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This thesis explores eco-conscious furniture design, specifically focusing on the utilization of cardboard layering to create environmentally friendly seating. The research begins by examining the environmental impact of the furniture industry and emphasizes the importance of adopting circular economy principles. In this research, sustainable materials for furniture production are explored, with an emphasis on cardboard as a viable and eco-friendly alternative. The study investigates employing cardboard in furniture design, highlighting its versatility. It also showcases practical examples of parametric design principles in the furniture industry. The thesis provides a comprehensive analysis of the design process, materials, layering, and construction techniques employed in crafting a full-scale cardboard chair for this project. The evaluation of the design process includes assessing its effectiveness while considering the challenges and limitations involved. The research concludes by presenting future research directions, emphasizing the ongoing need for exploration and innovation in eco-conscious furniture design. Ultimately underscores the significance of achieving a sustainable and environmentally responsible furniture industry.

ECO-CONSCIOUS FURNITURE DESIGN:

EXPLORING CARDBOARD LAYERING IN ECO-FRIENDLY CHAIR DESIGN

by

Kiandokht Maghsoud

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Approved by

Matthew Jones
Committee Chair

APPROVAL PAGE

This thesis written by Kiandokht Maghsoud has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I: INTRODUCTION

The furniture industry significantly affects the environment, contributing to global waste and pollution. Each year, more than 80% of furniture and furnishings end up in landfills, resulting in adverse effects like greenhouse gas emissions and resource depletion (EPA, 2022). Traditional furniture production, including wood, metal, and plastic, further contributes to resource depletion and environmental damage.

As consumer environmental awareness grows, there is an increasing demand for sustainable options in the furniture industry. These options include the use of sustainable materials and production methods. Sustainable materials have a minimal environmental impact throughout their lifecycle, from sourcing to disposal. Sustainable production methods focus on waste, pollution reduction, resource efficiency, and circularity. The circular economy, aiming to maximize resource use and minimize waste, is crucial in this context.

This thesis explores the feasibility of creating environmentally conscious furniture using corrugated cardboard as the primary material. The research objective is to develop a design for seating using corrugated cardboard. The study will assess the advantages and limitations of using corrugated cardboard for furniture production, considering mechanical properties, durability, and recyclability. Additionally, a prototype chair made from corrugated cardboard will be developed and evaluated in terms of sustainability, comfort, and stability.

This research is significant as it addresses the need for sustainable alternatives in the furniture industry and contributes to the broader movement toward sustainable materials and production methods. By demonstrating the feasibility of functional furniture made from corrugated cardboard, this study has the potential to promote sustainable practices and mitigate the environmental impact of the furniture industry.

CHAPTER II: LITERATURE REVIEW

Environmental Impact of the Furniture Industry

Furniture is necessary to support daily human activities and make a building functional. According to Statista, revenue in the furniture market amounted to US$252.70bn in 2023. The market is expected to grow annually by 3.95%. In global comparison, most revenue generated by furniture is in the United States, which is US$252.70bn in 2022. (Statista, 2023)

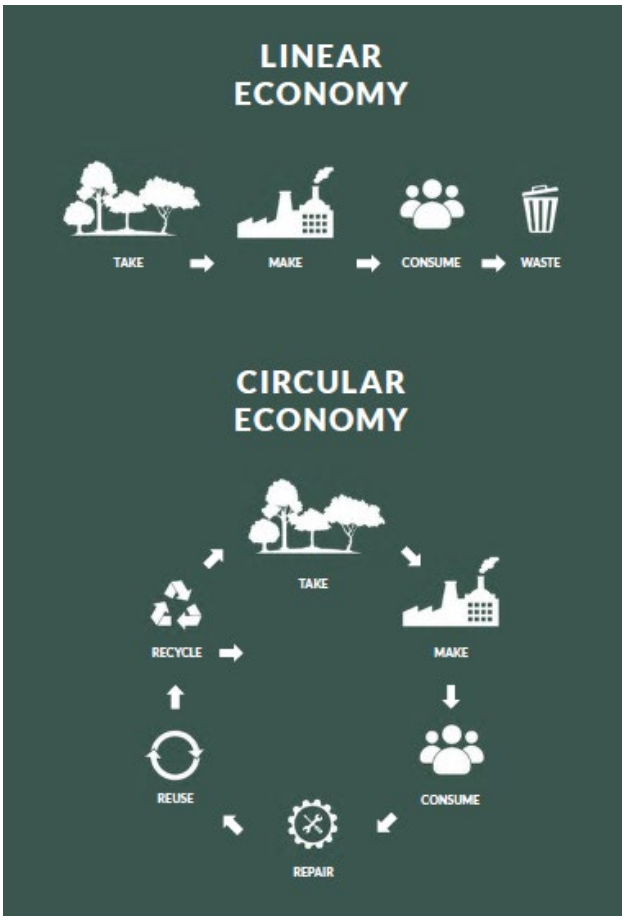
Furniture is an assembly industry of several different materials, leading to a complex value chain of many processes. With such large consumption, volumes and a complex value chain, significant environmental impacts on the furniture industry. Despite the considerable environmental impact of the furniture industry, there is a lack of comprehensive information available on its specific environmental consequences (Forrest et al., 2017). The industry contributes to carbon emissions, deforestation, resource depletion, and waste generation, highlighting its overall environmental impact. Manufacturing and distribution processes contribute to greenhouse gas emissions and waste generation. The industry's reliance on wood leads to deforestation and carbon emissions, while the extraction of non-renewable resources and the use of chemicals further deplete resources and cause pollution. Additionally, the low recycling rate of furniture contributes to landfill waste and greenhouse gas emissions. According to the EPA, furniture, and furnishings are the least recycled items in municipal solid waste, with a recycling rate of only 9.8% (EPA, 2022)

Circular Economy in Furniture Industry

The circular economy is an economic model that aims to maximize the use of resources, minimize waste and pollution, and regenerate natural systems. The circular economy concept emphasizes the importance of extending the lifespan of materials by promoting reuse, repair, and

recycling strategies to keep products and materials in use as long as possible. Circular economy also strives to eliminate waste and pollution and regenerate natural ecosystems, which are vital for achieving sustainable development. Design is at the heart of the circular economy, deployed up front as a powerful tool to determine how something is manufactured, used, and discarded. According to the Ellen MacArthur Foundation, design choices are responsible for 80% of the environmental impact of products, systems, and services. (Ellen MacArthur, 2012)

Figure 1. Circular Economy and Linear Economy



Note. Sourced from SOMA studio, 2022, Retrieved from http://www.somastudiomilano.com/2022/10/04/circular-economy-a-possible-future/

The circular economy model for furniture requires a shift away from the traditional linear model of furniture production, where materials are extracted, transformed into products, and ultimately disposed of.

Many strategies have been employed to implement circular economy practices in the furniture industry. One approach is designing products with modularity and durability in mind allowing for easy replacement or repair of components and using recycled or upcycled materials in products. Additionally, using renewable materials like wood from sustainably managed forests can help minimize the industry's environmental impact.

Figure 2. Mamá Cari Chair. Design for Disassembly, Enabling Easier Repair and Reuse

Note. Sourced from "Mamá Cari," Loose Part collection, Retrieved from https://www.loose.parts/collections/seating/products/mama-cari-chair

Companies can also adopt circular business models, such as leasing programs or product-as-a-service, to encourage the return and reuse of products at the end of their life cycle. These models help to create a closed-loop system that reduces waste and encourages more sustainable use of resources. For example, Herman Miller has implemented a closed-loop system for their Aeron chairs, allowing customers to return chairs for refurbishment and reuse.

The Smart Ocean chair by Humanscale is constructed using discarded ocean fishing nets, which are collected and recycled into plastic pellets. These nets, weighing approximately two pounds per chair, are shredded and melted to form the chair's plastic shells. As the first task chair built with recycled ocean plastic, the Smart Ocean chair meets rigorous sustainable manufacturing criteria and is certified by the International Living Future Institute. Additionally, its lightweight design and use of 100% recycled aluminum contribute to minimizing the chair's environmental impact. With its modular and easily maintainable structure, the Smart Ocean chair promotes sustainability by reducing the need for complete chair replacements. Moreover, it holds certifications such as GREENGUARD Indoor Air Quality, GREENGUARD Gold, and level® 2, ensuring its environmental friendliness.

Figure 3. Smart Ocean Chair by Humanscale

Note. Sourced from Humanscale. 2003. Retrieved from https://www.humanscale.com/products/seating/liberty-task-office-chair

Sustainable Materials for Furniture Production

Sustainable materials are those that are sourced and produced in an environmentally friendly manner and have a minimal impact on the planet's resources. Some of the most popular sustainable materials used in the furniture industry include:

Bamboo: Bamboo is a fast-growing and renewable resource that can be harvested every 3-5 years. It is durable and lightweight. However, the process of turning bamboo into functional furniture can involve the use of chemicals and energy-intensive processes. Additionally, while bamboo requires less water to grow than traditional wood species, it can still require significant amounts of water to produce. (Sharma, 2014)

SFC Certified Wood: SFC (Sustainable Forestry Initiative) certified wood is sourced from responsibly managed forests that promote reforestation and reduce waste and can be

harvested sustainably. However, the transportation of wood can result in high emissions, and the certification process can be costly.

Reclaimed wood: Reclaimed wood is wood that has been salvaged from old buildings or furniture and given a new life. It is an excellent choice for sustainable furniture as it reduces the need for new wood production and helps prevent waste. However, it can be challenging to source and transport reclaimed wood, which can increase its carbon footprint. Additionally, the process of preparing reclaimed wood for use can involve the use of harsh chemicals.

Recycled plastic: Recycled plastic furniture is made from post-consumer waste, which reduces the amount of plastic that ends up in landfills. It is durable and can withstand outdoor environments well. However, the recycling process itself can be energy intensive. Additionally, plastic furniture can be difficult to recycle at the end of its life, which can lead to it ending up in landfills. (Esirger, 2020)

Cork: Cork is a natural and renewable material harvested from the cork oak tree's bark. It is lightweight, durable, and has sound and thermal insulation properties. Apart from cork exploitation, cork forests are especially valuable because they are important reservoirs of biodiversity, and they act as carbon sinks. It represents a model of sustainability between human activity and natural resources. (Rivers, 2011) However, the extraction process can be damaging to the cork oak tree's ecosystem. Additionally, the process of turning cork into furniture can involve the use of harsh chemicals.

Hemp: Hemp is a fast-growing plant that requires minimal water and pesticides to grow. It is strong, durable, and has natural anti-bacterial and anti-fungal properties. However, it is often transported long distances, which can increase its carbon footprint. Also, turning hemp into furniture can involve energy-intensive processes and chemicals.

Cardboard: Cardboard is a lightweight and versatile material that can be easily recycled. It is a choice for sustainable furniture as it reduces waste and promotes circularity. Cardboard and its life cycle analysis will be explained in more detail in the next section.

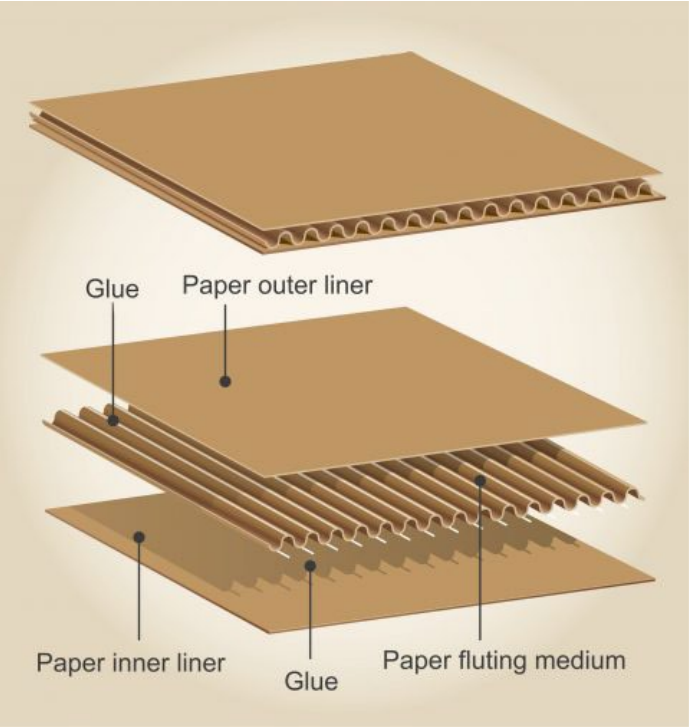
As mentioned, each of these materials for furniture production has its own distinct set of strengths and weaknesses that must be considered to ensure their optimal use in eco-friendly furniture design. Factors such as the availability of the material, its durability and performance, cost, and health and safety considerations are all crucial criteria that must be evaluated.

Corrugated Cardboard

Corrugated cardboard is a versatile material with a wide range of applications across different industries. Its features and sustainability make it an option for various functions, including packaging, construction, and furniture design.

The main ingredient of cardboard is wood pulp, sourced from the cellulose fibers in trees. This wood pulp is mixed with water and then processed to form a refined pulp, which is further mixed with additives like glue and starch to increase its durability and strength. The resulting mixture is then pressed and dried to make flat sheets of cardboard used for various purposes, including packaging and other products. The cardboard comprises multiple layers of paper, such as an outer liner, an inner liner, and a corrugated layer in between. The corrugated layer serves as a cushion and support, which makes it an excellent material for protecting items during storage and transportation.

Figure 4. The Composition of One Layered Corrugated Cardboard



Note: Sourced from OrCon industries. Retrieved from https://www.orconind.com/what-is-corrugated-cardboard-and-why-is-it-essential-for-shipping-goods/

These raw materials are available in many parts of the world, and cardboard production facilities can be found in most countries. In fact, the global cardboard packaging market is highly fragmented, with many small and medium-sized manufacturers operating locally or regionally.

The Life Cycle Analysis (LCA) of cardboard includes several stages: raw material extraction, transportation, manufacturing, use, and disposal. According to a study by Verma et al. (2019), the production stage of cardboard has the most significant impact on the environment, as it requires the use of water, energy, and chemicals. The study found that the electricity used in cardboard production has the most significant environmental impact, followed by water consumption and air pollution. However, the study also found that the environmental impact of cardboard production is lower than that of plastic or metal production.

The use phase of cardboard is relatively low in terms of environmental impact since it is lightweight, making it easy to handle and transport, reducing the carbon footprint of the transportation process.

When it comes to end-of-life options, one of the most significant sustainability features of corrugated cardboard is that it can be recycled multiple times at the end of its life cycle, reducing the need for virgin materials. The corrugated cardboard recycling process involves collecting used cardboard boxes and sorting them based on quality. The sorted cardboard is then processed to remove contaminants, turned into pulp, and used to create new cardboard products. According to the Fiber Box Association, Corrugated cardboard is recycled more than any other packaging material in the U.S. Plus, and the average corrugated box is made with 52 percent recycled content. (Fiber box association, 2021)

Cardboard in Furniture Design

Cardboard is a highly versatile and sustainable material. Below are some of the benefits of using cardboard in furniture design and production:

Lightweight: Cardboard is incredibly light compared to other materials such as wood, metal, or plastic. This makes it easy to move around, assemble and disassemble, and transport. This property makes cardboard furniture ideal for people who move frequently or for events where temporary furniture is needed.

Affordable: Cardboard is an inexpensive material in comparison to other materials used in furniture production, and its use in furniture production can reduce the cost of production, making it accessible to people on a budget. In addition, cardboard furniture is usually flat-packed, reducing transportation and storage costs.

Durable: Cardboard may seem fragile, but it is surprisingly strong and durable when used in furniture production. Cardboard furniture can withstand weights of up to 200 pounds, which is impressive considering its lightweight. With proper care, cardboard furniture can last for years.

Eco-Friendly: Using cardboard in furniture production reduces waste and carbon footprint, making it a sustainable and eco-friendly option.

Versatile: Cardboard can be cut, folded, and shaped into a wide range of furniture designs, from tables and chairs to bookshelves and beds. This versatility makes it an excellent material for creating unique, functional, and attractive furniture.

Wiggle Side Chair by Frank Gehry

Wiggle Chair is made entirely out of recycled cardboard. Designed by architect Frank Gehry in 1972, the chair is made from corrugated cardboard laminated together. Its unique wavy shape and organic form make it a choice for modern interior design.

Figure 5. Wiggle Chair Designed by Frank Gehry

Note. Photo courtesy of Vitra, Sourced from Architectural Digest,2023 Retrieved from https://www.architecturaldigest.com/story/the-story-behind-frank-gehrys-iconic-wiggle-design

Molo Studio Paper Product

Molo Studio is a design firm based in Vancouver, Canada, and is recognized for its expertise in utilizing paper as a versatile and sustainable material in designs. Their paper-based furniture showcases the studio's innovative approach, combining structural integrity with an organic aesthetic. Molo Studio's intricate folding techniques and use of durable paper fibers result in furniture pieces that are strong and functional. They create a diverse range of products beyond their famous paper-based furniture. By harnessing the unique properties of paper, Molo Studio creates designs that challenge traditional notions of materiality and demonstrate the adaptability of this eco-friendly resource.

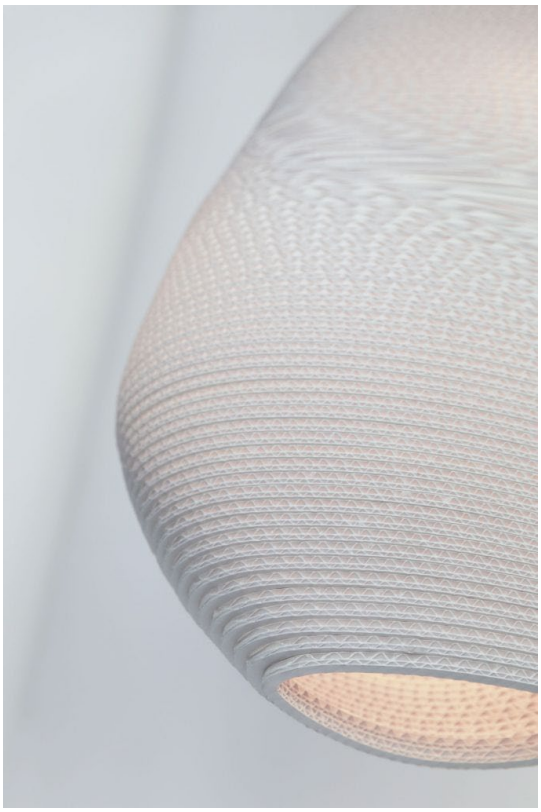
Figure 6. Molo Studio, Soft Seating Folding Paper Stool & Bench

Note. Sourced from Molo Design. Retrieved from https://molodesign.com/collections/furniture/softseating-folding-paper-stool-bench-paper-furniture/

Paper Chandeliers by Graypants

Graypants is a design company renowned for its lighting fixtures and innovative approach. Specializing in repurposed materials, particularly cardboard, Graypants creates sculptural lighting pieces that showcase a seamless fusion of aesthetics and sustainability. Their handcrafted pendant lights demonstrate meticulous attention to detail and expert craftsmanship. By transforming recycled corrugated cardboard into mesmerizing designs, Graypants exemplifies the possibilities of merging functionality and eco-consciousness. The company's commitment to responsible production practices and dedication to the principles of the circular economy further highlights their strong focus on sustainable design.

Figure 7. Scraplights White Pendant



Note. Sourced from Graypants, Retrieved from https://graypants.com/products/scraplights-pebbles/

TWIST chair by Lessmore, Italy

The TWIST chair is made from a combination of cardboard, wood, and aluminum. The chair showcases dynamic and circular forms, and the structural integrity of the chair is reinforced by a central circular cardboard compartment, supported by stretched cardboard on the sides and birch plywood finishes with Canaletto walnut. Part of Giorgio Caporaso's Ecodesign Collection, the TWIST armchair demonstrates sustainability through the use of recycled and 100% recyclable materials. Its components can be easily disassembled for efficient recycling or waste sorting.

Figure 8. Twist Chair

Note. Sourced from Lessmore, Retrieved from http://www.lessmore.it/eng/Twist-Chair.html

Parametric Design in Furniture Industry

Parametric design is a computational approach that utilizes algorithms and mathematical parameters to generate complex and adaptable designs. This design methodology has gained significant attention and application across various industries, including architecture, engineering, and product design. In recent years, parametric design has also made a notable impact on the furniture industry, changing the way furniture is conceptualized, created, and manufactured. Parametric design in the furniture industry enables designers to go beyond traditional limitations and explore new possibilities. It offers the freedom to create intricate and customizable forms, adapting to diverse user needs and aesthetic preferences. By defining specific parameters and variables, designers are able to generate an extensive range of design iterations. This dynamic process allows for exploring design alternatives and optimizing the overall design workflow.

Furniture designers often employ specialized software tools to achieve parametric designs that offer advanced computational capabilities. Autodesk's Generative Design, Grasshopper, and Rhinoceros 3D are commonly used software applications. These software platforms provide intuitive interfaces and powerful parametric modeling capabilities, allowing designers to edit and control the variables that define the design. In the furniture industry, parametric design has found diverse applications. It has been employed in the creation of chairs, tables, shelves, and other furniture pieces, enabling designers to explore innovative forms, intricate patterns, and structural efficiencies.

Parametric design in the furniture industry is essential for supporting sustainability. It can help designers use materials efficiently, minimize waste, and create eco-friendly furniture. By using specialized software tools, designers can customize furniture to meet individual needs,

make it adaptable, and extend its lifespan. Parametric design can also consider environmental factors like energy efficiency and user comfort, resulting in sustainable and practical furniture. Overall, parametric design in the furniture industry can help promote a sustainable approach, promoting responsible consumption and reducing environmental impact.

Heydar Aliyev Center, Baku, Azerbaijan: Designed by Zaha Hadid Architects

The Heydar Aliyev Center in Baku, Azerbaijan, designed by Zaha Hadid Architects, is a notable example of parametric design in architecture. The center's design features fluid and dynamic forms characterized by sweeping curves and smooth surfaces. Parametric design played a significant role in achieving these geometries, allowing for the creation of a structure that appears to be in constant motion. Zaha Hadid, an Iraqi-British architect, was renowned for her groundbreaking work in parametric design. She was a pioneer in the field, pushing the boundaries of architecture with her innovative and fluid designs. Hadid's architectural approach was heavily influenced by parametric design principles, which enabled her to create complex and organic forms that challenged traditional notions of space and structure. Her designs often incorporated biomorphic shapes, dynamic curves, and seamless transitions.

Figure 9. Heydar Aliyev Centre, Baku, Azerbaijan

Notes. Sourced from Zaha Hadid Architecture, Retrieved from https://www.zaha-hadid.com/architecture/heydar-aliyev-centre/

Figure 10. Heydar Aliyev Centre Conference Hall

Notes: Sourced from Architonic, Retrieved from https://www.architonic.com/en/project/mikodam-heydar-aliyev-centre/20175753

Parametric Furniture by CompassoAD, Italy

CompassoAD is an Italian design studio known for their parametric furniture. What sets CompassoAD apart is their ability to generate intricate designs that respond to specific parameters like user preferences and spatial constraints. This flexibility allows their furniture to be easily modified and tailored to individual needs. By combining advanced technology with traditional craftsmanship, CompassoAD creates unique and functional furniture that showcases elegant and organic forms inspired by natural geometries and patterns. Their parametric furniture has gained recognition internationally, positioning them as pioneers in this innovative field.

Figure 11. Parametric Furniture by CompassoAD

Note. Photo courtesy of CompassoAD Italy, Sourced from Big See, 2019, Retrieved from https://bigsee.eu/parametric-furniture-by-compassoad-italy/

Pipo Chair by Alejandro Estrada

The Pipo chair, a creation by Alejandro Estrada, stands as a subject for examination within the realm of parametric modeling in furniture design. Its Design is derived from a combination of natural materials, featuring a seat crafted from woven water hyacinth and a sturdy wooden frame. The chair's structural integrity is reinforced by its unique geometric design, incorporating triangular elements that distribute weight evenly and enhance stability. The designer believes that the use of renewable materials and traditional craftsmanship techniques evidence the chair's sustainable design ethos. The chair is made of two sheets of plywood. Composed of 29 main curved sections that are cut into two or three pieces overlapped, making it very efficient in the use of material.

Figure 12. Pipo Chair by Alejandro Estrada

Note. Sourced from Piegatto, Retrieved from https://www.piegatto.com/en/furniture/28-rest-chairs/4-pipo-chair

CHAPTER III: METHODOLOGIES

Design

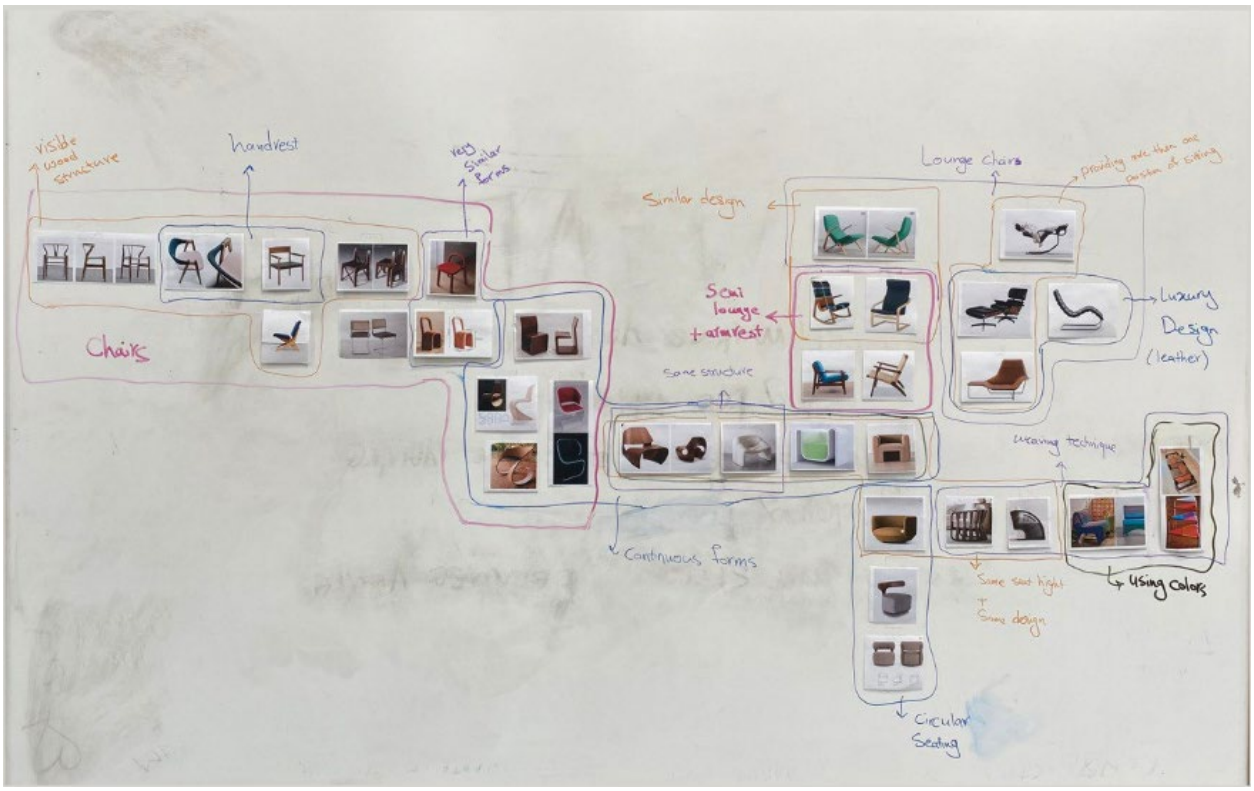
There were several crucial factors that required consideration during the design process of this chair. Careful attention was given to the environmental impacts associated with each stage throughout the design and assembly of the chair. Therefore, every aspect of the chair's design, materials used, and shape was meticulously examined to ensure minimal environmental harm.

The chair's construction relied mostly on the use of recycled cardboard sheets that are sourced from responsible facilities so that there was no toxic material used in the recycling process of the cardboard manufacturing.

The Process of Design

Visually captivating chair designs were examined, as depicted in Figure 10. Various aspects of these chairs, including purpose, materials, construction, and size, were carefully assessed. Factors contributing to their comfort or discomfort, such as design style, materials, and the ability to accommodate different body postures and movements while considering ergonomic principles, were also evaluated.

Figure 13. A Comparison between the Examined Chairs.



Regarding the form of the chair, the initial design was both straightforward and met the requirements for comfortable seating. One notable design characteristic was its ability to achieve a simple and transparent appearance. However, the absence of a backrest in this design could have potentially impacted its comfort level. Consequently, alternative designs were developed to better accommodate the ergonomic needs of individuals, considering the natural features of the human body.

Figure 14. Design Development Process in the First Selection

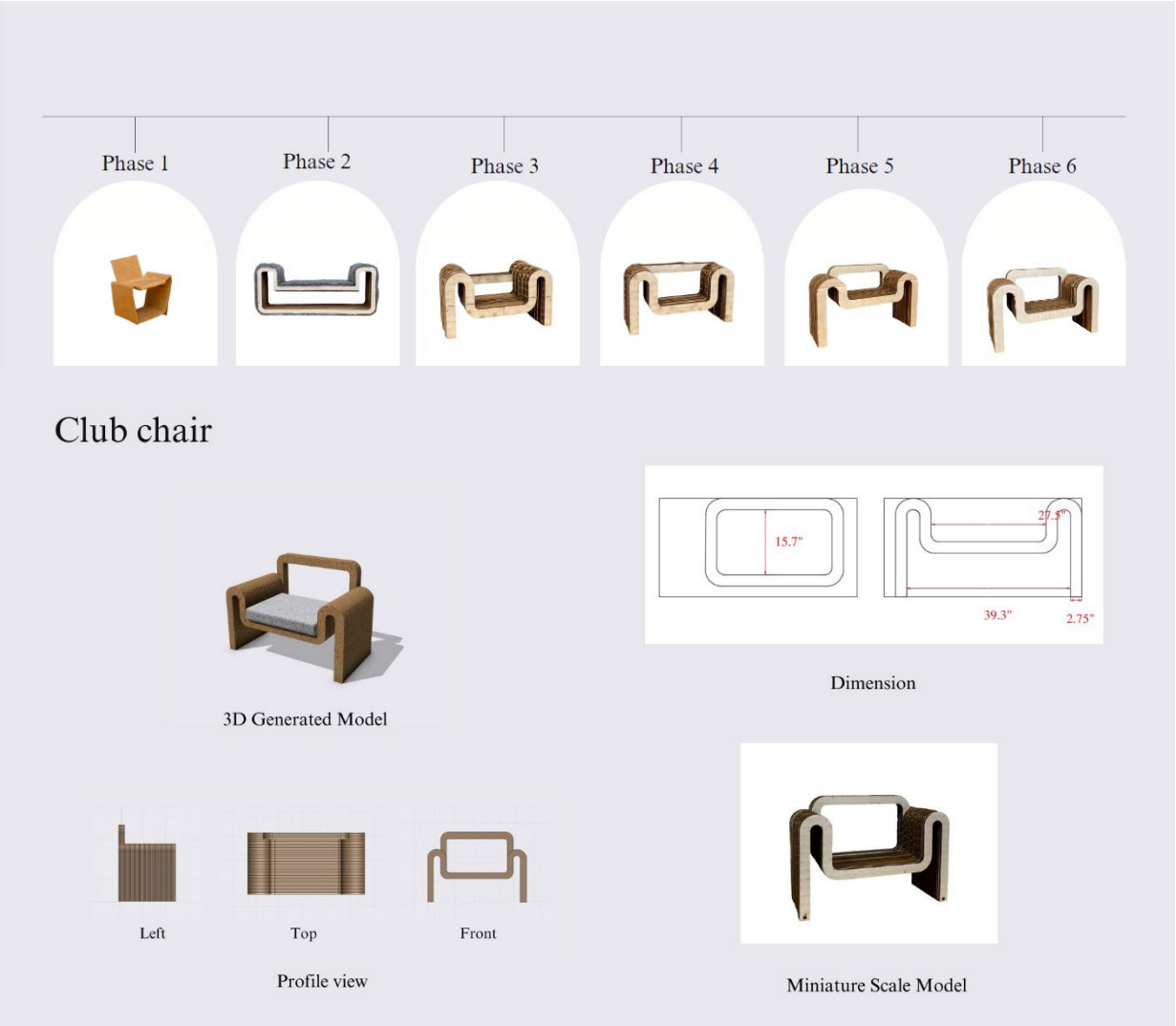
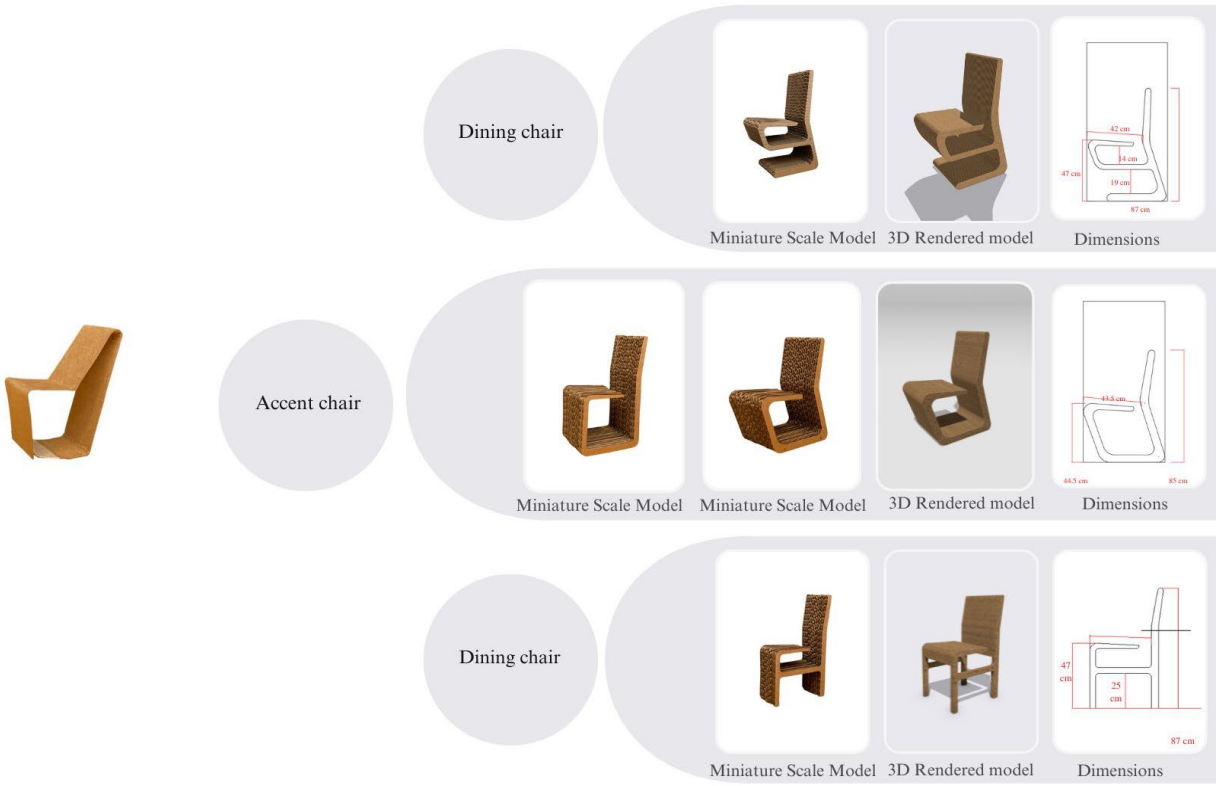


Figure 15. Design Development Process in the Second Selection



Throughout the process, ergonomic aspects such as dimensions and angles commonly associated with comfortable chairs were considered. Inspiration was drawn from successful seating designs across different time periods, and proficiency in using Rhinoceros 3D, a software for 3D computer graphics and computer-aided design, was developed to understand organic modeling concepts. This enabled the creation of the final shape of the chair.

Figure 16. 3D Model of the Final Design

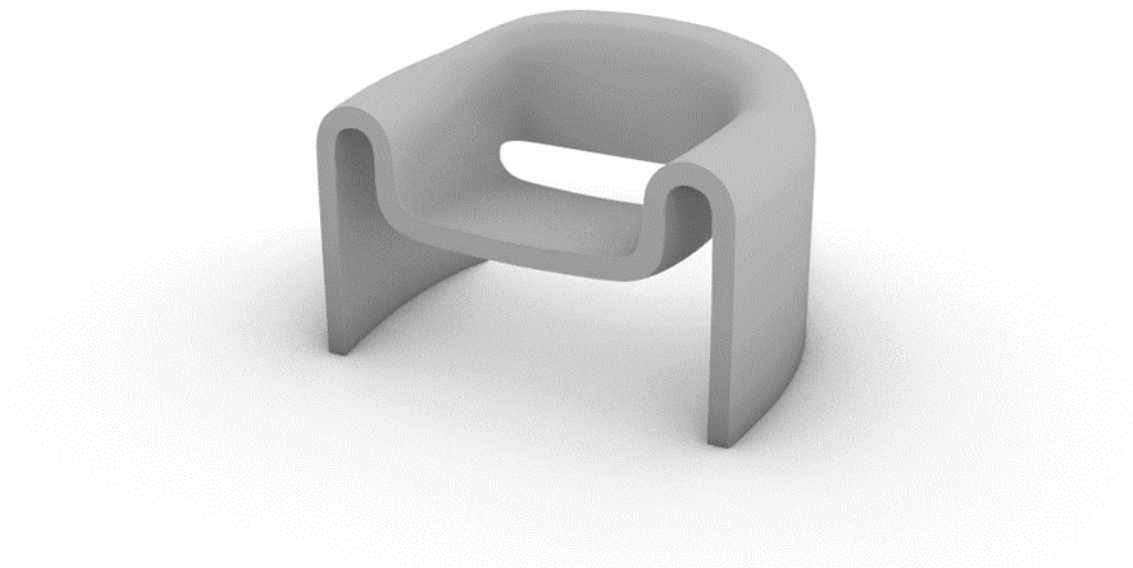


Figure 17. Top, Front, Right, and Perspective View of the Model

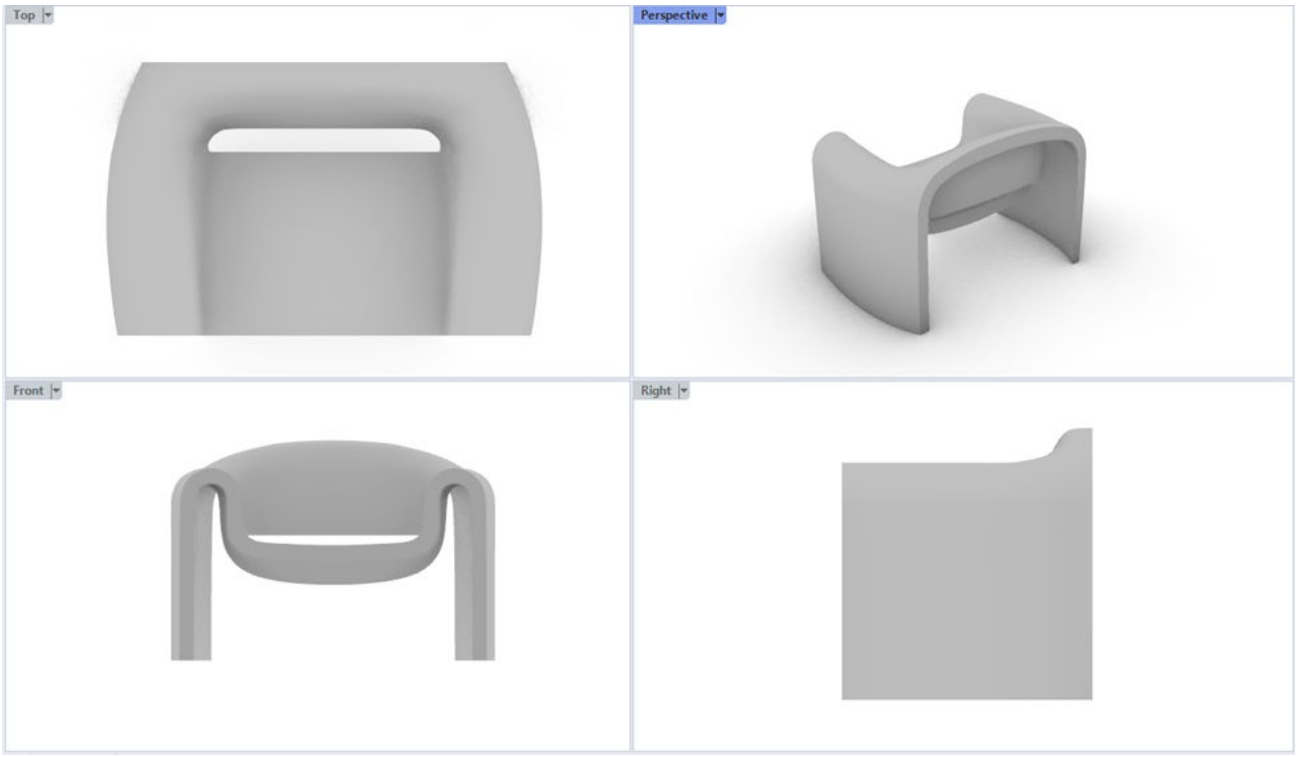
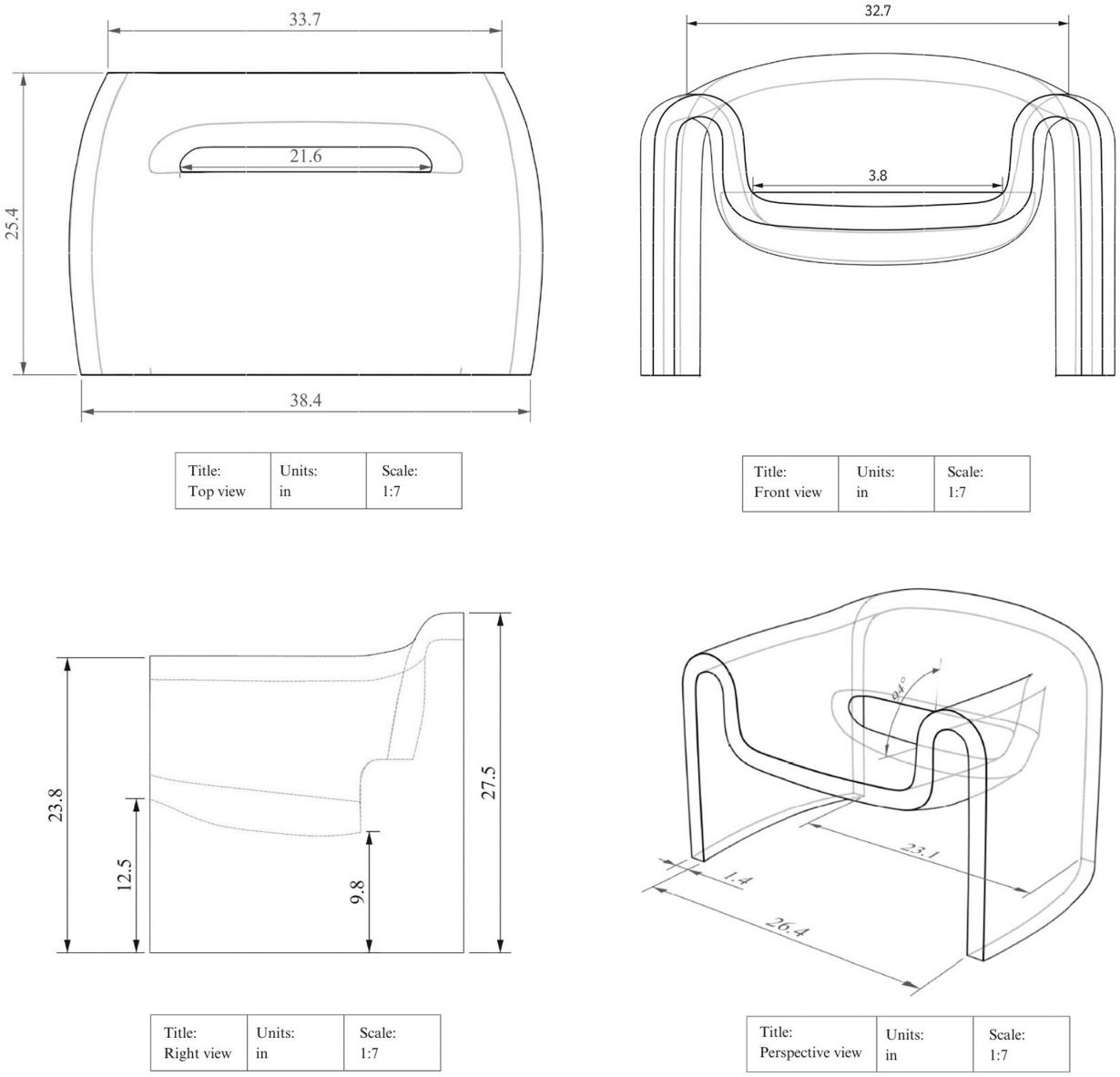


Figure 18. Measurement Diagrams



Analyzing Comfort in a Full-Scale Mockup

Creating a universally comfortable chair that accommodates diverse body types, preferences, and ergonomic needs presents a challenge. Nonetheless, the objective was to design chairs that provide a high level of comfort for a broad user base. Given the absence of cushions

in the chair design, ensuring comfort was of utmost importance. Therefore, the focus was on prioritizing ergonomic aspects and providing adequate support. Using the dimensions and angles from the 3D model, a full-scale prototype was constructed to evaluate its compliance with comfort standards. Final adjustments were made to improve both the chair's comfort and structural reliability.

Figure 19. The Mockup

To meet the criteria for fixability in the circular economy, the initial approach was to use wooden rods instead of adhesives to connect the cardboard layers. This strategy aimed to enable easy disconnection and recycling of defective layers. However, a technical issue arose, resulting in excess movement between each layer of cardboard, and consequently an unstable product. After extensive research and trial, it was concluded that sustainable adhesives should be used to

connect the layers, ensuring the recyclability of the entire chair. Four wooden rods were still incorporated into the design to aid the alignment accuracy of the layers.

Material

When considering materials for the chair, it was our top priority to choose eco-friendly options like recycled or renewable resources. This approach helps minimize harm to the environment and supports a circular economy. Furthermore, careful consideration was given to how the chosen materials would impact the chair's entire life cycle, from production to use to disposal. To simplify the recycling process at the end of their lifespan, three specific materials were utilized for this project. The focus was on using materials that can be easily recycled. This approach supports a closed-loop system, which reduces waste and minimizes the environmental impact. In addition to sustainability, factors such as durability, aesthetics, and comfort were taken into account during the material selection process. The aim was to ensure that the chosen materials met quality standards and contributed to both the functionality and appearance of the chair. By striking a balance between eco-friendliness and user satisfaction, the final product embodies responsible and sustainable design practices.

One hundred seventy-five layers of recycled cardboard, measuring 35 by 48 inches, with a thickness of 5/32 inches, was purchased from responsible recycling facilities. (Expenses covered by Greenfund scholarship)

Four FSC-certified wooden rods, each measuring 1/2 inch in diameter and 25 inches in length.

One gallon of Titebond III Ultimate Wood Glue. This water-based glue is environmentally friendly, with low levels of VOCs and non-toxic properties.

UNCG Sustainability and Greenfund

UNCG Sustainability is an initiative at the University of North Carolina at Greensboro dedicated to promoting sustainable practices on campus. They actively support student-led projects focused on sustainability. Following the review of my thesis proposal by the UNCG sustainability committee members, the chair was awarded a $1000.00 Greenfund grant for the sustainable seating project.

The Greenfund funding is allocated towards acquiring cardboard and lumber supplies for the project. Additionally, as a condition of the award, the Greenfund Committee has requested my collaboration in showcasing and exhibiting the chair for an unspecified duration. The committee aims to utilize the project as a means to stimulate discussions on personal consumption and environmental lifecycle assessments.

Layering Process and Developing Parametric Properties

To enhance the manufacturing process, Grasshopper, an advanced parametric modeling tool integrated within Rhinoceros 3D, was utilized. Through Grasshopper, a script was developed using generative algorithms, enabling precise cutting of layers to the desired thickness. Each layer was assigned specific numbers and separated into 175 separate planes measuring 35" by 48". Importing the model into Grasshopper provided the advantage of automatically reflecting any subsequent modifications on each cutting sheet. Additionally, the automatic sorting and numbering of the sheets greatly minimized the potential for human errors during the process.

Figure 20. Grasshopper Script

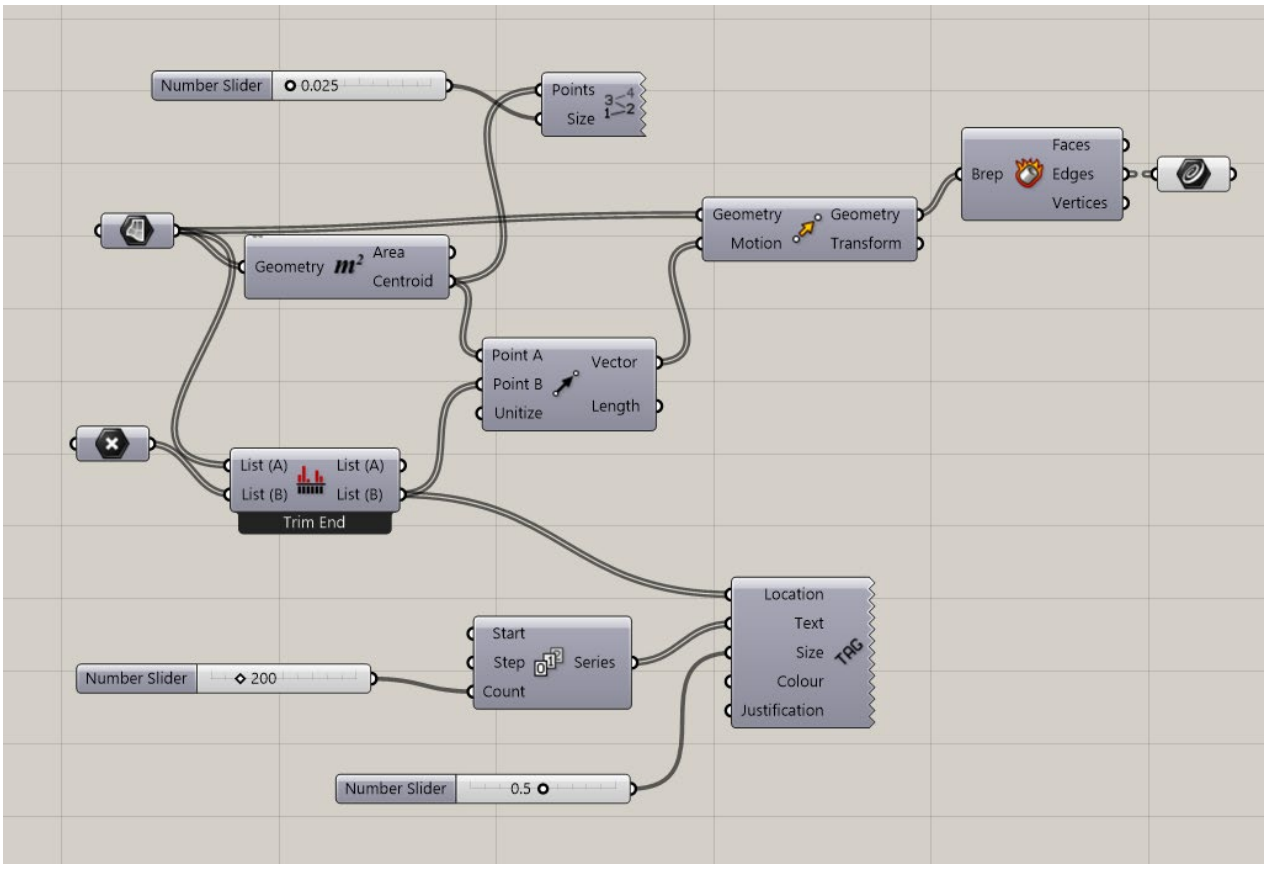


Figure 21. The Result of the Grasshopper Script

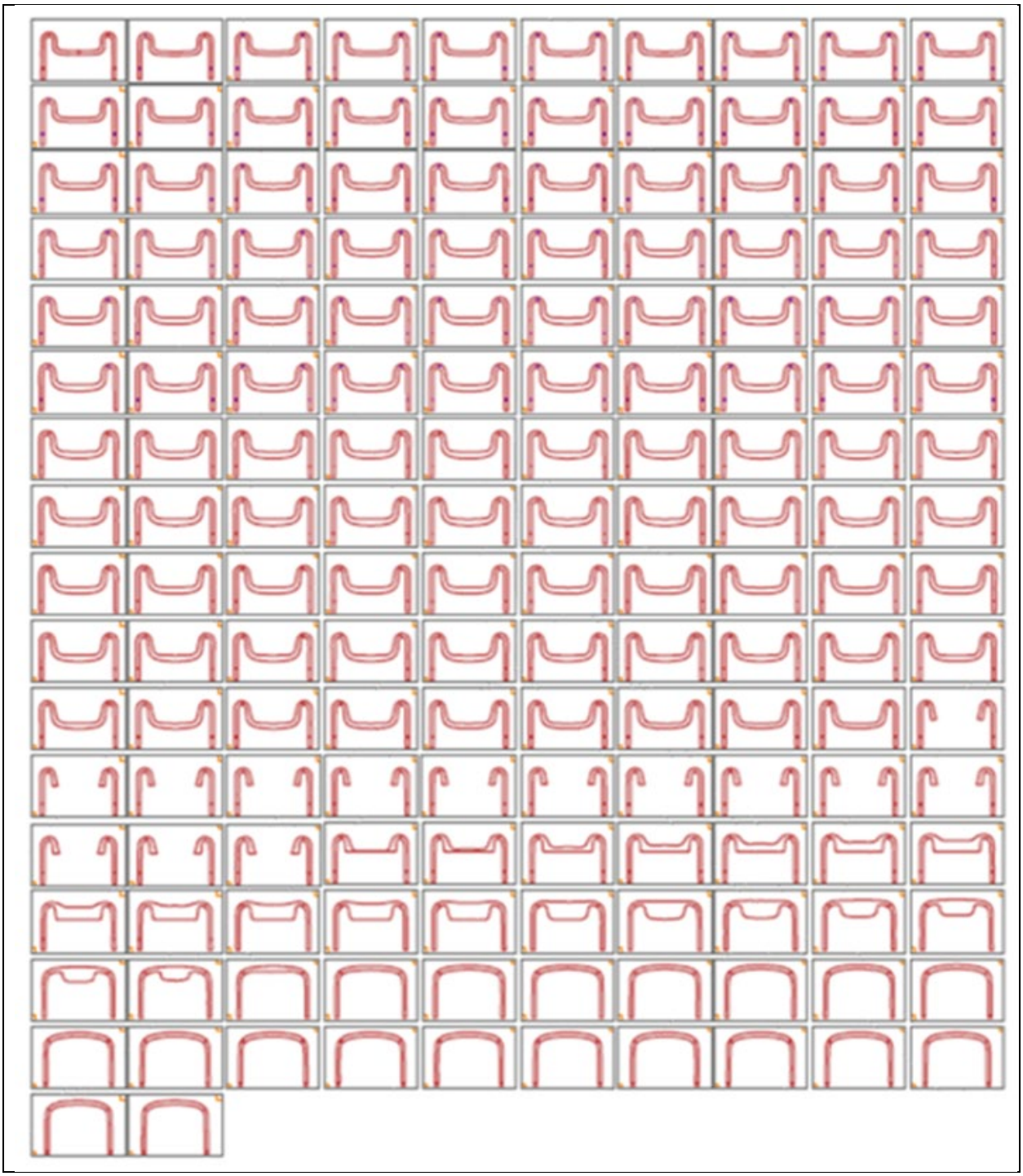
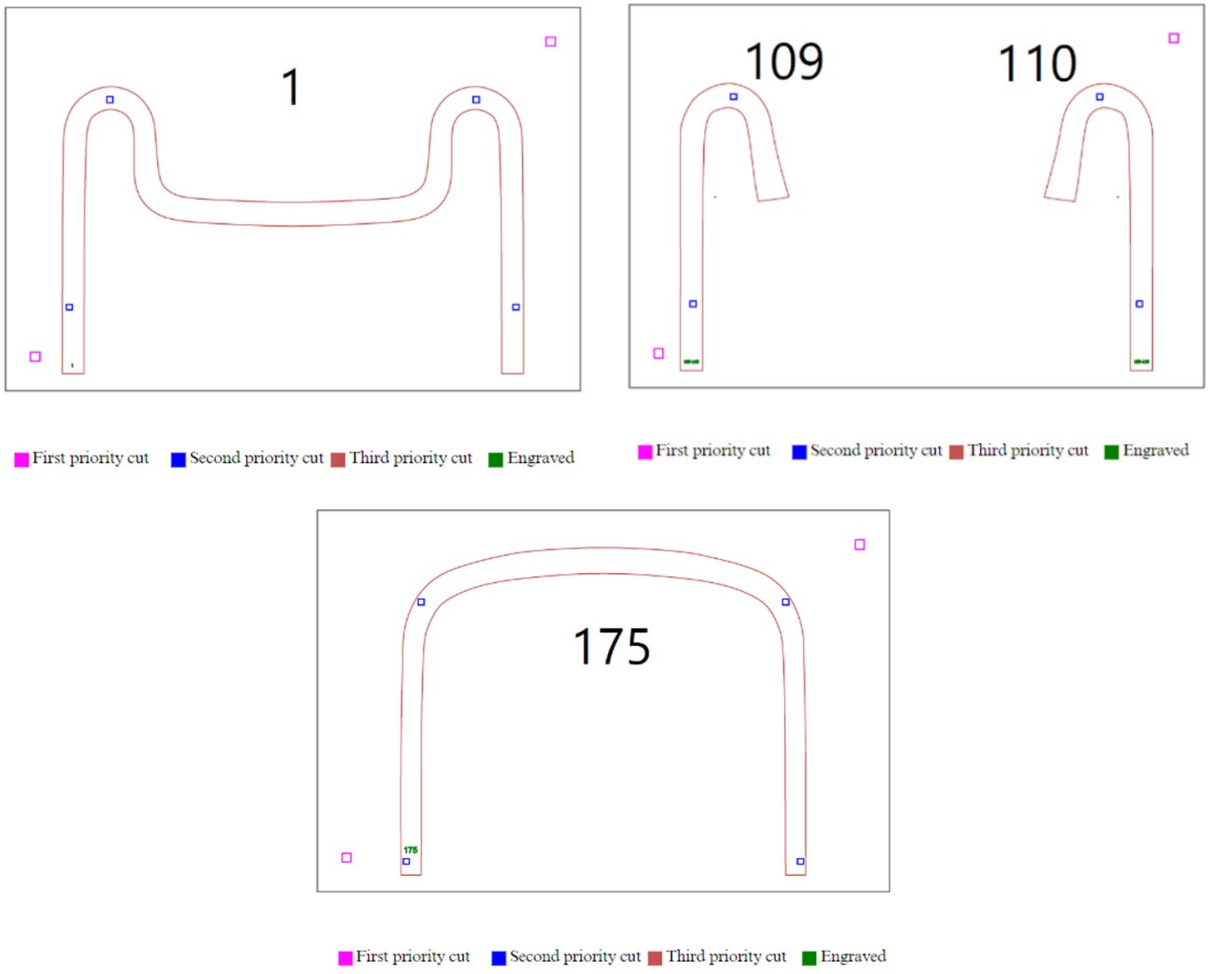
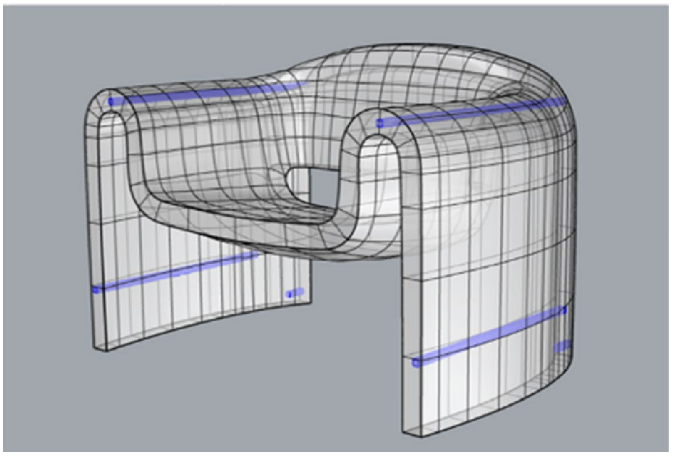


Figure 22. More Detailed View of the Layers



To enhance structural alignment, I designed four wooden rods to be installed, aiding in the positioning of the layers. As illustrated in Figure 18, Six 1/2-inch squares were cut in the cardboard to facilitate the installation of these rods.

Figure 23. Wooden Rods Embedded in the Design.



For the laser cutting stage, the Rabbit laser cutter machine (model number RL-XX-9060) at the Mixxer community maker space in Winston-Salem, NC, was employed. This laser cutter has dimensions of 35" by 45". To import the layout, make edits, and operate the laser cutter, LightBurn software was utilized.

On average, it took approximately 3.5 minutes to cut each layer, prepare the rods, and engrave the layer numbers. The entire process was successfully completed within a span of 5 days.

Figure 24. Numbers Engraved on Each Sheet

Construction Process

The process of assembling the cardboard involved a considerable amount of time and precision, as 175 layers needed to be glued together. Careful handling was necessary to achieve the desired outcome. It was crucial to apply wood glue evenly across all sections of each layer, while also preventing any leaks or excess glue from seeping out of the seams. Once the glue set, it formed a permanent bond that could not be undone. To aid in the gluing process, weights were placed on top of each layer after it was glued, ensuring a proper connection between the layers without exerting excessive pressure that might cause the cardboard to bend. Each layer required a substantial drying period. The construction process of the final prototype lasted for six days.

Figure 25. Gluing Process

Figure 26. Final Prototype, Isolated Shot 1

Figure 27. Final Prototype, Isolated Shot 2

Figure 28. Final prototype, Lifestyle Shot

Figure 29. Final Prototype, Scale Shot

CHAPTER V: RESULT

Process Reflection and Evaluation

Over a span of two years, dedicated research focused on design and material was conducted, resulting in the creation of multiple prototypes and models. The primary objective was to develop an optimal design that prioritized comfort, ergonomics, and the efficient connection of cardboard layers. Throughout this careful process, great importance was placed on considering sustainability at every stage, including material selection, minimizing waste, and optimizing energy usage. As a result, the chair achieves a remarkable level of stability, capable of enduring a considerable amount of weight. Furthermore, it offers exceptional comfort and radiates an aesthetically pleasing appearance.

Durability

While it is true that the cardboard chair may be prone to dents and its appearance may not stay as pristine as when it was new, and over time, the chair may show signs of wear and tear, the primary focus on sustainability remains paramount. The chair's purpose as a sustainable furniture piece can still be fulfilled, and the natural changes in its appearance can add character and a unique aesthetic, telling a story of its usage and contributing to its overall charm.

Cutting Process

While laser cutters are easily accessible machines almost everywhere, it is essential to recognize that laser cutting demands a substantial amount of energy. However, the overall energy consumption depends on factors such as the size and complexity of the chair design, as well as the efficiency of the laser cutter. It is worth noting that advancements in laser-cutting technology continue to improve energy efficiency.

There are potential alternatives that offer more environmentally friendly options. Die cutting, for instance, is a cutting method that could be considered as it can offer benefits in terms of energy consumption and speed. Die cutting involves using a specially designed die to cut materials, such as cardboard, into desired shapes. Compared to laser cutting, die cutting generally requires less energy and can be quicker in certain scenarios. Research conducted by Smith et al. (2020) found that a die-cutting machine was capable of cutting approximately 50 sheets of cardboard per minute. This efficiency in production could help reduce energy consumption and increase productivity. However, it is important to note that die-cutting may not have been feasible for this specific project, as each layer of the cardboard chair was unique. Die cutting typically requires uniformity in the shapes being cut. Therefore, laser cutting was a more suitable method for achieving the desired customization and complexity in the layer designs.

Waste

Regarding waste generation, laser cutting is a subtractive process that can result in significant waste, particularly when working with materials like cardboard. In fact, the waste generated for making this chair was heavier than the chair itself. However, waste can be managed and minimized through careful design planning and optimizing the cutting process. Implementing recycling initiatives, where the cardboard waste can be collected and recycled into new cardboard products, further reduces the environmental impact.

Another option is to use the extra space within each sheet to design multiple objects at the same time. This not only reduces waste but also lowers energy usage. Although this approach was initially desired for the project, it was time-consuming and couldn't be completed within the timeframe of the thesis project.

Parametric Modeling

Parametric design played a crucial role in the sustainability of the cardboard chair project. By utilizing mathematical algorithms and computational tools, I was able to create flexible and adaptable designs. This approach optimized material utilization, reduced waste, and improved resource efficiency during the construction process. Each of the 175 layers of cardboard was carefully engineered to provide strength and stability, ensuring the chair's functionality and durability. Parametric design can also allow for customization to meet various body types, ergonomic needs, and aesthetic preferences. This approach maximized the lifespan of the chair and promoted sustainable practices by reducing the need for frequent replacements. Ultimately, parametric design enabled us to harness the unique qualities of cardboard and create an eco-friendly seating solution.

Challenges and Limitations

It is important to acknowledge this chair's limitations regarding fire resistance and water resistance. Cardboard is susceptible to moisture absorption and can easily get damaged when exposed to water or high humidity. This restricts its usage in environments where moisture is a concern, such as outdoor settings or areas prone to spills. It is worth noting that achieving fire and water resistance typically involves the use of specific ingredients and sprays that can compromise the recyclability of the chair.

To enhance the chair's ability to withstand fire, certain chemical additives like flame retardants or fire-resistant coatings are commonly used. However, these additives often contain substances that make the chair less recyclable, such as halogenated compounds or heavy metals. Similarly, achieving water resistance may involve using coatings or sealants with chemicals that are not easily recyclable. It is important to carefully consider the trade-offs between fire

resistance, water resistance, and the overall sustainability goals of the cardboard chair. While additives can make the chair more fire and water resistant, they may go against its purpose as an eco-friendly solution and hinder its recyclability. In this project, the main focus was on sustainable manufacturing processes, recyclability, and the use of environmentally friendly materials, while acknowledging the chair's limitations in terms of fire and water resistance.

Future Directions

For this project, various eco-friendly glue options like rabbit glue, fish glue, cornstarch glue, and soy-based glue were considered as adhesives. However, the adhesives mentioned, lacked sufficient research regarding their strength and how they react with cardboard, making them less reliable choices. Therefore, I chose water-based wood glue due to its established strength and suitability for this type of application. It is worth noting that wood glue requires sufficient drying time, which resulted in some deformation in certain parts of the chair. Moving forward, further research and experience are required to identify the adhesive that offers optimal strength and sustainability. However, as mentioned before exploring alternative techniques for connecting the layers, apart from gluing, would be preferable to allow for disassembly and enhance the chair's ability to be fixed.

There is potential for further research and investigation into exploring various types of corrugated cardboard and their combinations. This includes examining double wall or triple wall cardboard, as well as experimenting with different flute sizes. The utilization of A flute cardboard with a flute height of 1/4", B flute cardboard with a flute height of 1/8", E flute cardboard with a flute height of 1/16", and F flute cardboard with a flute height of 1/32" would yield distinct outcomes in terms of design, aesthetics, comfort, cutting process, construction, layering process, and the energy required for cutting.

Additional experimentation and testing are required to refine the integration of rods into the design. It is crucial to explore the dimensions of the rods, identify the optimal positions for their placement, and determine the appropriate quantity to minimize their visibility. The current utilization of rods has resulted in some unintended deformation of the chair's overall form. Hence, further investigation is necessary to address and mitigate these unforeseen consequences. Additionally, it would be advantageous to consider using corrugated cardboard as wooden rods in the design. This modification would facilitate the recycling process and contribute to enhanced sustainability.

Further experimentation with alternative designs is also highly valuable. By incorporating parametric layering techniques, we can explore their application beyond just seating design and extend it to other furniture pieces. This exploration allows us to create innovative and distinct designs that challenge traditional furniture manufacturing methods. It opens up opportunities to experiment with different shapes, materials, and structures, resulting in furniture that is both visually appealing and functional. It is also worth mentioning that Parametric design, when effectively managed, offers a promising avenue for waste reduction. By embracing parametric design principles, we have the opportunity to not only reduce waste but also explore the utilization of environmentally friendly materials such as FSC-certified woods or cork. Incorporating these materials expands the scope of this study and allows us to push the boundaries of sustainable furniture design. By incorporating parametric design and selecting eco-friendly materials, we can contribute to a more sustainable and responsible approach to furniture production.

CHAPTER VI: CONCLUSION

The research and development of the eco-conscious cardboard chair project have yielded remarkable results. The careful process of designing and layering cardboard has led to the creation of a chair that excels in comfort, stability, and aesthetics. Throughout the project, sustainability was a top priority, evident in the consideration of material selection, waste reduction, and energy optimization. The chair's durability, although prone to natural wear and tear, aligns with its purpose as a sustainable furniture piece, adding character and a unique aesthetic that tells the story of its usage. The cutting process, while requiring energy consumption, can benefit from advancements in laser-cutting technology or alternative methods like die-cutting to enhance energy efficiency. Waste management strategies, such as recycling initiatives, help mitigate the environmental impact of waste generated during the construction process. Parametric design has played a crucial role in achieving sustainability goals, maximizing material utilization, and enabling customization. However, it is important to acknowledge the limitations of cardboard, particularly in terms of fire and water resistance, and carefully consider the trade-offs between these properties and overall sustainability. Future directions include further research on eco-friendly adhesives, exploring alternative techniques for layer connection, and enhancing the chair's fixability through disassembly. By continuing to refine and innovate in eco-conscious furniture design, we can contribute to a more sustainable and environmentally friendly future.

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