0 E300.390895
G1 F2400 X-7413.548828 Y74.103669 Z0 E315.841055
G1 F2400 X-7398.072722 Y79.169909 Z0 E332.125301
G1 F2400 X-7409.85682 Y67.931062 Z0 E348.409547
G1 F2400 X-7395.557963 Y44.025043 Z0 E376.265516
G1 F2400 X-7381.259106 Y67.931062 Z0 E404.121486
G1 F2400 X-7382.254824 Y68.77016 Z2 E406.508019
G1 F2400 X-7386.689203 Y61.037139 Z2 E415.42224
G1 F2400 X-7391.123583 Y53.304118 Z2 E424.336461
G1 F2400 X-7395.557963 Y45.571097 Z2 E433.250682
G1 F2400 X-7399.992343 Y53.304118 Z2 E442.164903
G1 F2400 X-7404.426722 Y61.037139 Z2 E451.079125
G1 F2400 X-7408.861102 Y68.77016 Z2 E459.993346
G1 F2400 X-7405.264975 Y72.236743 Z2 E464.988276
G1 F2400 X-7401.668848 Y75.703326 Z2 E469.983206
G1 F2400 X-7398.072722 Y79.169909 Z2 E474.978136
G1 F2400 X-7402.831537 Y77.641199 Z2 E479.976464
G1 F2400 X-7407.590353 Y76.112489 Z2 E484.974792
G1 F2400 X-7412.349168 Y74.583778 Z2 E489.973119
```

3.2.1. The Mediator Language

The G-Code is defined as a text that contains orders and tasks related to the 3D printer's movement and the amount of material extrusion. The orders in a G-Code are a combination of a letter and a number. It covers all the letters in the English alphabet. However, it has been programmed to use the letter G as the initiator of movement-related codes for the machine. This code can be read by the 3D printer's firmware and what is used in this study is Marlin G-Code[3]. The CAM (Computer Aided Manufacturing) software used for 3D printing is called Slicer. Because it slices the design geometry into layers as the tool path for the machine's movement. The most commonly used Slicers for 3D printing are Cura, Sli3r, and Simplify3D.[4] These options can be controlled by different factors and parameters, and yet, are followed by numerous limitations in the design-

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[2] Cuevas, Pugliese, *Advanced 3D Printing with Grasshopper.*

[3] Ibid

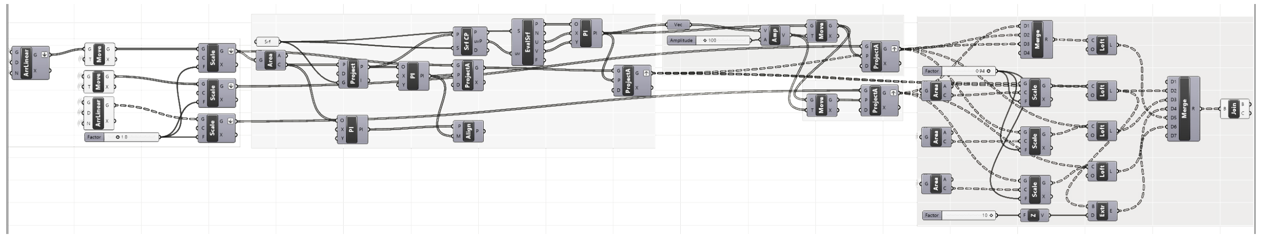
[4] Ibid

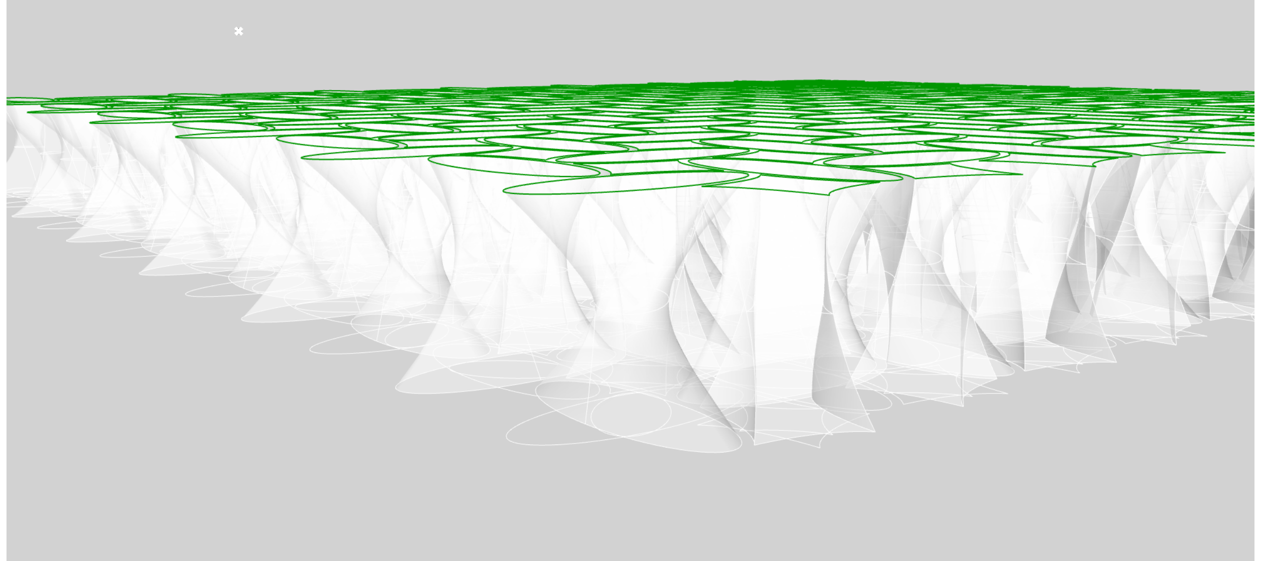
ing process. Thus, this study aims to use Grasshopper directly rather than Slicer to reduce the number of constraints in design. Grasshopper, a plugin in Rhinoceros modeling software, can be adapted to maximize the model and the design's possibilities.

The aim of using Grasshopper in 3D printing is to create a continuous polyline that can be defined as the tool path, controlling the machine's movement. The modeled form is directly exported to G-Code format for the 3D printer, instead of bridging the G-Code and the machine through Slicer.[5]

Figure 3.03. Top. The design is scripted in Grasshopper, a plugin installed on Rhino.

Figure 3.04. Bottom. The 3D modeled design in Rhino.





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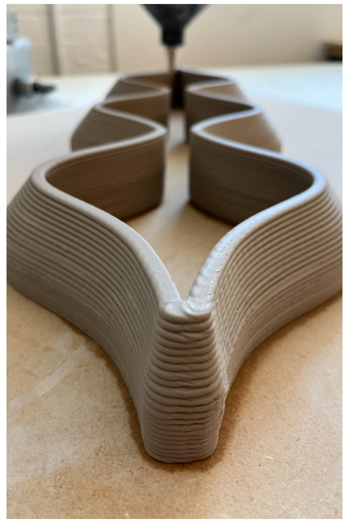
[5] Ochoa, Clarke-Hicks, *Grading Light.*

3.2.2. Clay 3D Printer

The 3D printed components were produced using Potterbot XLS-1, a SCARA printer that is capable to rotate almost 360 degrees with a maximum arm extension of 900mm. A 3600cc vertical acrylic cartridge is clipped to the end of the printer arm. The cartridge is loaded with clay using a pugmill. A rubber puck drives clay through a nozzle in a continuous bead, like a syringe. The puck is driven through the tube by a threaded rod attached to a high-torque stepper motor. Extensive rotational reach paired with robust extruder components makes this printer ideal for rapid prototyping large ceramic forms. Depending on the print speed and extrusion rate, a full 3600cc cartridge of clay empties in 80 to 110 minutes of printing. The Potterbot XLS-1 is one of the largest-capacity commercially available clay printers.[6] After the process of 3D printing, the pieces are maintained at room temperature for four to five days to be completely dry. This is a safety requirement before placing the bricks in the kiln, as there is a risk for pieces to explode, if not entirely dry.

Figure 3.05. Clay 3D printing with Potterbot XLS.



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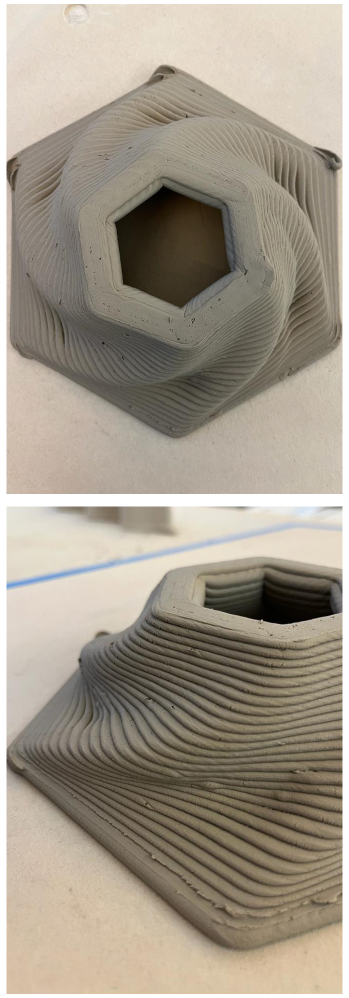
[6] Moore, Armstrong, McDonald, Yampolskiy, *Vulnerability analysis of desktop 3D printer software*. 46-51.

Figure 3.06. Top. Potterbot XLS-1, SCARA 3D printer.

3.2.3. Choice of Material

The material used to fabricate the light screens in this thesis is clay. As a natural material, clay has a range of qualities that we can benefit from in construction. According to this application, the type of clay to use for 3D-printing changes. The factors considered for choosing the type of clay in this thesis are the durability and strength that are required for a masonry facade system. The clay used in this project is white clay from the Pottery Supply House (PSH - #516 cone 6) that contains 25% water in the mix.[7] This is a special batch preparation with the maximum amount of water that PSH can add. To further soften the material and prepare it for printing, an additional 5% water is added to the mix. Therefore, for every 950g of PSH white clay, 50g of water needs to be mixed into the clay body before printing. After 3D printing the designed bricks with Potterbot, the pieces are assembled to create the screen. To attach the ceramic pieces white mortar is used and then the tiles between the bricks are coated with white grout to create a smooth and clean finish.

Figure 3.07. 3D printing With clay.



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[7] Smyth, *Material Mix.*

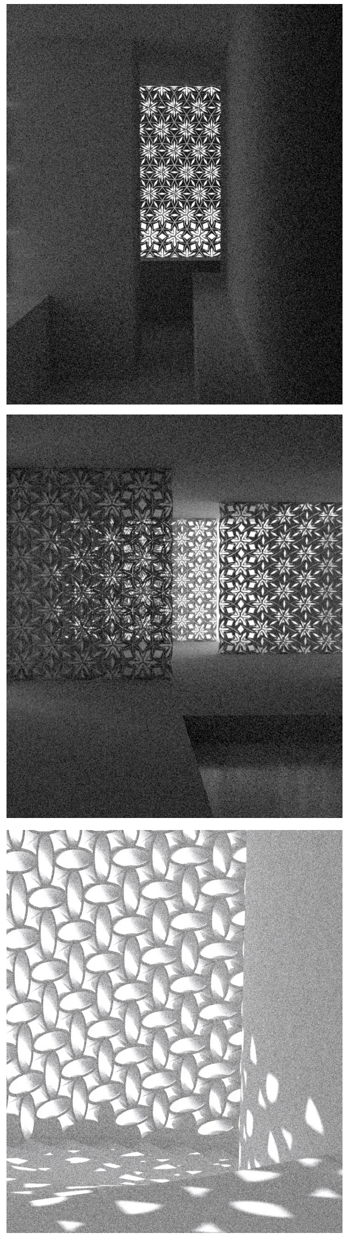
3.2.4. Evaluation

Human visual perception is based on relational observations and can be influenced by different environmental factors. This thesis aims not to quantify or qualify the existing view beyond the screen, but to investigate the impact of the proposed designs on visual connectivity between spaces. To evaluate the functionality of the screens and the resulting visual connection through them, this thesis proposes two strategies.

In the first strategy, the designed screens are digitally simulated in three separate spaces. Each space requires a screen that supports its unique atmosphere. This unique variation can be created through the control of visual connectivity and light modulation. This can provide visual privacy, connection with nature, or it can be used to evoke a sense of tranquility. This strategy helps us to better understand the created visual and light qualities in different spaces and how they influence one's spatial perception.

The second strategy computationally compares the created level of visual connectivity through the screens with different depths, orientations, and aperture sizes. To this end, this research uses a method named *vector raytracing*[8] which calculates the number of projected rays from human eyes that can pass through the screen within a 120-degree spherical cone of vision. Comparing this number to the total number of vectors, the script produces a percentage that allows the designer to evaluate the amount of visual coverage that the eye can see thorugh the screens.[9]

Figure 3.08. Digital simulation of the screens in three architectural applications.



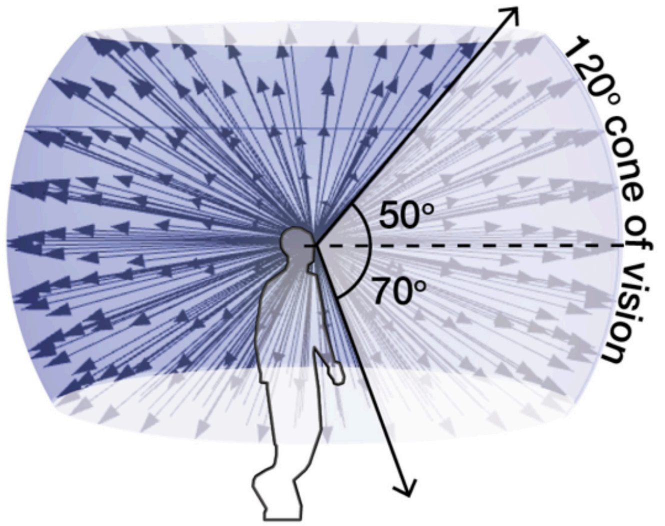


Figure 3.09. Vector raytracing within the 120-degree spherical cone of vision.
The rays are cast from the observer's eyes.

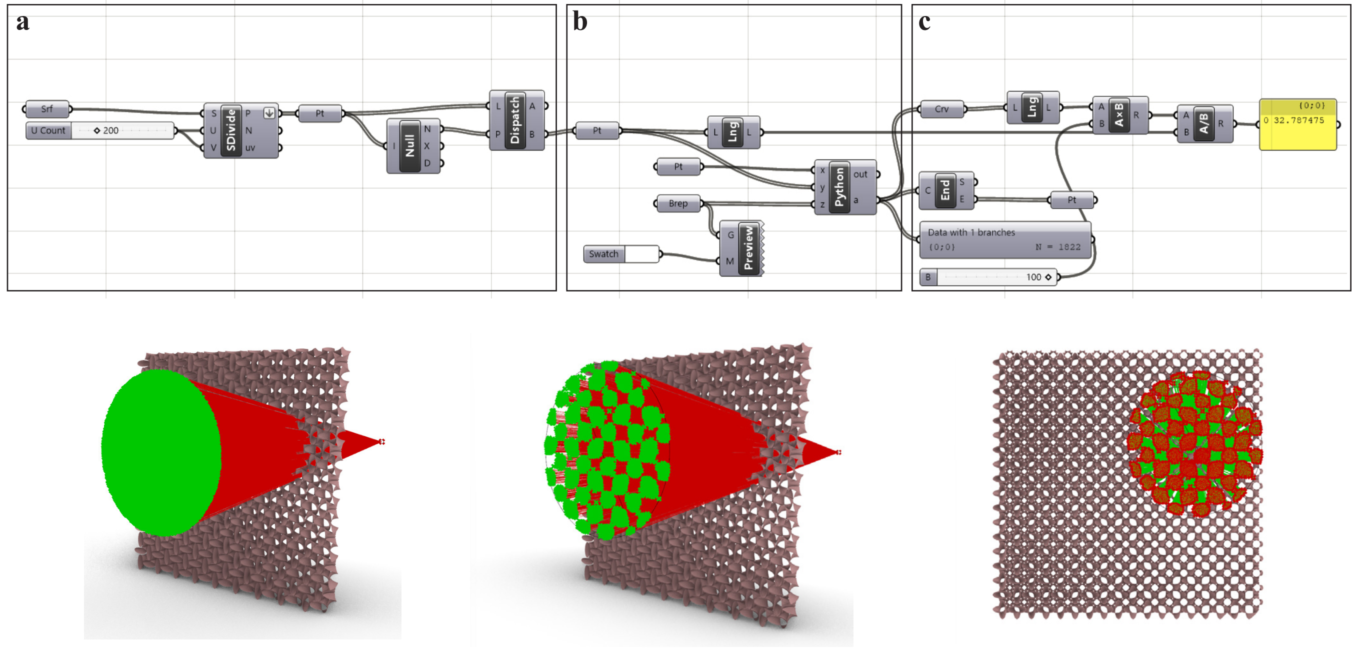


Figure 3.10. Vector raytracing script.
a. Populating points on the spherical surface of the 120-degree cone vision.
b. Calculating the number of rays that can pass through the screen's apertures.
c. Comparing the number of calculated rays to the total number of vectors for producing a percentage.

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[8] Turan, I., Reinhart, C. & Kocher, M. *Evaluating spatially-distributed views in open plan work spaces.*

[9] Ibid

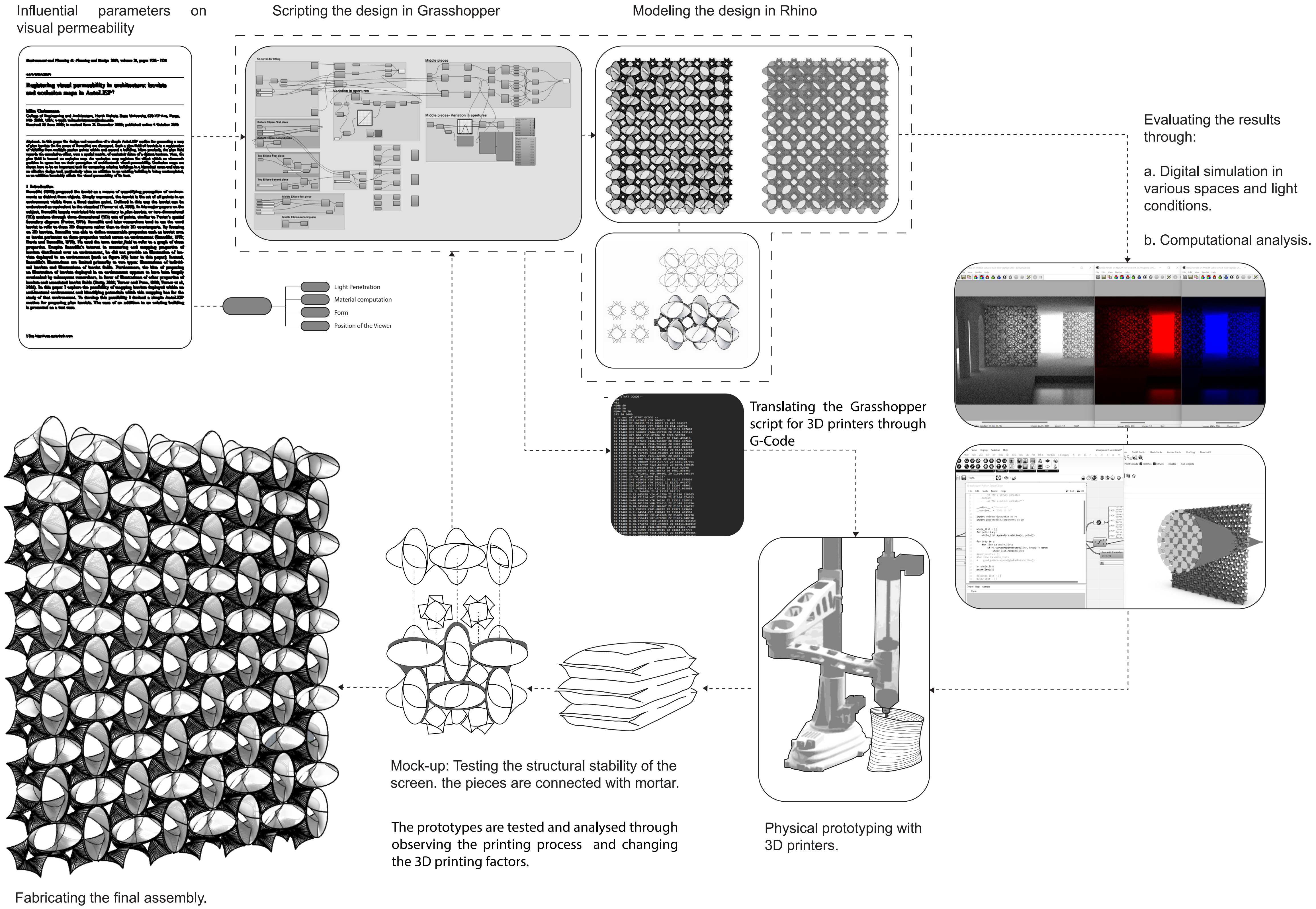

Figure 3.11. Different stages of the thesis process.

CHAPTER FOUR

Design and Fabrication

4.1. Design Concept and Digital Modeling

Learning from the existing research about light screens and establishing the major parameters of visual connectivity, two light screens have been developed. Both proposals allow the designer to adjust the level of visual connectivity through the screen and modulate light; However, light and visual qualities created by each screen are different. The investigations start with screen 1 which provides the required flexibility for changing the size of apertures as well as the depth of each piece in the assembly. To improve the design's customizability regarding the orientation of the apertures, a second screen is proposed. This section investigates the process of design and fabrication of these two screens and illustrates how each enhances the visual and light qualities in the space for the individuals.

a. Screen 1

The design of this screen is inspired by the concept of transparency as it corresponds to visual connectivity on many levels. Slutzky and Rowe believe that there are two types of transparency; Phenomenal transparency which explains the inherent quality of organization, and literal transparency which mentions the inherent quality of materials like glass or water.[1] The design of screen 1 is inspired by the shape of crystal ice as a transparent element, based on the definition of literal transparency (Figure 4.02).

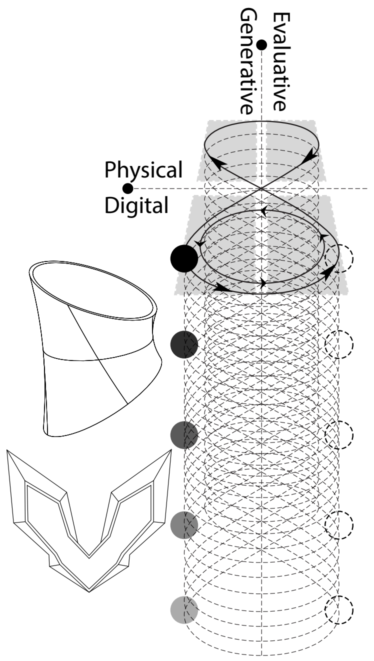

Figure 4.01. Thesis framework: Designing and modeling stage.

Figure 4.02. The shape of a crystal ice, by Craig L. Goodwin.

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[1] Rowe, Slutzky. *Transparency*, 45-54.

Reflecting on the internal order of the crystal's water molecules (two hydrogen atoms and one oxygen atom) the most efficient way for the molecules to attach is in a hexagon shape. Thus, every crystal ice is a hexagon and grows to shape larger ones as it develops. When assembling the bricks for screen 1, the creation of the hexagons from three primary pieces is visible. As the wall expands from different directions, smaller hexagons are embraced by larger ones creating a pattern that can be infinitely continued. Moreover, this design provides the required geometrical variety and evokes a sense of ambiguity, encouraging the observer to explore more and to see what exists beyond the screen. As a crystalline form, the surfaces of the primary bricks are designed and printed to create sloped edges. This quality is created to shape an undulating surface for the wall, attracting the observer's attention to the center of the three primary pieces.

Following the geometry of crystal ice, two general categories of pieces are defined. The first group contains the primary components that connect to two other similar pieces to shape the whole crystal (Figure 4.03).

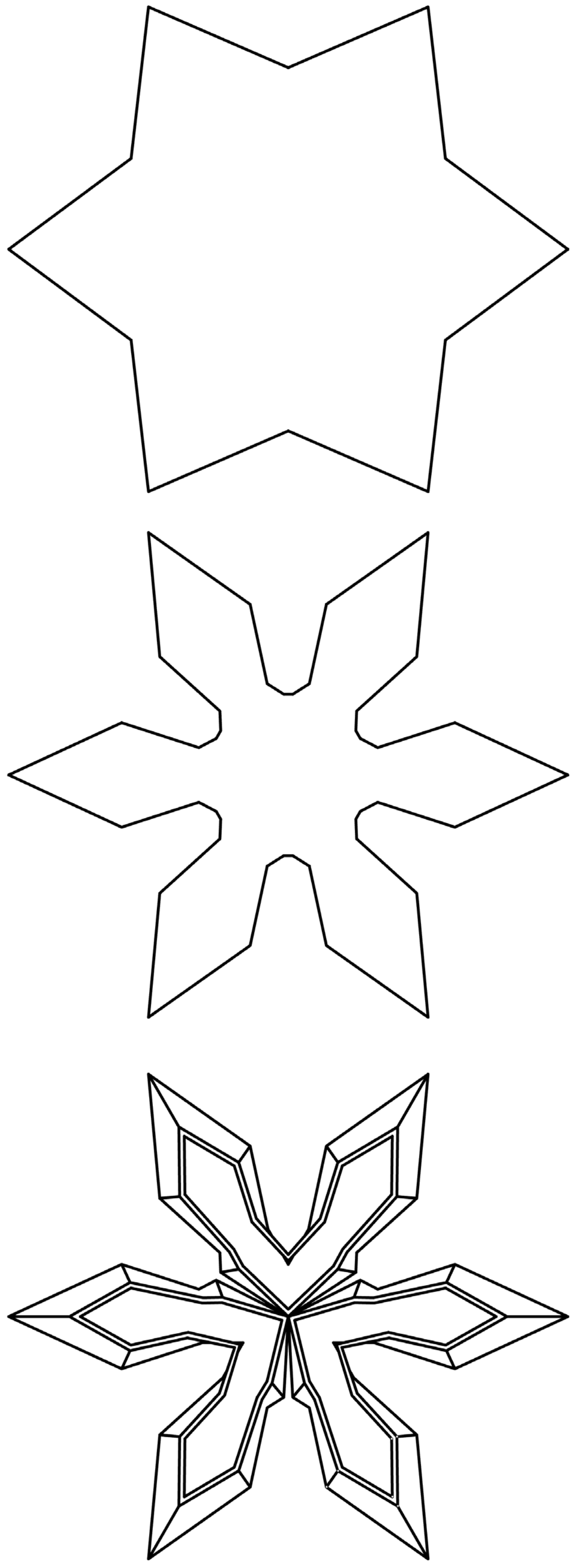
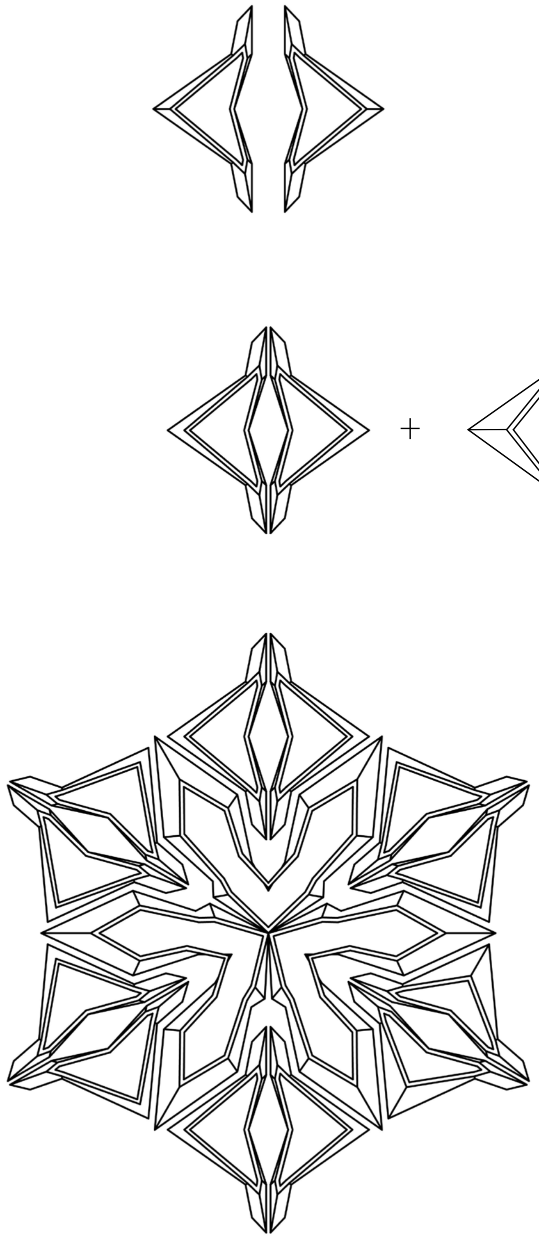


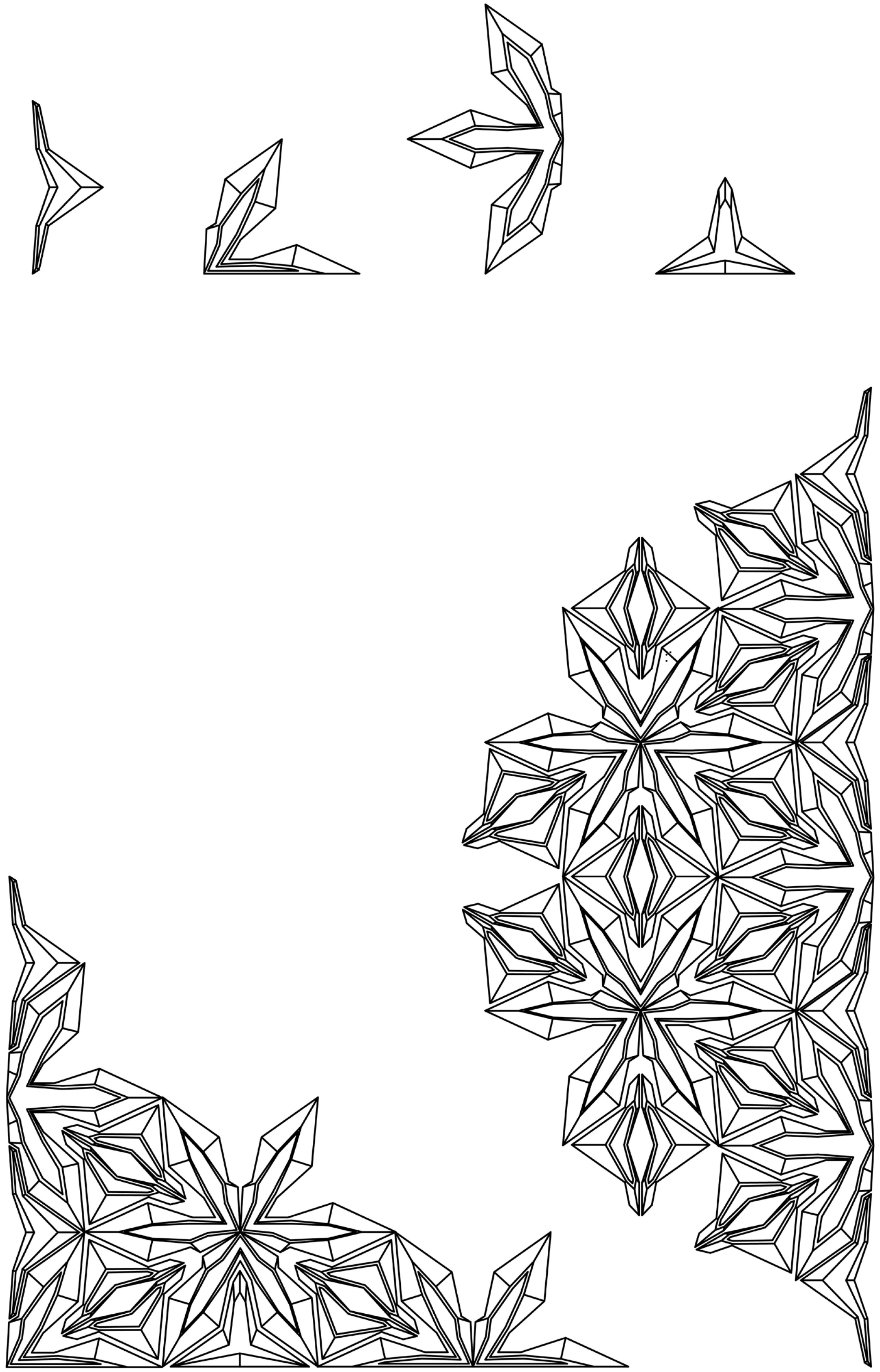
Figure 4.03. The process of form-finding for the primary pieces.

The second group consists of four different pieces that function as connectors, linking the primary bricks in the assembly. These pieces follow the geometry of the gaps created in between the primary bricks (Figure 4.05).

Figure 4.04. Left. The primary pieces and the middle connector bricks create the shape of a hexagon.

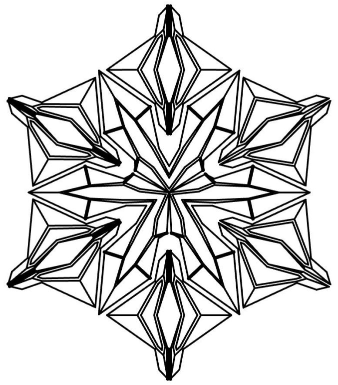
Figure 4.05. Right. Connector and finishing pieces that link the primary pieces in the assembly and define the shape of the wall's edges.

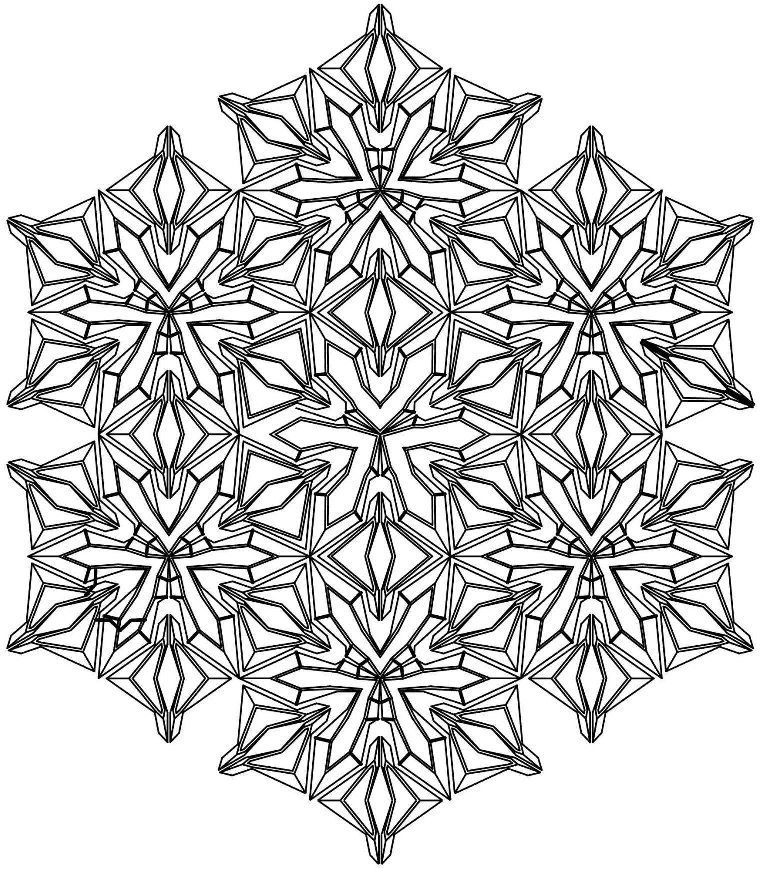


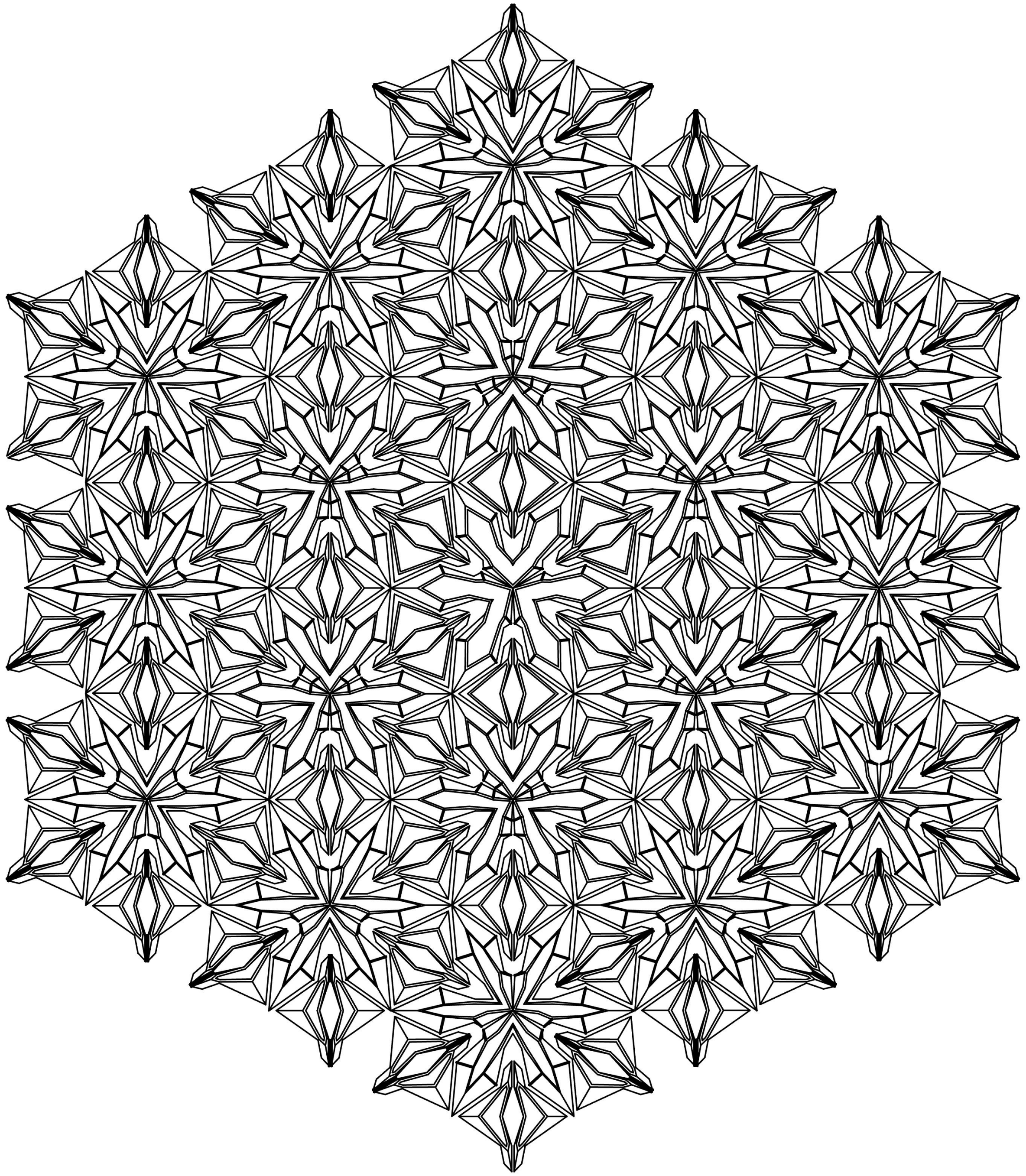


Adding the connector pieces to the assembly improves the ability for controlling the size of apertures, as well as the structural stability of the screen. As we continue to put more pieces together, larger hexagons are created that embrace the smaller ones (Figure 4.06).

Figure 4.06. The assemblage of pieces in three different stages, showing the expansion of hexagons.







b. Screen 2

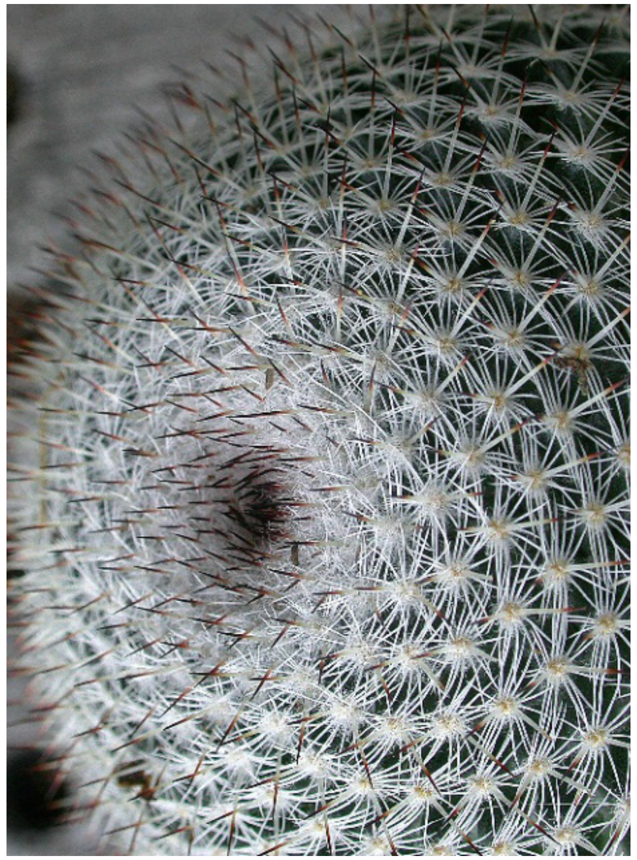
The design of this light screen is inspired by the form of a spiral. A spiral form has been discovered frequently in nature, creating well-balanced compositions. A spiral is known as a form that evokes a sense of exploration by attracting the observer's eyes to the center and therefore, improving visual permeability. This quality provides valuable geometrical opportunities that change the way one perceives depth.

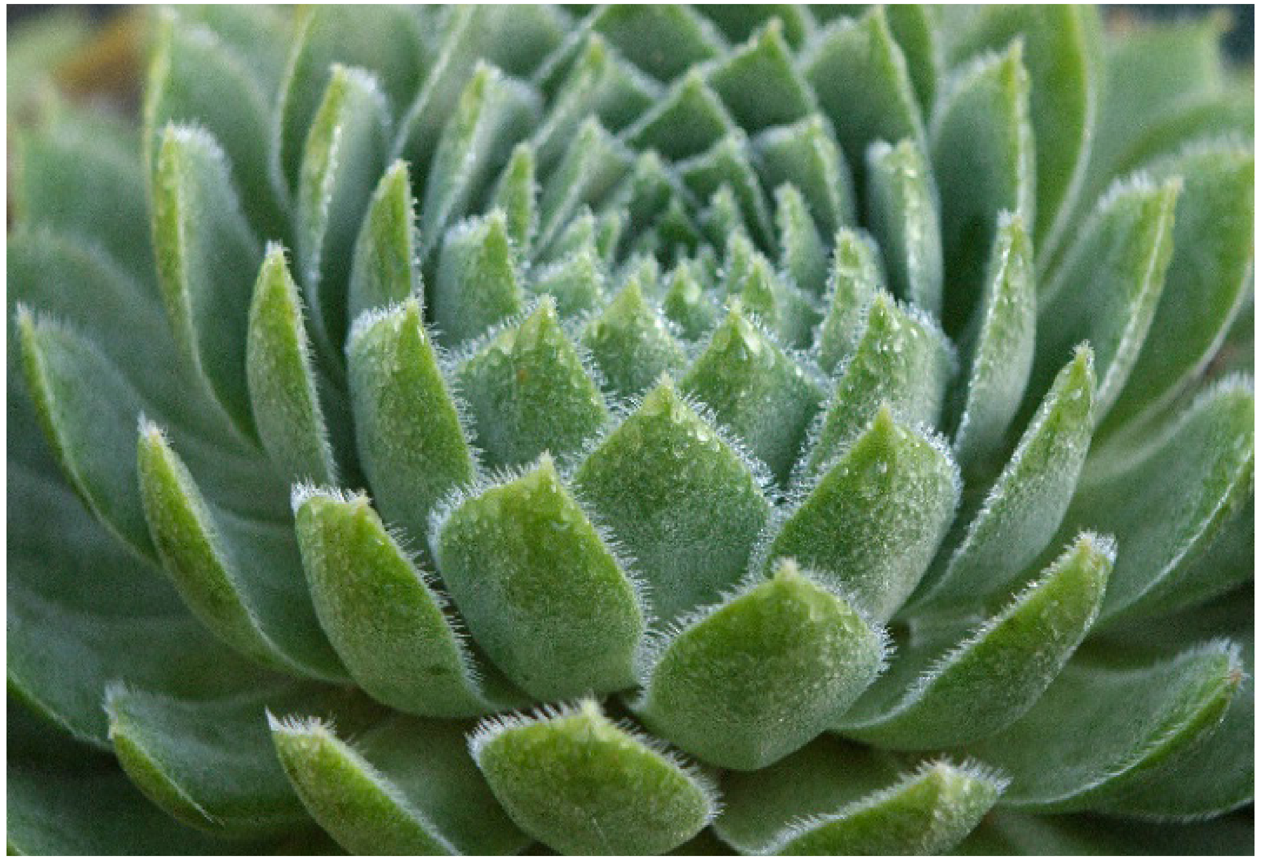
Based on this exploration regarding the spiral form, the second light screen is built from twisted-shaped bricks. The circular form of the spiral is replaced by an ellipse, as it offers more variation in the horizontal and vertical axes in the screen's pattern. The main pieces are created through lofting and then twisting two separate ellipses by 90 degrees. To enhance designers' capability for controlling the apertures in the assembly, a second piece is defined that follows the geometry of the created hole in between the primary pieces (Figure 4.10 and 4.11). This project proposes a second alternative for the design of the middle piece to minimize the gaps created between the assembled bricks. In this way, the amount of mortar needed to fill the gaps is much less. The designer can choose between the two options based on the required qualities in the application (Figure 4.12).

Figure 4.07. Top-Right. Spiral pattern in a pine cone. By Kevin Kopchynski. 2013.

Figure 4.08. Top-Left. Radiating Leaf Pattern. By Kevin Kopchynski. 2013.

Figure 4.09. Bottom. Cactus spine Spirals. By Kevin Kopchynski. 2013.





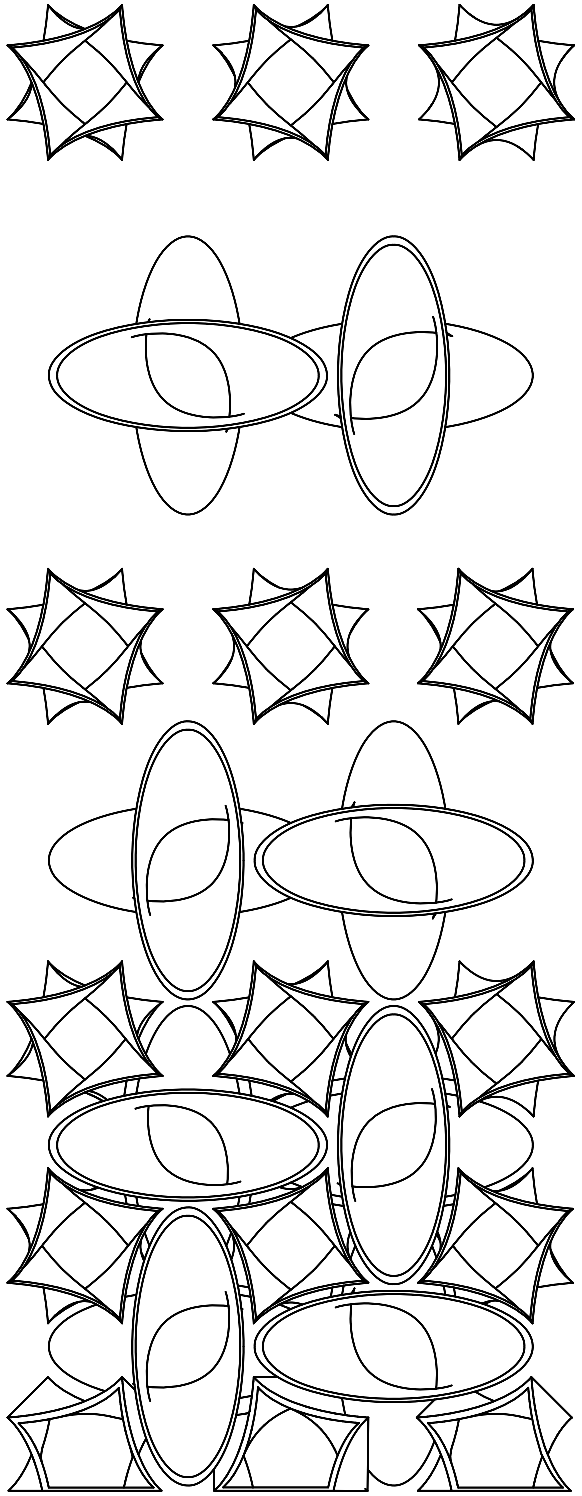


Figure 4.10. Left. The process of assembling the Primary and connector pieces.

Figure 4.11. Right. The primary and connector pieces as an assembly.

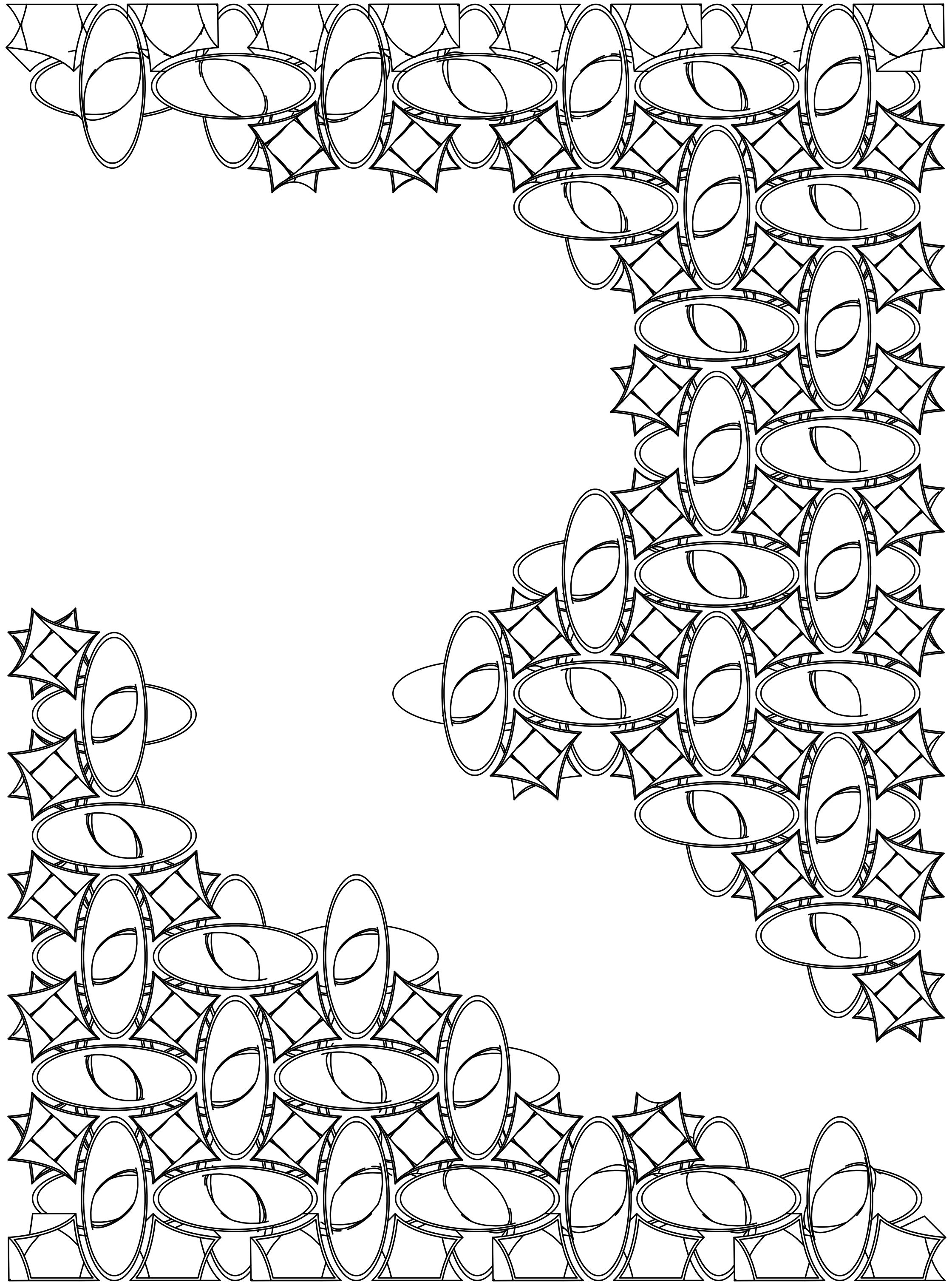
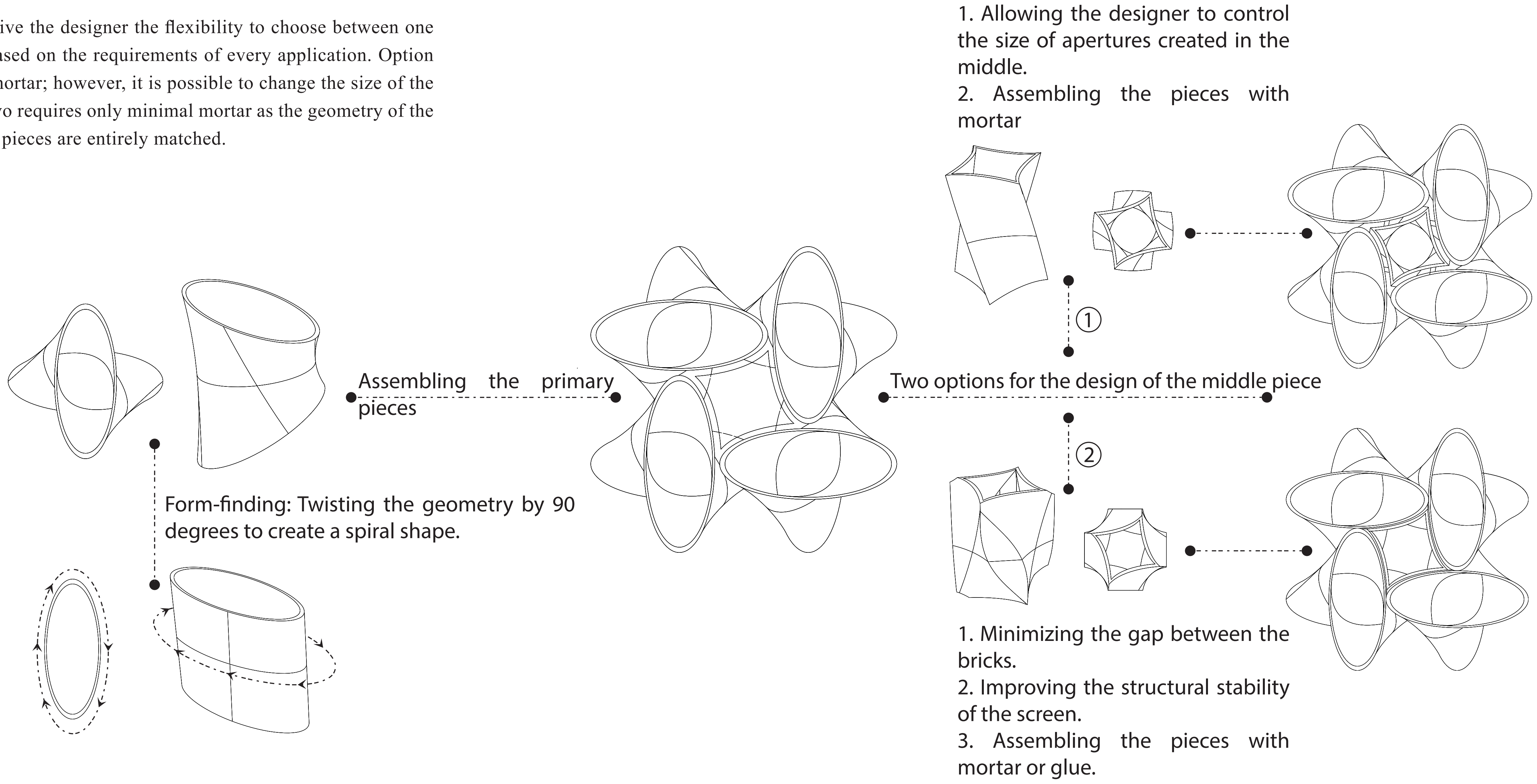


Figure 4.12. The two alternatives for the design of the middle piece.

- The two options give the designer the flexibility to choose between one of the two pieces based on the requirements of every application. Option one requires more mortar; however, it is possible to change the size of the apertures. Option two requires only minimal mortar as the geometry of the middle and primary pieces are entirely matched.



1. Allowing the designer to control the size of apertures created in the middle.
2. Assembling the pieces with mortar

1. Minimizing the gap between the bricks.
2. Improving the structural stability of the screen.
3. Assembling the pieces with mortar or glue.

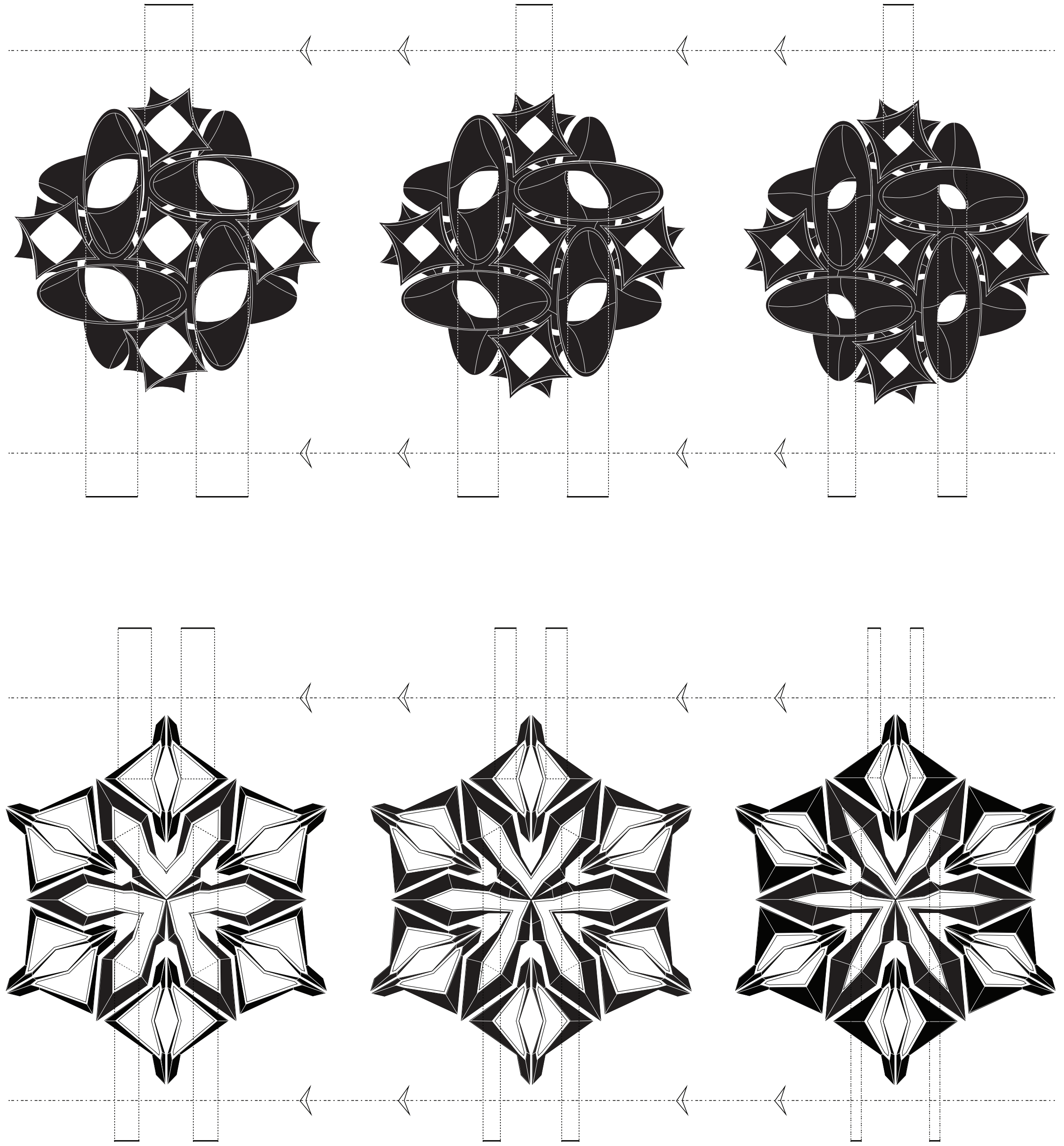
4.1.1. Variation in the size of apertures

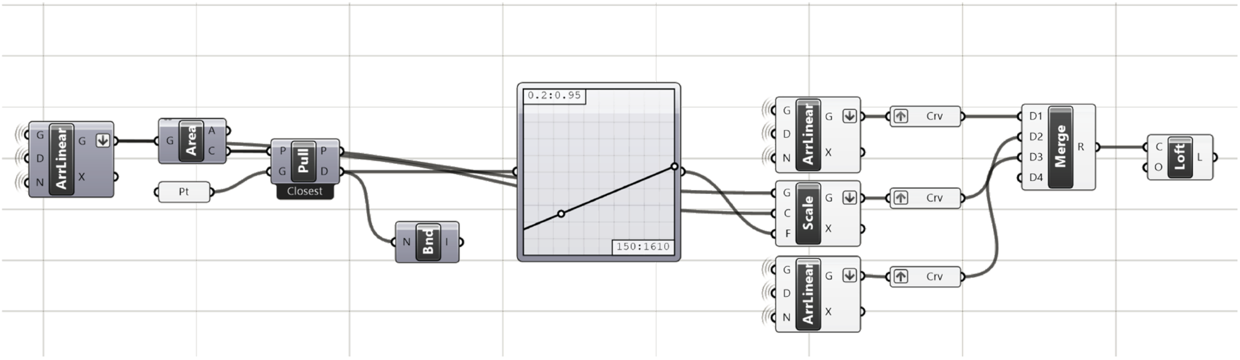
Every environmental change in the air where the crystal ice forms, influences its final shape. Depending on how high up in the clouds the crystals are, the shape of each is different. Therefore, no two crystals are exactly alike. Based on this idea, every single piece on screen 1 is designed as a unique block. The reason for this variation is to control the observer's visual connectivity in and to create dynamic light patterns in the space.

Screen 2 follows the same trend. The ellipses located in the middle of the vertical axes can be controlled through their allocated amount of radius. The connecting pieces in this assembly are also controllable by adjusting the middle polygon's radius. Therefore, this variation in the size of the apertures makes every piece different from another in the assembly.

Figure 4.13. Top. The size of bricks' apertures gradually changes to provide different visual and light qualities.

Figure 4.14. Bottom. The grasshopper script used for creating the variation in the apertures.





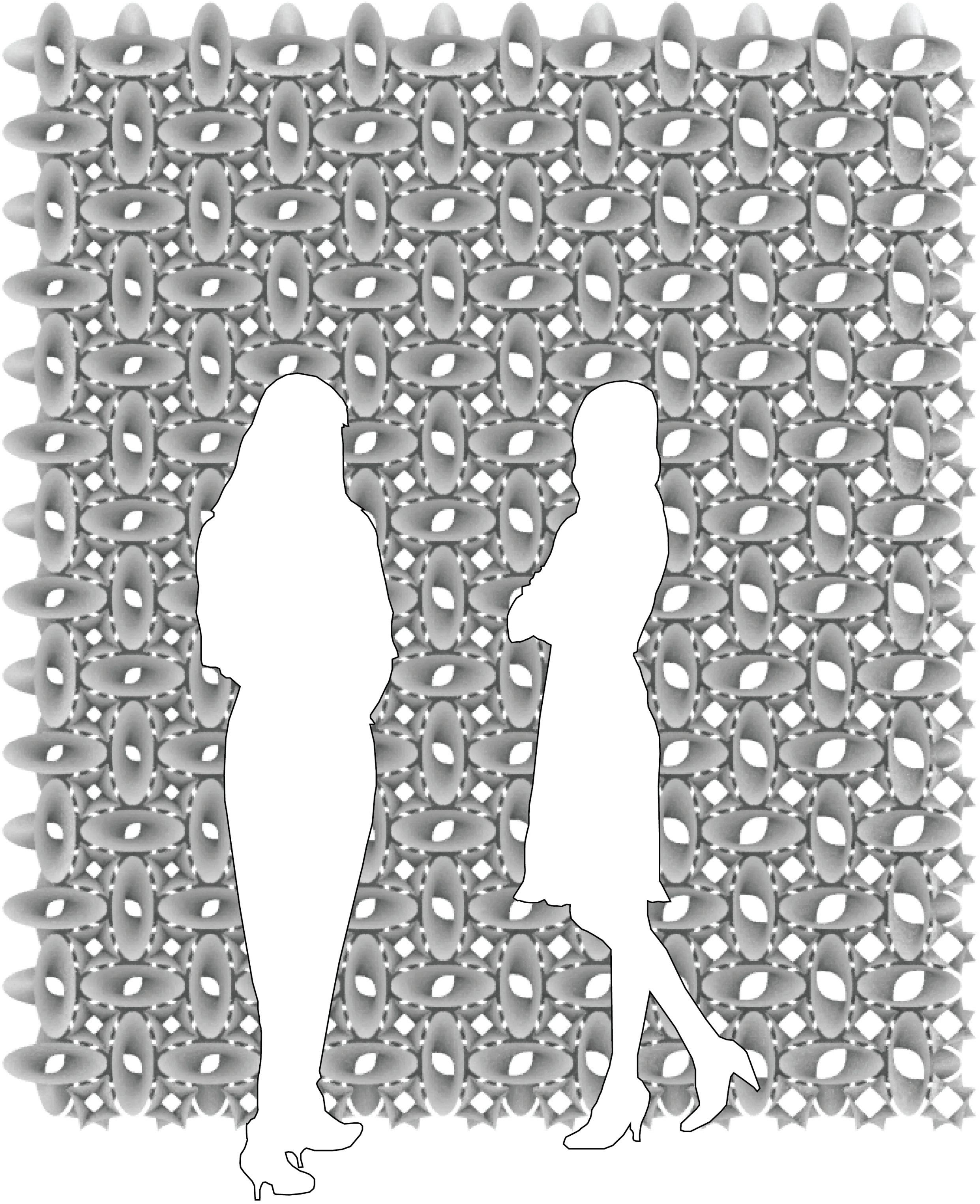


Figure 4.15. Variation in the size of apertures, Screen 2.

The variation in the size of apertures creates different levels of visual connectivity for the observers depending on their position and eye level.

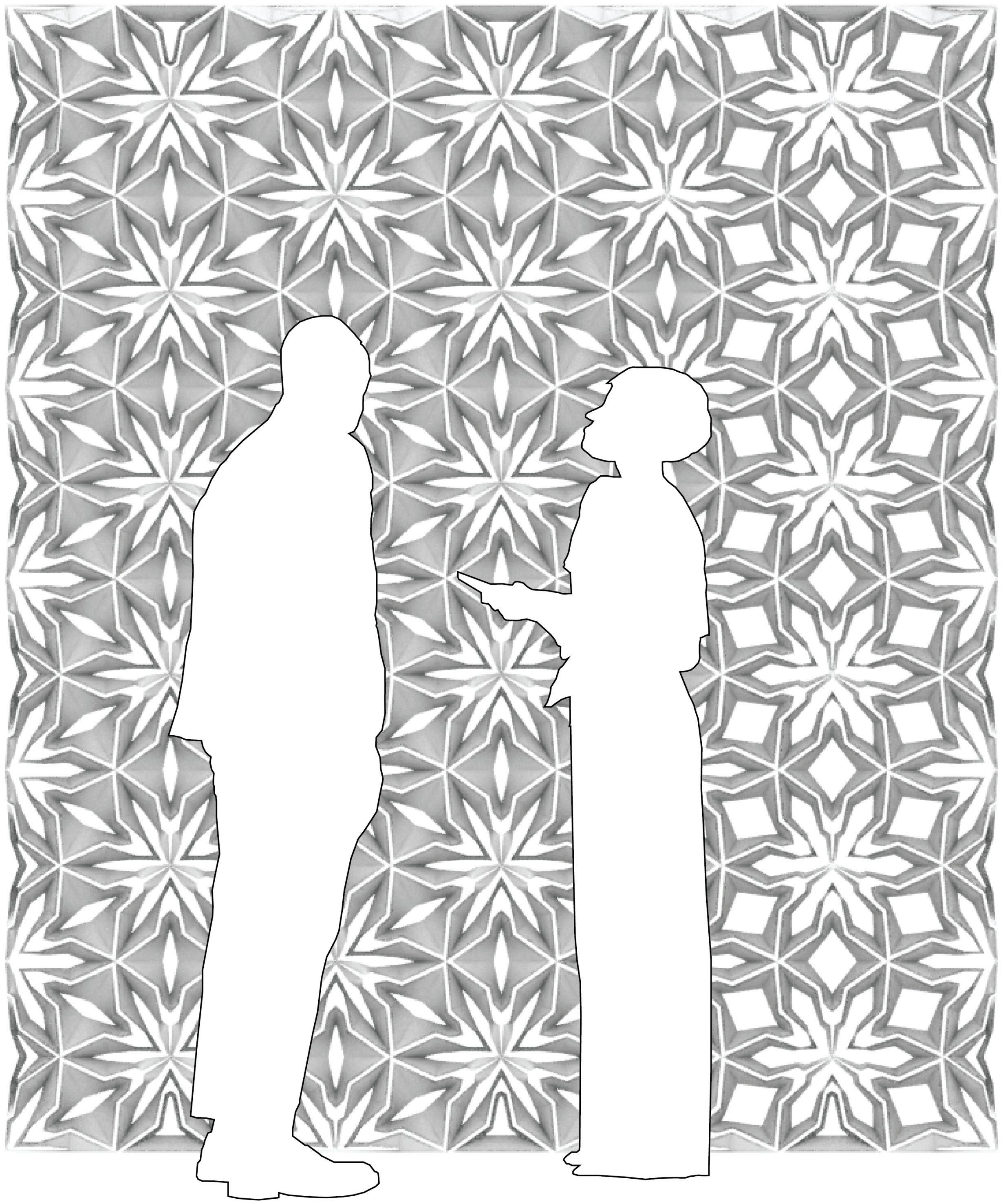


Figure 4.16. Variation in the size of apertures, Screen 1.

4.1.2. Observer's Viewing Angle and Depth of the screen

The variation in the aperture's size is only one attribute of form that affects the observer's visual continuity. In addition to this parameter, this design allows a decent range of flexibility for designers to customize the depth of the bricks in different parts of the wall. The depth of each brick is determined based on the observer's viewing angle in relation to the screen. The deeper the pieces are on the screen, the more it limits the observer's field of view. Also, deeper bricks allow less light to penetrate the space through the light screen (Figure 4.17).

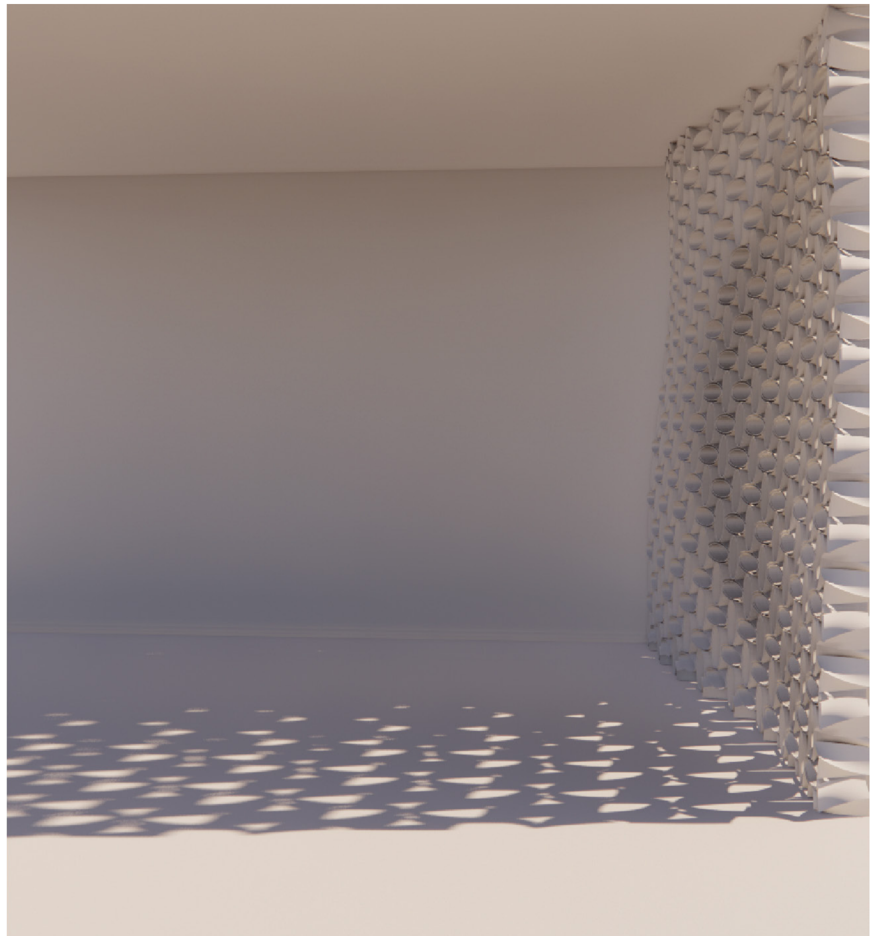


Figure 4.17. The light pattern resulted from the variation in the bricks' depth.

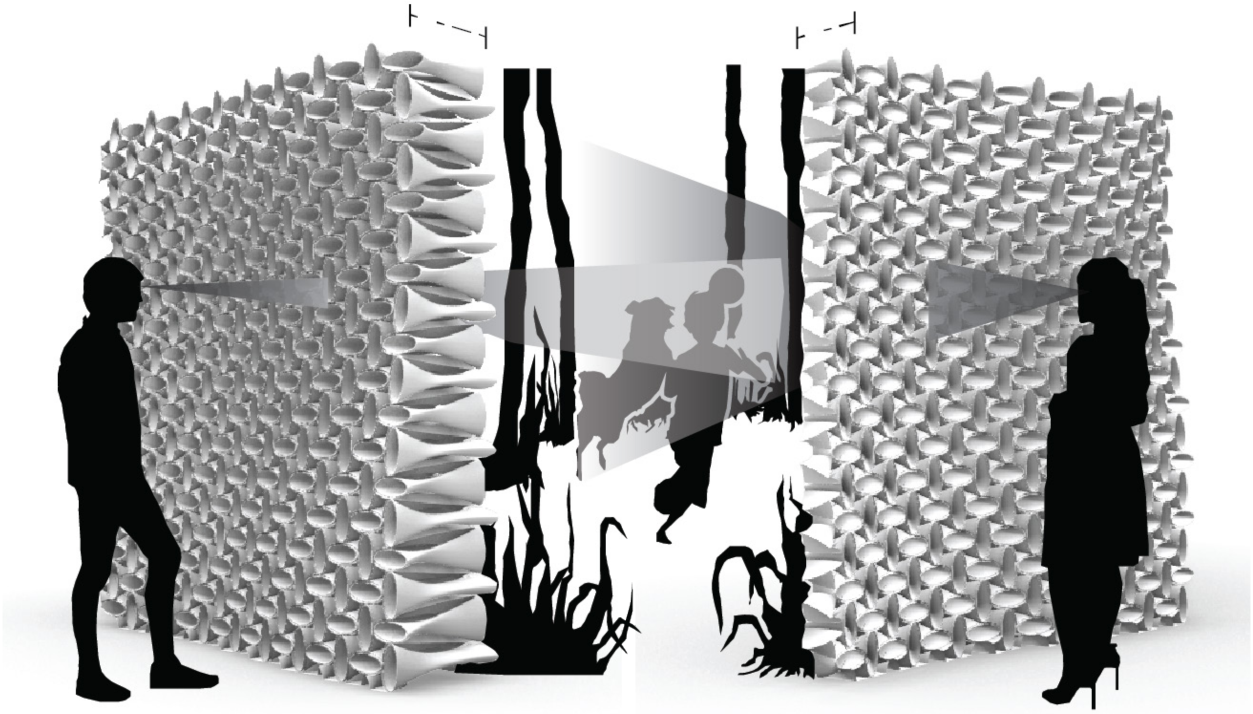


Figure 4.18. Top. The relationship between the depth of the screen and the level of visual connectivity. •The deeper the pieces are, the more it limits the observer's view. In the top right diagram, the observer's field of view is wider compared to the observer in the top left diagram due to the depth of each screen.

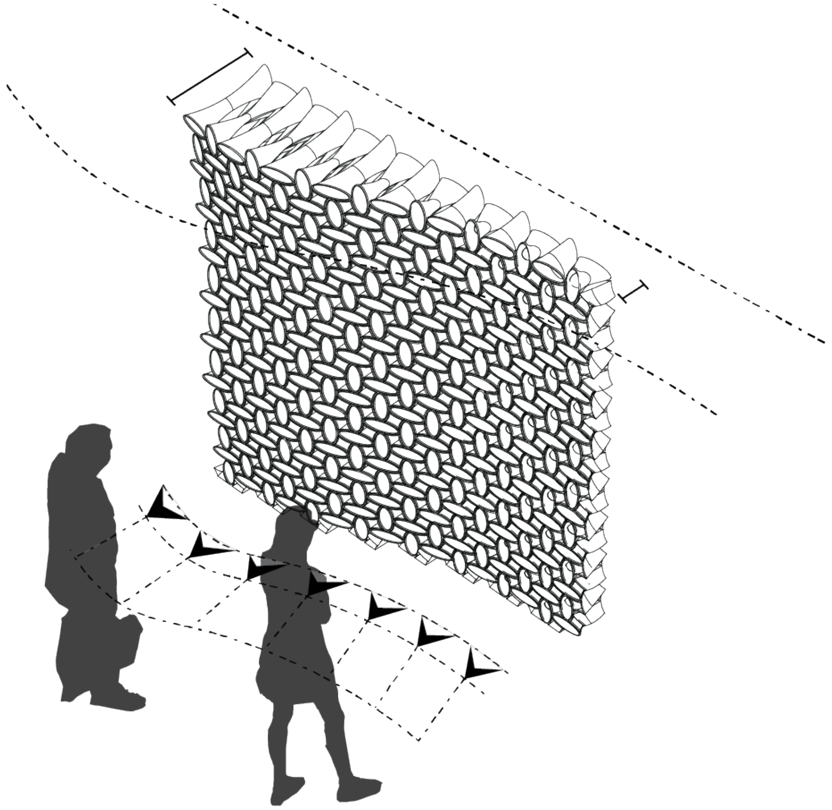
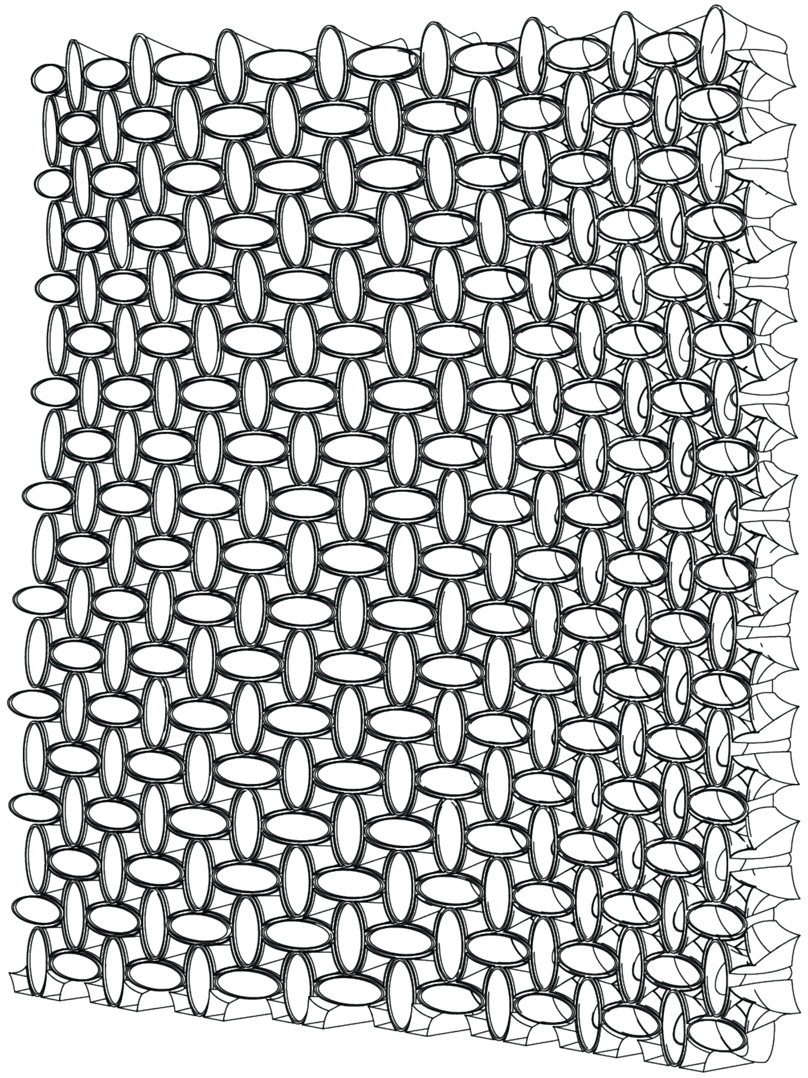
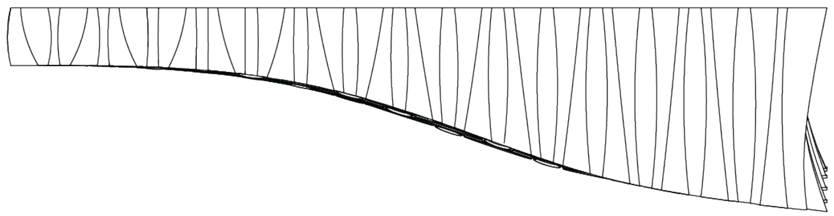
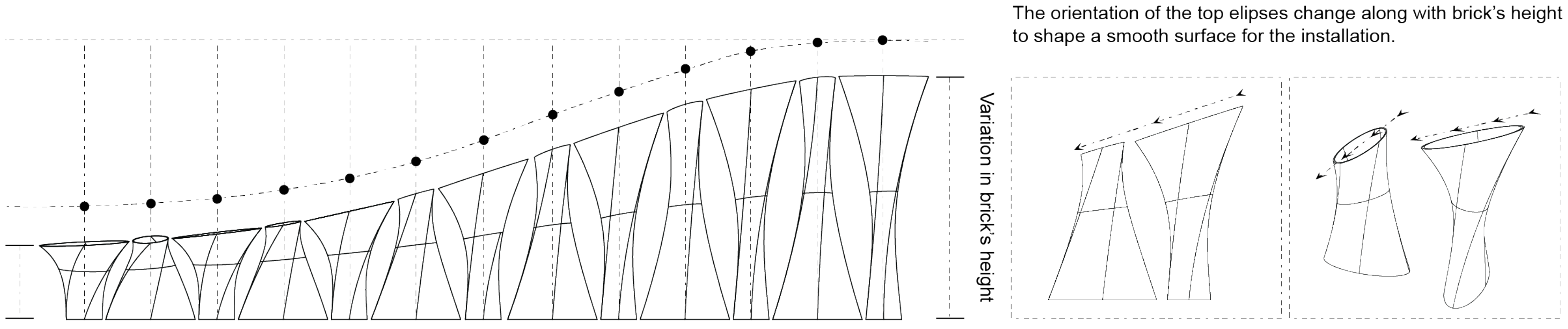


Figure 4.19. Bottom. Variation in the depth of the screen 2.







The orientation of the top elipses change along with brick's height to shape a smooth surface for the installation.

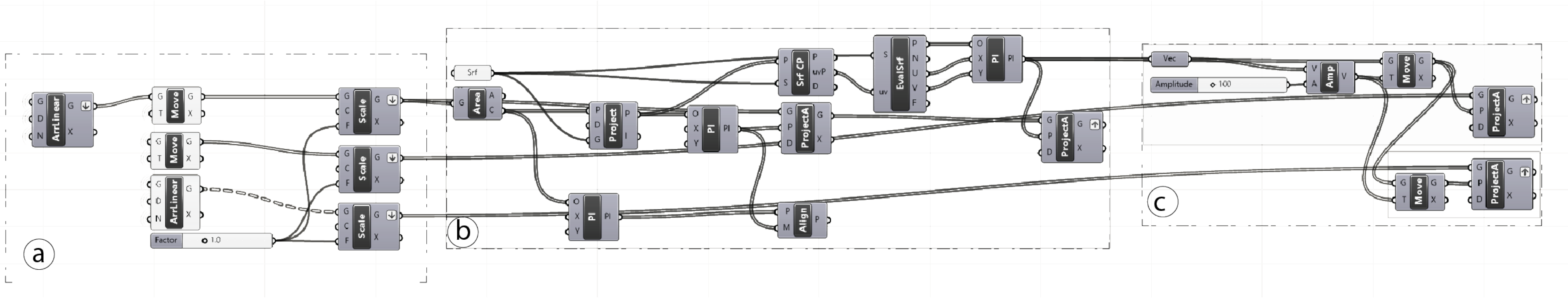


Figure 4.20. Top-Left. Screen 2. Perspective view.

Figure 4.21. Bottom-Left. Screen 2. Top view.

- In the design of screen 2, the depth of each piece can be controlled to achieve the required level of visual connection between spaces. In this diagram, the depth of different pieces can change compatible with the other pieces and the shape of the wall. This results in a smooth transition between the bricks in the wall.

The grasshopper script used for designing this screen contains four different sections:

a. In the first stage, the created geometries are scaled to be compatible with different walls' dimensions.

b. The required amount of wall all over the wall is determined through a form that can be formed by the designer. This strategy helps the designer to create a smooth transition all over the wall.

c. The other side of the wall can be flat or again, follow the shape of the first allocated surface. This script shows the second alternative where the two sides of the screen follow the form of one surface.

Figure 4.22. Left. The grasshopper script for creating variation in the depth of screen 2.

4.1.3. Orientation of the screen and the observer

Other than controlling the depth and aperture size of the pieces, it is possible to customize the orientation of the screens in relation to the space and the viewer. As illustrated in figure 4.19 the bricks can be designed and assembled into curved, zigzag, or L-shaped walls. This factor can contribute to limiting or improving one's visual continuity through the wall, depending on the orientation of the viewer. Changing the geometry of the wall alters the angle between the observer's line of sight and the screen and results in different levels of visual connectivity between spaces for the viewer. Therefore, the observer's movement path in the space determines the screen's orientation. This direction can be constant, or change along the wall, following the viewer's orientation in the space.

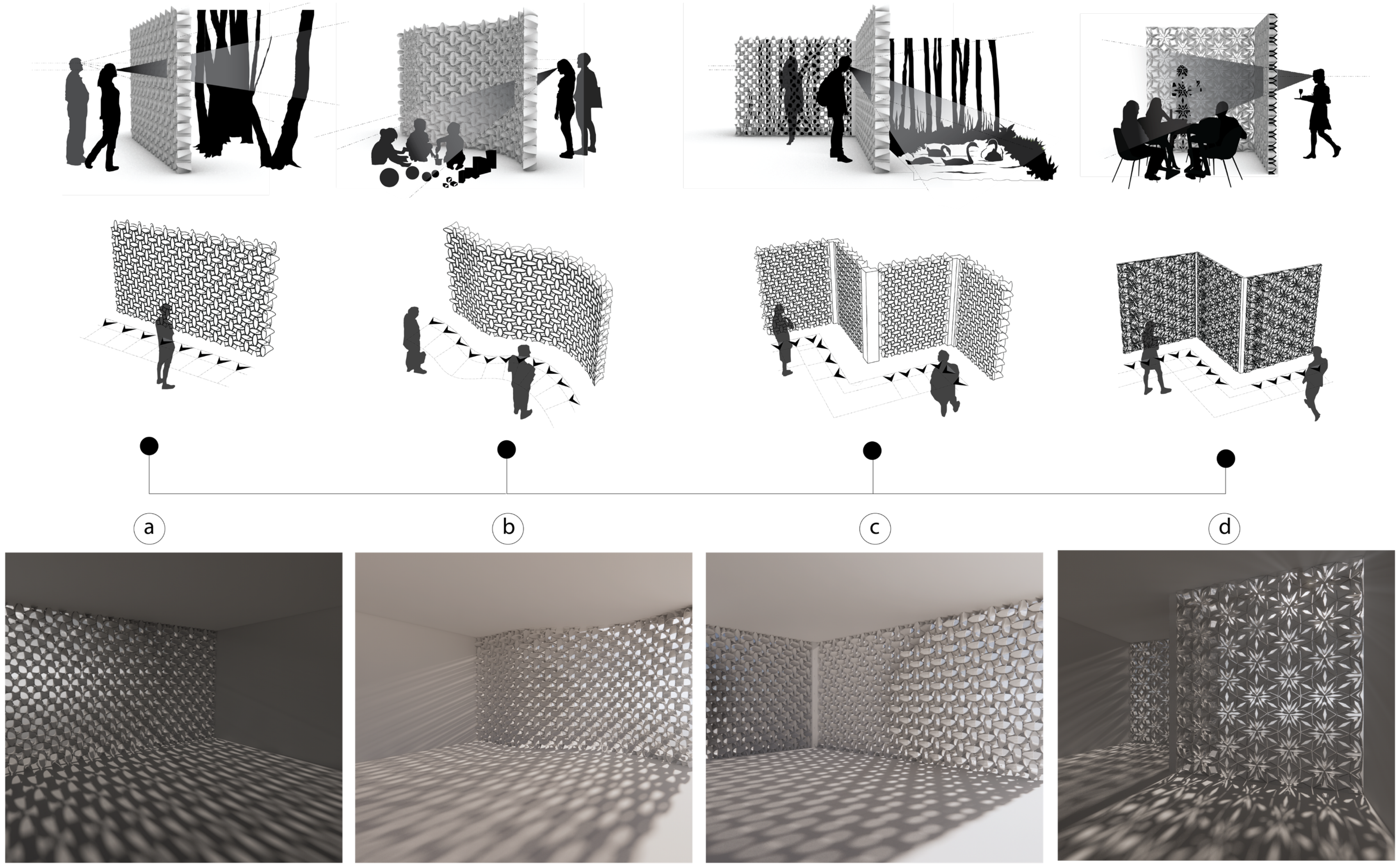


Figure 4.23. Investigating the level of visual connectivity and the resulting light pattern for the light screen in different orientations.

- Diagram (a) The orientation considered for this light screen provides the required visual connectivity for the observers to enjoy the nature that exists on the other side of the wall.
- Diagram (b) Along a curved shape, this screen allows the guardians to watch children playing in a circled shape room and at the same time, provides a sense of privacy for children.
- Diagram (c) demonstrates an L-shaped screen that gives the observer two different views in each direction, one to a small pond and the other to the birch tree forest.
- Line Diagram (b), diagram (d) limits the individuals' visual exposure while providing sufficient visual accessibility for the waitresses to the tables from two directions.

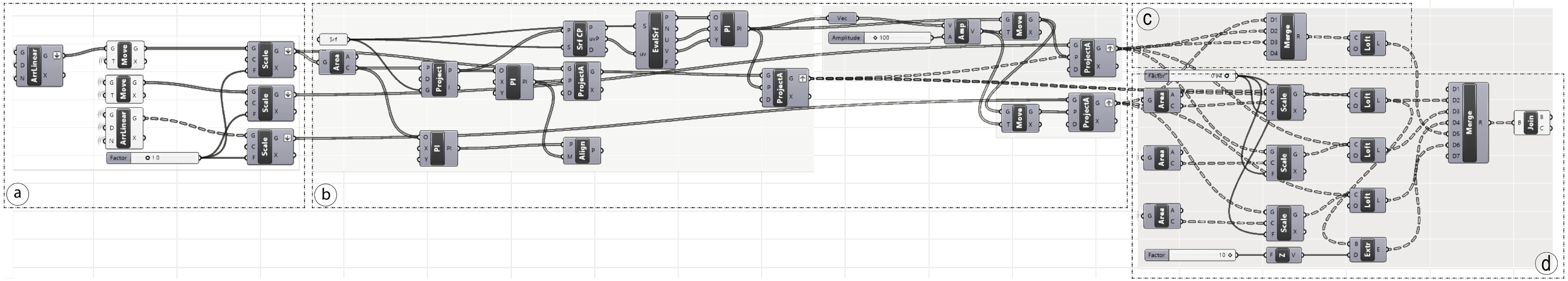
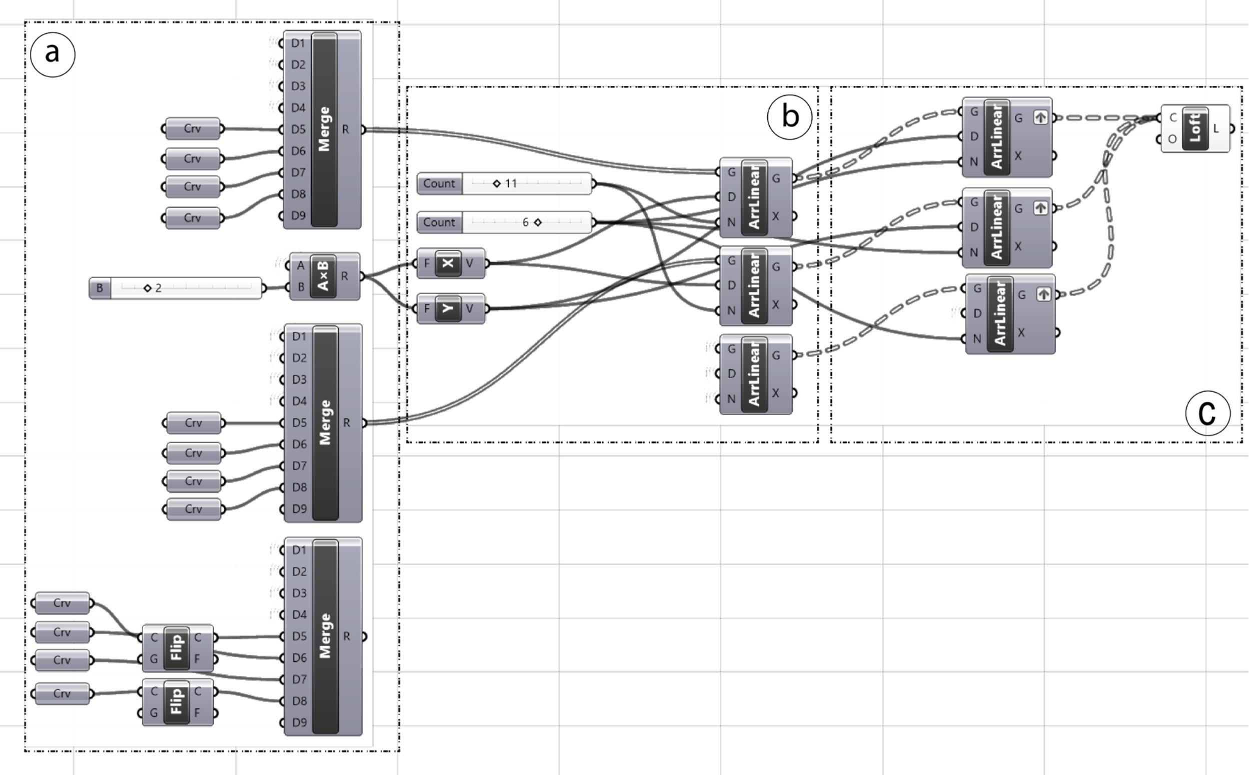


Figure 4.24. Top. The grasshopper script for creating different orientations for the light screen.

a. Adjusting the scale of the screen.
b. Defining the general form of the screen.
c. Lofting the created curves to produce the pieces.
d. Applying thickness to the created geometries.

Figure 4.25. Bottom. Grasshopper definition used to create a screen along a flat surface.

a. Defining a reference geometry: Four ellipses and one middle piece.
b. Creating a pattern based on the reference geometry: Arraying the reference geometry along X and Y axis.
c. Lofting the created curves to produce the pieces.



4.2. Computational Evaluation

This section provides the results achieved from the computational analysis on the screens with different orientations, depths, and aperture sizes. The effect of these parameters' variation on visual connectivity is calculated using vector raytracing and is displayed in figures 4.27, 4.28, 4.29, and 4.30 where different alternatives are evaluated.

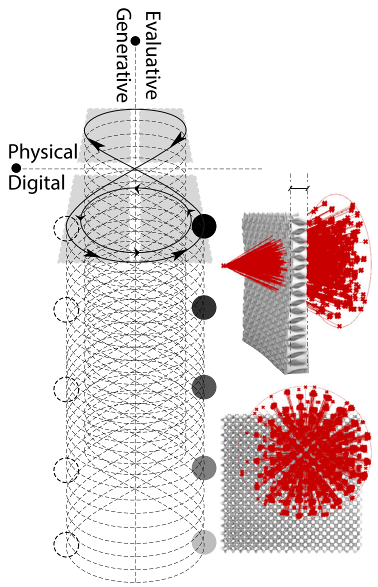
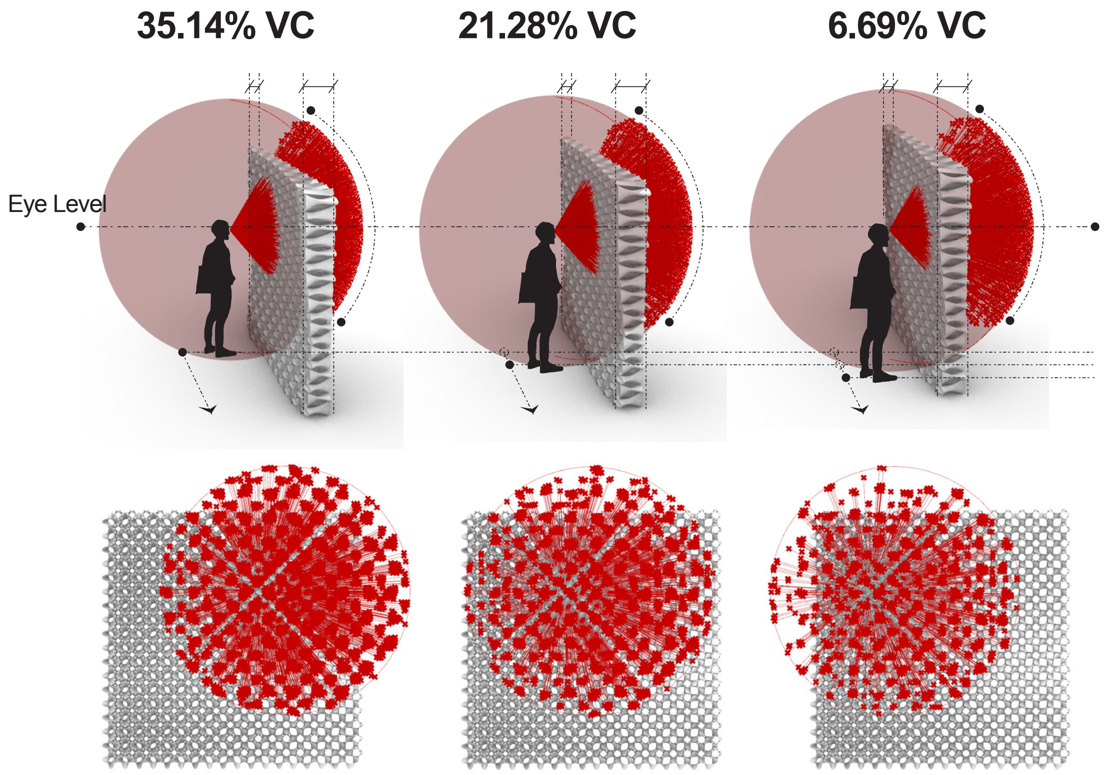


Figure 4.26. Thesis framework: Computational Evaluation.

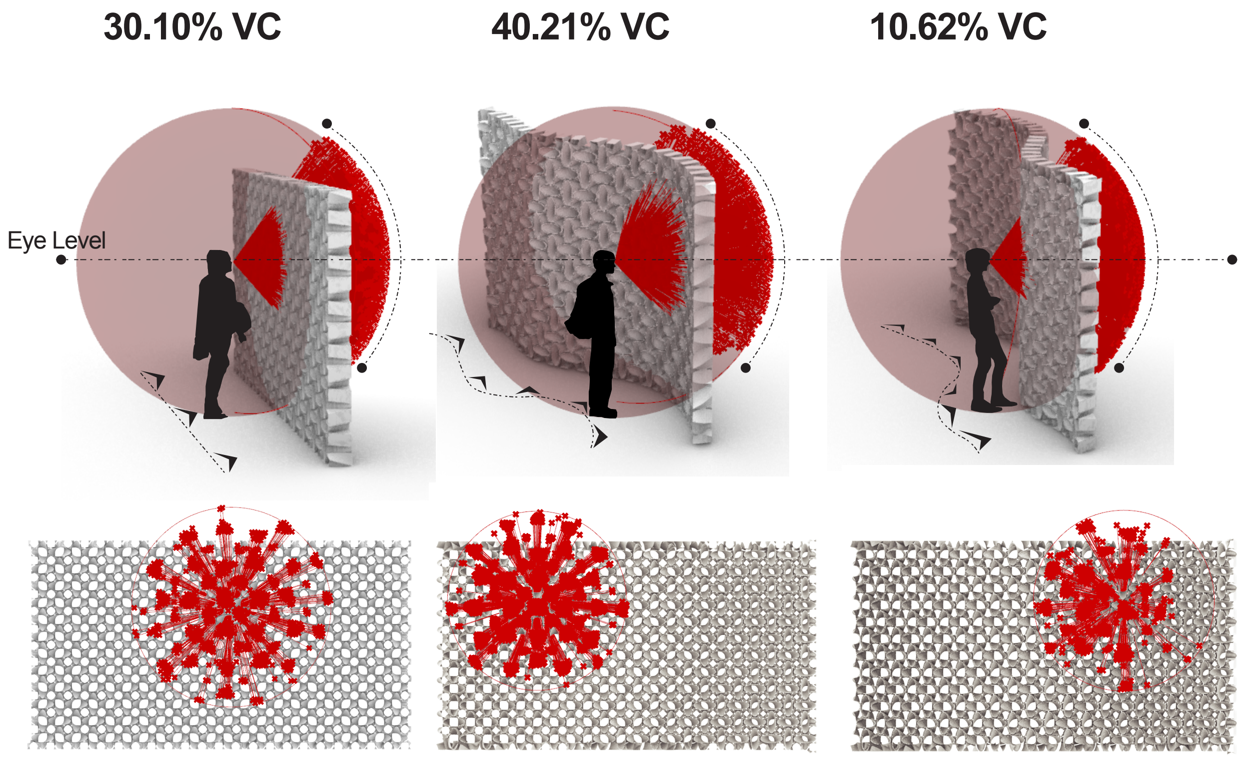
4.2.1. Variation in the Screen's Depth



- As the observer moves toward the deeper part of the screen, the number of traces that pass through the screen becomes less, and consequently, the viewer's visual connectivity would be more limited.

Figure 4.27. Left. Evaluating the impact of screen's depth on visual connectivity.

4.2.2. Variation in the Screen's Orientation

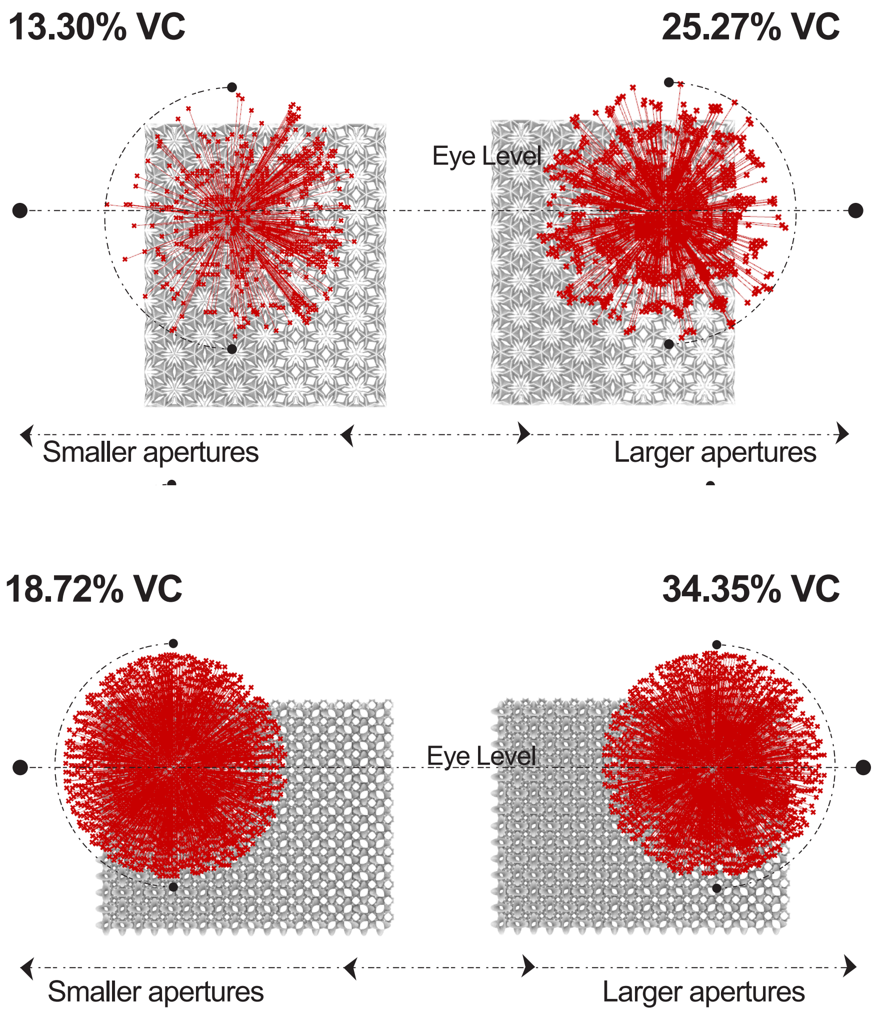


- Three different conditions are considered here to analyze the impact of the screen's orientation on visual connectivity. The middle diagram allows for the most visual connection between spaces as the number of traces passing through the screen from the observer's eyes is the most. While, when the screen is curved out in relation to the viewer's position, visual connectivitiy's percentage drops down to the minimum. However, the amount of curvature allocated to the shape of the screen (either curved in or out) can influence this percentage.

Figure 4.28. Right. Evaluating the impact of screen's orientation on visual connectivity.

4.2.3. Variation in the Size of Apertures

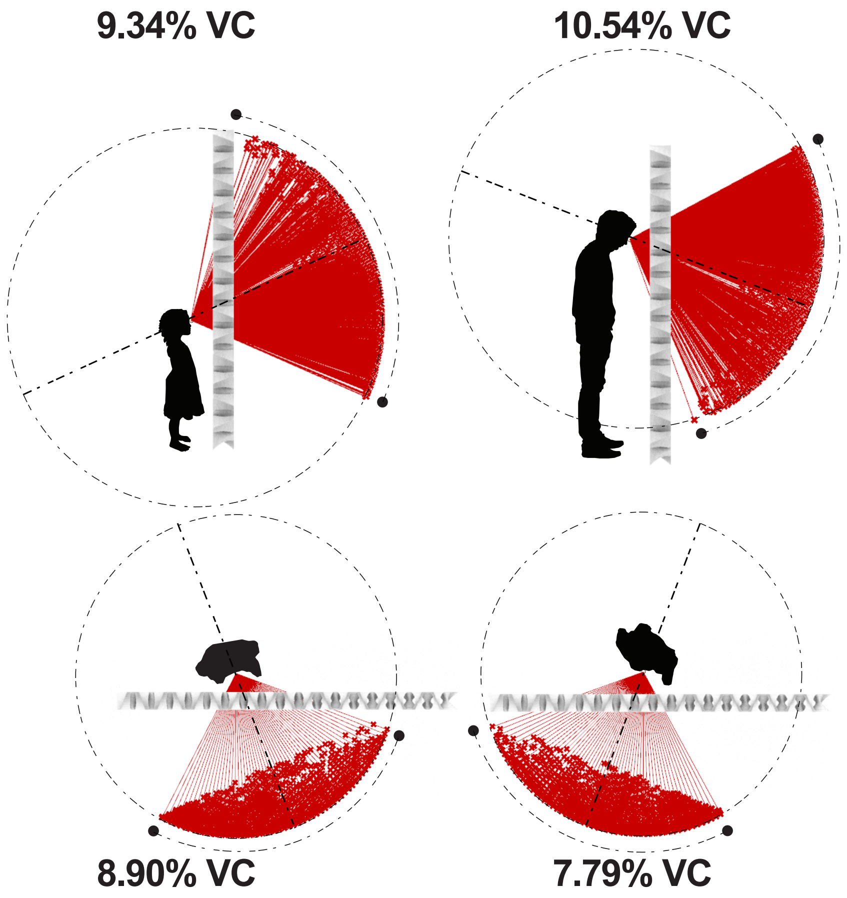
Figure 4.29. Evaluating the impact of apertures' size on visual connectivity.



- The larger the apertures are, the more visual connectivity between spaces is created for the observer. Figure 4.16 illustrates the resulting visual connectivity through both screens 1 and 2.

4.2.4. Variation in the Observer's Orientation

Figure 4.30. Evaluating the impact of observer's orientation on visual connectivity.

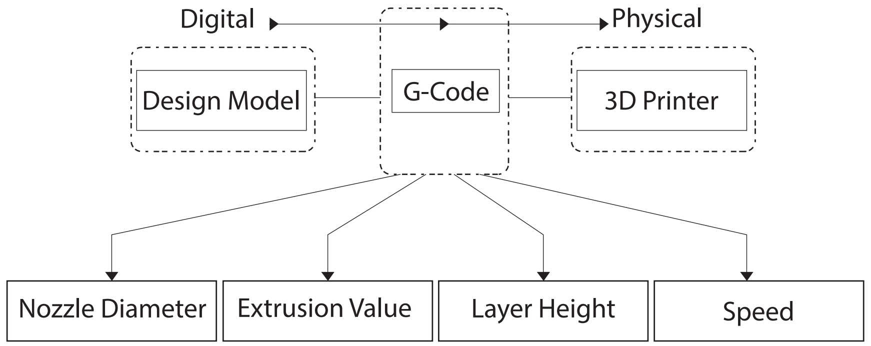


- Based on this analysis, it can be identified that when the observer's field of view is at a 0-degree angle relative to the screen, (The view is perpendicular to the screen) the visual connectivity is more, compared to when this angle changes. In diagram 4.28, the resulting percentage for visual connectivity is 30.10% when the viewing angle is 0. When this angle changes horizontally to 20 and 25 degrees on the same screen (Diagram 4.30- Bottom), the visual connectivity reduces to 8.90% and 7.79%, respectively. This also happens when the viewing angle changes in the vertical axis, reducing the visual connection to 9.34% and 10.54% (Diagram 4.30- Top). While this is generally true for most designs given the wall depth, the viewing angle can be designed so that some of the observers' viewing angles have higher visual connectivity in a specific angle. This is helpful when the designer is evaluating the right location and height level for the screen in the building or understanding its relationship with the movement corridors. Lower sectional depth in the design of the screens can also be helpful to improve the visual connection from different angles.

4.3. Fabrication and Prototyping

The process of physical prototyping started at the early stages of design to examine the possibility of printing the pieces and most importantly, to evaluate the influential parameters in the design. Therefore, in this thesis design and fabrication have constantly informed one another.

The fabrication process of the two screens is established based on the specific qualities of 3D printing clay, as the main construction material in this thesis. Depending on the proposed designs for each screen, 3D printing factors including the nozzle diameter, layers' height, printing speed, and clay extrusion change as well. These attributes can be regulated to achieve the required geometries in the design of the bricks. (Diagram of the factors will be added.)



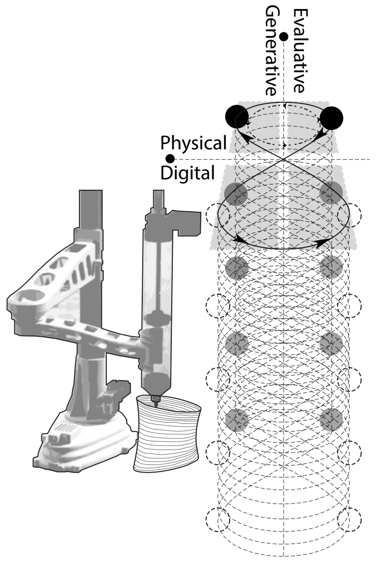
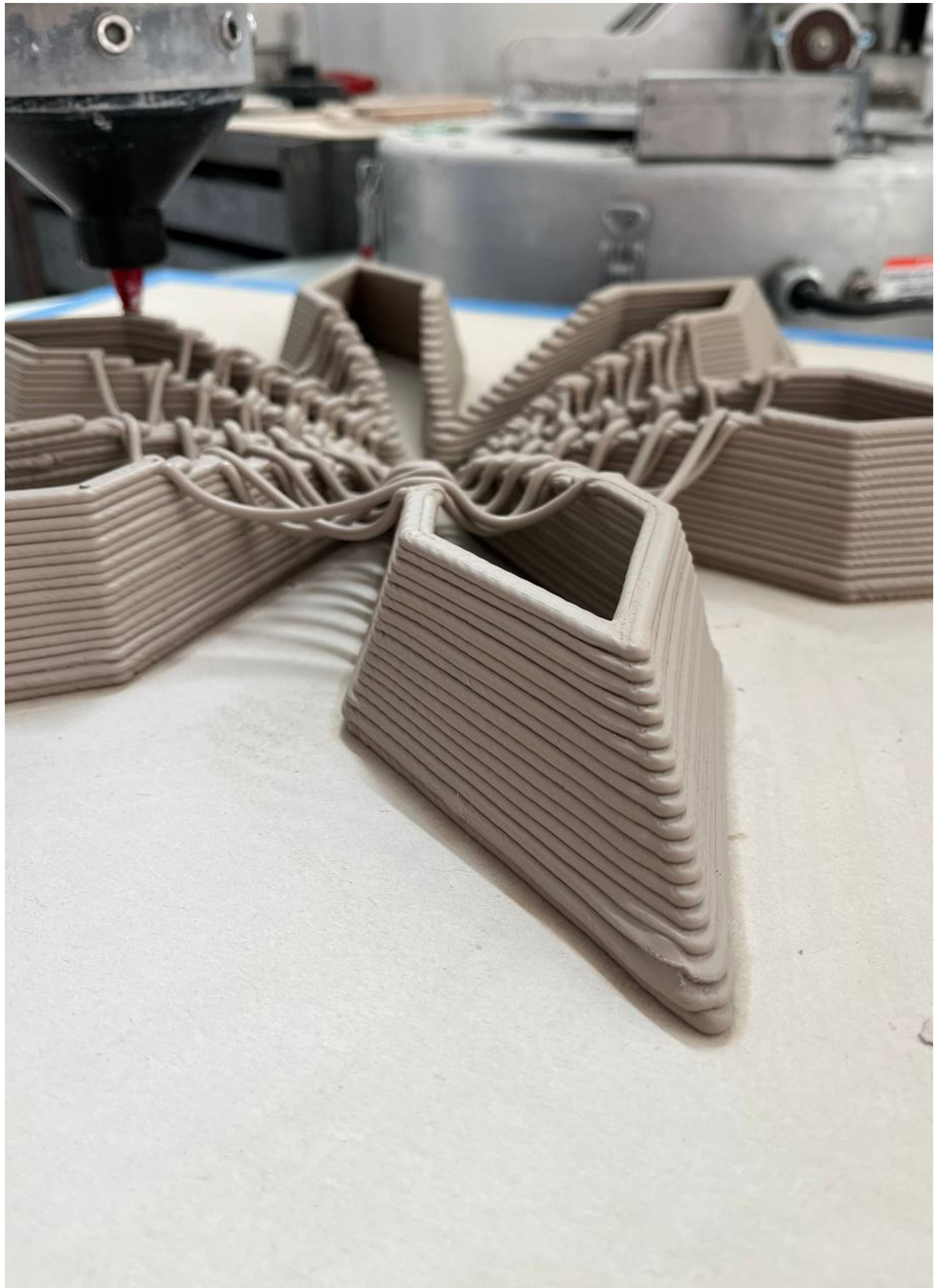


Figure 4.31. Top- Thesis framework: 3D printing physical prototypes and Evaluating the pieces by observing the printing process (physical) and changing the 3D printer's factors (digital).

Figure 4.32. Left. The 3D printing factors controllable through the Slicer.

Figure 4.33. Right. One of the initial prototypes of screen 1.



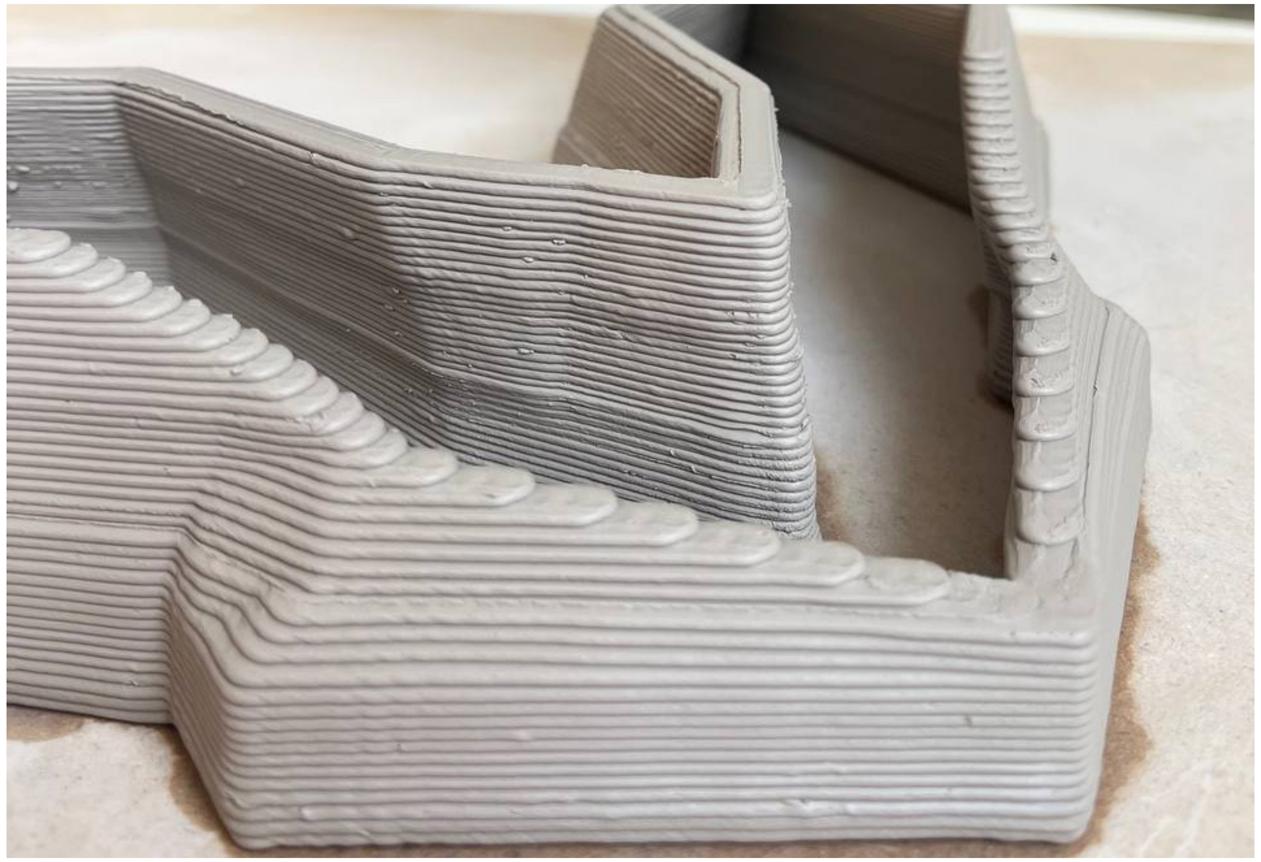
4.3.1. Screen 1

The proposed designs for both screens 1 and 2 offer specific geometrical qualities that can be created by manipulating material attributes and benefiting from the 3D printer's potential. In the design of screen 1, the primary pieces contain sloping faces that start from the corners of the hexagon and gradually go down toward the center (Figure 4.35). The steps are created where the 3D printer stops printing one of the layers and turns to extrude the inner layer.

Figure 4.34. Left. The slope starts from the center of the brick.

Figure 4.35. Right. Sloped edges in the design of the primary pieces.

Figure 4.36. Next page. Sloped edges are visible in the middle of each crystal, creating a dynamic surface for the assembly. This quality emphasizes the center and attracts the observer's attention to this part.

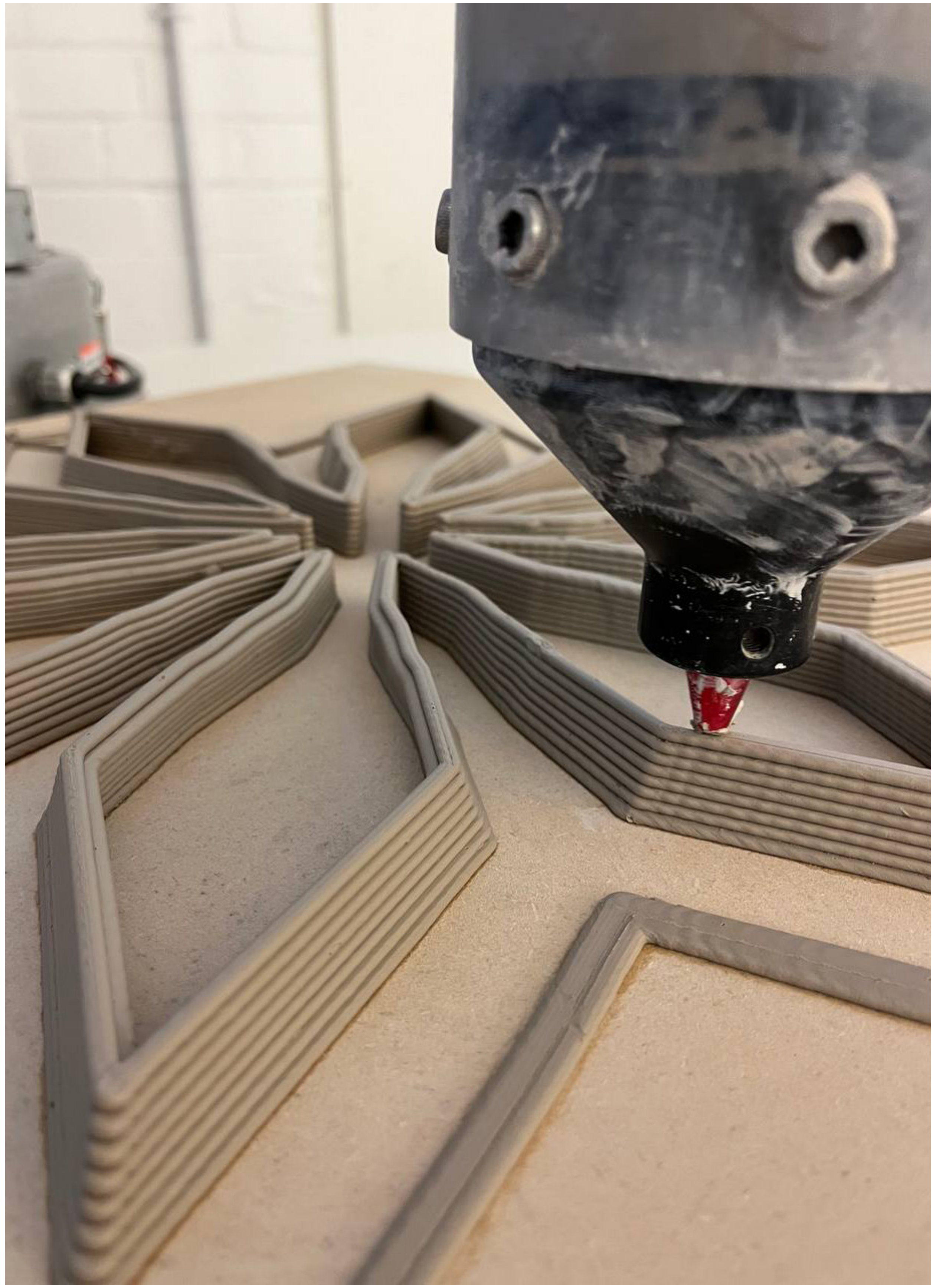


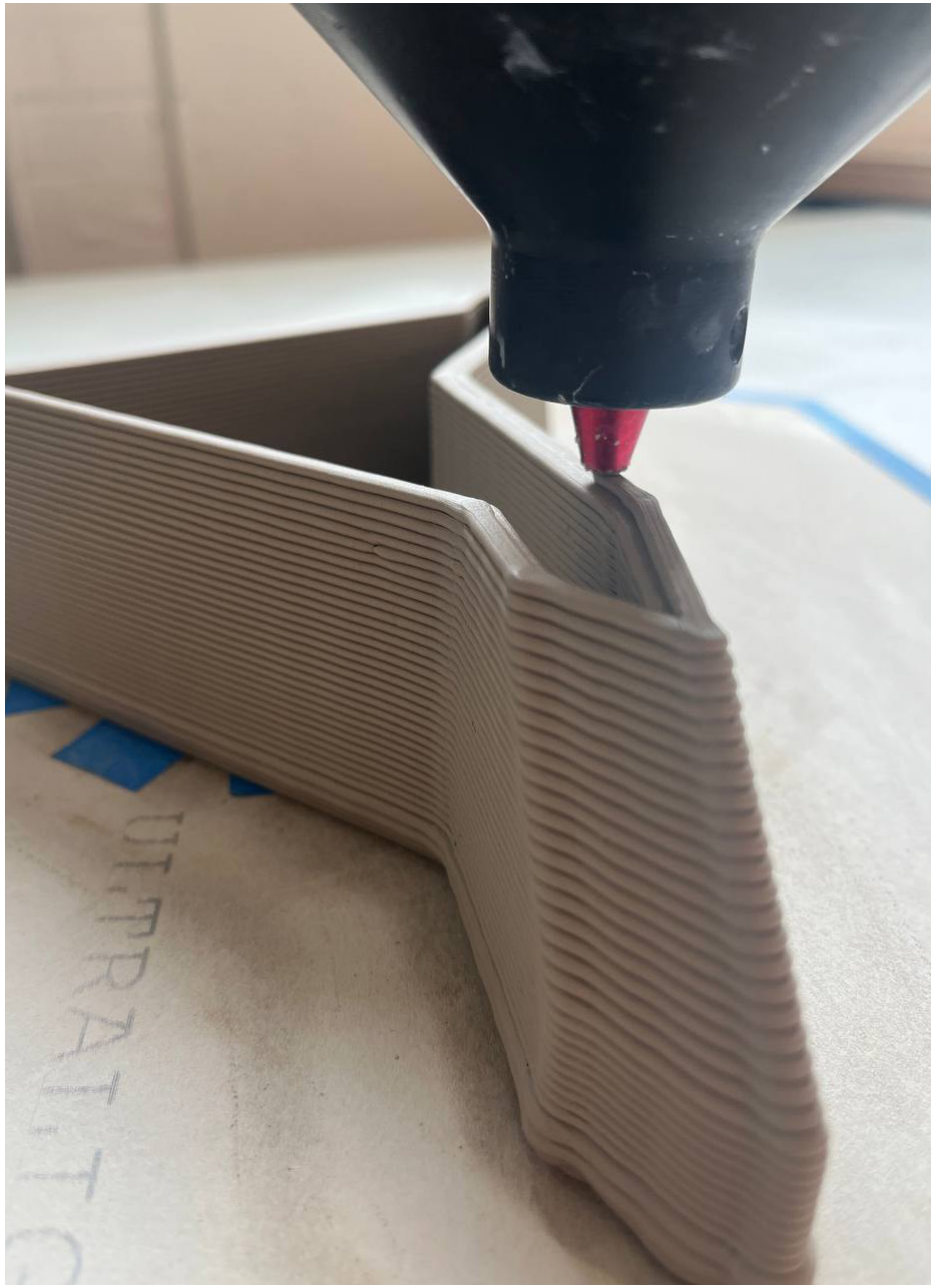
The sloped surfaces create height differentiation on the screen's surface and provide a dynamic form along the wall (Figure 4.36).

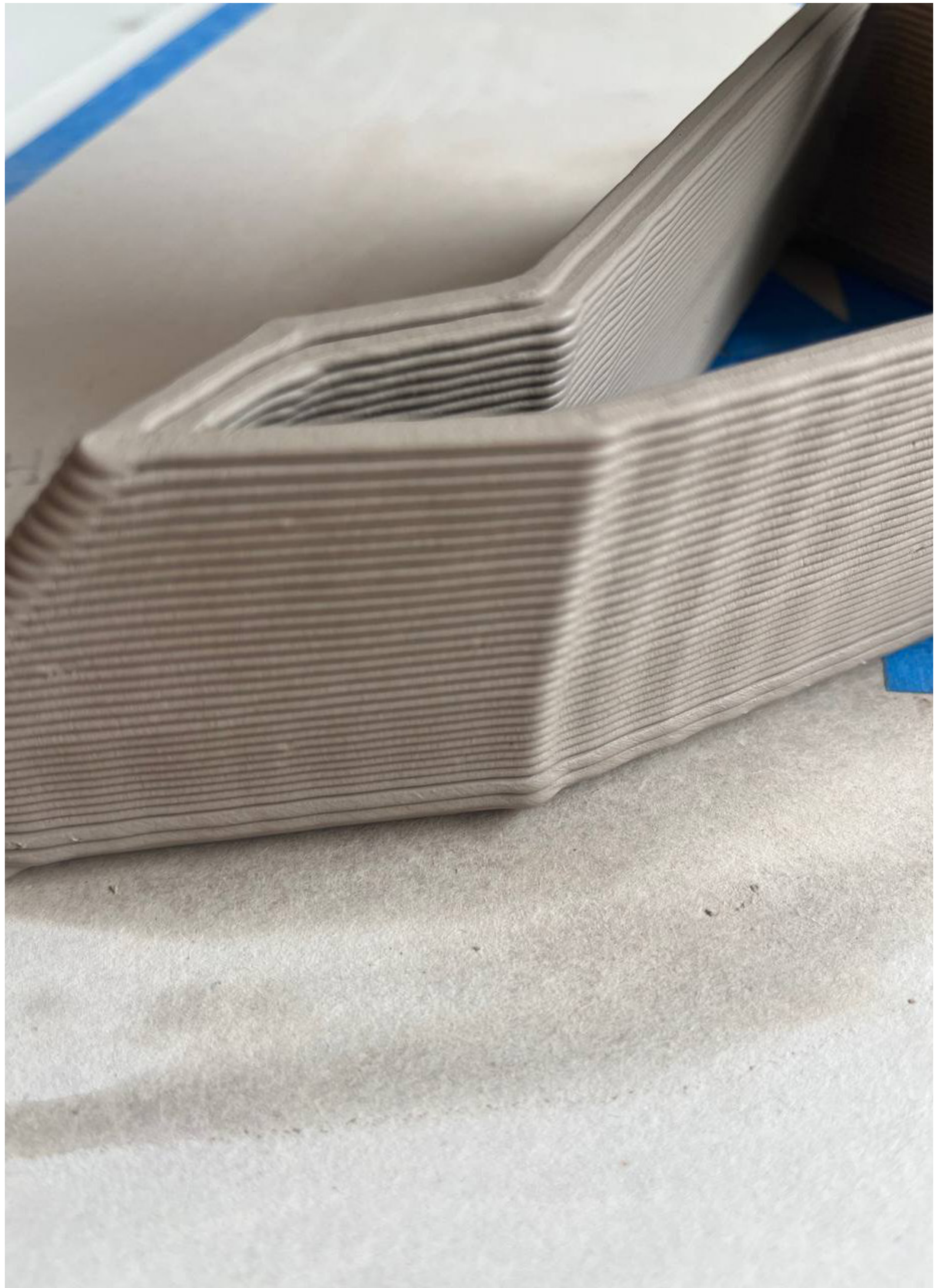
To be able to create this quality in pieces, a doubled-layer continuous tool path is defined for the machine; In other words, the printer prints two layers of clay at each step. The reason for this is to avoid the pieces from collapsing during the 3D printing process by extruding more clay and improving the strength of the surfaces (Figure 4.37 and 4.38).

Figure 4.37. Initial experiments for printing the double-layered geometry.

Figure 4.38. Next page. Double-layered geometry for printing the connector pieces.

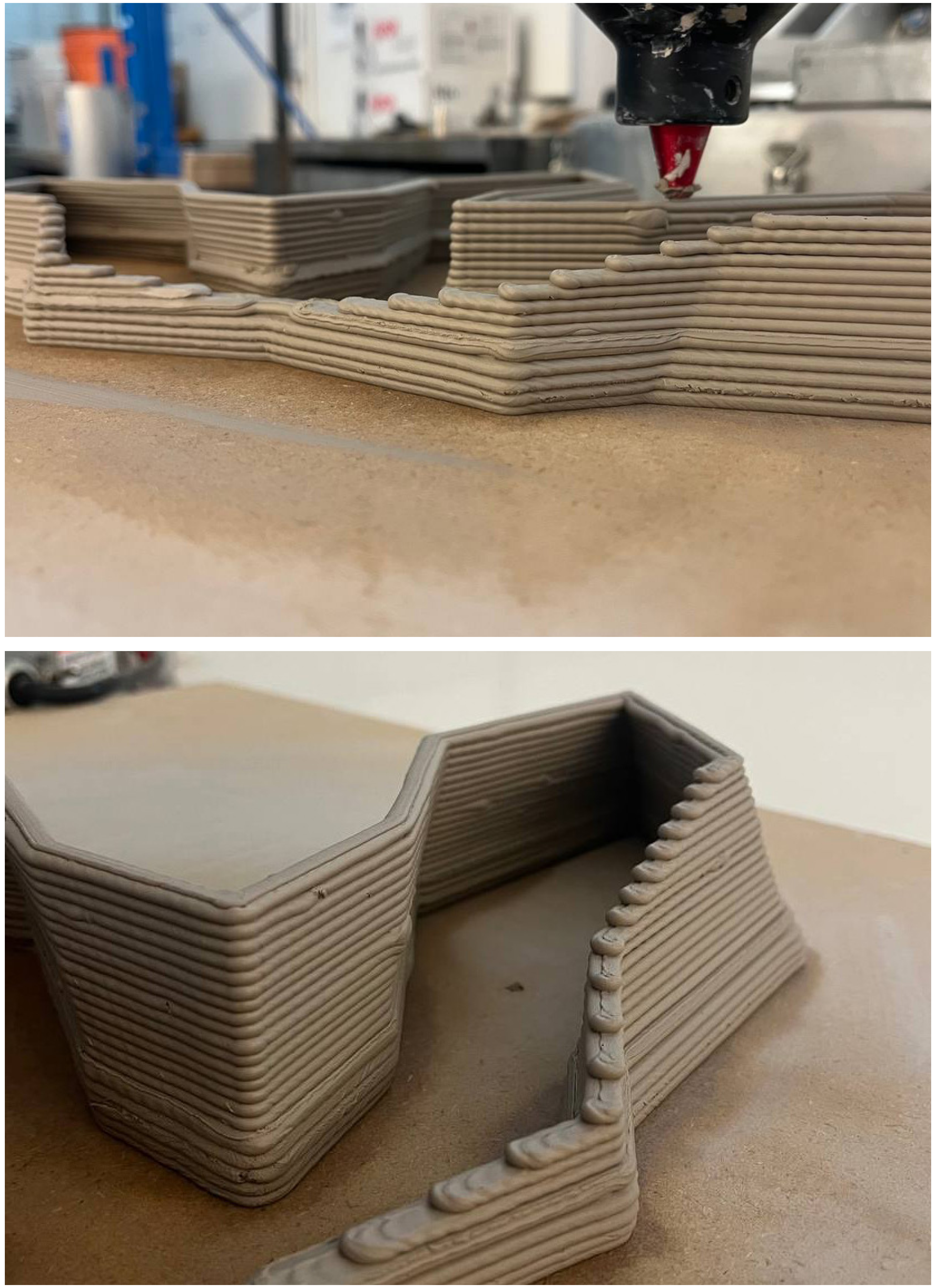






As the machine prints two parallel layers in a looped printing path, it leaves a trace where the nozzle needs to move up which creates an interesting quality that was not part of the initial design. Therefore, a new quality is added to the design of the bricks that is resulted from the specific qualities of the 3D printer and the material (Figure 4.39).

Figure 4.39. The geometry resulted from the 3D printer's trace when printing the sloped edges.



4.3.2. Screen 2

To be able to fabricate the twisted bricks for screen 2, another question needs to be answered. Printing a geometry that is twisted nearly 90 degrees is challenging as it creates a long cantilever on two sides of the brick. The gradual increase in the weight of the material in each layer without having any support from the bottom would end up in the pieces collapsing (Figure 4.43). To solve this issue, the ratio between the ellipse's radius one, radius two, and the height of each piece needs to be adjusted to ensure the material's weight distribution in the whole piece. Also helpful, is using the heat gun during the printing process to harden the bottom layers as the machine adds another layer of clay on top. In this way, the bottom layer is strong enough to hold more weight.

Figure 4.40. The twisted geometry of the bricks for screen 2.

Figure 4.41. Printing the primary pieces of screen 2.

Figure 4.42. The primary piece for screen 2.

Figure 4.43. The collapse of primary twisted pieces due to the material' weight.
The piece collapsed during the printing process due to the unbalanced weight distribution.

Figure 4.44. The twisted geometry of the bricks for screen 2.
The bottom part of the ellipses might need to be hardened, using the heat gun.

Figure 4.45. Left. The middle pieces for screen 2.

When assembling the primary pieces, two different shapes are created in between them. The faces of the first one are curved toward inside the brick and the second one, are curved toward outside.

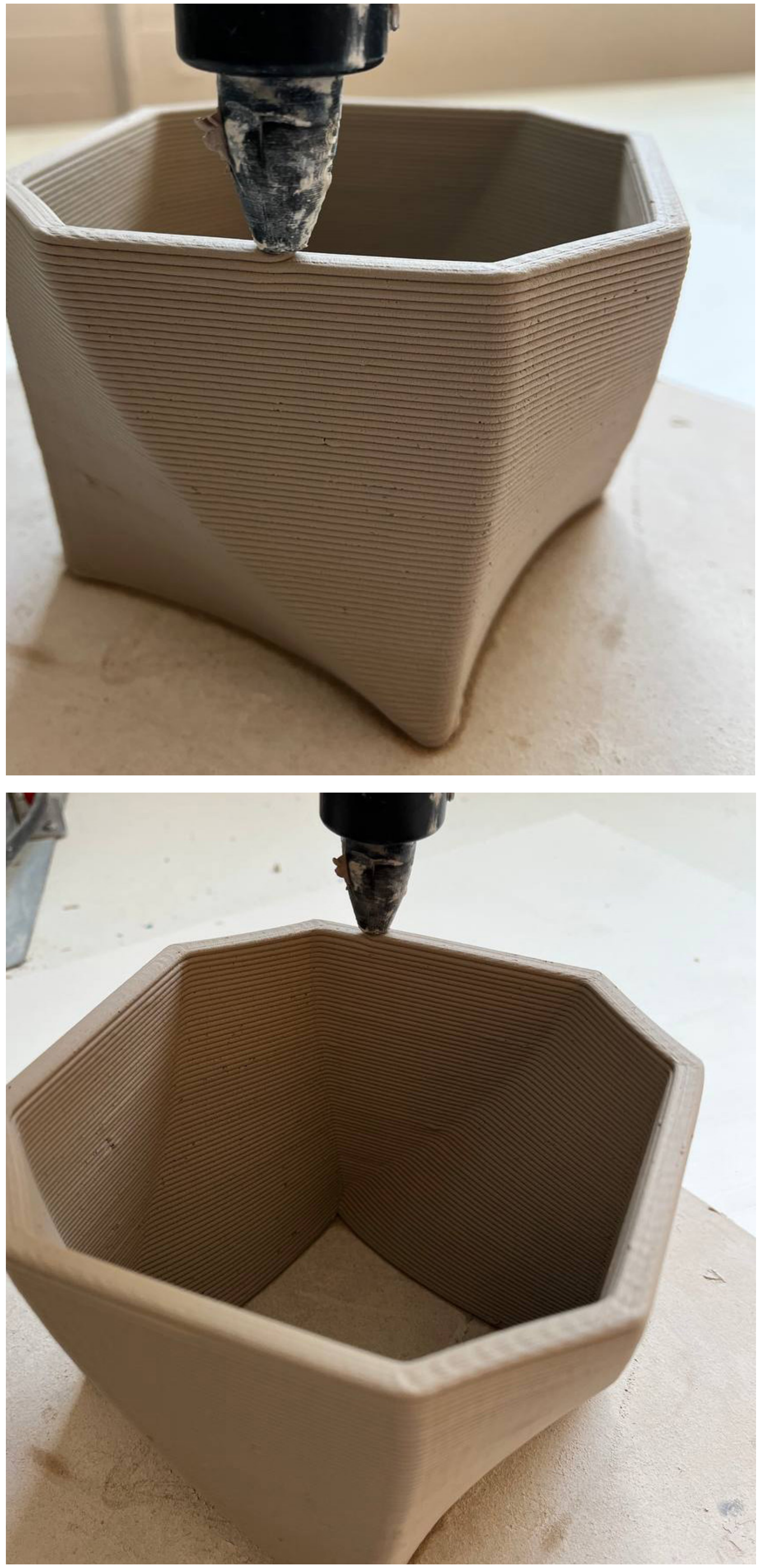


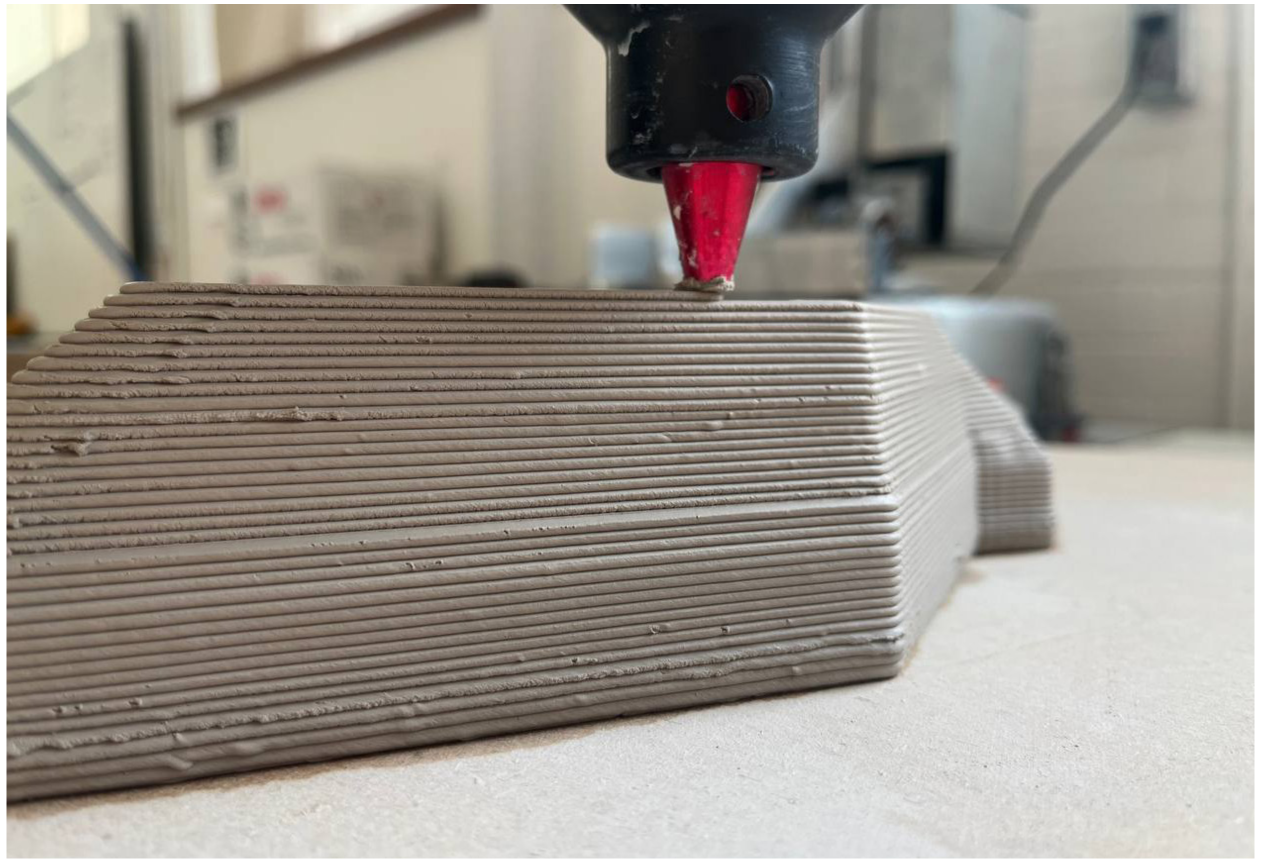
Figure 4.46. Right. The second middle brick with faces curved outward.

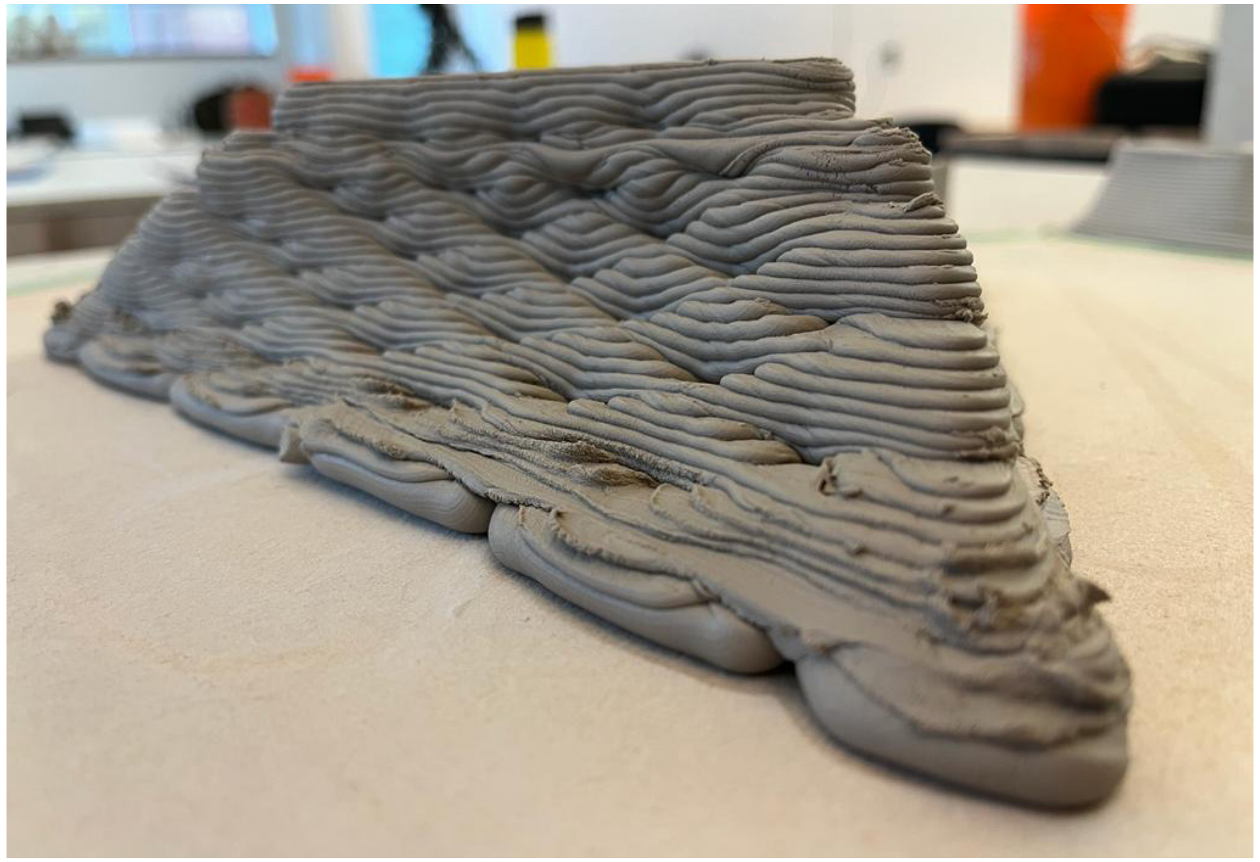
4.3.3. Nozzle Diameter

The size of the nozzle used for the 3D printer is an important factor that affects the way the pieces are modeled as well as the quality of the print. Depending on the geometry, size of the pieces, amount of time and clay, the size of the nozzle can change. In this thesis, two different nozzles are used: a five-millimeter and a three-millimeter nozzle. To print high-quality pieces for screen 1, it is important to adjust the space between the two layers based on the nozzle diameter. If the in-between space is less than the extruded layer thickness x 2, the printer won't be able to distinguish the layers from one another. As the result, the machine jumps from one layer to another on an irregular basis and creates errors in the model. Another possibility is that if the space is not enough, clay can move with the nozzle and result in an inconsistent layer (Figure 4.47). Therefore, based on the size of the nozzle, this space changes as well. To decrease the thickness of the layer and minimize the time of printing, a three-millimeter nozzle is used to print the doubled-layer pieces. This means that the machine prints a 6mm layer at each step, almost as thick as a single layer, printed with the five-millimeter nozzle.

Figure 4.47. Clay moves along the printing path with the nozzle on pieces as the space between layers is less than what is needed.

Figure 4.48. Next page- The primary pieces with different heights.





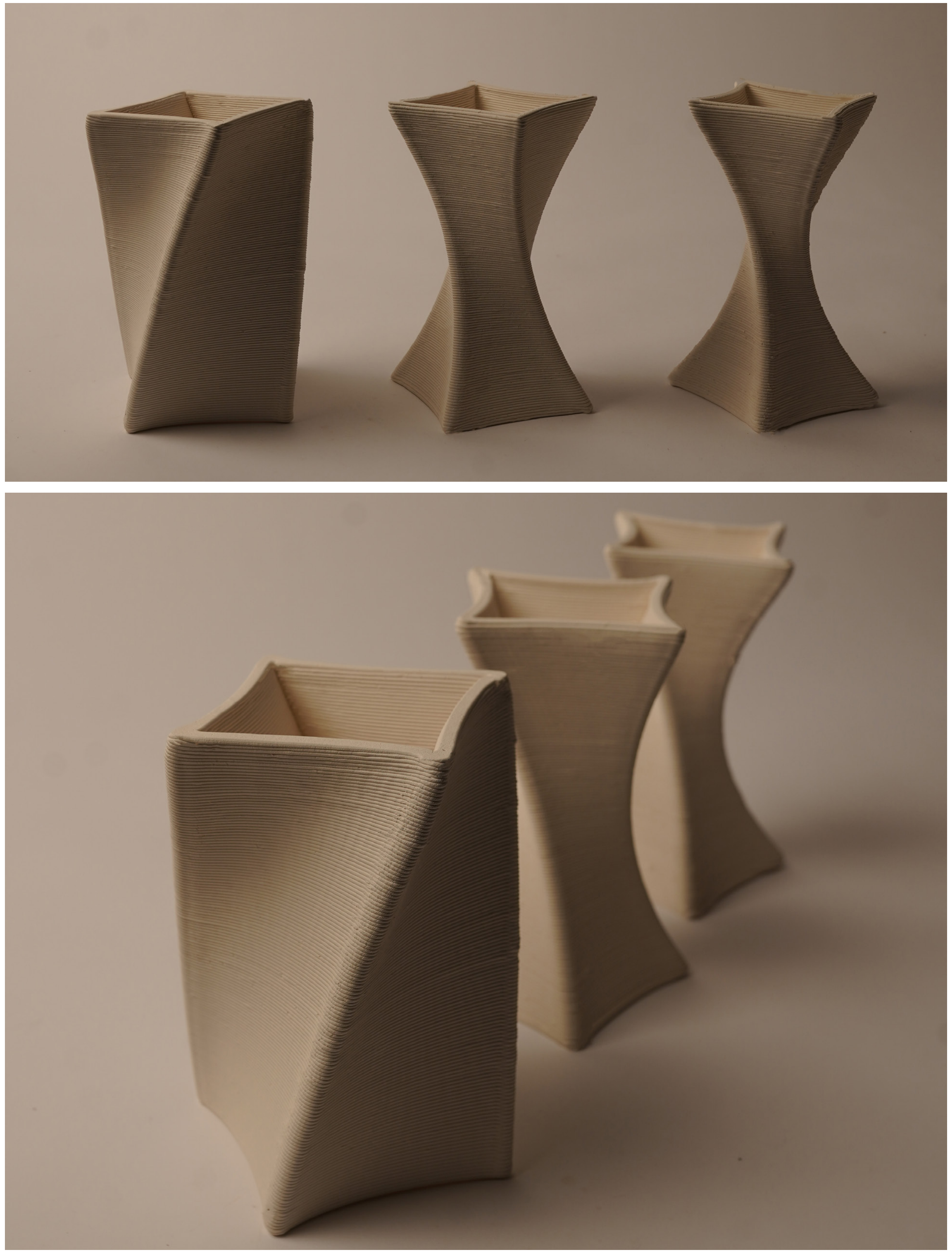


Figure 4.49. The middle pieces for screen 2 with diferent aperture size.

4.3.4. The Assemblage of Bricks

After fabricating the pieces, the 3D-printed bricks are assembled manually to form the screen. To be able to assemble the pieces, the space considered in between the bricks plays an important role in determining the quality of the final screen. This space establishes the amount of mortar needed to be applied between the pieces and more importantly, determines the ratio between the negative (apertures) and positive (bricks) parts on the screen. In the first stage, the process of assemblage is investigated by building mock-ups for each screen to test the required amount of space and mortar/glue between the bricks as well as the stability of each wall.

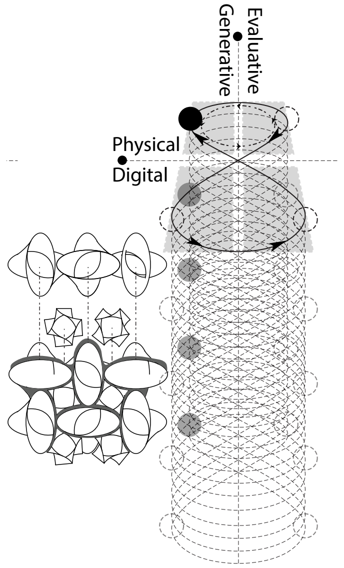


Figure 4.50. Thesis framework: Assembling the printed pieces and analysing the results.

a. Screen 1

The amount of required mortar or glue to attach the pieces was minimal and the considered amount of space between the bricks was enough (15 mm). However, more structural balance could be achieved by extruding out the flat side of the bricks to increase the area of pressure. This modification was considered in the fabrication of the final model.

Figure 4.51. The assembled model for screen 1.

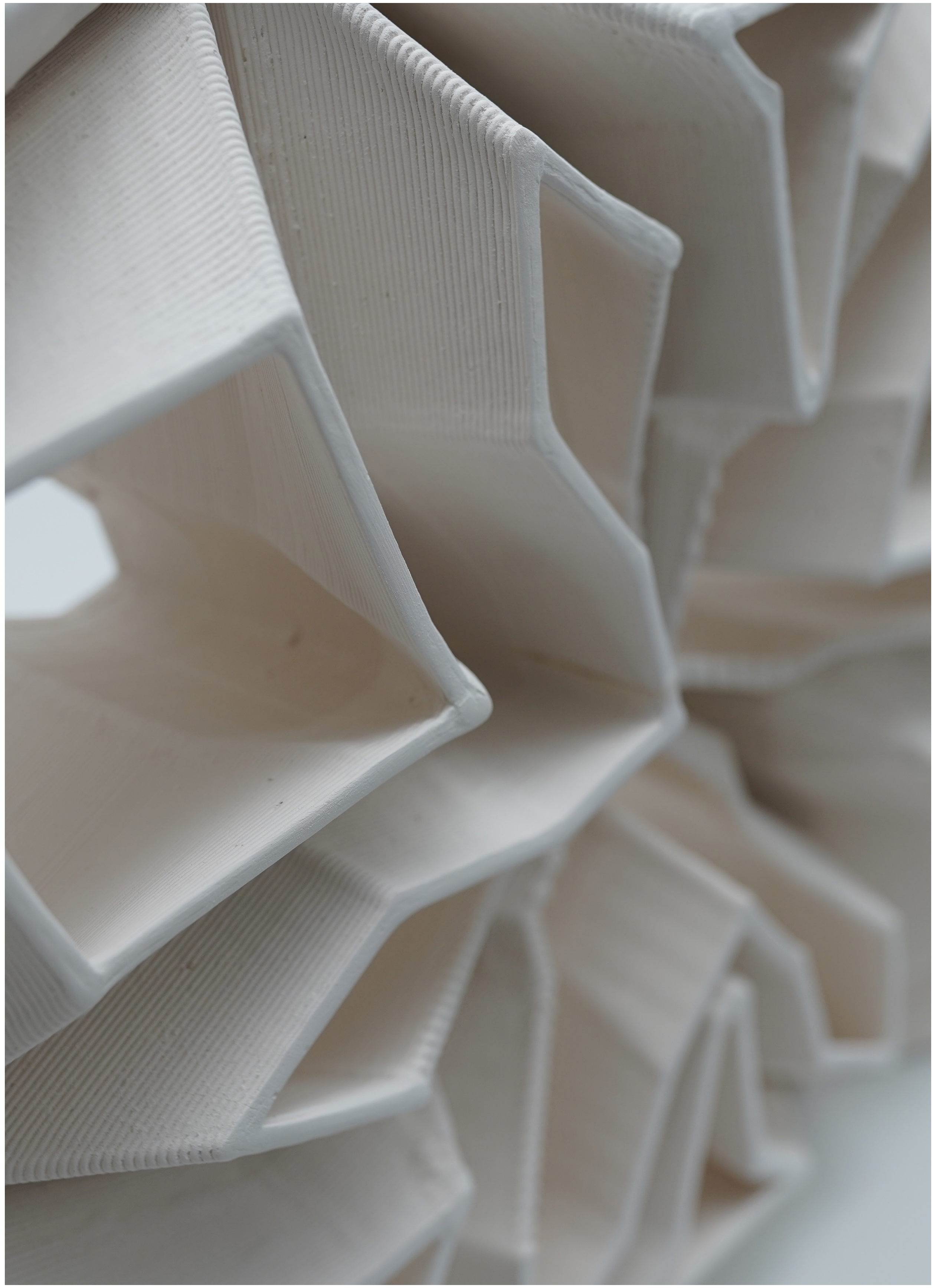


Figure 4.52. Left. Screen 1. Details.

Figure 4.53. Top-Right. Screen 1. Sanding the corners and edges.

Figure 4.54. Bottom-Right. Screen 1. View from top.

b. Screen 2

To attach the bricks together for screen 2, like screen 1, only a limited amount of mortar was needed as the bricks could almost be assembled and stand without any adhesive applied in between. The considered amount of space between the bricks was 10 mm and was increased to 15 mm to allow for more adjustment. The screen is structurally strong as a self-standing screen because of the depth of the pieces, ranging from 150 to 350 mm.

Figure 4.55. Screen 2, physical model.

Figure 4.56. Screen 2, Sanding the edges.

Figure 4.57. Screen 2, Details of the physical model.

Figure 4.58. Physical model of Screen 2, Investigating the light and shadow conditions.

Figure 4.59. Screen 2, increasing the aperture size of the pieces in the bottom layers.

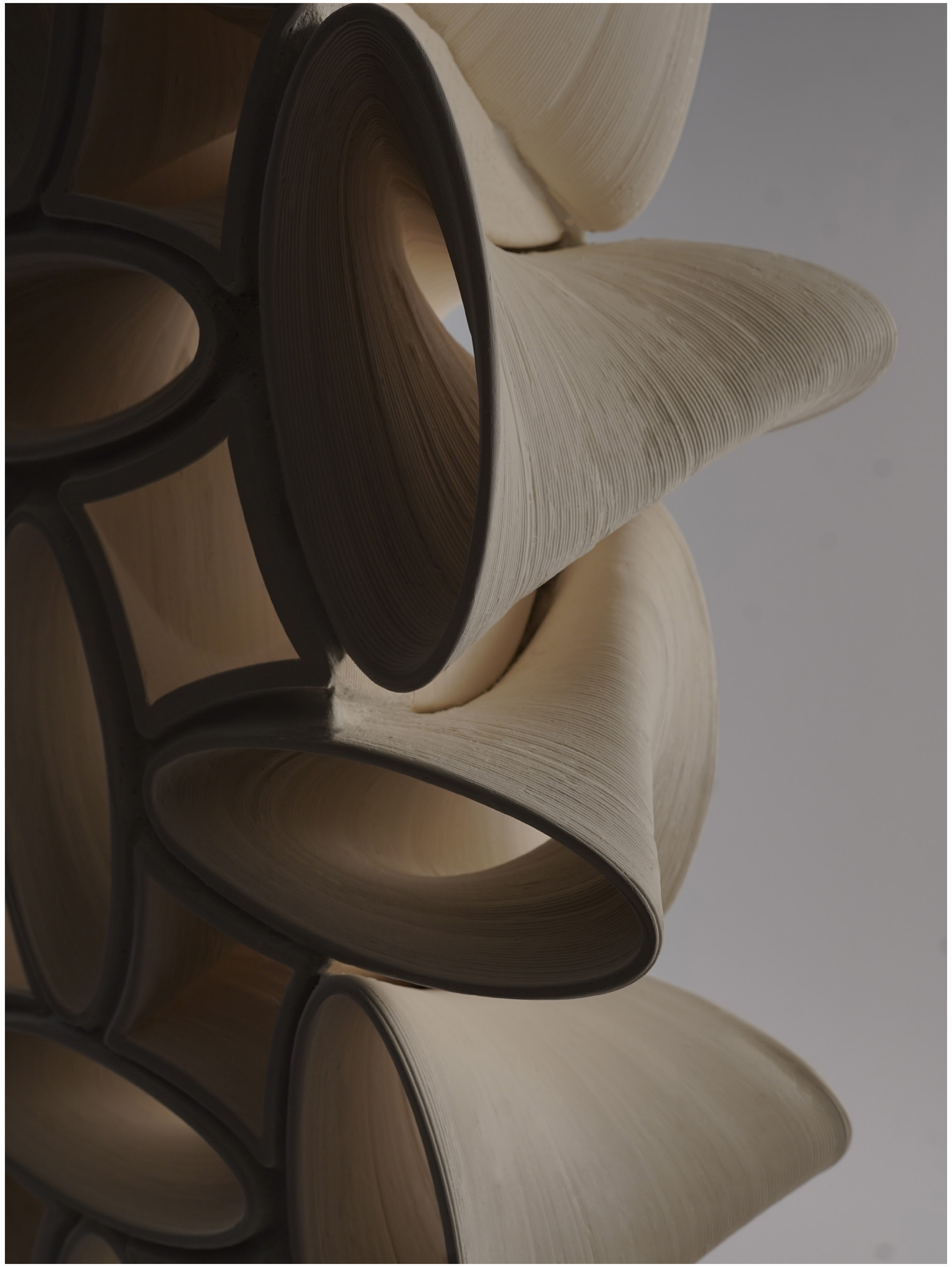


Figure 4.60. The edge condition of screen 2.

Figure 4.61. Finalizing the physical model of screen 2 by sanding the edges and the tiles.

Figure 4.62. Physical model of screen 2.

4.4. Architectural Applications

The proposed design for the light screens can be customized to have different orientations, depths, or aperture sizes. Changing each one of these parameters in the design script results in a different level of visual connectivity through the screens. To evaluate the assemblies' performance in space, the light screens are digitally simulated in three different spaces. Each space is defined as an architectural application, requiring a specific quality that can be achieved by regulating visual connectivity and light modulation. This section discusses the aim of each project and investigates the strategies taken to address each one. The resulting percentage of visual connectivity is also calculated to assist with evaluating the performance of the screens.

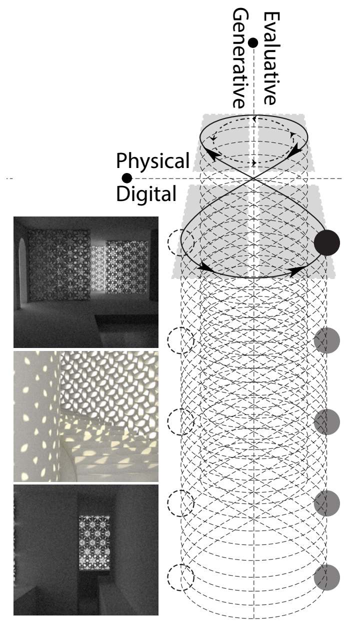


Figure 4.63. Thesis framework: Evaluating the screens through digital simulation.

4.4.1. Application 1

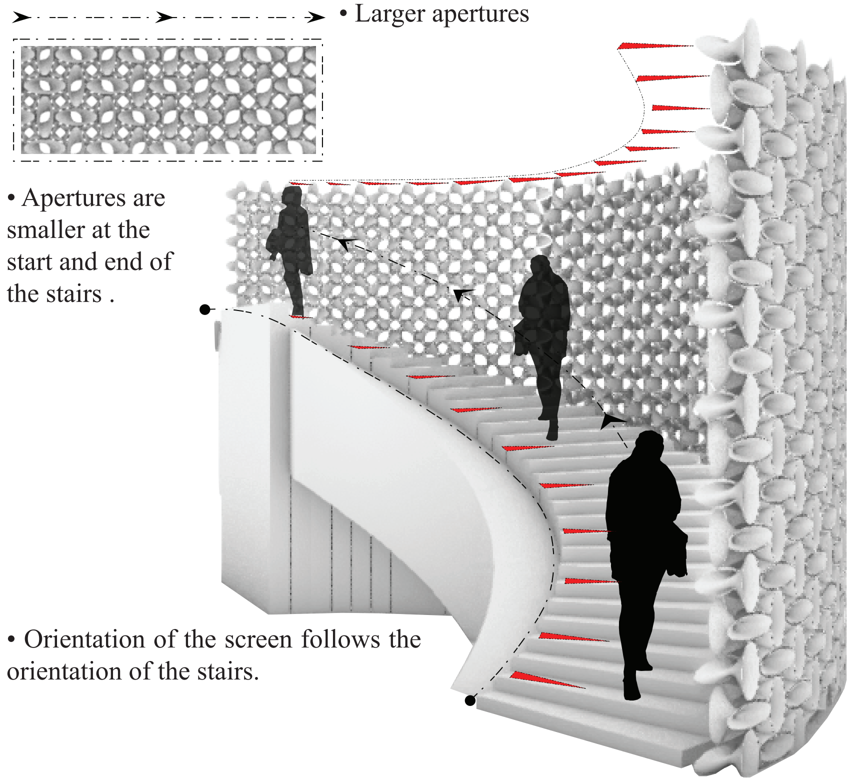
Aim

- Providing constant visual connectivity between the interior and exterior space and creating a dynamic light pattern in the staircase.

Strategies

- Creating variation in the size of apertures.
- Decreasing the depth of the bricks toward the middle of the stairs.
- Adjusting the orientation of the bricks compatible with the observer's movement path on the stairs.

Figure 4.64. Analytical diagram of Application 1.



• Orientation of the screen follows the orientation of the stairs to Provide constant visual connectivity along the wall.

This screen aims to provide consistent visual connectivity between the interior and exterior spaces for the observer passing through the staircase and to create a vibrant light pattern. To achieve this goal, the orientation of each brick is changed along the circular path of the stairs so that the observer's field of view to the other side of the wall maintains constant. The apertures start to grow more open gradually toward the center, as this is where more light penetration is required. This variation also allows light to enter specific parts of the space and create a mottled pattern on the steps and walls. In addition, the depth of the bricks becomes less in the middle of the pattern to secure more visual connection between the interior and exterior space.

Figure 4.65. Application 1- Creating scattering light patterns during day time and providing constant visual connectivity along the staircase.

Figure 4.66. Application 1- Night time.

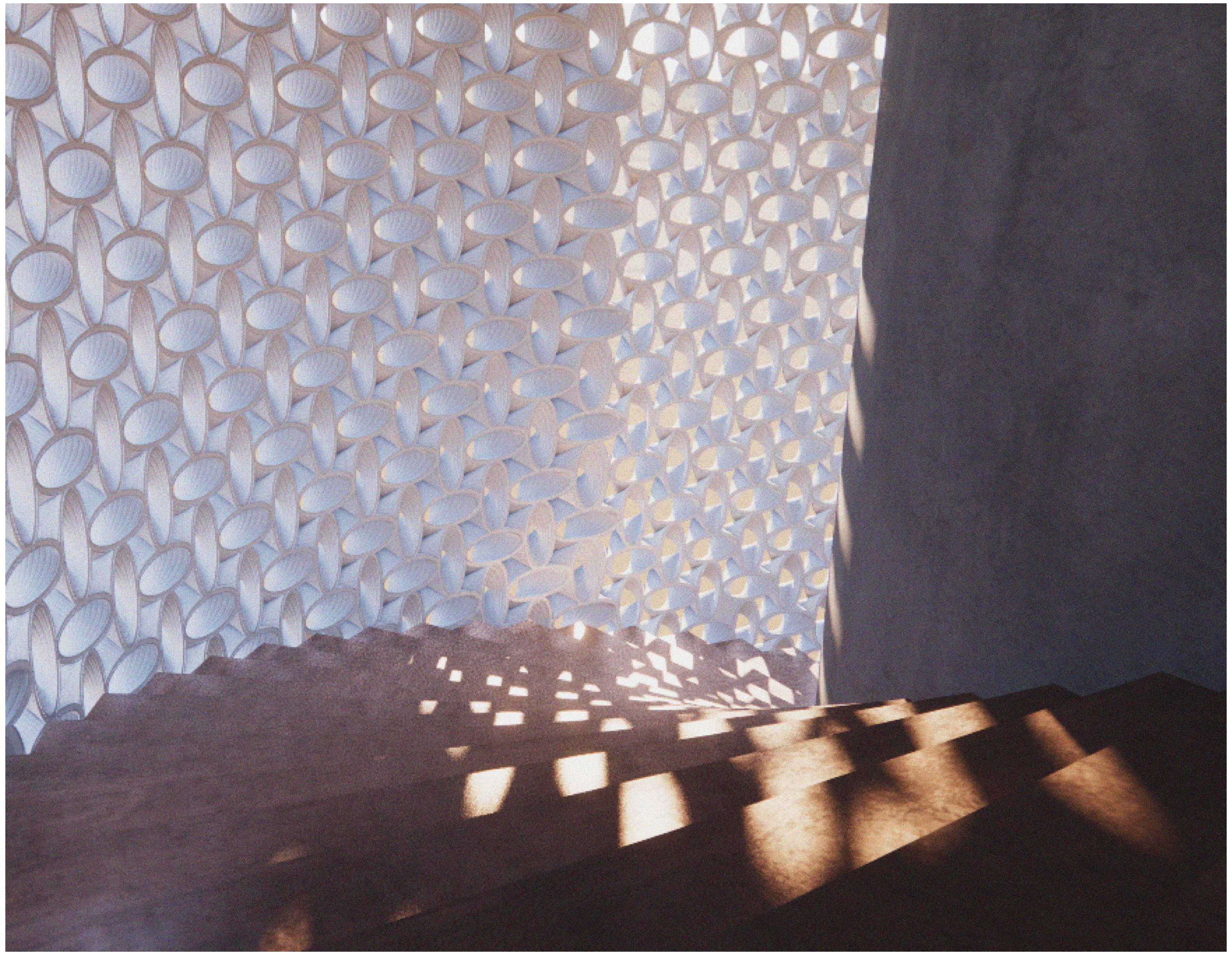


Figure 4.67. Application 1- Day time.

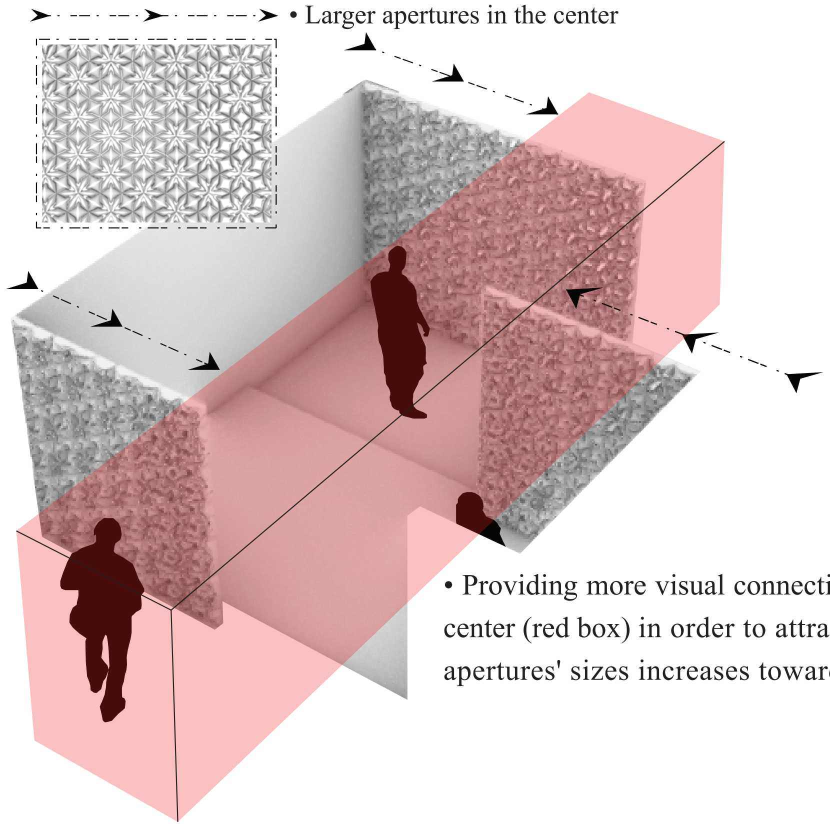
4.4.2. Application 2

Aim

- Captivating observers' attention and encouraging them to explore what exists behind the screens.

Strategies

- Increasing the apertures' size toward the center
  - More light enters the space through the apertures in the middle.
  - Stronger visual connectivity between the screens is created in the center.



• Larger apertures in the center

• Providing more visual connectivity and light penetration in the center (red box) in order to attract the observer's attention. The apertures' sizes increases toward the center.

Figure 4.68. Analytical diagram of application 2.

This space belongs to a building that is situated on a cliff and looks over to a beautiful view of a lake. The goal of this project is to evoke a sense of adventure for individuals to explore the space and establish a deep understanding of the spatial and light qualities in the room. To achieve this goal, multiple light screens are located in three different layers, creating a gradual link between the room and the view. The size of the apertures in the screens becomes more and more open as it gets closer to the center and therefore, more diffused light enters the space. This variation intensifies the light penetration in the center, encouraging the viewer to move towards the light and explore what is behind these screens. This quality also results in establishing more visual connectivity between the layers so the observer can understand the created depth towards the lake view.

Moreover, the dynamic shape of the crystals in the assembly compared to the simplistic design of the space creates contrast, amplifying the observer's attraction towards the screens. A shallow pool in the middle is designed to again, intensify this contrast by reflecting the screen's pattern in the water.

Figure 4.69. Application 2. Day time.

Figure 4.70. Application 2- Night time.

4.4.3. Application 3

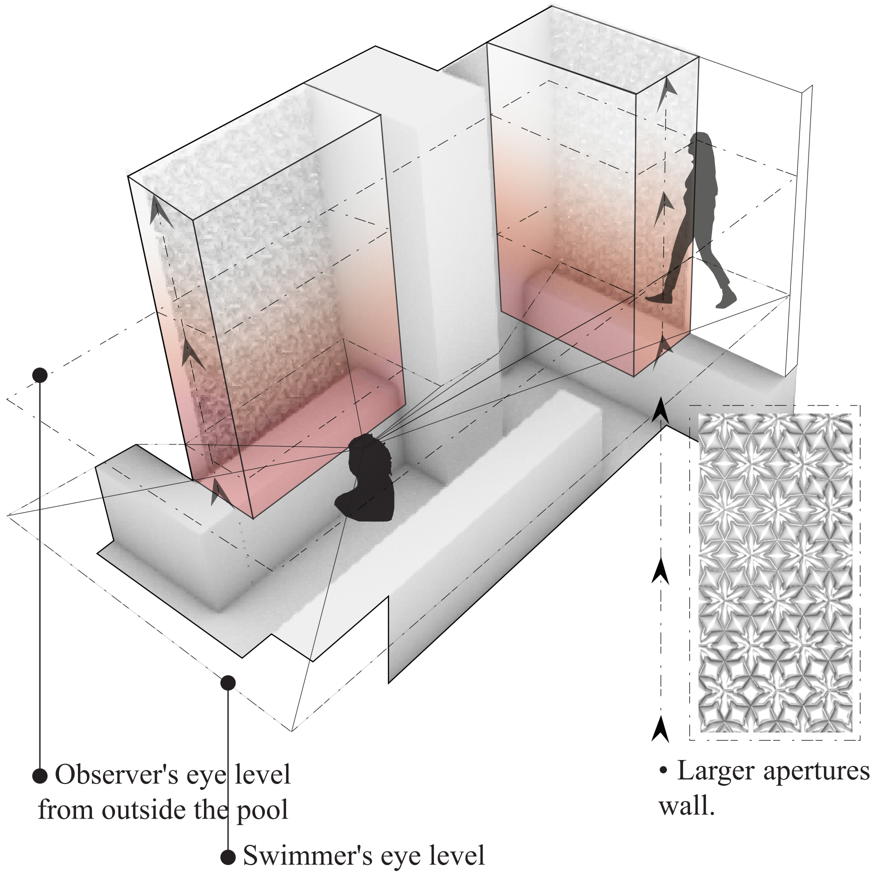
Aim

- Providing visual privacy while creating a spiritual and peaceful atmosphere using natural light.

Strategies

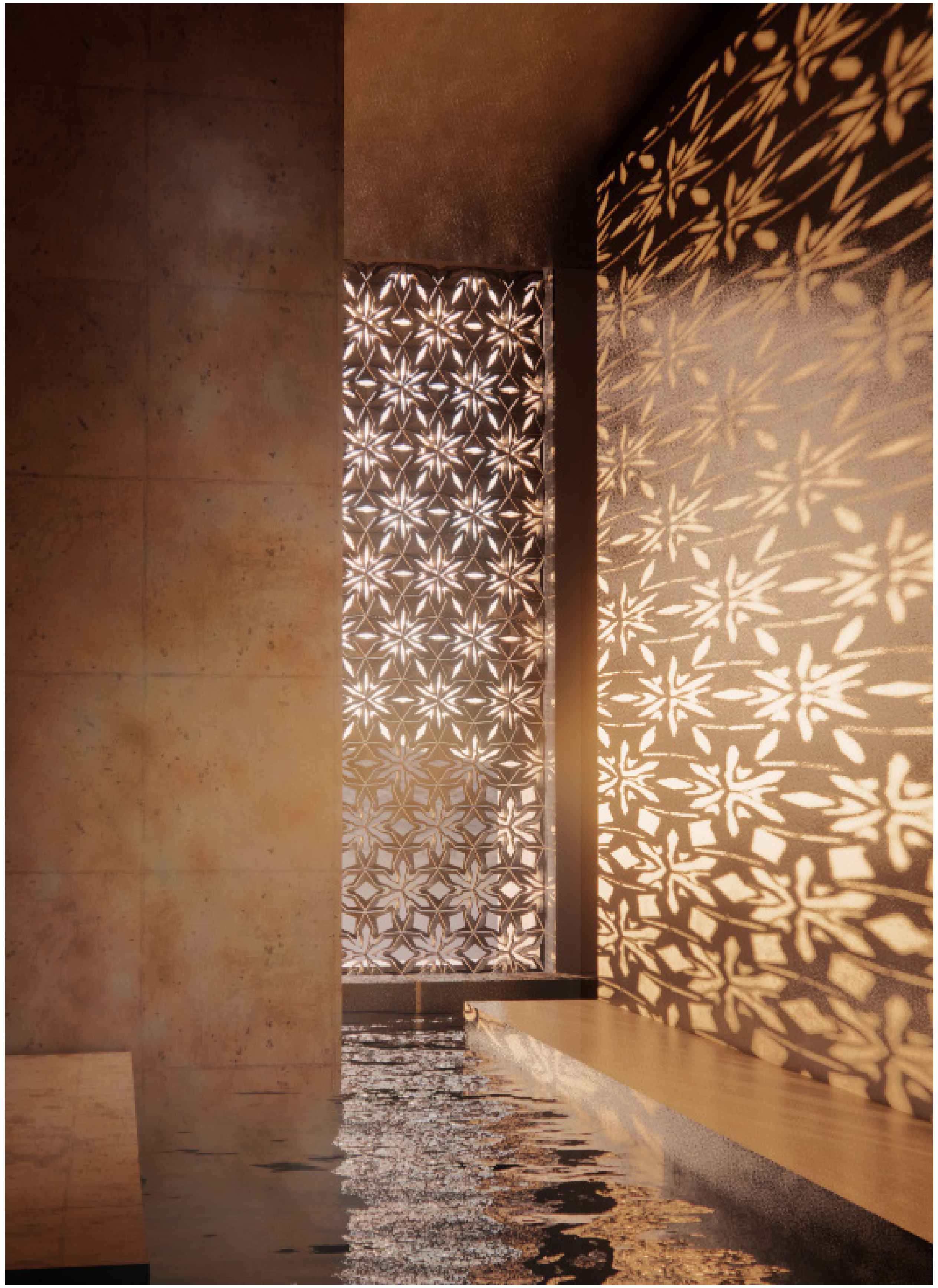
- Creating variation in the size of apertures.
  - Reflecting light using water to create light scattering patterns.
  - Increasing the aperture's size on the bottom of the wall. (Aligned with the swimmers' eye level)

Figure 4.71. Analytical diagram of application 3.



This project focuses on modifying the visual and light qualities of the semi-private section of a public pool. The goal of this application is for swimmers to experience a sense of tranquility, away from any disturbance. The designer attempts to create this quality by regulating the swimmer's visual exposure and visual accessibility. The size of the apertures in the screen is determined by the swimmer's eye level. In other words, the apertures are more open on the bottom so that the swimmer can engage with nature outside the pool. The apertures are smaller at the eye level of the individuals who pass by the pool (outside) to minimize their visual accessibility and the swimmer's visual exposure. Parallel to this, natural light can enter the space through the apertures and create graceful light patterns. Like application 2, this design uses water as an element to reflect light through the screen. the sunlight bounces on the pool's surface located outside the space and behind the screen, resulting in the creation of a peaceful atmosphere in the room.

Figure 4.72. Next page-Left. Application 3. Comparing the lighting condition and the resulted visual privacy for the swimmers.



CHAPTER FIVE

Discussion and Research Outlook

5.1. Challenges and Opportunities

The design section of this thesis starts with screen 1, proposed for investigating the aim of this thesis. This screen provides the required level of flexibility to adjust visual connectivity for the observer through the 3D-printed screen. The geometrical variety in the crystal shapes of the pattern encourages the viewer for further exploration. Scattered lighting patterns created through the screen's apertures would also improve viewers' spatial perception, leading to the creation of different knowledge of the space. In the next stage, screen 2 was proposed to develop the visual and lighting qualities of screen 1. Following the shape of a spiral form, these pieces improve the visual permeability through the screen by attracting the observer's attention to the center of the spiral.

The geometry of screen 2 is more adjustable compared to screen 1 as it allows the designer to change the height, width, depth, and orientation of each piece; While, due to the variety and the number of pieces in screen 1, it is not possible to control the orientation of the pieces. Another advantage of screen 2 compared to screen 1 is that the variation in the size of apertures can be easily applied to the pattern; To create the same level of alteration in screen 1, more time and effort are required. Moreover, in screen 2, the number of required pieces for making a wall with a specific height, width, and depth is almost half of what is needed for screen 1. Therefore, the process of assembling is more convenient and efficient.

Figure 5.01. Top. Physical model of screen 1.

Figure 5.02. Bottom. Physical model of screen 2.

Regarding the fabricating and 3D printing of the pieces, a few challenges needed to be resolved. For screen 2, the challenge was to print the cantilevered part of the bricks. To overcome this issue, the ratio between the height of the bricks and the radius of the ellipses needed to be adjusted. Hardening the bottom printed layers with a heat gun was also helpful as they became stronger to hold the newly printed layers. Another challenge that needed to be addressed was printing the sloped surfaces of the pieces for screen 1. The strategy taken to solve this issue was a doubled-layer geometry that would make it possible to print sloped surfaces. Printing two layers would allow the printer to move in a looped path and leave traces where it needed to switch to another layer. This strategy would also make the pieces more stable during printing. The required time for printing the pieces of screen 1 range from 30 (small pieces) to 45 (primary and larger pieces) minutes. For screen 2, this range decreases to 20 to 35 minutes. The reason for this is that the pieces of screen 1 have two layers and therefore, require more time to be printed.

Overall, considering the challenges and the opportunities that each screen provides, screen 2 could better capture the aim of this thesis, compared to screen 1. In the next stages, screen 1 has the potential for further development and to achieve the same level of customizability, affordability, and scalability as screen 2 for building high-performance light screens.

5.2. Customizability, Scalability, and Affordability

Visual connectivity and light modulation can significantly enhance individuals' perception of the space by redefining spatial qualities. The aim of this thesis was to define a framework for designers to be able to regulate visual connection and modulate light through 3D-printed light screens. The application of the proposed method goes beyond the three simulated spaces demonstrated in the previous section as it offers a significant level of customizability to change the design attributes. In a reciprocal manner, the major parameters work together to improve the designer's architectural ideas. Moreover, these attributes can be controlled to match the size, shape, and general structure of different buildings and create the required qualities in the spatial program. Therefore, this method can be considered a customizable and scalable approach for producing high-performance light screens. Considering the economical benefits and the amount of time needed to produce the screens compared to casting techniques, this process improves the affordability and accessibility of the 3D printed components. The shorter the process of production, distribution, and assemblage, the better chance it provides for commercial implementation. These are the criteria required for mass-producing customizable building components.

Furthermore, the distinction between the produced design information by architects and the quality of the actual outcome can be significantly reduced by relying on digital fabrication processes. 3D printers can produce complex and unique building blocks with a high level of accuracy. Digital fabrication and digital materiality are about defining the relationships and sequences that inhabit architecture, based on the digital rules, weight, and priority allocated to each of the driving parameters. This process provides a dynamic set of factors for the architects to control the design, enabling them to change it even in the last stages, from design to fabrication.

5.3. Conclusion

In this thesis, a design and fabrication framework was developed for regulating visual connectivity and modulating light through 3D-printed light screens. The synchronization of digital design, 3D printing, and architecture was investigated through two physical experiments. The design of both assemblies was informed by major parameters on visual connectivity, including material, form, the position of the viewer, and light penetration. These attributes work together to enhance the observer's visual connectivity between spaces and to create lighting qualities. To do so, three formal factors of orientation, depth, and aperture size of the bricks were investigated. Based on where the observer is located or oriented in the space and the desired location of the light source and its intensity, these factors are regulated to establish the level of visual connection between spaces. While there is a wide range of materials that can be used for this application, clay was selected due to its plastic deformation potential, low cost, and resistance. The key contribution of this thesis is a new approach to designing and fabricating light screens using clay 3D printing. Within this method, physical assembly and digital simulation are combined to improve the screen's performance. Through careful consideration of the form, structural stability, material use, and resulting visual and lighting qualities, a new framework emerges that can be employed for different architectural applications.

5.4. Research Outlook

The framework defined in this section provides an opportunity to go beyond the scope of this thesis; An opportunity to explore how to create new visual and light qualities and improve the design and fabrication processes.

5.4.1 Robotic fabrication, Robotic assemblage

The integration of robotics and digital design into the existing construction methods has provided a significant opportunity for automating the design and fabrication processes. This opportunity boosts the construction process to be more efficient regarding the amount of time and cost required for procuring high-quality and high-performance products. This thesis investigated additive manufacturing and proposed a framework where it can be used for creating functional 3D-printed light screens. In this framework, the bricks are built using 3D printers and are assembled manually to create the screen. The process of assembling the components can be automated by using robotic arms that can execute ‘grab’ and ‘place’ tasks with high precision. In this method, bricks are grabbed from a specific location and accurately placed in their exact position in the wall. If applicable, mortar or glue can also be applied to the bricks automatically after assembling each row. This opportunity is advantageous in many ways, including the amount of time, cost, and the number of labor required to build the wall as well as the level of accuracy in assembling the pieces.

5.4.2. Orientation of the apertures independent of the bricks’ orientation

In this project, the proposed design allows the designer to adjust the orientation of each brick in the assembly. Therefore, each piece can be directed differently, independent of the other bricks’ orientation. However, this flexibility can be improved. The size of the pieces’ aperture is controlled by changing the ellipse’s radius, located in the middle of the brick. In the proposed design, the orientation of the middle ellipse follows the direction of the whole piece. While it can be designed to have a different orientation from its piece. Having this opportunity, the orientation of the bricks in the wall can follow the orientation of the space, while the apertures aim at a different view for the observer. This feature can limit or improve observers’ field of view at some specific angles or regulate from which part of the screen light can enter the space. A few projects, including Hex screen, have considered this quality. However, the variation domain in the bricks’ orientation is very little as both sides of the wall are flat and the geometry can only move along the flat surface. Changing the form of the wall’s surface to curved or free-form shapes can assist in expanding the alteration domain along with the screen’s depth in different parts of the wall.

Figure 5.03. Hex screen. By Brian Peters. Pittsburgh, PA. 2022.

5.4.3. Optimizing the pieces' geometry

The objective of this thesis was explored through 3D printing separate pieces that were eventually assembled as a wall. One aspect that can be explored here is the possibility of connecting separate pieces and printing them as one brick.[1] This strategy simplifies the process of design and making in many ways. The process of printing would be shorter since multiple pieces are merged and consequently, the amount of clay needed for each piece would be much less. A shorter process of fabrication results in a more affordable and economical building component. Moreover, the expenses regarding the human labor to assemble the pieces are less. The reason for this is that the number of connections between different bricks is less and therefore, assembling the pieces would be easier. In addition, the geometry of the pieces can be optimized regarding the amount of light penetrating the space. To do so, it is possible to define different tool paths for the 3D printer to create undulating textures for every piece. This strategy can be employed to create small perforations in each brick's geometry for light modulation. Additionally, it can change the amount of light penetrating into the space and affect the level of visual connectivity for the observer throughout the day.

Figure 5.04. Combining the geometry of every four pieces and printing them as one.
HIVE, By Cho. Y, She. J, Taylor. am, Correa. D, Clarke-Hicks. J, Ochoa, I. Waterloo, Canada. 2021.

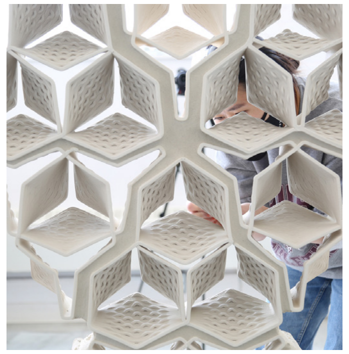
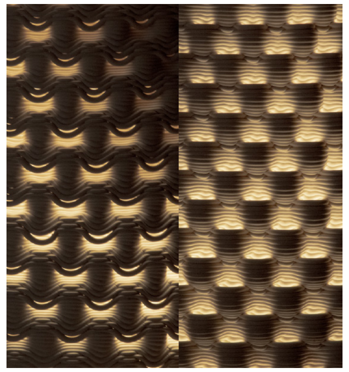


Figure 5.05. Grading light through the ceramic 3D printed pieces.
Grading Light. By James Clarke-Hicks, Isabel, Ochoa, 2021.



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[1] Cho. Y, She. J, Taylor. am, Correa. D, Clarke-Hicks. J, Ochoa, I, *HIVE.*

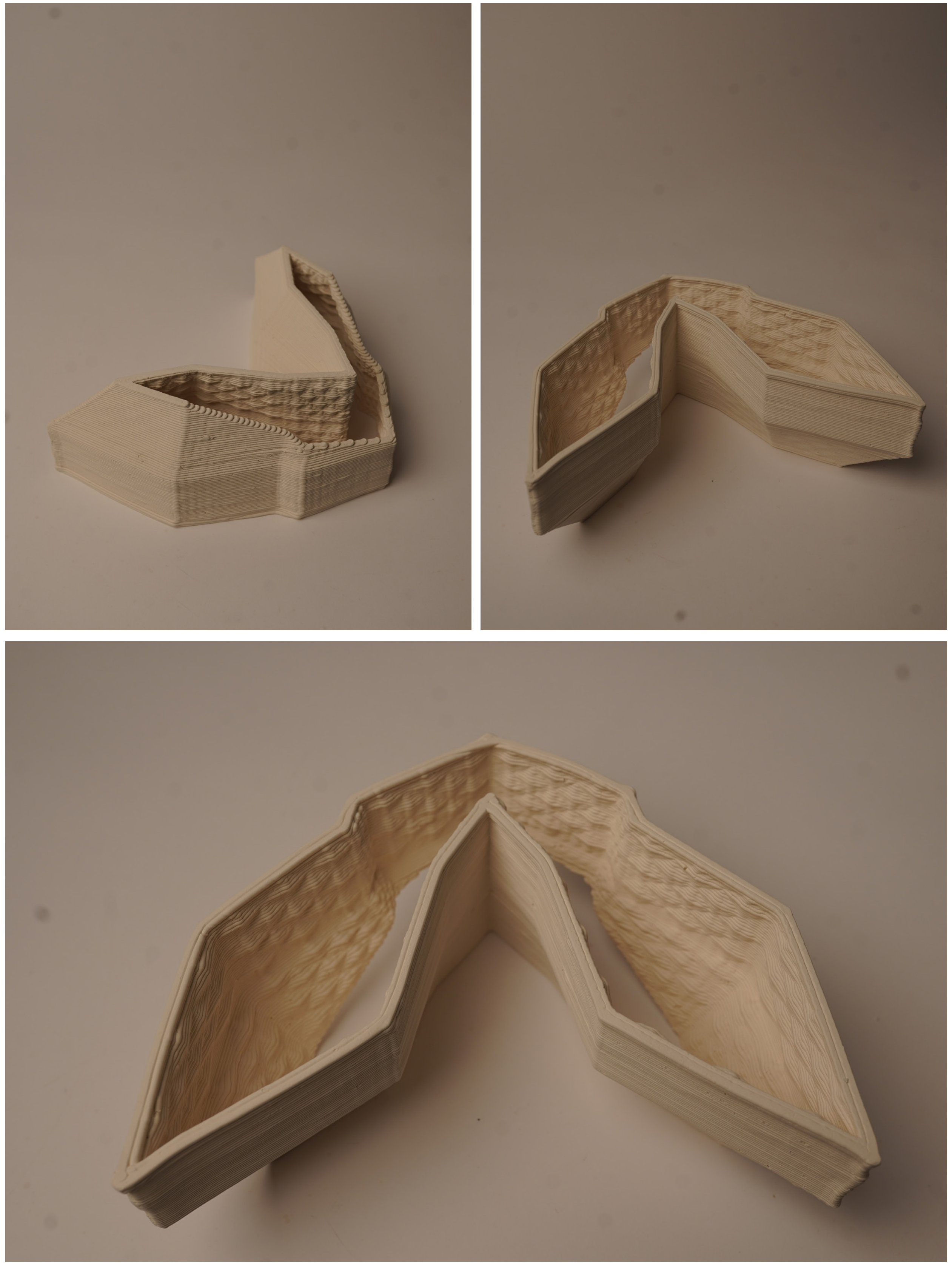

Figure 5.06. Investigating undulating textures for the inner geometry of the pieces.

5.4.4. Material exploration

Based on their inherent attributes, every material provides a different level of opacity through the brick's surface, after being printed. This research can be developed regarding the choice of material and the 3D printing techniques associated with it. The level of materials' transparency and the amount of light that can penetrate through the screen's surface are very important when it comes to visual connectivity and light modulation. This investigation can start with prototyping with different types of plastics, glass, or more environment-friendly alternatives such as wood fibers. The thickness of the printed layers, depending on the materials' specifications can be considered an influential factor in the resulting opacity.

5.4.5. Glazing the bricks

Glazing ceramic bricks is a technique used for many years in pottery that adds long-lasting qualities to the space for different purposes. This technique can also define additional layers for the design of the bricks in masonry facade systems, made of clay. The project can benefit from the qualities glazing provides such as resistance to water, reflection, luminosity, and color which can improve the aesthetics as well as the durability of the installation.

Figure 5.07. Licorice, cover Lynnette's Opal. By Alisa Clausen. Aabenraa, Denmark. 2018.

What resulted from this thesis is a basis for improving the design, fabrication and assemblage processes for producing high performance light screens. The strategies that were discussed here allow for a deep invesigation beyond the defined scope in this thesis. Further reseacrh provides the opportunity to consider more aspects of the issue and to develop the application of the system in a real world architectural context.

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