THREE-DIMENSIONAL CLADDING WITH BIO-BASED MATERIALS:

a parametric design following the seamless tiling concept

Master Thesis in Building Technology

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_ ABSTRACT

The development of three-dimensional cladding in architecture has witnessed significant advancements, particularly from the computer-driven design era, which started to enable the creation of intricate and elaborate shapes. However, examining various case studies has revealed the considerable environmental impacts of the materials typically employed in three-dimensional cladding. These impacts include material extraction and production, energy consumption, waste generation - and further carbon emissions - underscoring the urgent need to address these challenges.

This research aims to investigate and develop a design solution rooted in circular principles for mitigating the environmental impact of the construction industry and promoting waste-driven design. To this end, bio-based materials produced through a moulding process have been identified as promising alternatives with lower environmental footprints.

The adoption of circular strategies, including modularity and flexibility, dematerialization, the use of safe and circular materials, and design for disassembly, serves as the guiding framework for enhancing sustainability in the three-dimensional cladding. As a specific design solution, the concept of *seamless tiling* has been developed, enabling the continuous pattern and flexible placement of modular panels within the facade while ensuring versatility. Applying parametric design techniques is instrumental in realizing the modular panel system and accentuating its adaptability by creating diverse and versatile façade configurations that exemplify the system's adaptability and flexibility.

Finally, to validate the material's performance within the developed design, a prototype will be constructed and evaluated. This empirical testing will provide insights into the proposed design solution's practicality, feasibility, and effectiveness, serving as a vital step towards practical implementation.

This academic research contributes to the discourse on sustainable architectural practices by advocating using bio-based materials with moulding and integrating circular design strategies in the three-dimensional cladding. Through the comprehensive exploration of these approaches, the study aims to advance the understanding and realization of how three-dimensional architectural interventions can be developed with minimized impacts and, eventually, fostering a more sustainable built environment while maximizing design flexibility.

_ ACKNOWLEDGEMENTS

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To my mom, who may still believe my thesis is about eggshells, nevertheless remains my number one fan.

To my dad, for his determination, calmness, and unwavering support during challenging times.

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It is crucial to acknowledge those who have assisted in the realization of this research. However, it is equally important to recognize that the achievements you are now celebrating are entirely yours. Even if you may not fully realize it, this success belongs to you.

As your mom always says, *“if you truly desire something, I am certain you will achieve it, whatever it may be.”,*

and guess what? She was right.

_ ACRONYMS

CE	Circular Economy
CNC	Computer Numerical Control
DFD	Design for Disassembly
EDM	Elecritical Discharge Machining
EMF	Ellen McArthur Foundation
EoL	End of Life
GFRC	Glass Fiber Reinforced Concrete
GHG	Global Greenhouse Gas Emissions
IRP	International Resource Panel
LCA	Life Cycle Assessment
OECD	Organization for Economic Co-operation and Development
PA	Polyamide
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PP	Polypropylene
PVB	Polyvinyl Butyral
VIP	Vacuum Infusion Process

1. INTRODUCTION

2. LITERATURE RESEARCH

1_ INTRODUCTION

1.1_ CONTEXT

Architects and engineers have been exploring new planning possibilities in recent years by employing sophisticated design, material, and manufacturing techniques. These advancements have allowed for the realization of complex designs beyond the traditional constraints of form composition.

This pursuit of pushing boundaries is reminiscent of the mindset that emerged during the 80s and 90s architectural movements. During this period, architectural movements like Deconstructivism and Blobitecture challenged the conventional notions of form and structure by creating complex and non-rectilinear forms. These movements embraced a sense of exuberance and free-form discovery, inspiring architects and engineers in recent years. (Craven, 2018).

Therefore, these innovative designs have been followed by new technologies and tools developed in the XXI century, which helped designers easily visualize such three-dimensionalities configurations in a very short time: Computer-driven Design.
This technological advancement has further expanded the boundaries of architectural expression and creativity (Manahl et al., 2012).

These mentioned forms shapes predominantly find their manifestation in the external layer of the building, known as the *cladding*. The choice to focus on the cladding arises from its significance as the outermost layer that interfaces directly with the surrounding environment.

Furthermore, it is crucial to recognize that the production of these complex three-dimensional elements can have a significant environmental impact in terms of materials and manufacturing processes. Consequently, there is a growing need to analyze and study cladding, particularly concerning the four domains of circularity: *design*, *material*, *manufacturing*, and *management* (Fig. 2).

By adopting a circular approach to cladding *design*, architects and engineers can minimize waste, optimize material usage, and facilitate easy replacement of single elements.

In terms of *materials*, a circular approach entails evaluating a low-impacting material by analyzing its life cycle assessment (LCA), from its raw material extraction to its End of Life (EoL).

The *manufacturing* phase also plays a crucial role in achieving circularity in cladding. Implementing efficient and resource-conserving manufacturing techniques can help reduce energy and material consumption, waste, and overall environmental impact (Fig.1).

Management is the fourth domain of circularity which involves strategic decision-making, coordination, and collaboration among various stakeholders to ensure the successful integration of circularity principles (Ioannou et al., 2022).

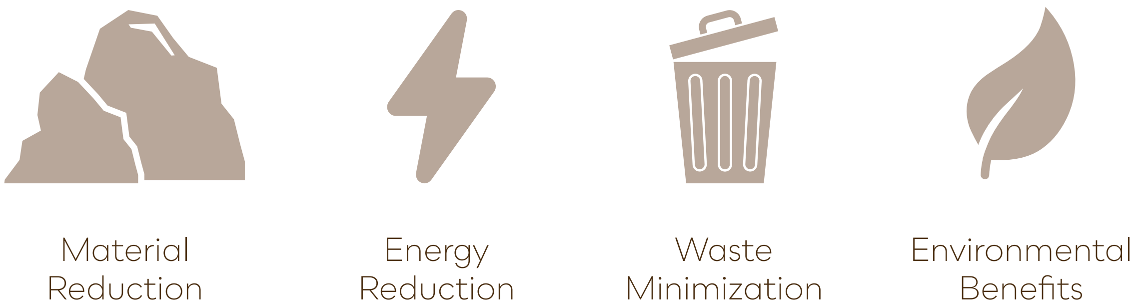


Figure 1. Circular strategies benefits, own ill.

The graduation research will consider the first three domains as the basis for conducting a literature review, performing analysis, and guiding further design aspects. These domains provide a comprehensive framework for the research, ensuring a well-informed and methodologically sound approach to the study.

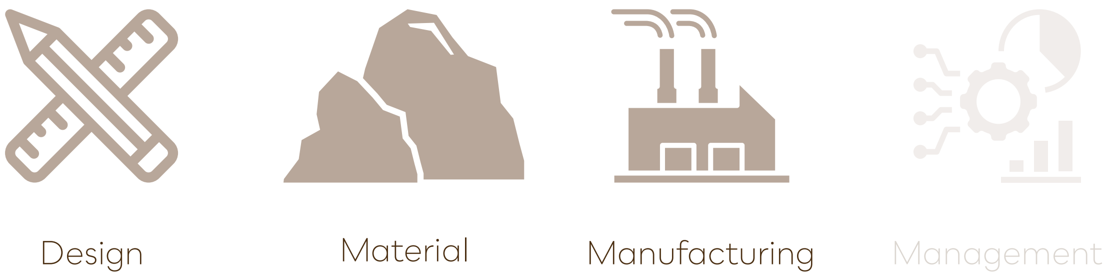


Figure 2. Four Domains of Circularity, Illustration adapted from Circular Product Design Lecture by O. Ioannou , 2022

CIRCULARITY

Circularity is a system aiming to tackle environmental challenges, including pollution, waste, biodiversity loss, and climate change (Ellen McArthur Foundation [EMF], n.d.).

The circular economy (CE) has been enhanced lately in contrast to the *take-make-waste* linear model - as represented in Fig. 3 - in which production and consumption are the main focus, leading to drastic impacts on the planet.

CE principles are founded on optimizing resource productivity while minimizing waste by designing out of it. Embracing circular design focuses on harnessing the potential to create new products or materials through continual reuse (Fig. 4) (EMF, n.d.).

This concept aspires to the ideal Cradle to Cradle principle developed by William Mcdonough and Micheal Braungar. The core idea behind Cradle to Cradle is to shift from the traditional Cradle to Grave linear model - where products are created, used, and discarded as waste - to a Cradle to Cradle circular model. (EPEA, n.d.) (Guldager Jensen et al., 2016).

Thus, materials are no more considered as matters to be used and thrown away once there is the product end of life. However, they start becoming resources that can be, at best, reused or treated with one of the other products' end-of-life solutions, which are collected in the R-strategies (Fig. 22) (Potting et al., 2017) (Guldager Jensen et al. et al., 2016). In this way, the material cycle reduces material use, waste collection, energy consumption, and consequent carbon footprint emissions.

In recent years, there has been a growing recognition of the environmental impact of the construction industry, leading to the introduction of circular economy principles in building practices. One particular focus has been on designing buildings to facilitate repair and replacement without compromising the integrity of the elements and materials used - *Design for disassembly* (Fig. 4).

Regarding circular principles, the cladding requires special attention as it is directly exposed to the environment. Due to its vulnerability to weather conditions and wear and tear, the cladding is prone to damage and eventual rupture.

Consequently, this layer presents increased chances for the consumption of new materials, energy, and waste accumulation, highlighting the importance of prioritizing circular strategies to prevent further environmental degradation.

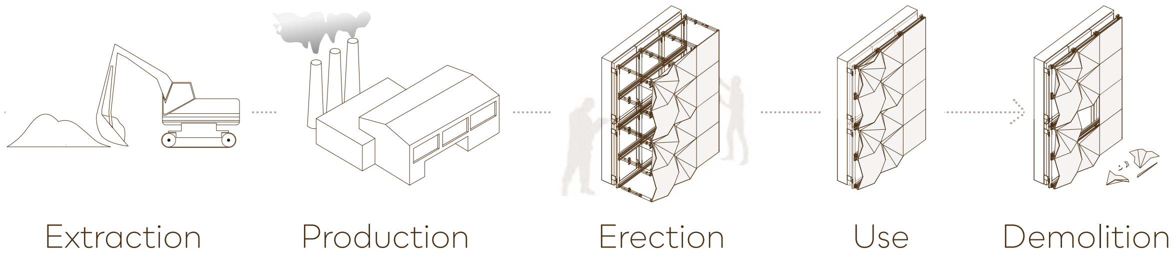


Figure 3. Linear Economy Illustration
own ill.

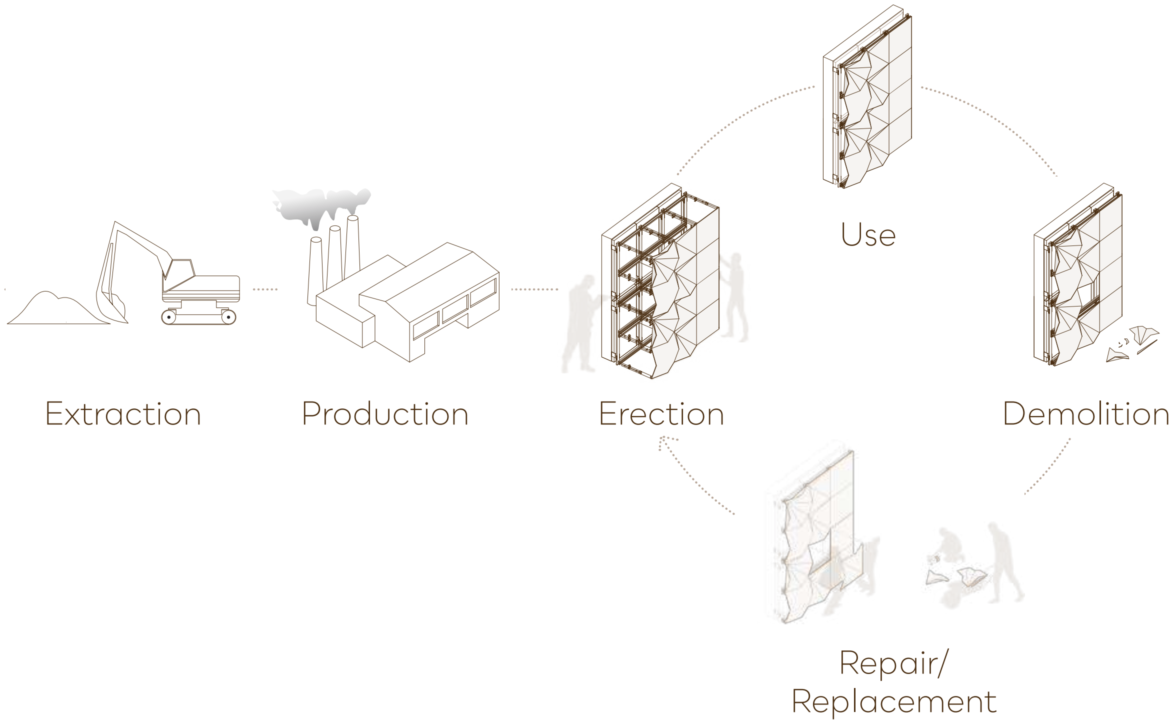


Figure 4. Circular Economy Illustration
own ill.

CLADDING

Cladding plays a vital role in protecting the external walls of a building, safeguarding its inhabitants from the harsh effects of the environment. It acts as a shield attached to the primary structure and serves as a defensive layer (Reardon, 2013).

Cladding comes in various forms and can be categorized as elements that interfaces the external or internal, which will be further labeled as *external* and *internal cladding*. External cladding shields the building envelope from external factors such as rain, wind, sunlight, temperature fluctuations, and pollutants. It acts as a barrier, preventing moisture penetration, reducing heat loss or gain, and enhancing energy efficiency (Knaack, et al., 2007) (Polo, n.d.) . On the other hand, internal cladding is used for decorative - enhancing the aesthetic appeal of the internal spaces -acoustic and insulative purposes, or as spaces dividers (Taylor, 2022).

In terms of its physical characteristics, cladding can be two or three-dimensional. Two-dimensional cladding is typically a flat surface covering the walls, while three-dimensional cladding offers a textured and intricated appearance : the research will focus on three-dimensional cladding.

THREE-DIMENSIONAL CLADDING

From a geometric perspective, three-dimensional cladding can be categorized as high-relief or bas-relief, depending on the volumetric depth along the third axis.

Cladding designs can vary significantly, offering a multitude of configurations. These designs are influenced by the desired functionalities, which can range from emphasizing the conceptual expression of the building to optimizing energy requirements - the mentioned statement has been said after case studies analysis explained in Chapter 2.

In recent times, three-dimensional claddings have predominantly been constructed using modular panels. This approach facilitates the production of complex cladding systems and contributes to creating buildings that align with principles of circularity. Modular panels enable easier assembly and disassembly, promoting flexibility, sustainability, and efficient use of resources (Nowak T. et al., 2018).

MODULARITY

A modular design comprises *standardized components* or units that can be assembled to realize a product.

Standardized components are created following specific protocols with the consensus of all the stakeholders in the industry. In this way, they are composed in such a way as to fit into modules, avoiding the creation of *integral* and non-interchangeable products (Ioannou et al., 2023)(Klein, 2023) (Nowak T. et al., 2018).

Modularity is a circular principle recently introduced in the building industry because of its several benefits.

For instance, by adopting modular design, it is possible to make refurbishment, repair, and upgrade much easier what has to be fixed, prolonging product lifetimes and lowering the number of products and resources that become waste too soon (Meilani, 2019). These results are because modular elements are easily replaced when damaged or up to date, simplifying the disassembly and reassembly processes (Fig. 4) (Campagnolo et al., 2010) (Mazahit et al., 2011).

Additionally, modularity brings about cost and resource savings throughout the entire life cycle of a product or system by reducing the number of processes required to produce its constituent elements. This reduction in processes not only minimizes expenses but also contributes to a decreased carbon footprint (Gershenson et al., 1999) (Kremer et al., 2013).

Lastly, this principle simplifies the manufacturing process because of its more accessible and repetitive design that can fit to accomplish more complex ones (Guldager et al., 2016).

To generate and evaluate the most performant designs to facilitate modular system realization, computational design can help. By utilizing algorithms and simulations to optimize the performance, assembly, or configuration of modules, it would be possible to modify parameters to make fabrication modular and more efficient in terms of time, costs, and impacts (Austern et al., 2018).

The computational design field that changes with specific settled parameters is *parametric design*.

PARAMETRIC DESIGN

Parametric modeling involves creating geometric elements with editable attributes, known as design variables. These attributes are expressed using parameters, allowing for seamless swapping of values. This flexibility opens up many possibilities for generating diverse design solutions and enables the rapid visualization of alternative designs (Turrin et al., 2016).

Optimization algorithms can be employed to determine the most optimal variation from the extensive range of solutions. The optimization process involves systematically testing these solutions to achieve the highest possible performance while adhering to specified constraints (Baños et al., 2011). The fields where parametric design and potential optimizations can be used are plenty.

Regarding circularity, computational optimizations can promote the most high-performing design that spreads material and energy use minimization.

These performances can inspect material explorations, understanding how the structural properties can withstand the most efficient design using the least amount of material; moreover, they can be about design explorations, and therefore, creating a design that facilitates modularity and flexibility; finally, they concern on general efficiency exploration aimed at reduction of material, energy, and waste during the manufacturing process (Tedeschi, 2014).

In conclusion, having settled design criteria and parametric geometry, the choice of the material needs to take into the design phase for both the extraction and production understanding of the effective panel manufacturing realization and the environmental impacts.

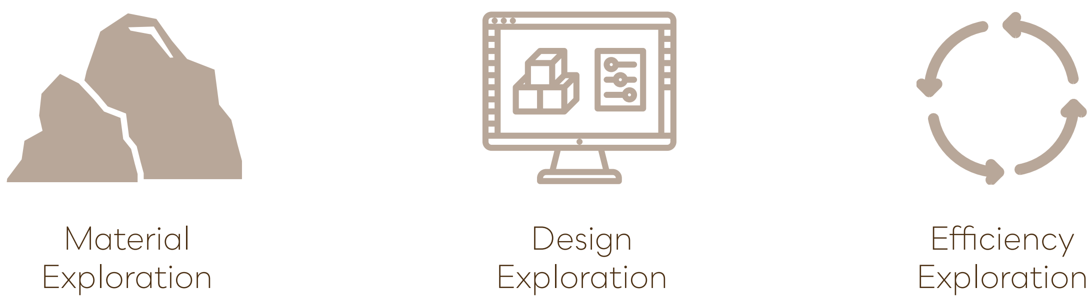


Figure 5. Parametric Design Benefits regarding Circularity own ill.

BIO-BASED MATERIALS

Between the extended range of potential materials, attention is given to bio-based for several reasons in terms of sustainability.

Biobased materials are made from substances generated from living matter (biomass) and consider renewable resources (EPA, 2014).
Moreover, they generally do not need energy-intensive productions to be realized, and they can be treated to be easily reused or repurposed; they can also return to their biological cycle by composition after their EOL (end of life) (CoE BBE., 2021);
Lastly, they can be made of either local renewable resources or waste streams to decrease landfill and transportation emissions sharply.

Therefore, the production of bio-based materials, life cycle management, and waste management can be linked to having a relevant positive impact on the environment (Brunklaus, 2018).

Historically speaking, they have been used from the beginning of civilization. Although these materials have a prolonged historical usage, they were overshadowed by materials like steel and iron during the Industrial Revolution. However, in the 21st century, there has been a renewed recognition of bio-based materials' environmental and sustainability benefits, prompting their resurgence as a valuable resource in construction.

To summarize, a careful analysis of the potential impact of bio-based materials will guide the selection of the most suitable option for the new design. Additionally, it is crucial to consider the environmental consequences of the manufacturing process when striving for a more circular approach.

Figure 6. Bio-based materials properties, own ill.

MANUFACTURING PROCESS

Manufacturing processes play a pivotal role in achieving feasible designs with a positive environmental impact. To create high-performing and sustainable designs, it is imperative to have a comprehensive understanding of the manufacturing processes involved.

By gaining insights into the realization of products (Fig.A_3) and comprehending how these processes impact the planet, designers can make informed decisions that lead to the creation of more efficient and circular designs.
Specific processes, such as metal smelting and refining, chemical manufacturing, cement production, and glass manufacturing, have significant environmental footprints, consuming substantial energy and resources (Chryssolouris et al., 2021) (Ift Rosenheim, 2019).

Choosing a manufacturing process that aligns with the complexity of the design, the material choice, and enables the implementation of circular strategies is crucial. Hence, when considering bio-based materials, a thorough analysis will be conducted to identify the most relevant manufacturing process that best suits the objective of reducing material consumption and minimizing waste generation (Fig. 7).

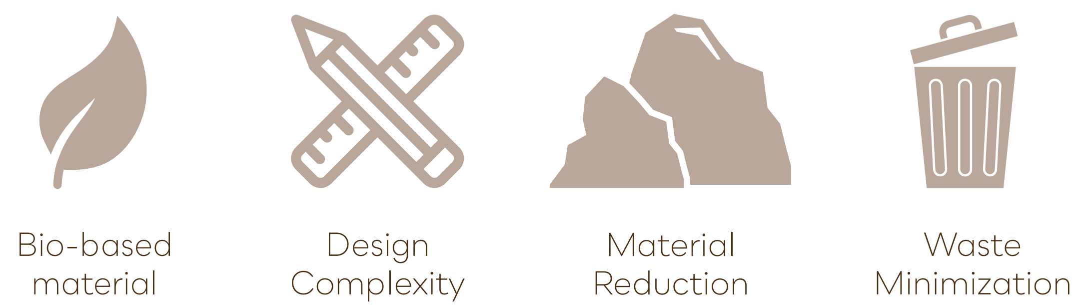


Figure 7. Criteria for Manufacturing Processes Selection , own ill.

1.2_ PROBLEM STATEMENT

The realization of three-dimensional claddings typically relies on materials such as steel, aluminum, and concrete, which have high global emissions and a significant carbon footprint because of their extraction, production, and energy consumption. Moreover, to produce such products, a considerable amount of waste is collected during the whole process of the material lifecycle, which will be unused resources.

According to the Circularity Gap Report 2021, material treatment and usage contribute to 70% of global greenhouse gas emissions (GHG) and account for around 90% of the impacts related to water stress and biodiversity loss (International Resource Panel [IRP], 2019) (Circle Economy, 2023). Within these percentages, the construction industry alone is responsible for 40% of worldwide material usage (Circle Economy, 2023).

In particular, the construction industry contributed to over 30% of natural resource extraction (Benachio et al., 2020), 36% of final energy consumption, and 39% of carbon emissions in 2018 (GlobalABC et al., 2019) (Bastianoni et al., 2007). Furthermore, it accounts for 25% of global solid waste (Benachio et al., 2020).

Between the resources that are causing such dramatic percentages, the particular materials used in the production of three-dimensional claddings are receiving considerable attention due to several factors: firstly, there has been a gradual increase in their usage over time; secondly, these materials' extraction and production processes involve energy-intensive stages to achieve the desired purity level (Helbig et al., 2020).

Therefore, the extraction of these materials has tripled since 1970, and it is projected to double by 2060 (Fig. 17) (Circle Economy, 2023) (Helbig et al., 2020). This significant trend contributes to the gradual depletion of such non-renewable resources (Helbig et al., 2020) (Elkins et al., 2019).
Moreover, within the mentioned carbon emissions percentages related to energy consumption previously mentioned, 11% are related to manufacturing the mentioned materials (GlobalABC et al., 2019).

In conclusion, alternative approaches and materials must be explored to address these challenges. Sustainable and innovative solutions, such as natural renewable, and circular principle designs, are emerging. Embracing these changes in the construction industry can contribute to our planet's more resilient and sustainable future (Jones, 2017).

1.3_ RESEARCH AND DESIGN QUESTIONS

RESEARCH AND SUB-RESEARCH QUESTIONS

The research considers realizing a three-dimensional geometry for external cladding using circular principles and less impacting materials such as bio-based, considering the moulding as a manufacturing process. The defined research question reads as follows:

*"How can external **three-dimensional** cladding be realized using **circular strategies**, **bio-based materials** and being manufactured with **moulding**?"*

Having settled the core of the research, the following sub-research questions are formulated:

"What is the relevance of three-dimensionality in external claddings?

"How does circularity affects the final product realization?

"What are the available bio-based materials that can be used for external cladding?"

"What are the relevant moulding processes for such bio-based materials?"

DESIGN AND SUB-DESIGN QUESTIONS

Considering that the aim of the research is realizing a product, the main design question is framed as well, stated as follows:

*"How can the external three-dimensional cladding be **parametrically** designed to **minimize** the number of **modular** moulds while allowing **flexibility** in diverse façade configurations?"*

Moreover, the following sub-design questions are shown:

"Which will be the design variables that allow flexibility in different façade configurations?"

"What are the limitations and opportunities of the final product?"

1.4_ AIM AND OBJECTIVE

This thesis aims to advance the knowledge and realization of three-dimensional cladding with bio-based materials, developing and realizing a new circular design system that minimizes the number of moulded panels by maintaining design flexibility.

Therefore, having stated the impact that usual materials used for three-dimensional cladding are causing on the earth, the intent is to show how these geometries can eventually be realized, diminishing global gas emissions with more circular solutions. This principle is innovative regarding the integration between materiality and design. Considering the manufacturing process, instead, the moulding process will be selected and utilized with traditional procedures, minimizing the material and energy consumption by reducing the number of panels and moulds.

Finally, the design flexibility will be respected by creating a design system that allows the developed products to be freely placed in different configurations without the need for additional elements.

1.5_ METHODOLOGY

This research project will be based primarily on research by design.

The literature research is where the thesis starts, in which needed information will be absorbed and used as a base for further steps.

This part starts with the knowledge of the building envelope and understanding the added values of three-dimensional cladding through several case studies, analyzing them in terms of the selected three over four domains of circularity: design, material, and manufacturing.

Considering the design domain, the case studies were the basis for understanding how to compose a three-dimensional façade: different configurations and surface treatments have been understood as basic knowledge to develop the own design further.
Furthermore, the material domain is taken into account. There is a general knowledge of the usual materials used for three-dimensional cladding realization and their impact on the environment: the mentioned impacts will be mostly related to the extraction and production process.

Finally, general knowledge of how these three-dimensional claddings have been manufactured is absorbed to understand further which criteria should be considered for the design manufacturing realization.

Having stated the problem statement, an alternative material with theoretically lower impact and carbon emissions needs to be implemented. Therefore, bio-based materials are researched, considering their positive aspects as natural and renewable resources.

The manufacturing process will be selected based on bio-based availabilities and the capability of responding to complex three-dimensional and circular principles.

The moulding process will be selected based on what is absorbed by analyzing bio-based products.
In this way, the design will respect circular principles by reducing the material used and minimizing the number of panels and moulds.

Considering what was just mentioned, having the theoretical information of existing resources for producing the design, there will be an understanding of how to realize three-dimensional cladding.
The parametric design will be considered, and theoretical knowledge of minimizing panels using parametric design will be absorbed. Tools such as parametrization, rationalization, and optimization will be studied: a case study will also be considered.

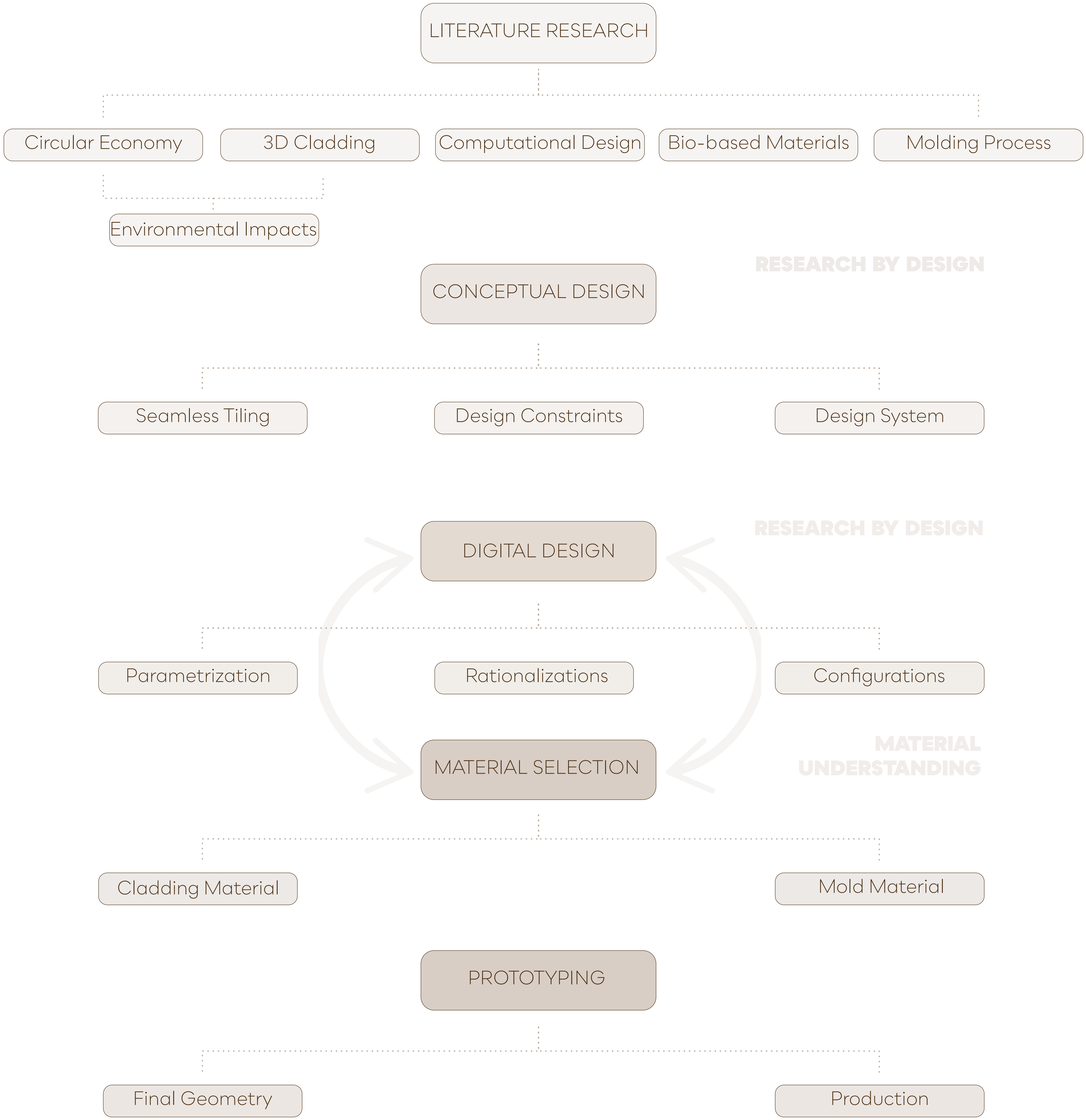
Finally, having the appropriate information for understanding the mentioned premises, the research by design process can start with the conceptual design step.

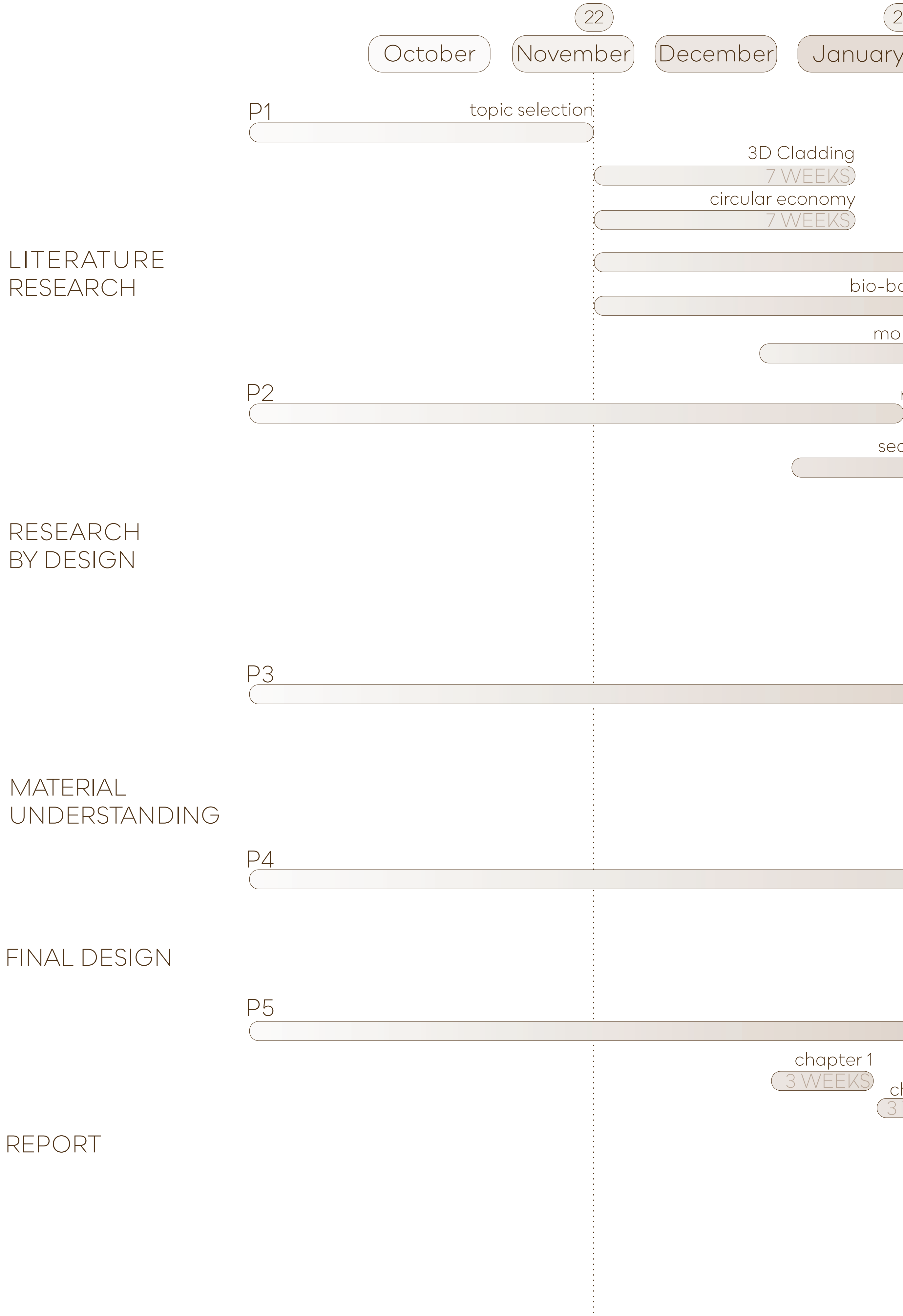
This part is related to sketches, maquettes, and abstract ideas of the ideal 3d mould and, consequently, the product (Fig. A_1, A_2).

The seamless tiling concept is developed as a potential solution for maintaining flexibility by reducing the number of moulds.
The design will follow specific guidelines and constraints that will be further translated into parametric design variables, creating a flexible design system. During the conceptual design process, all these ideas started to be framed.
During the third part, research by design and a theoretical understanding of cladding and mould materials coexist. In this way, on the one hand, there is the parametrization and rationalization of the selected panels for further creating the flexible design system.

On the other hand, there is an understanding of the properties of the selected certified bio-based product and the eventual choice that suits the design the best and vice-versa.

Finally, after concluding the design system with the selected proper certified material, the last part will be the prototyping step, in which the chosen material will be moulded into the designed moulds, realizing the final production - the whole process will be visually shown on the next page.


LITERATURE RESEARCH
Circular Economy
3D Cladding
Computational Design
Bio-based Materials
Molding Process
Environmental Impacts
RESEARCH BY DESIGN
CONCEPTUAL DESIGN
Seamless Tiling
Design Constraints
Design System
RESEARCH BY DESIGN
DIGITAL DESIGN
Parametrization
Rationalizations
Configurations
MATERIAL UNDERSTANDING
MATERIAL SELECTION
Cladding Material
Mold Material
PROTOTYPING
Final Geometry
Production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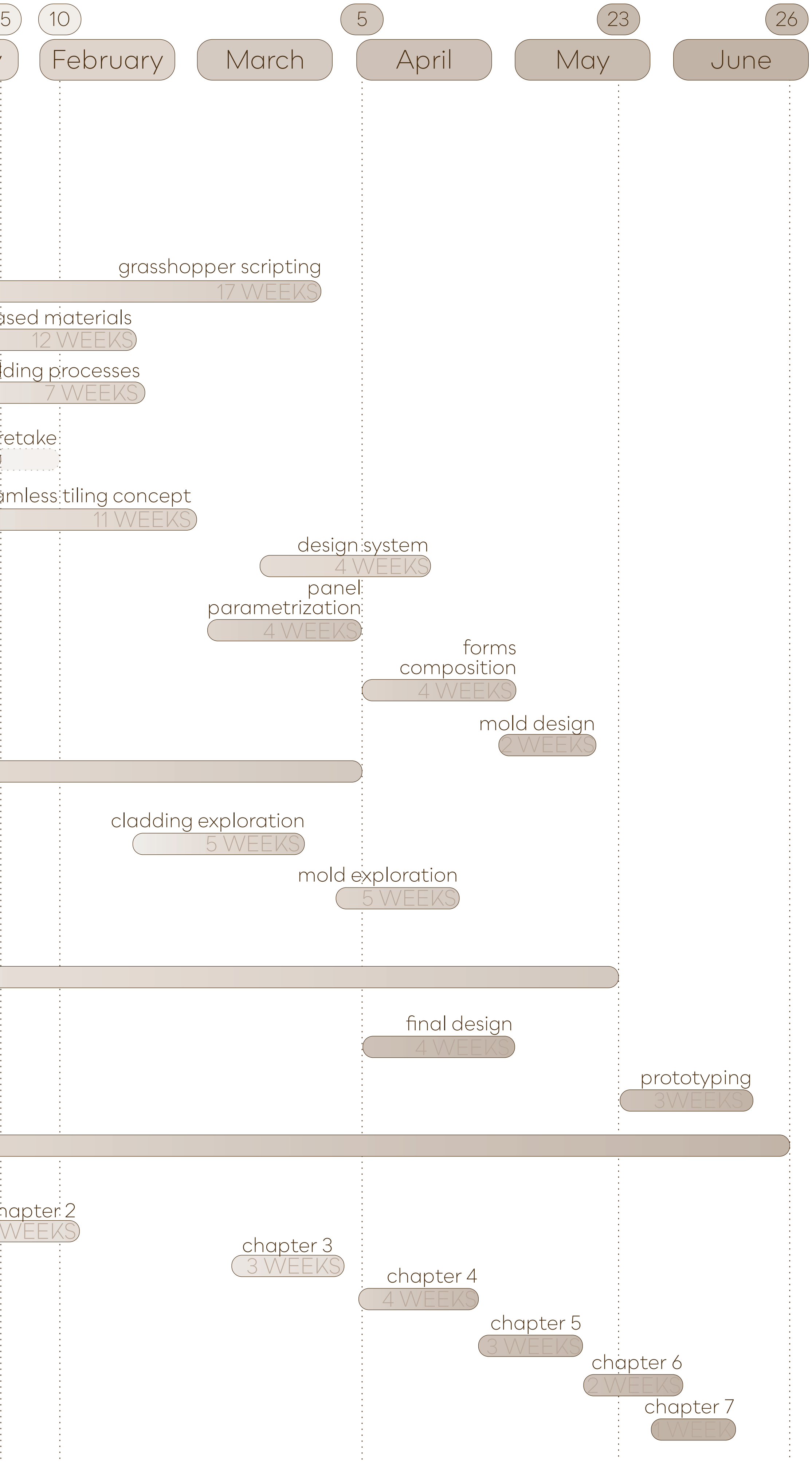


Figure 8. Research Plan Diagram

_2 LITERATURE RESEARCH

2.1_ THREE-DIMENSIONAL CLADDING

THE BUILDING ENVELOPE

The external building is typically called the building envelope, consisting of the skin-shearing layer attached to the structure-shearing layer (Fig. 9).

The shearing layer concept - elaborated by Steward Brand - analyzes the building as a collection of components with different life-cycle duration. Between the shearing layers is the skin, consisting of the external cladding, foundations, roof, windows, and doors, which is expected to last around 20 years.

Historically, the known building envelope started to exist as a protection from the environment since external and internal surfaces were not distinct elements. Then, it gradually acquired aesthetic and technical improvements such as qualitative performances and architectural purposes, reaching all the performant layers that compose the building envelope nowadays (Sandak et al., 2019).

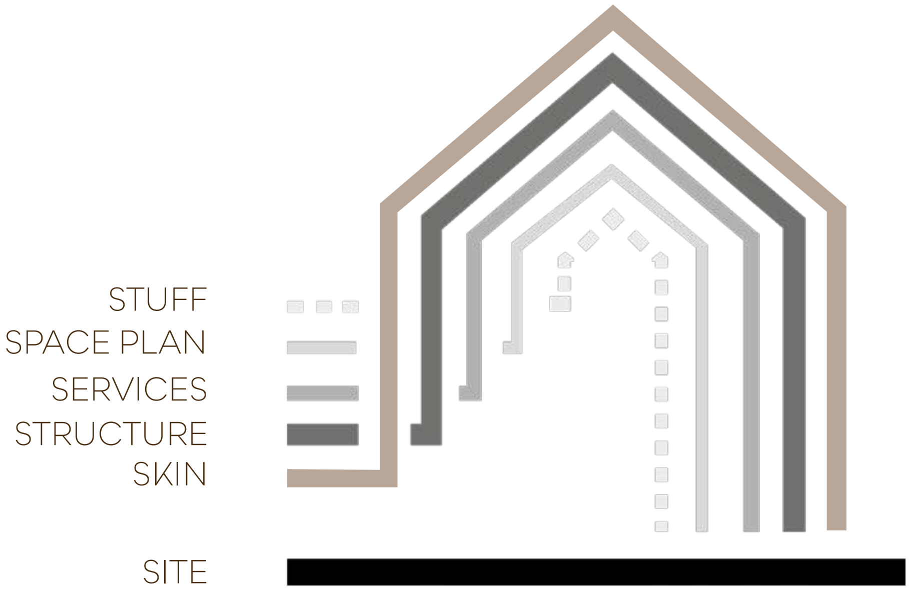


Figure 9. Shearing Layer by Steward Brand; Illustration adapted from Abdelsabour et al., (2019)

Besides the main scope, the building envelope should be able to respond to several requirements.

WEATHER AND MOISTURE RESISTANCE

First and foremost, it must effectively resist environmental elements such as rainwater and wind penetration. To achieve this, the building envelope must exhibit exceptional durability and withstand significant wind loads without allowing any water or humidity to seep through.
Additionally, long-term durability and maintenance considerations must be considered to ensure the building envelope remains intact and resilient over time (Knaack et al., 2007) (Polo, n.d.).

THERMAL, ACOUSTIC, AND VISUAL COMFORT

Moreover, the building envelope is vital in guaranteeing comfort in several terms.
It must provide efficient thermal insulation to regulate indoor temperatures, preventing excessive heat loss or gain. Adequate acoustic insulation minimizes sound transmission and ensures a comfortable indoor environment.
Moreover, the building envelope should offer adequate sun protection to reduce glare and excessive heat from solar radiation.
Lastly, visual comfort is also an essential aspect, and the design should incorporate appropriate openings, fenestration, and shading devices to optimize natural light levels and views (Knaack et al., 2007) (Polo, n.d.).

FIRE RESISTANCE

Another critical aspect is the ability of the building envelope to resist the spread of fire. Building regulations and codes have stringent requirements to ensure fire safety. Compliance with these regulations is essential to obtain building control approval. The specific certification requirements and building scale can vary for each building envelope component, such as cladding materials, fire-resistant barriers, and insulation systems. Adhering to these regulations helps enhance the overall safety of the building and protects the lives of its occupants (Envirobuild, 2022) (Knaack et al., 2007).

VENTILATION

Additionally, ventilation is a crucial consideration for the building envelope. Adequate airflow and fresh air exchange are necessary to maintain consistent indoor air quality and create a comfortable and healthy environment for occupants. Ventilation can be achieved through natural means, such as carefully placed openings and air vents, or mechanical systems.
The ventilation strategy must be carefully designed to ensure optimal air circulation while considering energy efficiency and noise control (Knaack et al., 2007) (Polo, n.d.).

Having mentioned the most relevant requirements of the building envelope, attention will be given to one of the specific components: the *external cladding*.

EXTERNAL CLADDING

The cladding is the building envelope's outermost layer.
The primary function of the cladding is to protect the building's inner layers from the environment (Polo, n.d.).

Besides the just mentioned technical requirements, external claddings differentiate by their materiality and geometrical appearance.
There are plenty of cladding materials, from most traditional stoned cladding to the most recent innovative cladding façade: the selection of the cladding material has to suit the project type, cost, and functionality (Mccoy Mart, 2022).

In terms of geometry, different configurations of external claddings are available that could differ due to different scopes.
The primary differentiation is between bi-dimensional and three-dimensional claddings.

Special focus will be dedicated to three-dimensional claddings due to the captivating added values they bring to the building through their unique geometric designs.

THREE DIMENSIONALITY

Three-dimensionality in cladding appeared for the first time in the wall caves in which some of the earliest known bas-reliefs appeared, having the first significant impact during the Ancient Greeks era (Britannica, n.d.). Following the centuries, sculptural relief techniques on flat surfaces improved, and three-dimensional geometries started to be implemented and developed, reaching the most recent design and manufacturing processes.

Considering the volumetric geometry, three-dimensional cladding configurations mainly differ by surface treatment and typology.

For instance, three-dimensional claddings can be composed of flat sheets that can be bonded together to get a three-dimensional shape (Fig. 8, 9); eventually, engraving might be implemented. Otherwise, panels can be shaped three-dimensionally, aiming at either single-curved (Fig.11), double-curved, conic, or free-form configurations - as shown in Fig. 10 (Coleman, 2017).

The incorporation of three-dimensionality in cladding enhances the aesthetic appeal and brings significant value to the overall building. This added value can manifest in various aspects, including emphasizing the aesthetic concept, improving structural integrity, enhancing thermal performance, and optimizing acoustic properties. By analyzing relevant case studies, it would be possible to gain insights into how geometric considerations optimize the building's functionality.

The just mentioned case studies will be analyzed following the three over four domains of circularity: design, material, and manufacturing. This method will give the whole idea of what, why, and how these buildings are erected.

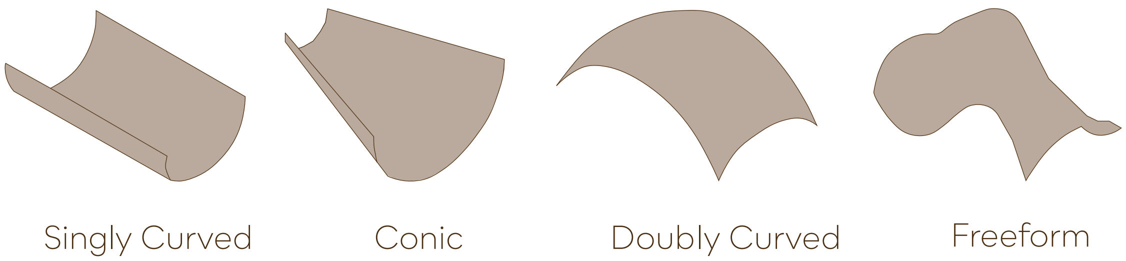


Figure 10. Three-Dimensional Surface Typology
Illustration adapted from Coleman, (2017)

CASE STUDIES

NORTHEASTERN UNIVERSITY INTERDISCIPLINARY SCIENCE AND ENGINEERING COMPLEX - PAYETTE (2016)

DESIGN

The Interdisciplinary Science and Engineering Complex is an extension of the Northeastern University of Boston, designed by Payette Architects in 2016 (Fig. 11).
Attention is given to the southwestern façade, composed of curved fins that establish a free-form shape. This result is given by undulating in plan and splitting in elevation the fins as they march across the curved office building. Through computational modeling, ARUP and Payette were able to let the fins help with daylight and thermal performance by reducing solar gains from the southwest while permitting views out and sunshine to enter. (Payette, 2022), (ARUP, n.d.).

MATERIALS

The façade comprises 1400 unique custom-engineered panels: the eastern side is characterized by gray ribbed metal panels, while the western side is by curve-bronze coated aluminum fins (Suffolk, 2022).

MANUFACTURING

The parametrically designed fins have been first extruded, then bent by Permasteelisa Group. Moreover, these profiles have been transported to the Netherlands for the cutting and machining processes by Scheldebouw NL since every fin has its length.
Finally, they have been collected, one next to the other in the proper order, and shipped to the US for construction (Tossings, 2023).

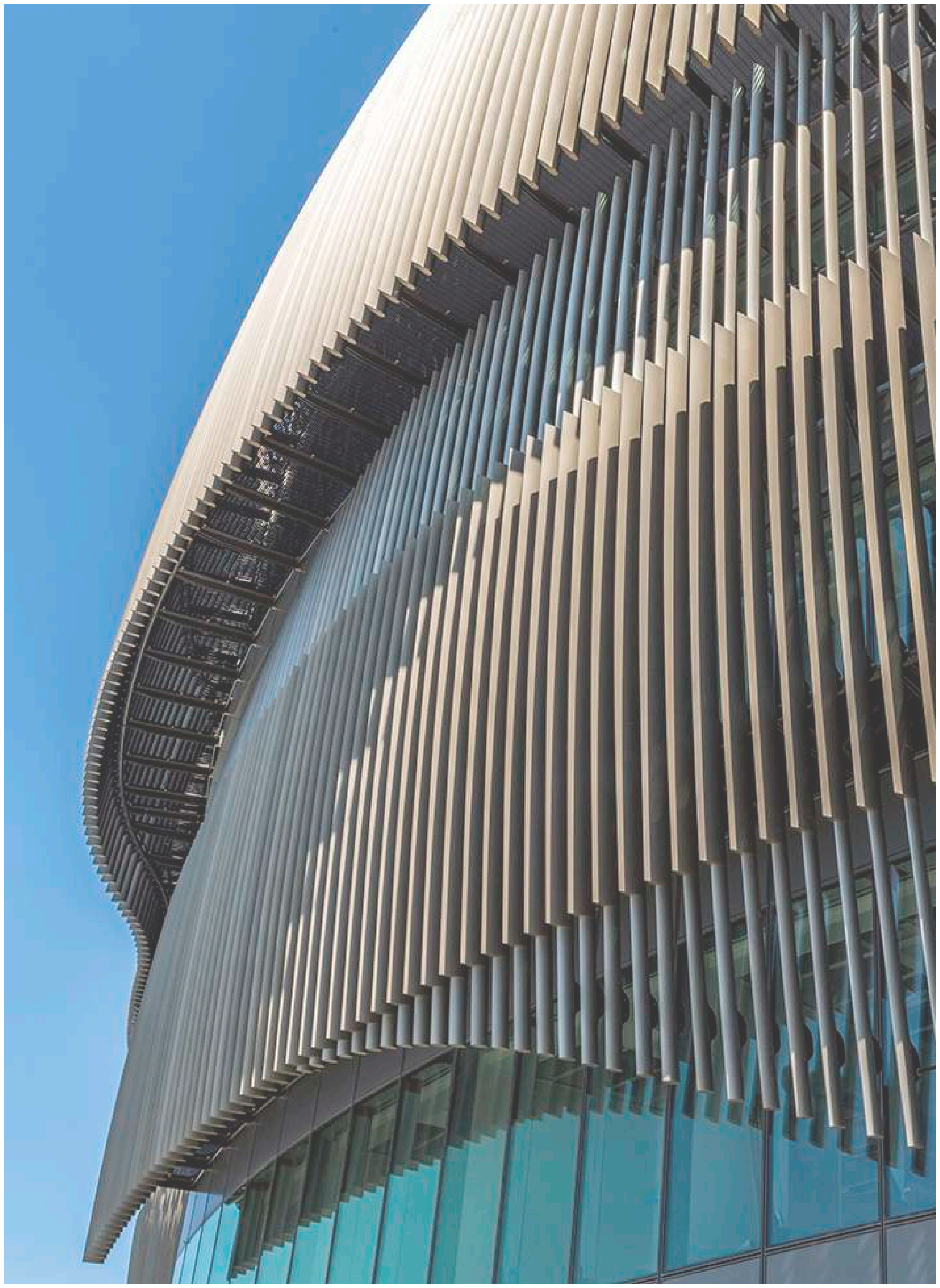


Figure 11. Southwestern façade detail of Northeastern University of Boston Stoughton, (2016)

THEATRE ZUIDPLEIN - STUDIO RAP (2020)

DESIGN

In 2020, Studio Rap, in collaboration with ARUP and Aldowa, designed the acoustics walls of Theatre Zuidplein, realized by De Zwarte Hond. The fully digital design has been the result of structural and acoustic optimizations for realizing the best acoustic solution in terms of both reflection and diffusion in every corner of the auditorium (Fig.13). Furthermore, the shape of the whole cladding combined with the choice of the material and color breaks up the light into infinite color tones, resulting in a dynamic and various environment (Studio Rap n.d.).

MATERIALS

Aluminum composite sandwich panels have been used to realize 5400 unique triangles, which are easy to machine with a CNC machine. The sandwich panels consist of two thin layers of aluminum of half a millimeter with 5 millimeters of plastic in between. The material could be milled by processing the plates with a V-cutter (June 2020).

MANUFACTURING

The manufacturing process starts with a sheet of composite material CNC milled following a Grasshopper script. Then, the final milled shapes are embedded together by folding, creating an iconic three-dimensional internal cladding (Fig. 12) (Studio Rap n.d.).

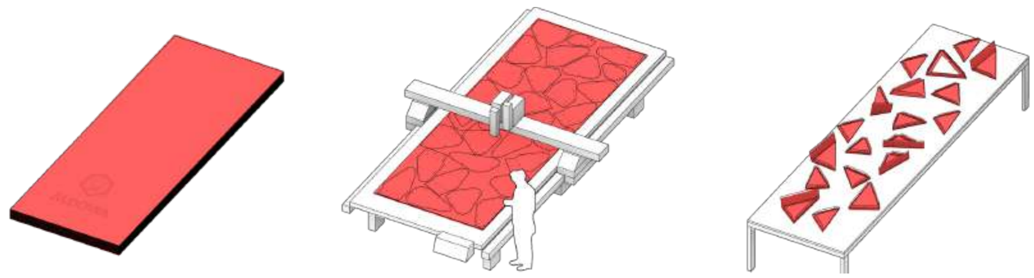


Figure 12. Manufacturing Process Studio Rap (n.d.)

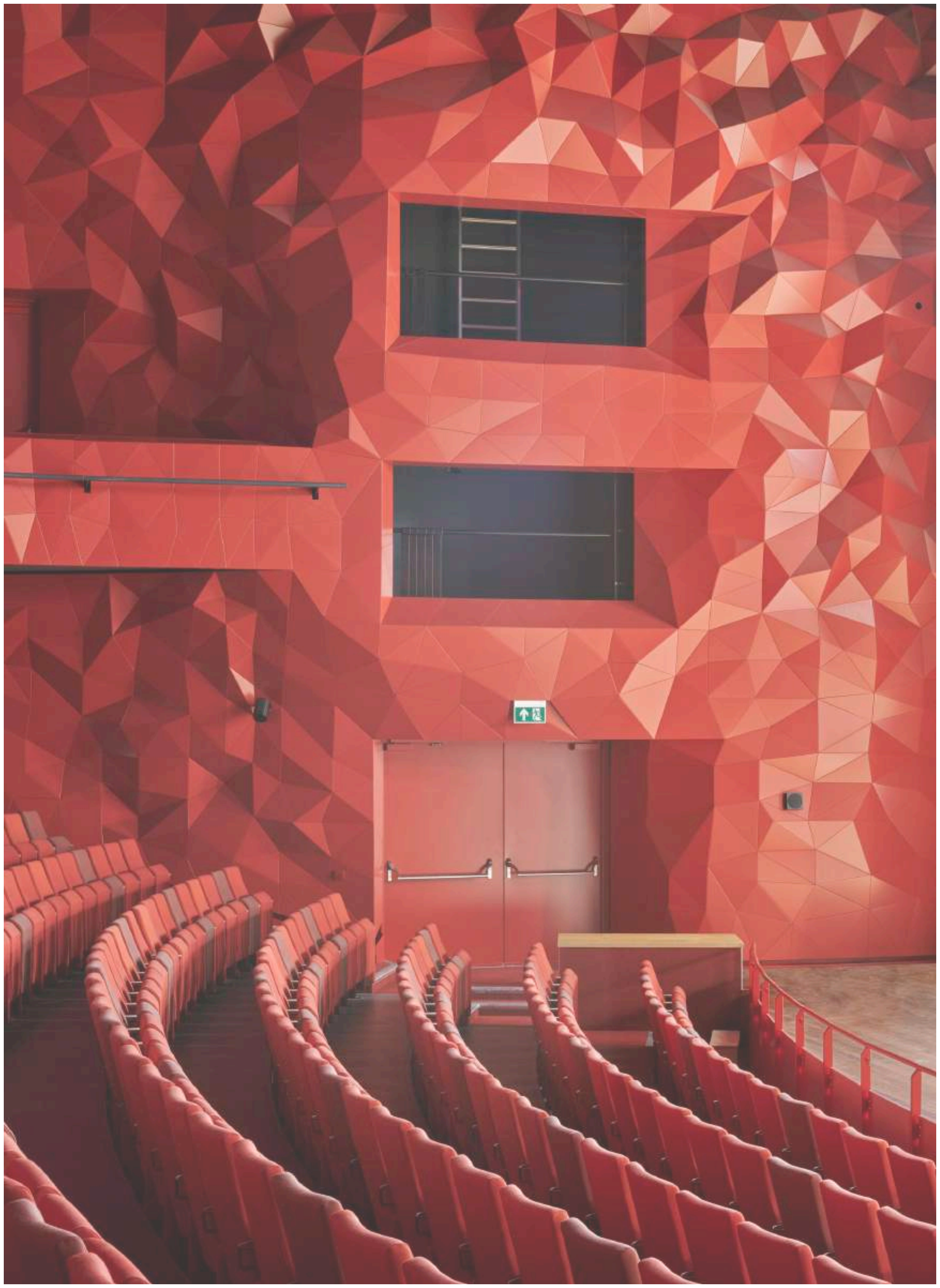


Figure 13. Internal Aluminium Cladding of Theatre Zuidplein
Studio Rap, (n.d.)

THE BROAD - DILLER SCOFIDIO + RENFRO (2015)

DESIGN

Diller Sconfio + Renfro designed The Broad Museum in Los Angeles in 2015. Attention is given to the so-called cladding "veil" of the building, which is composed of rhomboidal modular panels that are parametrically shaped in such a way as to act as a brise-soleil, protecting the internal from the direct sunlight in each season of the year. A wormhole in the façade's skin provides a singularity among a field of panels with subtle differences, signaling an unusual space within the auditorium (Fig. 14) (Giovannini, 2015).

MATERIALS

A cellular exoskeleton structure of 2500 glass-fiber-reinforced concrete (GFRC) panels surrounds the vault storage area (Baldwin, n.d). To realize the entire building, concrete, steel, glass-fiber reinforced concrete, and fiberglass-reinforced gypsum have been used (The Broad, n.d.).

MANUFACTURING

In the manufacturing process of 2500 modular panels, 380 distinct foam moulds underwent sanding and sealing to form the negative shape. The "oculus" element of the veil, which possesses a highly curved form that causes the veil to be recessed into both the building and the vault, constitutes only 30% of the complete veil mould (The Broad, n.d.).

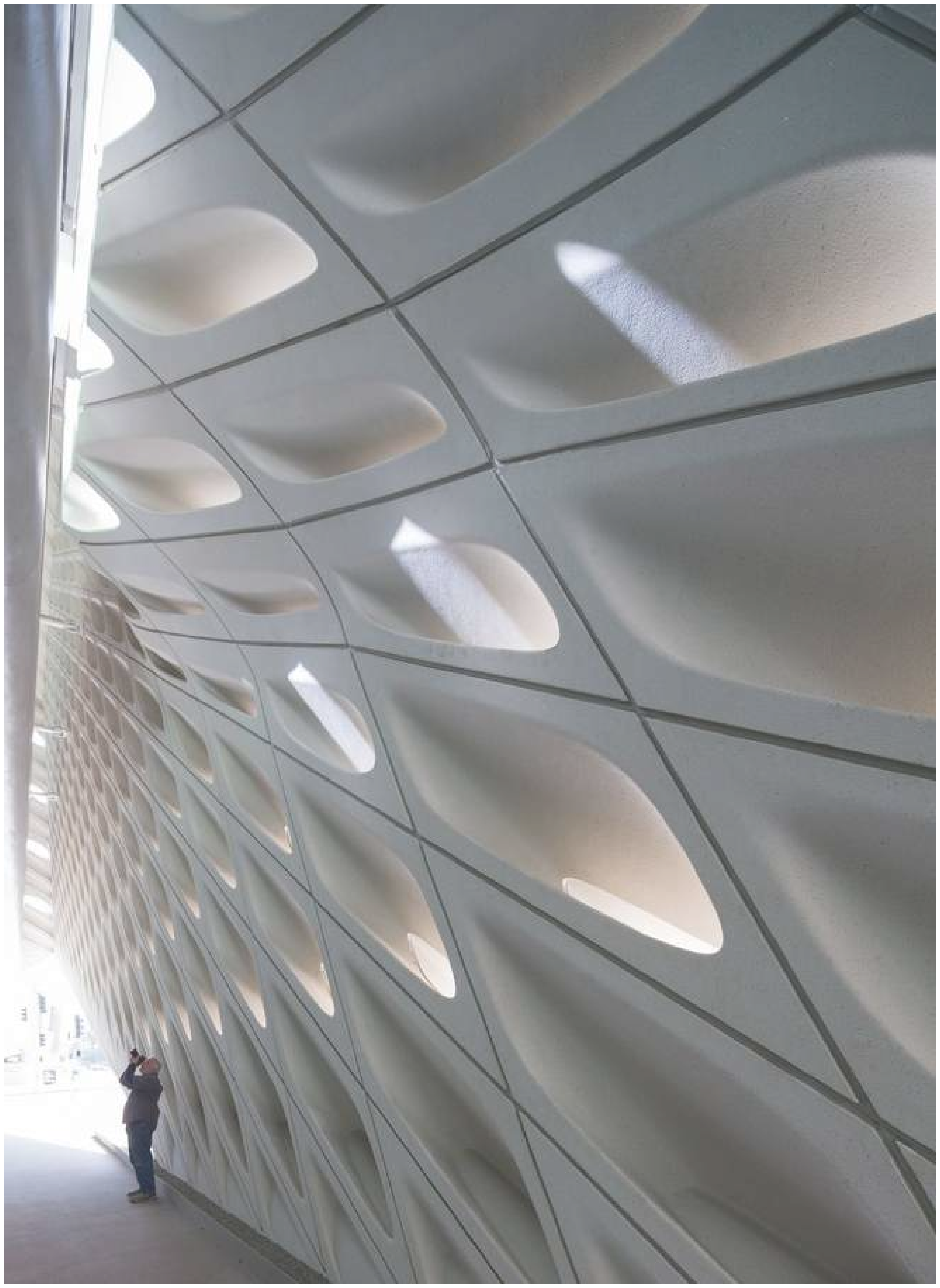


Figure 14. Cladding veil detail of The Broad
The Broad (n.d.)

HARPA CONCERT HALL AND CONFERENCE CENTRE - HENNING LARSEN ARCHITECTS (2005 - 2011)

DESIGN

Harpa Concert Hall and Conference Centre facades have been designed by Henning Larsen Architects, Olafur Eliasson, and Rambøll and ArtEngineering GmbH in Reykjavik. The main facade is realized by the use of the quasi-brick modules - which are twelve-sided polyhedron volumes consisting of rhomboidal and hexagonal faces (Studio Other Spaces, 2005) - that form a crystalline structure that catches and reflects light in different ways throughout the day and year (Fig. 15), creating a connection between the building, the city, and the surrounding landscape.

The quasi-bricks are used three-dimensionally only on the south façade. At the same time, the other sides of the building are composed of two-dimensional cladding created by vertical sections through the quasi-bricks (Henning Larsen Architects, 2011).

MATERIALS

The quasi-bricks comprise 110 unique elements of GEWE-tec ® glass, 1500 tons of steel, and 18 tons of silicone (SCHOLLGLASS, n.d.). Between the produced glazing panels, the GEWE-safe ® laminated safety glass, GEWE-safe ®, and GEWE -dur®-H have been used (SCHOLLGLASS, n.d.). The laminated safety glass GEWE®-tec comprises two or more glass panes with in-between layers of translucent, extremely tearing-resistant polyvinyl butyral foils (PVB) (SCHOLLGLASS, n.d.).

MANUFACTURING

SCHOLLGLAS company manufactured the GEWE®-tec glass. The panes were first cut, ground, and prelaminated to let them have their typical polished appearance.
Moreover, these elements were combined with PVB foils in an autoclave at 12 to 14 bars and 140 °C to create one solid piece (EN 12543, n.d.) (SCHOLLGLASS, n.d.).

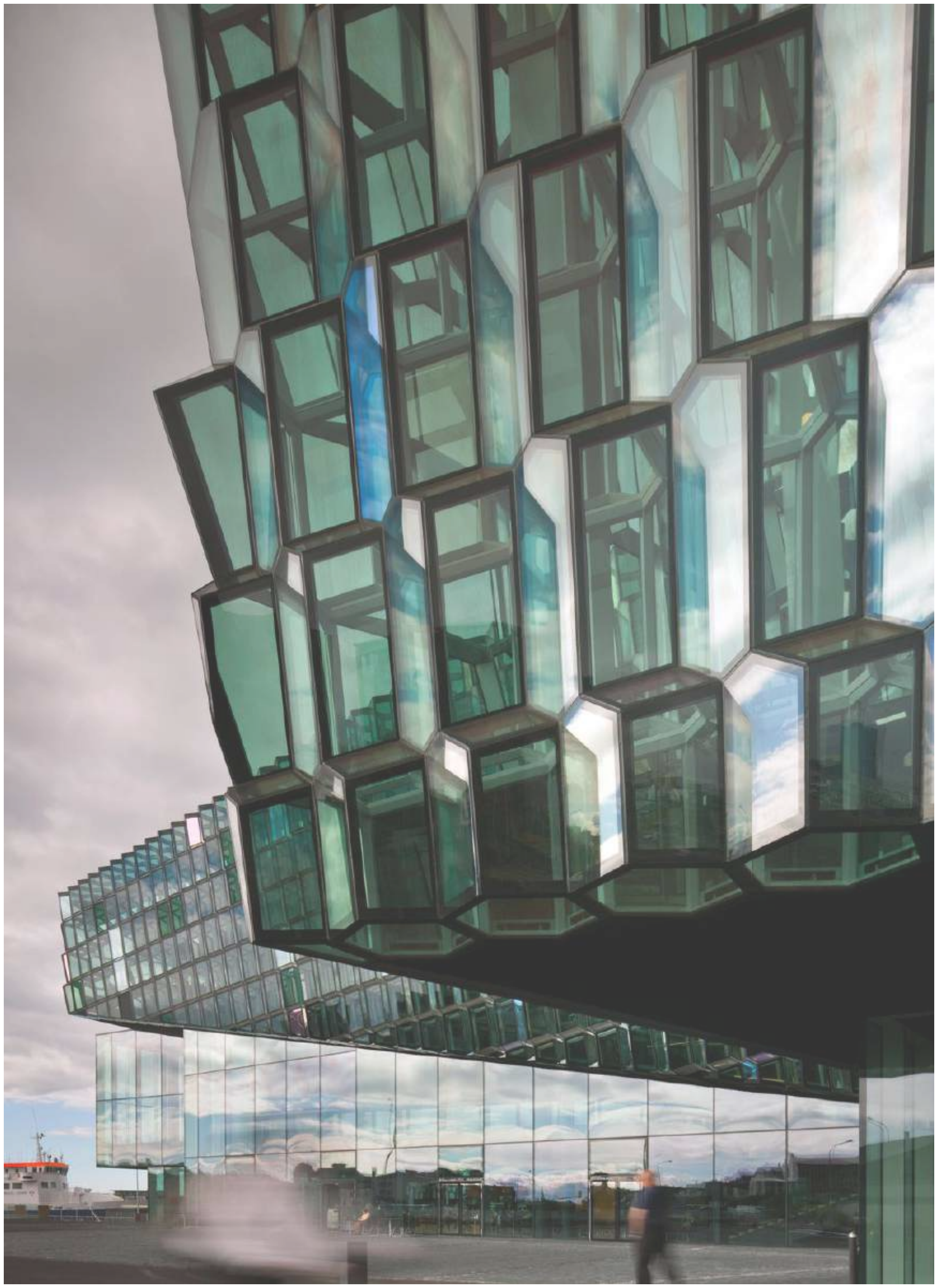


Figure 15. South Façade Quasi-Bricks
Henning Larsen Architects, (2011)

2.2_ TOWARDS A CIRCULAR ECONOMY

CONTEXT

In recent years, more attention is given to how buildings are designed, not only for their thermal and structural performances but for their environmental impacts.
This latest attention is primarily attributed to the awareness that the built environment significantly contributes to land system change, accounting for approximately one-quarter of such transformations.

What makes addressing these concerns even more pressing is the staggering statistic that approximately 40% of global greenhouse gas (GHG) emissions are just linked to the handling and utilization of building materials. This places a tremendous burden on the construction industry and the treatment of the resource, as construction and demolition activities alone account for one-third of the world's total material consumption (Circle Economy, 2023).

In particular, the building industry's material use and energy consumption contribute to over 30% of global natural extraction and energy consumption and 25% of solid waste worldwide (Benachio et al., 2020).
These percentages are dramatic because such used and produced materials are mostly non-renewable resources with a limited lifetime (Claude et al., 2022).

Furthermore, it is essential to acknowledge that the environmental consequences associated with buildings extend beyond carbon emissions. The impacts on water resources and biodiversity loss are also substantial, with buildings responsible for around 90% of these detrimental effects (IRP, 2019).

In conclusion, the shift towards environmentally conscious building design emphasizes the importance of addressing ***material extraction and production***, ***energy consumption***, and ***waste management*** (Fig. 16): these factors significantly contribute to environmental impact and greenhouse gas emissions. Adopting and switching toward a circular economy can create a more resilient and environmentally friendly future. (Ashby, 2022)

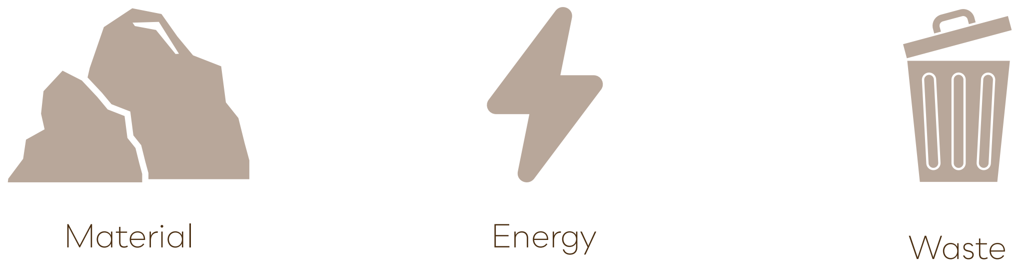


Figure 16. Environmental Impacts of Construction Industry Focus own ill.

MATERIAL EXTRACTION

The extraction of minerals has become a crucial driver of economic growth, supplying raw materials for industries like manufacturing and construction. With the global population booming in the past 50 years, there has been a greater need for extracting and producing more materials for construction projects (Circle Economy, 2023).

As a result, material extraction and production have skyrocketed. Between 1970 and 2017, the number of materials extracted globally grew at an average rate of 2.6% per year, going from 27.1 billion tons to 92.1 billion tons (Circle Economy, 2023) (Global Resource Report [GRP], 2019).
Metal ores, for example, increased by over three times, reaching 9.4 billion tons, while non-metallic minerals like cement and glass made up almost half of the total extraction at 42.8 billion tons (Circle Economy, 2023).

This surge in demand for construction materials is expected to continue, with projections showing a doubling of demand by 2060 - as shown in Fig. 17 (OECD, 2018). The use of resources like metal, cement, and glass, which contribute significantly to energy consumption and carbon dioxide emissions, is a growing concern.

The increasing demand for these materials is depleting resources and causing environmental impacts like soil erosion and landscape changes (Helbig et al., 2020). The replenishment of mineral deposits takes a significantly longer time (thousands to millions of years) than typical mines' lifespan (30 to 50 years). This means these resources are being used up faster than they can be naturally replenished, making them non-renewable (OECD, 2018).

Studies have raised alarms about the consequences of this rising demand, suggesting that certain metals may be depleted within the next 50 years or even sooner (Helbig et al., 2020).

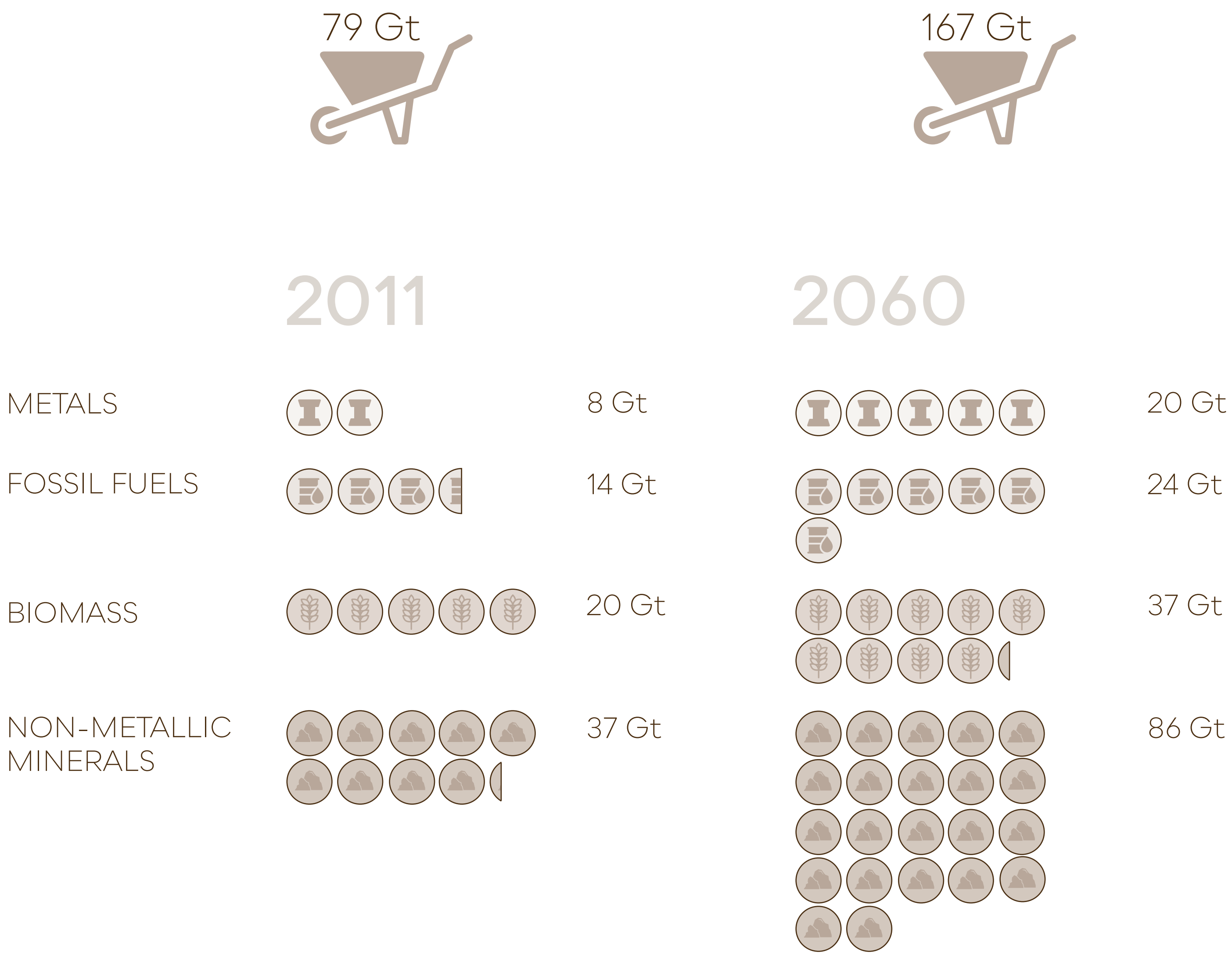


Figure 17. Material Demand Expectations
Illustration adapted from OECD, (2018)

ENERGY PRODUCTION

The extraction and production of specific materials in various industries significantly impact energy consumption.

In the context of the building industry, which heavily relies on fossil fuels as an energy source, these processes result in substantial greenhouse gas (GHG) emissions and contribute to environmental degradation (Claude et al., 2022) (Britannica, n.d.).

The manufacturing processes for materials such as metals and cement are energy-intensive, generating a large amount of the mentioned emissions. In the case of metals, the journey from raw ore to the final metallic form involves multiple steps, including ore mining and concentration, smelting or separation, and refining. Each of these stages requires significant energy inputs, leading to the release of GHGs into the atmosphere (Helbig et al., 2020) .

Similar results are present for the cement production, including crushing and grinding raw materials, blending them in specific proportions, and then subjecting them to high-temperature kiln burning, followed by the final grinding of the resulting product (Britannica, n.d.). The burning of fossil fuels in cement kilns is a significant source of carbon dioxide emissions, contributing to the industry's overall carbon footprint. As a matter of fact, it is estimated that cement production alone accounts for approximately 7% of global CO2 emissions (Circle Economy, 2023).

To better understand the separation of impurities and byproducts in various stages of material processing, the aluminum example will be analyzed (Fig. 18).

The process begins with autoclave digestion, followed by a series of chemical reactions such as clarification, precipitation, and calcination. The final step involves electrolysis, where a direct electric current is applied to achieve the desired purity (Jahanshahi et al., 2007).

It is important to note that each mentioned raw material has its unique refining process. However, those all share a common characteristic: energy-intensive stages that require careful regulation to achieve the desired levels. These stages frequently rely on energy inputs from fossil fuels, either directly or indirectly, for heat and electricity generation (Eckelman et al., 2014), causing therefore significant sources of greenhouse gas emission (EEA Report, 2021).

These emissions contribute to the environmental impact of material extraction and production, highlighting the need for more sustainable alternatives in the industry.

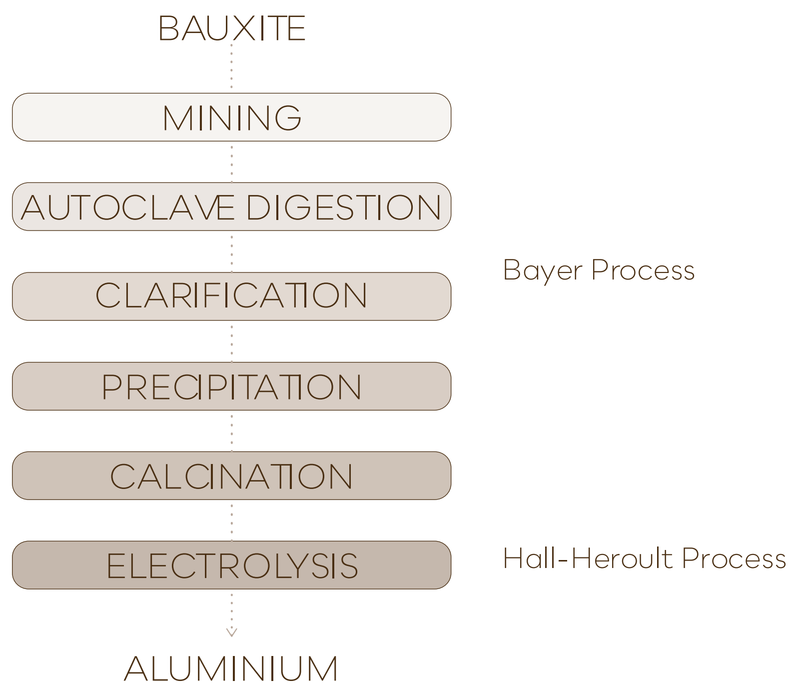


Figure 18. Aluminium Mining and Production
Illustration adapted from Jahanshahi et al., (2007)

Besides the energy demand, the extraction and production processes also cause a considerable release of toxic pollutant emissions to the biosphere (Helbig et al., 2020).

Minerals extracted by the mines are processed by chemical and physical reactions that differ concerning the material to be produced.
Chemical reactions release chemical pollution through the ingress of reagents used in material production, while physical ones expel suspended particulates in the air, water, or land - such as dust (Kosai, 2018).

These pollutants released by the mined materials provoke relevant global impacts such as acidification, water ecotoxicity, climate change, and all the mentioned in Fig. 19 (OECD, 2018).

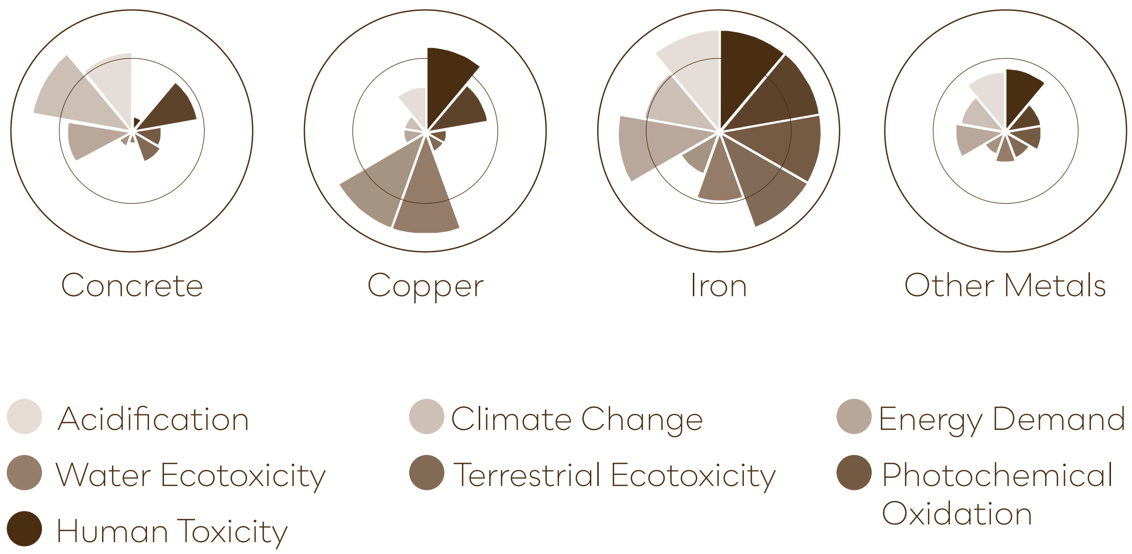


Figure 19. Global environmental impacts due to extraction and production of materials Illustration adapted from OECD, (2018)

WASTE

The decisions made during the design phase play a crucial role in determining the environmental impact of a project, as potential environmental consequences are established at this early stage.
Unfortunately, poor decision-making during design can contribute to approximately 80% of waste and pollution generation (EMF, n.d.).

Mineral extraction and production, particularly in mining metals such as copper, zinc, gold, and nickel, stands as the most significant global waste producer. To put this into perspective, mining just seven grams of gold can waste a whole tonne of material, excluding the overburden (EEA Report, 2021).

Furthermore, waste accumulates throughout the entire lifecycle of materials. It starts with extraction and production, continues through the manufacturing process, and persists until the end-of-life stage of products (Fig. 20). While some of the waste can potentially be recovered through secondary processes, a significant portion still ends up in specialized incinerators or, in worse cases, in landfills through open burning practices.

The construction industry is responsible for a substantial amount of waste generation. Hence, it is estimated that around 25% of the world's solid waste can be attributed to this industry. (Benachio et al., 2020). The waste produced from these processes and landfill activities contributes to the degradation of our planet, exacerbating environmental concerns (Ashby, 2015).

Following the "from cradle-to-grave" principle, the linear economy approach focuses on depleting natural resources for production purposes without adequately considering the potential of resources after their end of life (Helbig et al., 2020). This unsustainable approach perpetuates waste generation and limits resource recovery and recycling possibilities.

Shifting towards a circular economy model, where resources are continuously reused and recycled, is crucial for minimizing waste, conserving resources, and reducing environmental impacts.

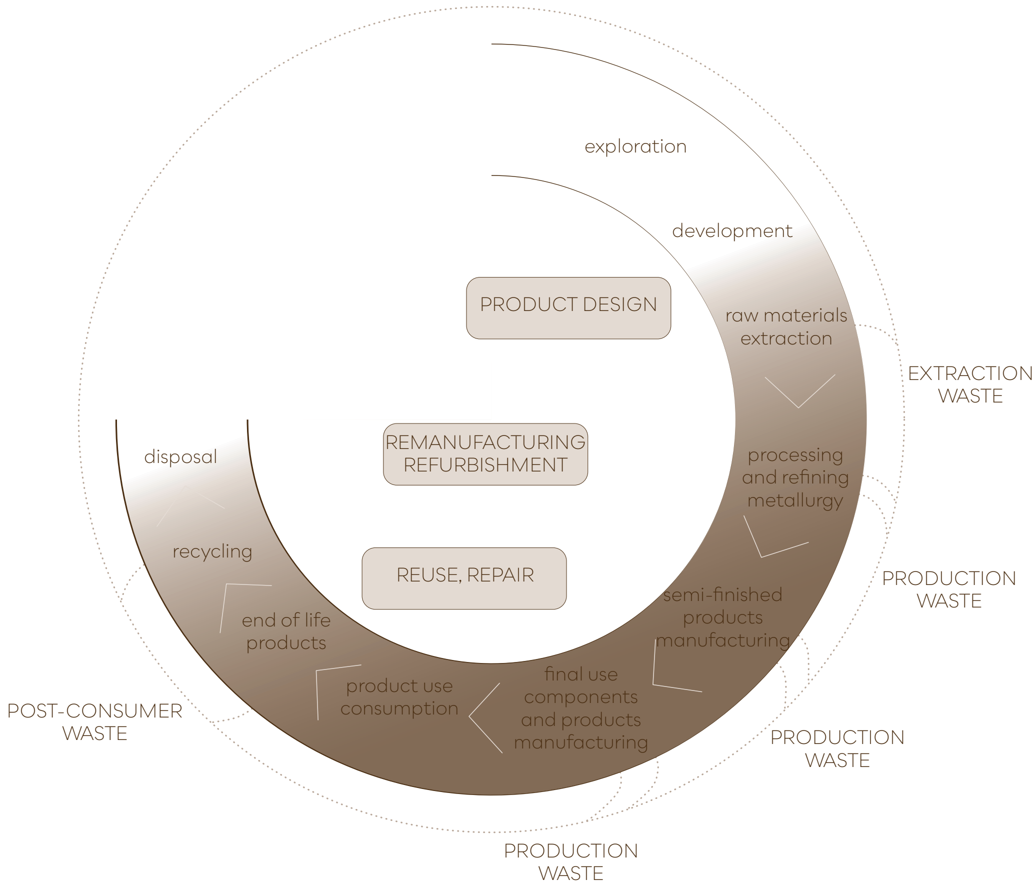


Figure 20. Waste production in the material lifecycle
Illustration adapted from EIP, (2021)

FROM LINEAR TO CIRCULAR

The current economy operates in a linear fashion: i*t takes, makes, uses, and throws away* (EMF, n.d.).

Products have traditionally been designed for a single purpose, and once they serve that purpose, they are no longer considered valuable within the economic system (The circular economy, 2019).

The problem with this approach is that products are not designed to be used in different phases throughout their lifespan. As a result, there is a loss of materials, money, energy, and labor when the product's use comes to an end, as depicted in Figure 21.

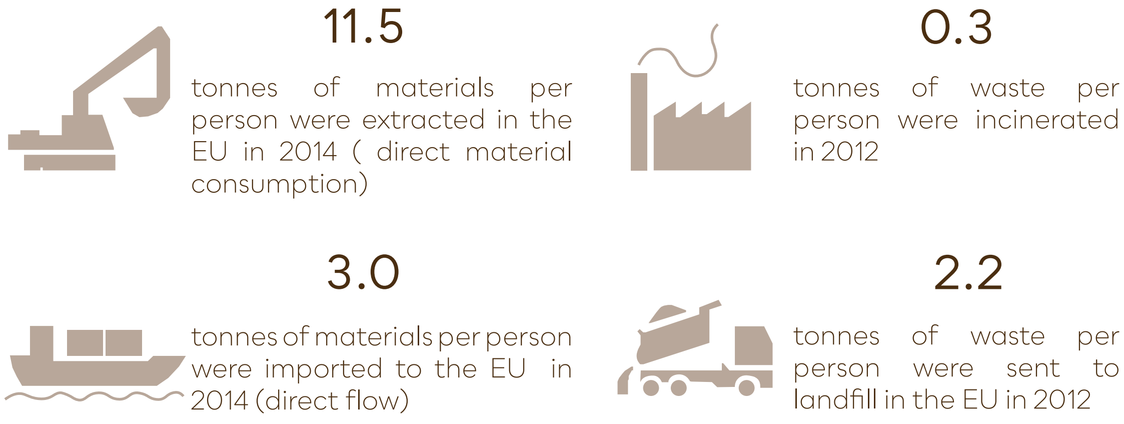


Figure 21. waste and materials datas
Illustration adapted from EEA, (2015)

To address these challenges, a shift towards a circular economy is crucial. The circular economy encompasses an economic system that replaces the concept of "end of life" with a focus on respecting environmental conditions by increasing the use of renewable or recyclable resources while minimizing the consumption of raw materials and energy (Elkins, 2019).

The essence of the circular economy lies in considering the entire lifecycle of a product, with the goal of reintegrating materials back into the economy after their use instead of extracting new resources. By doing so, it is possible to reduce global greenhouse gas emissions and minimize the loss of limited resources (Elkins, 2019) (EEA Report, 2/2016).

This approach centers on maintaining a continuous flow of resources, treating products in a way that maximizes their value and minimizes waste by *designing out of it* (EMF,n.d.).

To guide these principles, R-strategies serve as the main guidelines.

These strategies follow a hierarchical structure, where the most effective solutions are at the top, gradually descending to less circular approaches when more effective strategies are not applicable.

The first three strategies—refuse, rethink, and reduce—are the most impactful as they focus on the pre-design stage, aiming for inherently circular outcomes.

The subsequent macro-group involves actions taken with existing resources. Starting with reuse, there will be an extension of the lifespan of products or their components, extracting maximum value from them.

When all previous options are exhausted, recycling and recovery come into play to retain some value. While recycling is a commonly employed end-of-life scenario, it demands significant energy input, making it a less desirable choice (Ioannou et al., 2022).

CIRCULAR ECONOMY

Smart products use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a different product
	R1 Rethink	Make product use more intensive (i.e. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend Life-span of products and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful Applications of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

LINEAR ECONOMY

Figure 22: The R-strategies
Illustration adapted from RLI, (2015)

Given the guidelines, the main step that composes the circular economy will be more clear.

The visual explanation of the circular economy is given by the Butterfly Diagram, in which a distinction between biological and technical cycles is represented (Fig. 23).
In the technical cycles, attention is given to the highest lifespan of products in the economy, while, in the biological ones, the objective is to repair natural capitals while reintroducing nutrients to the biosphere (EMF, n.d). Non-biodegradable materials, such as metals, are primarily associated with the technical cycles.

The technical main path is following the R-strategies (Fig. 22)(RLI, 2015), considering as the most efficient step the reuse and maintenance of the products - since existing products are the attention, R0, R1, and R2 are not taken into account- preserving their longevity as much as possible (EMF, n.d).

On the other hand, the concept of biodegradable cycles pertains to materials like those derived from food or wood, which are considered renewable and capable of decomposing naturally. Utilizing these materials

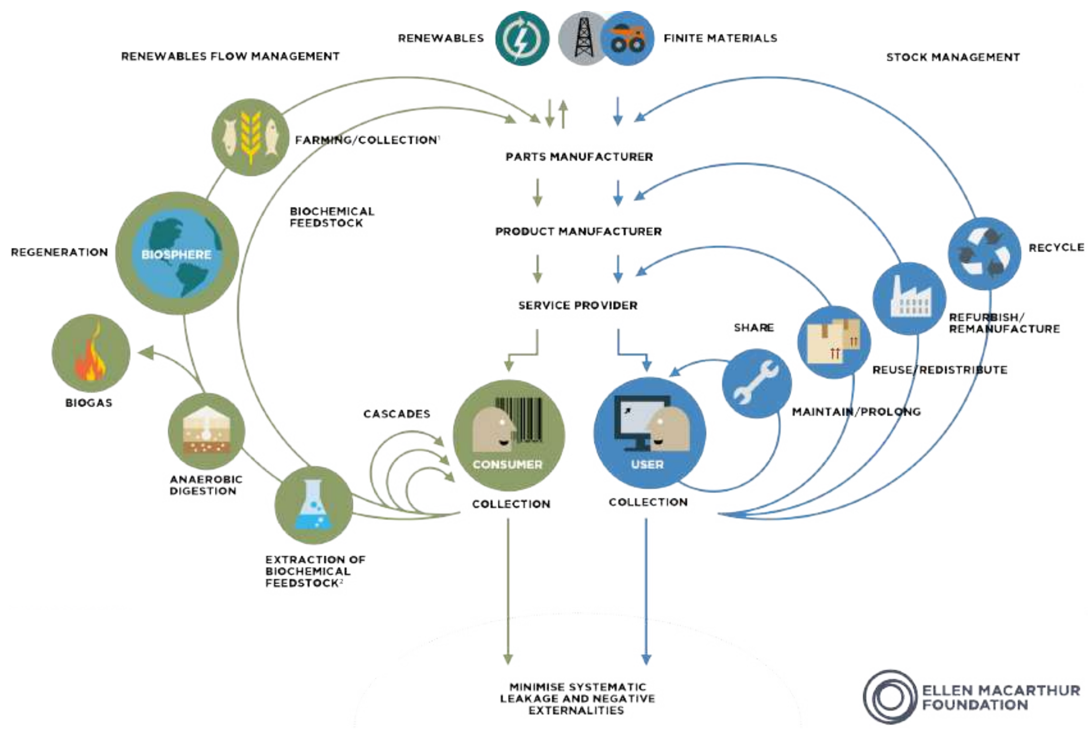


Figure 23: The Butterfly Diagram
Source: EMF, n.d.

in a cascading approach offers significant benefits for their application in various fields.
Through composting or anaerobic digestion, vital minerals can be recovered from organic waste that can no longer be utilized. These recovery measures reduce systemic leakages and harmful externalities. In recent years, these resources have also found application in the construction industry (EMF, n.d.).

In conclusion, the main aim of a circular economy is to incorporate closed supply chains, regenerative design, and revers logistics that increase the life of products, thereby maintaining for a longer period the value in their materials and the overall value derived from them to minimize the need for additional energy and material inputs while lowering environmental pressures brough onby resource exploitation, emissions and waste, as shown in Fig. 24 (Elkins, 2019).
However, embracing circularity right from the pre-design phase is crucial to avoid less circular solutions found at the bottom of the R-strategy pyramid. This underscores the importance of effectively and sustainably managing natural resources throughout their entire lifecycle, going beyond waste prevention (EMF, n.d.) (EEA Report, 2/2016).

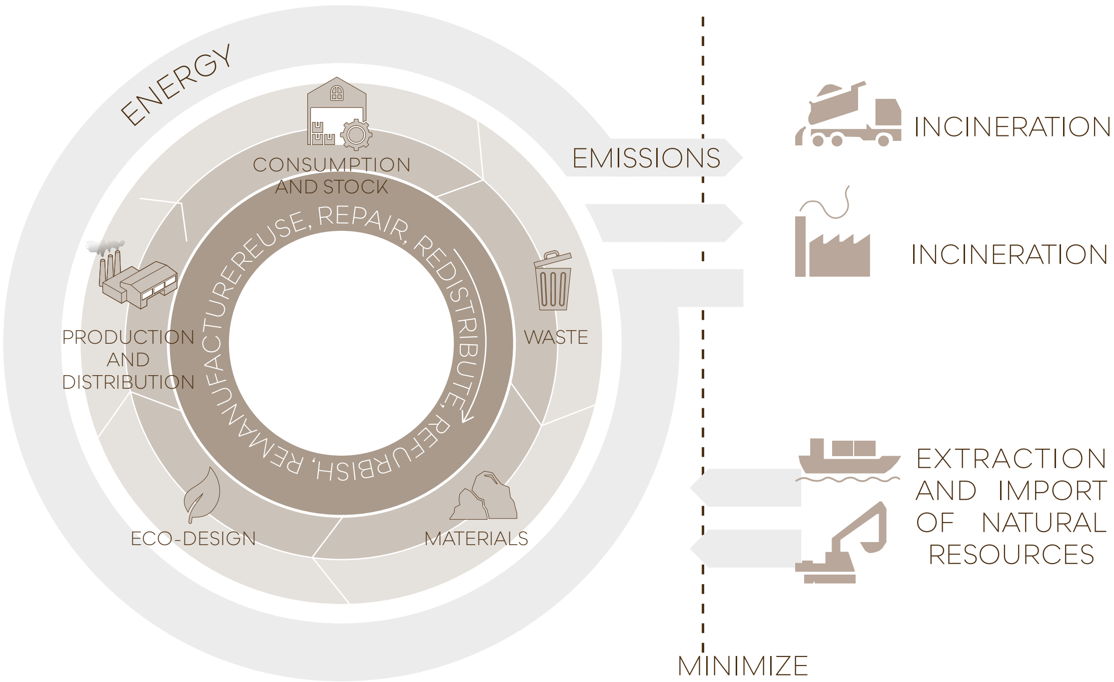


Figure 24. A simplified model of the circular economy for materials and energy
Illustration adapted from EEA, (2019b)

BENEFITS

Considering this *new economy* and its principles, it is also important to dive into the advantages and challenges of the CE. Discover how this regenerative approach offers resource conservation, economic opportunities, and resilience, while also recognizing the complexities that come with its implementation. Gain insights into the potential *benefits* and *limits* of adopting a circular economy framework.

RESOURCE BENEFITS

The adoption of a circular economy offers a multitude of benefits when it comes to resource conservation. By actively promoting the practices highlighted in Figure 22, the circular economy minimizes the need to extract new raw materials. If implemented across these four global systems, it has the potential to reduce virgin material extraction by approximately one-third (34%), resulting in a substantial decrease from 92.7 billion tonnes to 61.2 billion tonnes (Circle Economy, 2023). This reduction in material extraction significantly alleviates the strain on natural resources, preserving them for the well-being of future generations. Furthermore, the circular economy fosters the extension of product lifecycles, enabling products to be used for extended periods and minimizing waste generation (EEA Report, 2/2016).

ENVIRONMENTAL BENEFITS

In addition to the resource conservation mentioned earlier, which yields environmental benefits by reducing the strain on limited resources and mitigating impacts like soil erosion and landscape changes, implementing a circular economy brings about positive outcomes in other environmental aspects (Helbig et al., 2020). As previously noted, reducing energy consumption leads to decreased emissions, resulting in fewer impacts on water resources and reduced biodiversity loss (IRP, 2019).
Furthermore, adopting a circular economy helps minimize chemical pollution associated with extraction activities, as illustrated in Figure 19, reducing natural toxicities and mitigating climate change.

Overall, by effectively reducing waste and pollution, as demonstrated in Figure 24, there is a significant decrease in global greenhouse gas emissions (GHG). In fact, from 2015 to 2035, it is estimated that CO_2 emissions will be ideally reduced by 424 to 617 million tonnes (EC, 2015b): an illustration of how circular economy ideally reduces emissions in Europe is shown in Figure 25.

SOCIAL BENEFITS

One of the significant advantages is the potential for job creation and economic opportunities. As businesses transition to circular practices, new roles and industries emerge, leading to employment opportunities and economic growth. This not only stimulates local economies but also promotes job stability and resilience. However, it is essential to note that the potential for jobs and growth may vary depending on the sectoral structure, trade dynamics, and employment patterns. General predictions mention a rise of up to 178000 new jobs by 2030 (Van Ewijk, 2018) (EC, 2015b).
Furthermore, the circular economy encourages education and awareness about sustainable practices. Through educational programs and awareness campaigns, individuals are empowered with the knowledge and skills to participate in sustainable living actively (Van Ewijk, 2018).

ECONOMIC BENEFITS

A resource-efficient circular economy brings significant societal benefits by safeguarding natural resources that underpin economic activity. While measures to enhance resource efficiency and protect the environment may initially impede economic growth, many industries can reduce production costs by utilizing their material inputs more efficiently. These “win-win” opportunities can facilitate the transition towards a resource-efficient circular economy.

It is crucial to recognize that the economic benefits vary depending on companies’ characteristics and evolving needs over time. Moreover, it is essential to distinguish between the short-term and long-term benefits of a resource-efficient circular economy. In the long term, the entire economy stands to gain from the preservation of critical natural resources. In the short term, businesses experience benefits in the form of cost savings on material inputs. The greater the resource efficiency of a company, the lower its expenses for material inputs per unit of output. This leads to increased productivity, enhanced competitiveness, and reduced vulnerability to volatile resource prices, but still gives an uncertainty of proper economic benefits (Van Ewijk, 2018).

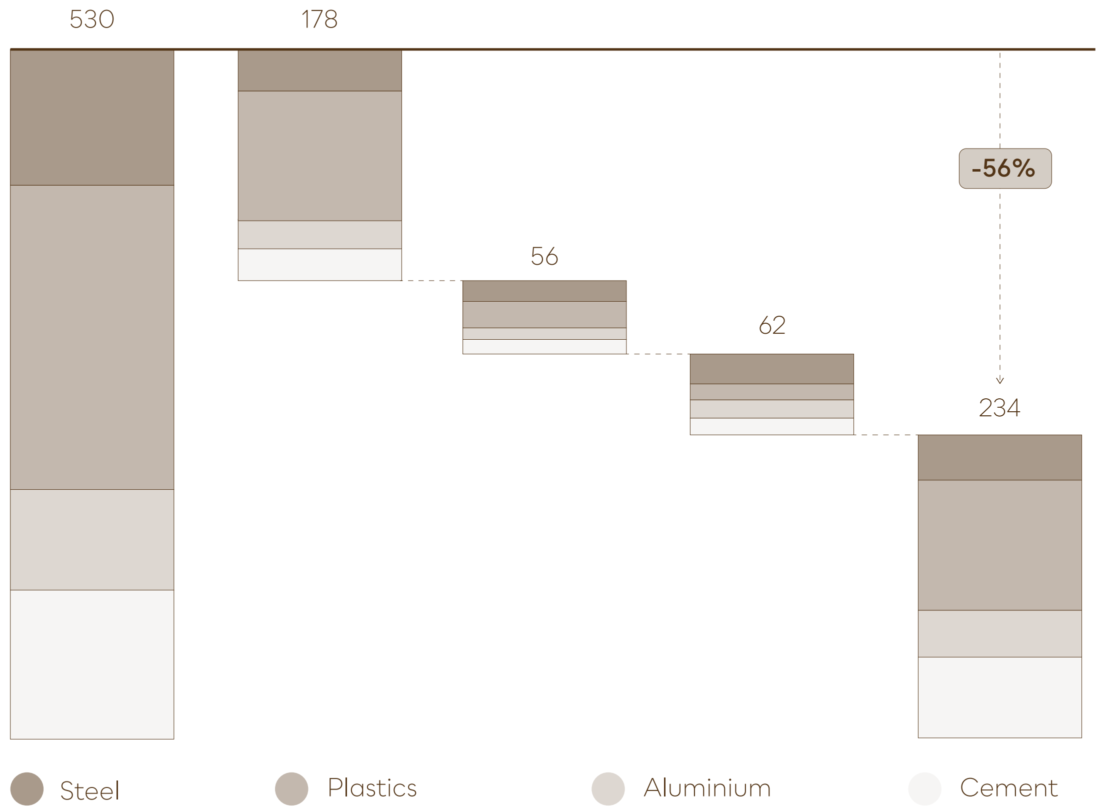


Figure 25. EU Emissions reductions potential from a more circular economy, 2050
Illustration adapted from Material Economics, (2018)

LIMITS

While the circular economy approach has significant advantages, it is important to recognize that it also has some limitations that need to be considered.

"A perfectly circular economy with a 100% efficient use of materials cannot exist because of physical and practical limitations regarding the processing of materials" (Van Ewijk 2018).

TRANSITIONAL LIMITS

As in most cases, when new strategies emerge, some friction could be visible during the transitional moment between one approach and the other (Guldager Jensen et al., 2016): the proper fulfilment of the circular economy requires a discrete amount of time (EEA Report, 2/2016).

Secondly, the moment in-between linear and circular economies - the present - can cause an increase in industries' competitiveness, causing a rise in product costs (Guldager Jensen et al., 2016).

ECONOMIC LIMITS

Moreover, cost-related factors represent another significant challenge associated with the circular economy. Since the circular economy approach has yet to be fully established in all industries, producing circular products can be more expensive than manufacturing conventional products due to the need for specialized machinery and processes to reuse or remanufacture resources, which can be time-consuming and, therefore, more costly.
As a result, consumers may opt for less sustainable but more affordable products rather than circular ones, which may hinder the adoption of circular economy practices in some industries.
Furthermore, the process of moving to a circular economy involves significant modifications to the production-consumption systems that have an impact on the environment.
These include tax policy, consumer behaviour, financial mechanisms, government action, and technical, social, and commercial innovation (EEA Report, 2/2016).

SCALE LIMITS

The successful implementation of circular initiatives at more minor scales or within specific industries is often observed.
However, scaling up these practices to a broader level is the challenge. Achieving circularity across entire supply chains or global systems necessitates extensive coordination, collaboration, and systemic changes, which can prove challenging in practice (Van Ewijk, 2018).
It requires engaging multiple stakeholders, including manufacturers, suppliers, consumers, and policymakers, to align their efforts and transform existing linear models into circular ones. Overcoming logistical complexities, infrastructure limitations, and varying regulations across regions pose additional obstacles to achieving widespread circularity.
Therefore, while the concept of a circular economy is promising, its practical implementation on a large scale necessitates concerted efforts and systemic transformations (Bleeker, 2023).

SOCIO-CULTURAL LIMITS

Adopting a circular economy can face socio-cultural limits, including cultural barriers, lack of information, inadequate political will, incoherent regulations, and the need for a holistic vision. Cultural norms and values may resist shifting to circular practices, and raising awareness is essential. Political commitment and supportive regulations are crucial but can be lacking. Consistent regulations and fragmented policies help progress.
A holistic vision is needed to consider interconnectedness.
Overcoming these limits requires education, awareness, stakeholder engagement, policy coherence, and a collective vision. These are just a few examples of slowing the shift towards a circular economy, shown in Fig. 26.

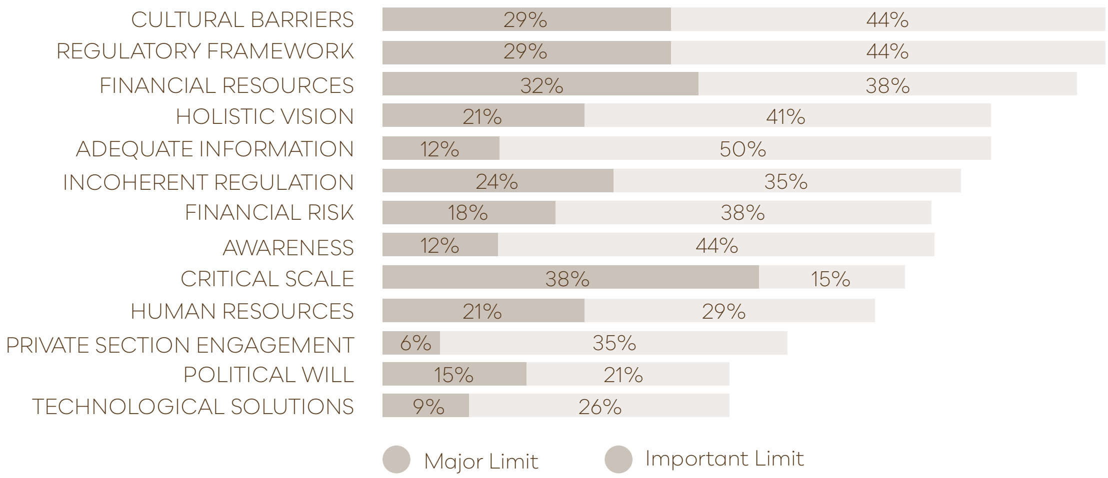


Figure 26. A simplified model of the circular economy for materials and energy Illustration adapted from OECD, (2019)

DESIGN STRATEGIES

Design and the circular economy share a direct interdependence. Once the theoretical knowledge of circular principles is assimilated, it becomes essential to translate this understanding into design practice. How a product is designed plays a pivotal role in facilitating the manufacturing process and determining how products and services are utilized throughout their lifespan.

According to Ellen MacArthur, the design process in a circular economy is an ongoing and iterative endeavour (Fig. 27). While there is no definitive formula for designing circularly, common strategies can be pursued to create more sustainable products (EMF, n.d.). By adopting these strategies, designers can contribute to developing products that minimize waste, promote circularity, and have a positive environmental impact. (EMF, n.d.)

Figure 27. Circular process design own ill.

DESIGNING FOR INNER LOOPS

As mentioned before, the circular economy focuses on the product's complete life cycle, considering enhancing productivity and taking care of the amount of waste.

A promising approach in circular design is designing for inner loops. This approach aims to create products that can be quickly reintegrated into the life cycle, thereby extending their lifespan and facilitating their treatment through the R-strategies (Fig. 22) (EMF, n.d).

MOVING FROM PRODUCT TO SERVICE

Another crucial aspect of the circular economy is the transition from ownership to access. This paradigm shift involves a shift in consumer behaviour and business models towards product sharing, rental, or limited-time usage. Instead of individuals owning products outright, they can access and utilize them for a specific period. Subsequently, the products can be passed on to other users or returned to the service provider.
This shift promotes the efficient utilization of resources as multiple individuals can utilize products throughout their lifespan, maximizing their value and minimizing unnecessary duplicates. This transition to access-based models fosters resource conservation, encourages collaborative consumption, and reduces the need for excessive production and consumption (EMF, n.d).

PRODUCT LIFE EXTENSION

Designing products focusing on durability and repairability is fundamental to the circular economy. Selecting materials that can withstand damage and wear and ensuring products can be easily repaired can extend their lifespan. This approach reduces waste, conserves resources, and promotes a more sustainable and responsible consumption model. Designing for durability and repairability is essential to transition to a circular economy successfully. (EMF, n.d).

SAFE AND CIRCULAR MATERIAL CHOICES

As explained in sections “material extraction”, “energy production”, and “waste”, materials do primarily affect the environment. Therefore, attention is given to the design performance and the material itself. Moreover, some materials are more durable than others - in specific climate conditions -thus helping the design strategy (EMF, n.d).

DEMATERIALIZATION

Finding ways to give utility while using the least amount of material is the primary goal of this method.
Computational Optimization is one of the tool for realizing this circular strategy, described in section 2.3. By optimizing digital models, it is possible to minimize as much as possible both materials and manufacturing products (EMF, n.d).

MODULARITY AND FLEXIBILITY

As explained in Chapter 1, modularity is a crucial design strategy for adhering to circular principles. Modular panels are individual components that can be combined to create a product. Modularity stands in contrast to integral products, which are composed of interchangeable components or cannot be disassembled. With integral products, if the entire item reaches the end of its lifecycle, none of its components can be reused or treated to extend their lifespan (Ioannou et al., 2023)(Klein, 2023) (Nowak T. et al., 2018).

In contrast, modular panels offer greater flexibility for replacement. They can be easily replaced if damaged, reducing costs and effort while minimizing environmental impacts. Additionally, modular systems provide the advantage of customization, allowing products to adapt to changing consumer needs. This capability ensures that items remain in use for more extended periods, mitigating the issue of obsolescence.

By incorporating modularity into the design, the circular economy can be effectively supported, promoting resource conservation and sustainable product lifecycles. Modular panels enable greater reusability, reduce waste, and enhance the overall environmental performance of products. (EMF, n.d.) (Guldager et al., 2016).

DESIGN FOR DISASSEMBLY

Design for disassembly (DFD) is a prominent architectural circular strategy. It entails a holistic design approach to ensure a product can be easily disassembled into its components. By utilizing dry connections to join panels, damaged sections can be replaced without affecting the integrity of other intact layers.

Modularity plays a significant role in implementing this strategy, as modular panels are more readily replaceable in the event of damage, facilitating disassembly (Meilani, 2019).

Another compelling reason to adopt the design for disassembly strategy is for buildings, particularly pavilions, that have a predetermined lifespan and are intended to be dismantled. In such cases, all the products involved are designed with easy disassembly in mind, enabling their reuse in other construction projects. This approach aligns with the principles of circular economy, promoting resource efficiency, reducing waste, and facilitating the reuse of building components.

Several fundamental principles must be considered to implement the design for disassembly strategy effectively.
Firstly, selecting **materials** is crucial, as they should possess properties that ensure their suitability for reuse and reintegration into future projects.
Secondly, a thorough understanding of the anticipated **service life** of the project is essential, as it informs the design decisions regarding the durability and adaptability of the components.
Additionally, the design should incorporate modules compatible with potential **future** expansions or adaptations.
Using dry and reversible **connections** allows for repeated assembly and disassembly without compromising the structural integrity.
Lastly, the design should account for the eventual **deconstruction** of the building, ensuring it can be efficiently and safely dismantled (Guldager Jensen, 2016).

A great example of what has been explained is The Circular Building by Arup.

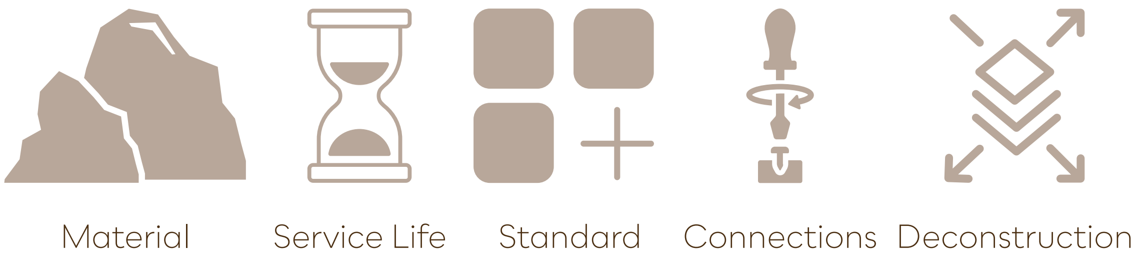


Figure 28. Five principle of DFD
Illustration adapted from Guldager Jensen, (2016)

CASE STUDY

THE CIRCULAR BUILDING - ARUP

One of the central exemplifications of a building that embraces circular strategies is The Circular Building. This architectural marvel, conceived by ARUP, is specifically designed to be entirely disassembled and reused. Through ingenious construction techniques, the full-scale prototype of The Circular Building utilizes materials that can be dismantled without incurring any damage, thus preserving the intrinsic value of each component.

In accordance with the research conducted by Fernàndez (2016), The Circular Building stands as a theoretical model showcasing the practical implementation of circular principles. Every single constituent part of this structure, ranging from window frames to minute fasteners, has been affixed with a digital technology in the form of a QR code. These codes encompass detailed information regarding the optimal methods for reusing each component, thus facilitating the principles of the circular economy.

By enabling the repurposing of materials and the extension of product lifecycles, The Circular Building exemplifies the potential of QR code labeling to advance the circular economy (Arup n.d.)

CONCLUSION

In conclusion, the adoption of a circular economic model in the construction sector has the potential to fundamentally transform the industry into a less impacted resource for the environment by reducing the use of new resources, minimizing the materials and energy and, lastly, by minimizing the waste by designing out of it (EMF, n.d.).
On the other hand, the ideal principle of circular economy can not still completely respected yet because it represents a profound paradigm shift in the industry; the switch will encounter several limits and obstacles before its proper fulfilment, as mentioned in the previous section (Guldager Jensen et al., 2016).

Design strategies play a vital role in overcoming these challenges and facilitating the transition to a circular economy. Prioritizing durability, modularity, and disassembly - and all the just mentioned strategies - in product design reduces environmental impact and enhances resource circularity.

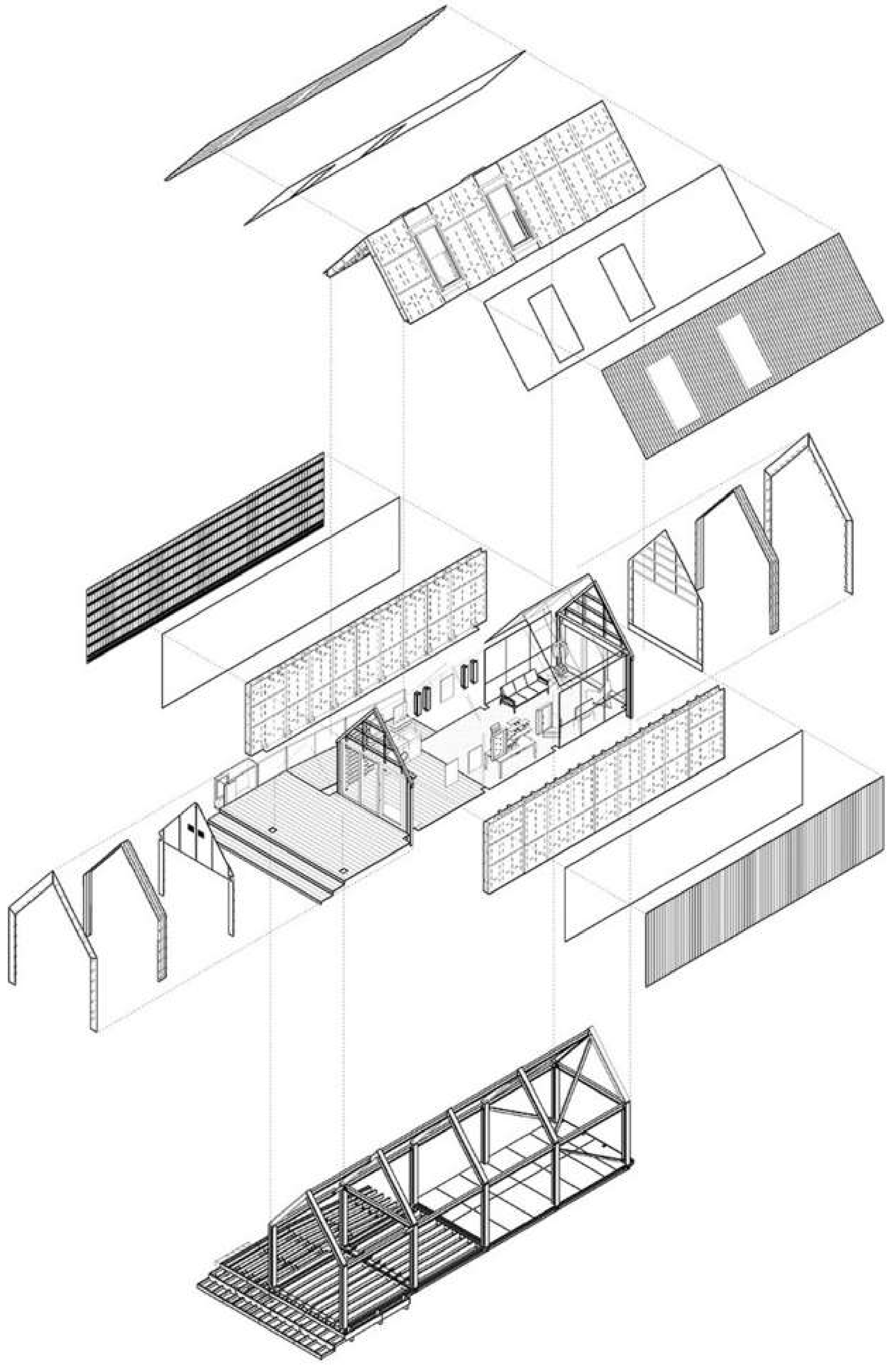


Figure 29. Exploded Axonometry of the Circular Building
Source: Arup, (2016)

2.3_ COMPUTATIONAL DESIGN

HISTORICAL OVERVIEW

The first use of computers in architecture occurred in 1963, during the 2D drafting era. Ivan Sutherland developed Sketchpad, the earliest program to utilize a complete graphical user interface. From that moment, computers and software started to be developed, having the most profound progress in the late 1980s (Remage, 2022): the popular AUTOCAD, Rhinoceros, etc., were developed in that period.

Therefore, designers soon realized that computer software could manage geometrical complexity easily and rapidly compared to human capabilities. This complexity can be reached by programming languages that convey comprehensible instructions to the computer. (Tedeschi, 2014) This process is called computational design, a method that relies on algorithms and parameters, which are the basic steps to solve design issues. (Remage, 2022).

An *algorithm* is a process that uses a finite number of fundamental and clearly defined directions to return the answer to a query or carry out a specific activity. Algorithms are based on the human tendency to break a problem down into easy-to-compute steps.
Although closely related to computers, algorithms can be described independently of programming languages (Tedeschi, 2014).
A *parameter* - according to the Oxford Dictionary - is " *a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation*" (OED, n.d.).
The field of computational design that relies on how the parameters vary and how the variation occurs is called parametric design.

PARAMETRIC DESIGN

The term parametric design was coined by the Italian Architect Luigi Moretti in 1939. His research - with the help of the mathematician Bruno de Finetti - ends with his models' realization of his project for a football stadium.

Moretti's design criteria focused on viewing angles and financial viability, and the final shape of the stadium was achieved by computing pseudo-isocurves that optimized views from every point in the stadium (Tedeschi, 2014).

In subsequent decades, with the advent of computers, the parametric design evolved into a process for defining relationships and customizable attributes in geometric entities, known as associative design (Turrin et al., 2016). According to Aish and Woodbury (2007), these customizable attributes generate many visual representations, each defined by specific values assigned to the model's variables, which can be either independent or dependent.

The *independent values*, often called independent parameters, act as inputs to the model, causing changes in both the model itself and the dependent values, which they directly influence (Turrin et al., 2019). This enables a faster visualization and understanding of the optimal variables and design solutions for a project, leading to significant time and cost reductions.

However, establishing relationships between the values in the parametrization process can be challenging. Since the variables determine all possible solutions, the model must be constructed to satisfy the desired objectives.
As mentioned by Turrin et al. (2011), it is crucial to establish a hierarchical chain of dependencies among the geometric entities, starting from the independent values. To begin building a parametric model, it is essential to understand and identify the desired design objectives and the corresponding performance criteria.

Once the aim of the process is precise, the next step is to determine the variables that influence those performances, generally known as the *design variables*. Each resembling a story chapter, proceeding with smaller steps is essential to navigating the design process effectively. Even when a "chapter" is concluded, it is necessary to continuously update and improve the entire model to maintain the coherence and strength of the whole story.

Having shown the process, the story ends when there is a conclusion: however, due to the infinite number of possible solutions resulting from different values assigned to the design variables, determining the most optimal solution based on the defined criteria can be challenging.
Given the research interest in three-dimensional shapes and the environmental impact of the material and energy production, the interest

would be moved towards those tools that can help to realize the most efficient design.

Therefore, complex geometries could create some difficulties and energy-intensive processes in manufacturing realization. Thus, for incorporating fabrication restrictions into the design of intricate architectural geometry, in order to realize the rationalization process has started to be used (Austern et al., 2018).

RATIONALIZATION

Glymph was among the pioneers in practically adapting architectural manufacturing constraints into the design process (Lindsey, 2001).
This approach gained significant popularity around the turn of the millennium as architects and engineers increasingly sought to create intricate, double-curved geometries. As defined by Fischer (2007, p.45), design rationalization involves approximating the intended form using a well-defined generative principle to facilitate the execution of the building. Rationalizing complex shapes aims to triangulate or regulate them for more efficient production, offering a more straightforward and economical solution than quasi-equal volumetric structures (Ham, 2012).

The rationalization process can be integrated with other computational techniques to shape panels effectively, reducing the total number of panels required and minimizing material, energy consumption and waste. Through the rationalization and optimization process, more straightforward, fewer, and reusable flexible moulds can be achieved, contributing to resource efficiency and sustainability in construction.

OPTIMIZATION

Optimization, as a critical aspect of parametric design, aims to determine the inputs to a function that yield the optimal value while considering any constraints or limitations (Pardalos et al., 2002).
The numerous results generated through parametric design can be analyzed by leveraging optimization algorithms, considering the predetermined parameters, to identify the best solutions that align with specific constraints and criteria (Turrin et al., 2019).

The rationalization and optimization processes exemplify their efficacy in the context of panel fabrication, as demonstrated in Figure 25. Employing these strategies significantly reduces the number and cost of panels, resulting in a more streamlined and cost-effective production process. Consequently, the waste associated with moulds is greatly minimized, contributing to resource efficiency and sustainability in construction (Hawkins et al., 2017) (Austern et al., 2018).

OPTIMIZED BUILDING

NON-OPTIMIZED BUILDING

moulds	-	115	107	107	65	65
panels	442	4523	264	264	88	88

moulds	-	2005	133	21	139	-
panels	414	8569	417	33	1351	-

Figure 30. Comparison between an optimized and non-optimized panelization
Source: Eigensatz (2010)

SEAMLESS TILING

In order to implement circular strategies effectively, as discussed in this section and previous sections, while ensuring flexibility and versatility, seamless tiling emerges as a practical approach. Seamless tiling refers to the seamless continuity of patterns across cladding panels, enabling the expression of visual coherence and unity.

By adopting seamless tiling, the design of modular panels gains a sense of dynamism and fluidity. This concept creates a cohesive visual experience, despite the panels being separate and modular. Integrating seamless tiling with the rationalization and optimization processes presents an intriguing case study, demonstrating how these design approaches can be combined synergistically. A comprehensive exploration of this innovative solution, including a detailed explanation of the entire process, will be provided in Chapters 3 and 4.

UAE PAVILION MILANO EXPO 2015 - FOSTER + PARTNERS

The United Arab Emirates pavilion for Milan Expo 2015 (Fig. 31) was designed by Foster + Partners.

The central concept of the cladding panels is to resemble the dunes of the desert by considering how their formation and ripple patterns happen in real life.
After understanding how the sand dunes can be translated into mathematical operations that the computer can formulate, attention is given to the procedure to create the three-dimensional pattern that is continuous through the different panels both in position and in the tangents of the central curves of the ripple ridges.
In order to achieve this, the first stage in the procedure was to create a basic starting pattern. To ensure that all the created patterns matched, the boundary of this first pattern was saved and later used as a component of the beginning conditions for the remaining ripple tile simulations.

Furthermore, considering the infinite solutions that can be realized by considering the guidelines just created, the rationalization process helped to simply the baselines to let them fit as closely as possible: an example of how the patterns can be generated in different panels is shown inFig.30.

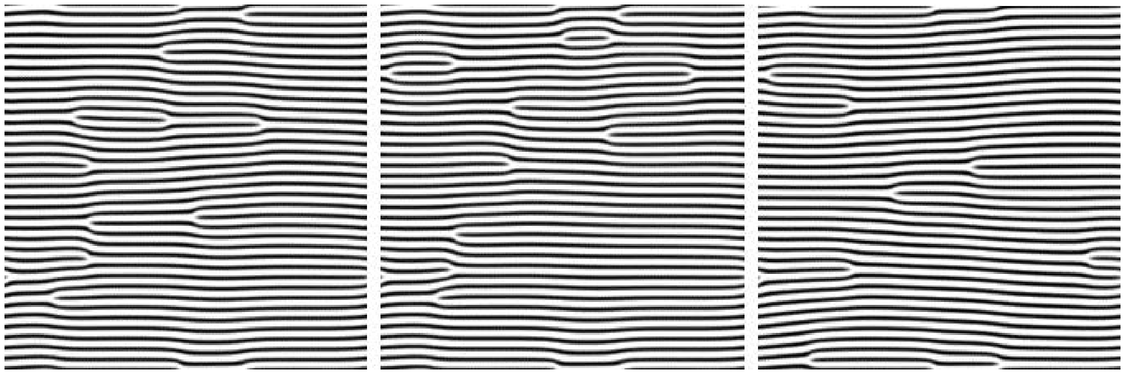


Figure 30. Example Pattern Configuration
Source: Malm et al., (2015)

In conclusion, the best panel placement along the walls was determined using a multi-objective optimization approach that maximized panel randomization while reducing the overall number of moulds. Therefore, just eight moulds have been realized for designing the whole pavilion but creating a dynamic end seamless tiling concept that seems to be categorized by all unique pieces, as shown in Fig. 31 (Malm et al., 2015).

DATA MANAGEMENT

To effectively utilize the computational tools mentioned earlier, it is crucial to have a secure knowledge of data management for the entire script. Data management involves managing the complex relationships among objects that generate data not directly visible within the Rhino model. Through these intricate relationships, Grasshopper creates a hierarchical and controlled data structure. This data structure is essential for the proper functioning of the computational tools. It ensures that data is organized and structured in a way that facilitates efficient analysis and processing.

Grasshopper collects information in different ways, depending on how it is created. This information can be organized into trees, branches, or lists. By connecting these groups, Grasshopper stores data according to a Parent-Child logic. This logic creates subsets for each parent data path, enabling efficient data organization and manipulation.

To achieve the desired outcomes, the data structure can be manipulated based on specific needs. There are various tools available for this purpose, such as Flatten, Graft, Flip Matrix, and many others (Tedeschi, 2014).

By understanding and effectively managing the data through Grasshopper's capabilities, users can harness the full potential of the computational tools and achieve precise and desired outcomes in their scripts.

CONCLUSION

In conclusion, computational design has emerged as a powerful architectural tool, revolutionizing how designs are conceived and implemented. Parametric design, in particular, has significantly enabled architects to visualize complex designs quickly and easily.

By defining design parameters and establishing relationships between them, architects can explore a wide range of design possibilities and generate variations efficiently. This has greatly enhanced the creative process and expanded the horizons of architectural design.

Furthermore, computational tools provide the means to study and analyze how to deal with aspects - such as environmental, topographic and many others - helping architects make informed decisions that align with sustainable practices.

One notable example of the impact of computational design is the UAE Pavilion designed by Foster and Partners. This iconic structure showcases the potential of parametric design in realizing complex architectural forms while minimizing panels and maintaining flexibility. The pavilion's intricate geometries and structural efficiency were achieved through a deep understanding of rationalization and optimization, made possible by computational tools.

Lastly, a solid data management and manipulation foundation is essential to fully grasp and leverage the parametric design's potential. Architects and designers need to comprehend how to handle and structure data effectively and employ various tools for data manipulation.

In conclusion, computational design has transformed the world of architectural design, offering unprecedented opportunities for innovation and sustainability. By embracing parametric design principles and an understanding of data management, architects can visualize complex designs, incorporate environmental considerations, and optimize the realization of architectural concepts.

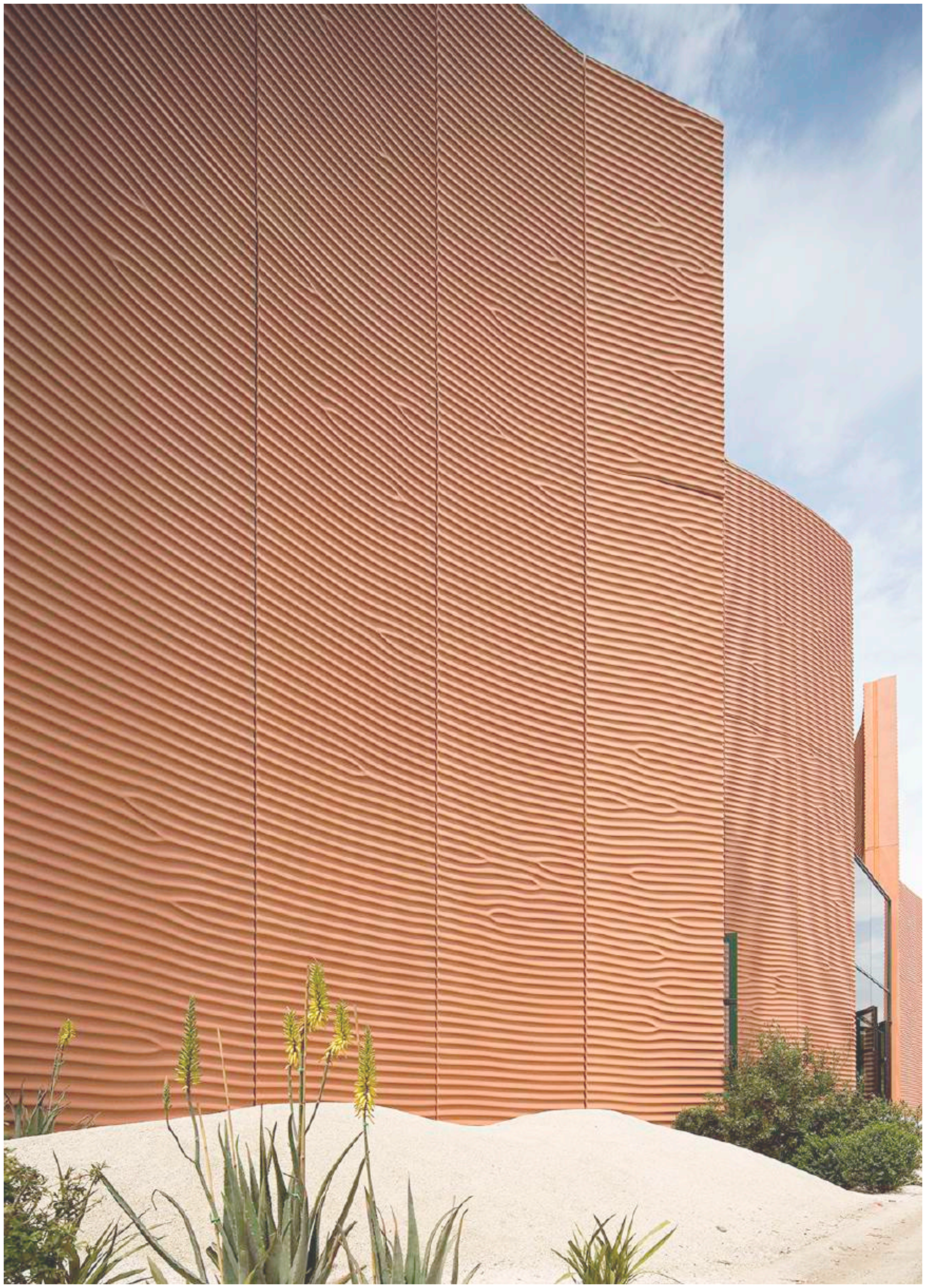


Figure 31. UAE Pavilion External Cladding
Source: Archdaily, (2015)

2.4_ BIO-BASED MATERIALS

The Netherlands Standardization Institutes defines biobased as:

"derived from biomass, can have undergone physical, chemical or biological treatment(s)".

Moreover, biomass is defined as:

"material of biological origin excluding material embedded in geological formations and/or fossilized"

(NEN, 2014)

Since ancient Roman times, bio-based materials have been employed in construction. However, their extensive utilization witnessed a significant decline during the advent of the Industrial Revolution in 1750, coinciding with the commencement of coal mining operations. This pivotal turning point marked the ascendancy of steel extraction and production, leading to a sharp reduction in bio-based materials.

Furthermore, in the 19th century, the production of various metals gained momentum, while the introduction of Portland Concrete further solidified its dominance in the construction of industrial buildings. As the 20th century unfolded, metals, concrete (further reinforced with steel), and plastics emerged as the primary materials employed in the building industry (Admin, 2020).

However, in recent years, driven by the urgent environmental crisis discussed in Chapter 1, bio-based materials have once again captured the attention of the building industry.
Extensive research and evidence demonstrate that these materials offer numerous environmental benefits across multiple domains. Firstly, they exhibit reduced reliance on fossil fuels. Moreover, their production processes are designed to be more sustainable, aiming for a less ecological impact. Lastly, bio-based materials can even be derived from waste streams, enabling the utilization of abundant and underutilized resources (NEN, 2014).

CATEGORIZATION

Following Jones' categorization, bio-based materials are mainly divided into two groups: wood and non-wood bio-based materials (Jones D. et al., 2017).

WOOD

Wood has been used as a renewable raw and engineering material for centuries in the built environment due to its attributes like lightweight, processability, good mechanical properties, sustainability, aesthetic appearance, and technological applicability (Rowell, 2005) (Fengel et al.,1989) (Hill, 2006) (Ermeydan et al., 2014).

Wood is subdivided into three main types: softwoods, hardwoods, and engineered woods. The first two are the naturally occurring woods that differ from each other by the species of the tree from which they originated. In contrast, engineering wood is industrially manufactured and results from smaller residual pieces that are bound together (Popescu, 2017).

NON-WOOD

Non-wood bio-based materials, instead, are all the remaining biological resources derived from biomass (such as flax, hemp, and reed) that have recently become an area of growing importance (Nunes, 2017). Unlike forest products, they do not need to be rotated for a long time, and when used as thick insulation for external walls, they have a higher capacity to store carbon (Habert et al., 2017).

Furthermore, more benefits have been discovered. Therefore, their importance is growing sharply in the built environment. One of the main interests in bio-based materials is that they might be manufactured from local waste. Thus, waste-based procedures will convert waste into economic value, reversing the value chain from an end-of-life resource to a circular economy and requiring adaptation in life cycle modelling methodologies (Brunklaus et al., 2018).

Non-wood bio-based materials provided in the building industry can either be bioplastics or biocomposites.

BIOPLASTICS

Biobased plastics are made from biological sources and offer similar properties as common plastics. In many circumstances, they provide further benefits like reduced carbon footprint or extra waste management alternatives such as composting (European Bioplastics, 2021).

Therefore, bio-based plastics can be biodegradable - such as starch and cellulose -and, thus, can biodegrade in specific conditions and at their end of life. In this group, compostable plastics are available. However, they must be composted in industrial facilities (European Commission, 2018). Moreover, bio-based plastics can also be non-biodegradable - such as in the case of PE. Even though they can not be biodegradable, they still have environmental benefits by decreasing the products' emissions: they can easily be mechanically recycled (European Bio-plastics, 2021).

Finally, non-biobased biodegradable plastics have been developed - such as PBAT - that are fossil-based (as shown in Fig. 32) (European Bioplastics, 2021).

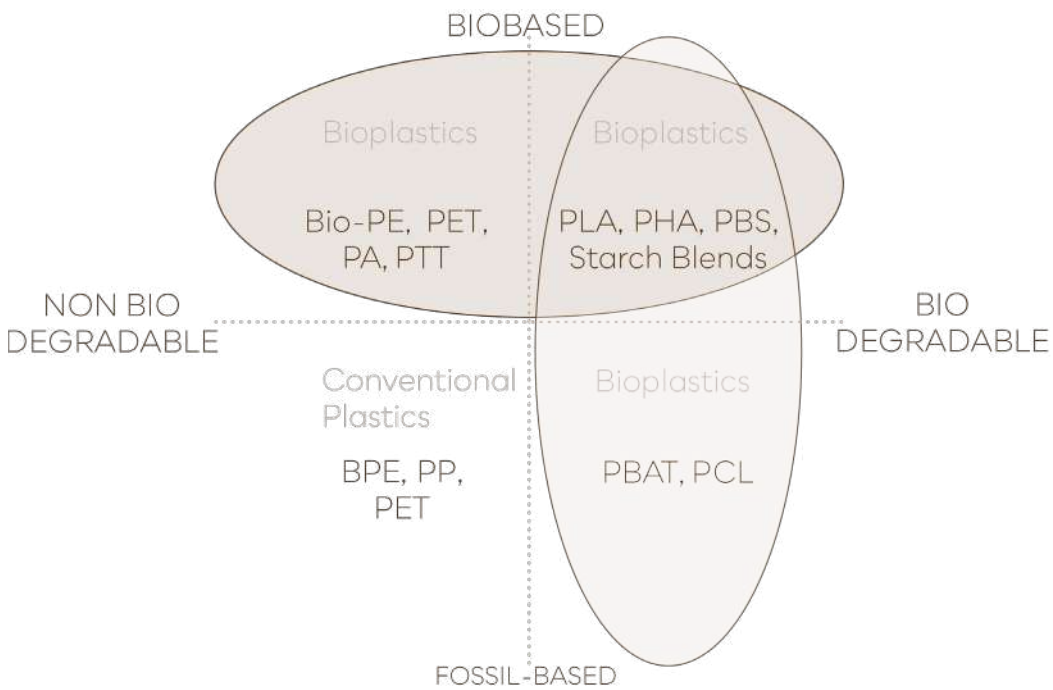


Figure 32. Bio-plastics categorization
Illustration adapted from European Bioplastics, (2021)

BIOCOMPOSITES

Biocomposites represent a category of materials consisting of two essential components: a matrix and a reinforcement.

The matrix serves as the primary element responsible for cohesive integrity, while the reinforcement enhances the mechanical properties of the matrix material (Chawla, 2012).

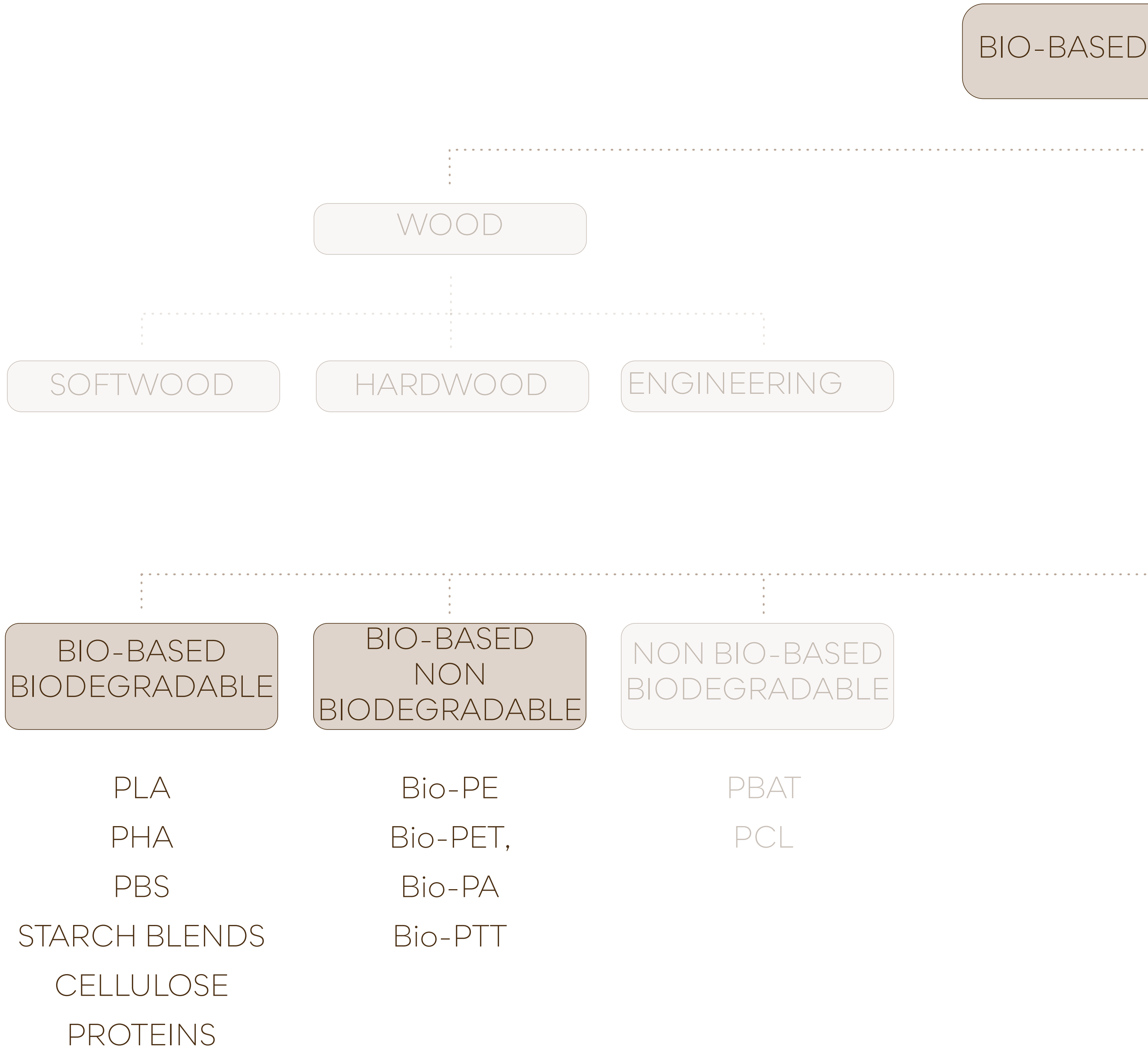
Despite the longstanding historical use of composite materials, the scientific community has recently turned its attention towards natural plant fiber-reinforced composites, owing to their noteworthy attributes of affordability, lightweight nature, high specific strength, renewability, and biodegradability (Chollakup et al., 2015).

Bio-based composites can be manufactured either entirely or partially from environmentally sustainable constituents. Partially eco-friendly materials combine natural fibres with petroleum-derived plastics, such as polyester, polyethene, and polypropylene.

On the other hand, eco-friendly composites are crafted using natural fibres and plastics derived from renewable resources like soy, cellulose, and polylactic acid (PLA). Moreover, most circular products in this domain comprise natural fibres integrated with matrix materials derived from waste streams, further contributing to a circular economy approach (Chollakup et al., 2015).

Furthermore, a diverse array of natural fibres is utilized in the production of biocomposites. Plant-derived fibres, predominantly composed of cellulose, form one category. Another category encompasses animal-derived fibres, which consist of proteins found in materials such as hair, silk, and wool. Lastly, mineral-derived fibres constitute another category (Chollakup et al., 2015).

Having shown all the macro-groups that compose the bio-based materials (Fig. 33) a selection need to be taken considering specific settled criteria that are coherent with the research aim and the further three-dimensional design.


BIO-BASED
WOOD
SOFTWOOD
HARDWOOD
ENGINEERING
BIO-BASED BIODEGRADABLE
BIO-BASED NON BIODEGRADABLE
NON BIO-BASED BIODEGRADABLE
PLA
PHA
PBS
STARCH BLENDS
CELLULOSE
PROTEINS
Bio-PE
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Bio-PTT
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PCL

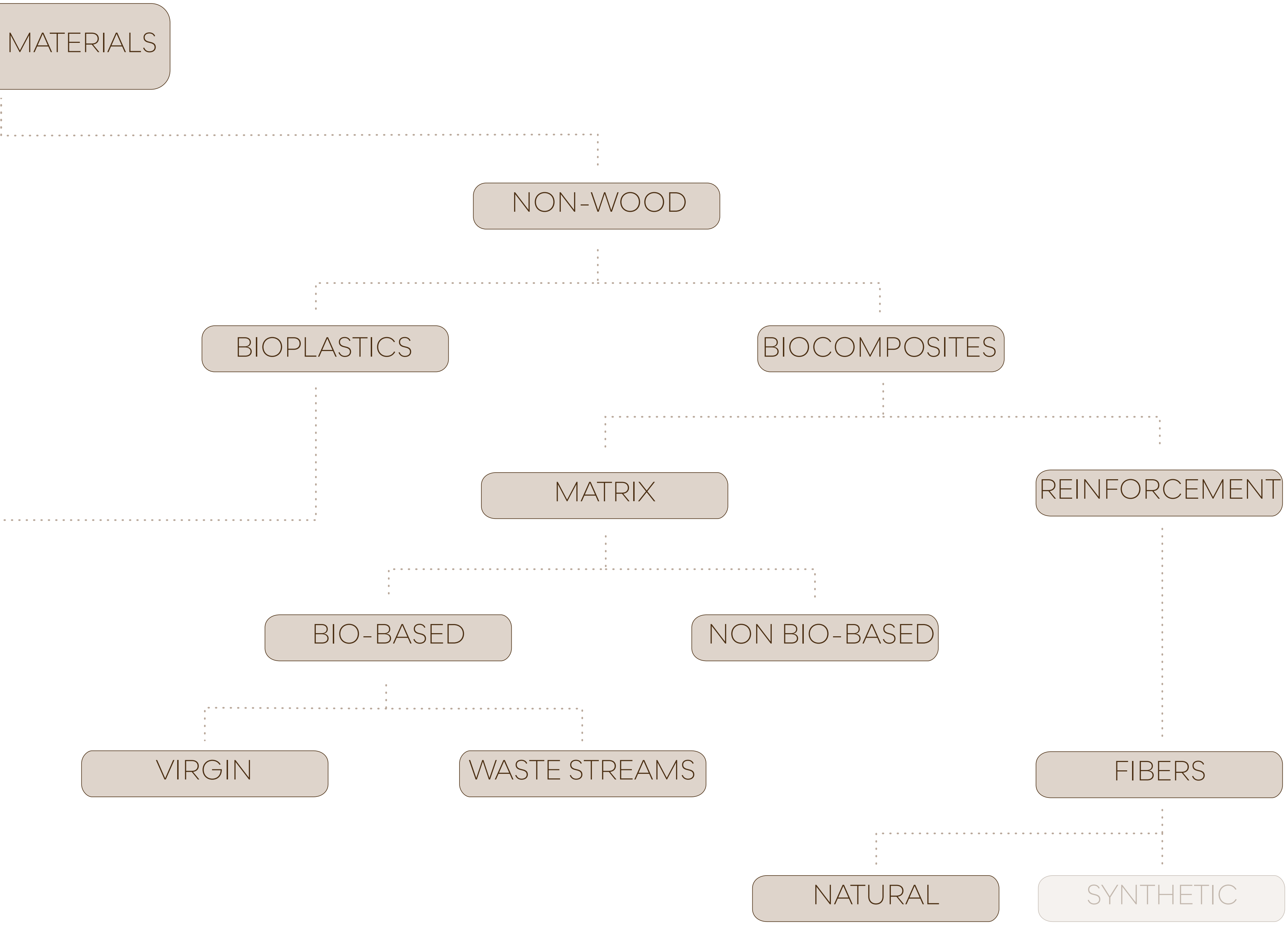


Figure 33. Bio-based materials categorization, emphasizing the interested ones own. ill

MATERIAL SELECTION

After analyzing the theoretical bio-based materials differentiation, finding the appropriate material for product realization is essential.

As mentioned in Chapter 1.4 - the main aim is to realize a new three-dimensional product with bio-based materials. Therefore, given the attention on the design, while the materiality can be conceived as just a tool for the realization, experimentations will be held in the design field while considering existing and certified materials for external claddings.

Considering the central premise, some criteria have been prioritized for the material selection.

SUITABILITY TO THE THREE-DIMENSIONAL DESIGN

As mentioned, the three-dimensional design will be quite challenging to prove that more circular and environmentally safe materials can withstand such complex shapes as those mentioned in Chapter 2.1.
Therefore, the main criteria for choosing the material (and, further, the manufacturing process) will be the suitability for three-dimensional realization.

WASTE STREAMS REUSABILITY

As mentioned in Chapter 2.2, attention is given to the amount of waste generated by the construction industry and how this can be conceived as a potential resource for designing out of it. Thus, the amount of waste within the certified materials will be considered crucial.

R-STRATEGIES ADAPTABILITY

Another fundamental aspect to take into account - which depends, however, also on the design - is the R-strategies adaptability, meaning the capability of the material to be treated in such a way to extend its lifespan through higher levels than recycle and recover within R-strategies (Fig.22).

WATER RESISTANCE

Since the aim is creating a design for external cladding, water resistance is important to fulfill for considering the further product as a potential product for the construction industry,

FIRE SAFETY

As in the case for the water resistance, to provide an external cladding - as mentioned in chapter 2.1 - it needs to fulfill proper requirements to be a final product for the construction industry.

Furthermore, some other criteria could be taken into account but considered less relevant for the research, such as cost, aesthetics, thermal properties, and chemical compatibility with the environment.

Finally, the last consideration for the material selection is the actual proximity of the company, and the practical feasibility of obtaining the material for prototyping purposes is also considered.

NPSP is the leading considered company. Therefore, they developed the first three material products listed in the following paragraphs: Nabasco 5010®, Nabasco 8010®, and Nabasco 10010®.

The following two materials are classified as experimental materials. Hence, they have yet to be introduced in the market. However, due to the significant potential for the reuse of waste streams, they are being considered as potential options: the first material is RE-PLEX, a material that is a collaboration between NPSP, TU Delft, AMS Institute, Chain Craft, and Bam Infraconsult; The second experimental material is Fabulous, developed by NPSP, TU Delft, AMS Institute, Paques, and Orgaworld.
Finally, the last selected material is Resysta, a German company that offers this biobased material in the market.

Nabasco - NPSP

The considered biobased and circular family materials Biocomposite Nabasco® is composed of natural fibers, partially or 100% natural-based resins that can vary - but often soya beans, linseed oil, or waste from biodiesel production are used -, and fillers - usually calcite took from drinking water companies waste(CACO3).

They were initially labelled concerning their percentages of bio-based material within the materials (50,80,100). However, following time and more experiments, these macro-groups started having different series in relation to their components.

The analyzed materials will be those provided in the market; therefore: Nabasco 50s®, Nabasco 80s®, and Nabasco 100s®. However, other 80s series will be further compared, potentially prototyped, and shown in the following chapters.
The lifespan of this range of material is still not realistically provided, but after exposing the product to the accelerated ageing machine, they test the specimen's strength. Because of this, they can provide information on a range of lifespan between 50 and 100 years.
The materials can be shredded and repurposed at the EoL of the claddings made with Nabasco products. Therefore, the created powder will become part of the filler to realize a new cladding reducing the use of calcium carbonate (Bottger, 2023).

Nabasco 50s

Nabasco 50s® marks the pioneering bio-composite material developed by NPSP. It merges natural long fibers with a polyester resin, with variations in the resin composition that may include soya beans, linseed oil, or waste from biodiesel production.

The manufacturing process employs vacuum infusion, wherein the resin replaces the air during the vacuuming process, creating the final product. Nonetheless, it is worth mentioning that this material requires significant labor input, as each component necessitates manual cutting, resulting in elevated costs. Additionally, its fire properties are inferior to those of other Nabasco materials; therefore, it is essential to consider the choice of this material in terms of the building scale and requirements.

Figure 34. Gas Reception Station Dinteloord
Source: NPSP, (n.d.)

Nabasco 80s

Nabasco 80s is a thermoset biocomposite material made of resin, filler, and fibres in a state of a bulk-moulding compound.

The filler is calcium carbonate extracted during water waste management, the resin is partly bio-based (50%) and made from leftover biofuel resources, and there is an extensive list of potential fibres such as flax, hemp, reeds, and recycled denim (A_4).
The selection of the fibres differs in both the narrative envisioned by the designer for the building and the mechanical properties of the fibres themselves: the stronger the fibres, the cheaper and thinner the panels.

The manufacturing process is the hot pressing process, which involves placing the bulk moulding compound into double-sided metal moulds. The mixture is then uniformly spread throughout the mould and subjected to a temperature of 140°C and at 100 bars for a few minutes.

Finally, the mould is opened, and the final product is released.
The bulk moulding state of Nabasco 8010 permits essential freedom in the cladding realization, a peculiarity that differs from the other Nabasco products (Bottger, 2023).

It results in a panel that can suit both indoors and outdoors, is lightweight, durable, and with good fire resistance properties (NPSP, n.d.) (Biobased Bouwen, n.d.).

Figure 35. Nabasco 8010 with different fibers
Source: NPSP (n.d.)

Nabasco 100s

Nabasco N-100s® is another bio-based and circular material developed by NPSP. It is made of natural fibres with 100% dark-brown natural-based resin made of sugar cane that is solved in water which gives its peculiar colour finish (Bleeker, 2023).
The main goal obtained by developing this material is complete reusability after use, becoming a material with a high potential to be fully circular. The panel suits both indoors and outdoors, is lightweight, and is fire resistant.

The manufacturing process for Nabasco 100s realization is the same as for the Nabasco 80s. Therefore, the state of the material is still a bulk-mounding compound subjected to hot pressure from a double-sided mould.

Even though this material has high performance in terms of circularity, the manufacturing process is still under research. Therefore, there is still the will to solve the problem of the hot press temperature since if it goes over 100°C, the water will turn into steam, giving extra pressure and steam pockets in the resin.

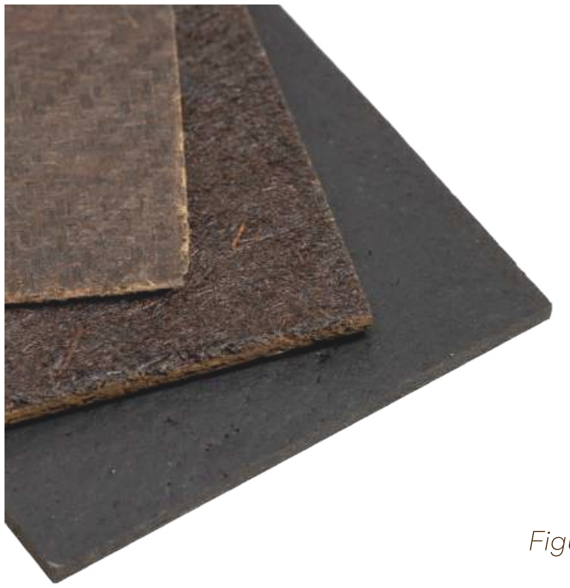


Figure 36. Nabasco 10010 with different fibers
Source: NPSP (n.d.)

RE-PLEX - BAM INFRACONSULT | NPSP | CHAIN CRAFT | TU DELFT | AMS INSTITUTE

This material is a fully bio-based material made with wastewater fibers - mainly produced by toilet paper - and the so-called Kaumera bio resin produced by bacteria.
The mentioned institutes and companies are still researching the external applications of this material, but the COMPRO building is a prototype 1:1 in which this innovative material has been used (AMS Institute, 2020).

The costs of the material are cheaper than usual composite bio-based materials since it takes advantage of the usual water treatment that has to be done (Kaumera process) in every city for health reasons. Therefore, by cleaning dirt and water, kaumera resin has been created.

The production of samples is made by hot pressing with moulds. However, the manufacturing process for building the mentioned case study is still underway.

In conclusion, it has been experimented that this material can follow the cradle-to-cradle principle by grinding and hot-pressing again, maintaining the mechanical properties (Mooij, 2023) sufficiently.

Figure 37. Re-plex structure sample
Source: AMS Institute, 2020

PHBV FABULOUS - PAQUES| ORGAWORLD | TU DELFT | NPSP | AMS INSTITUTE

The Fabulous project represents a collaborative effort involving Paques, Orgaworld, TU Delft, NPSP, and AMS Institute. This undertaking is focused on the development of a bio-plastic material, specifically a PHBV material. PHBV is a subcategory of PHA, which belongs to the realm of bio-based and bio-degradable bio-plastics.

The process entails extracting this material from bacteria found in urban organic waste sources such as orange peels, tomatoes, and grass. Subsequently, a two-step conversion process is employed to produce the desired bioplastic. It is important to note that the manufacturing process for this material is still undergoing refinement and development.

At present, there is no definitive confirmation regarding the material's suitability for outdoor applications (Mooij P., 2023).

Figure 38. Fabulous sample
Source: Water AllianceNL, (2022)

RESYSTA - RESYSTA

Resysta, an innovative bio-composite material, has been developed by the German company Resysta. This unique material composition consists of approximately 60% residual rice husks, 22% salt, and 18% oil. The oil component plays a crucial role in forming the polyvinylchloride matrix, which effectively binds the rice husks together.

Despite the fact that polyvinylchloride is a thermoplastic material and not derived from bio-based sources, Resysta exhibits remarkable versatility in terms of its processing capabilities. It can undergo various fabrication techniques such as cutting, deforming, machining, and thermoformed. This characteristic enables Resysta to be shaped and formed according to specific design requirements, despite the non-biobased nature of the polyvinylchloride matrix (Mac Lean, 2018).

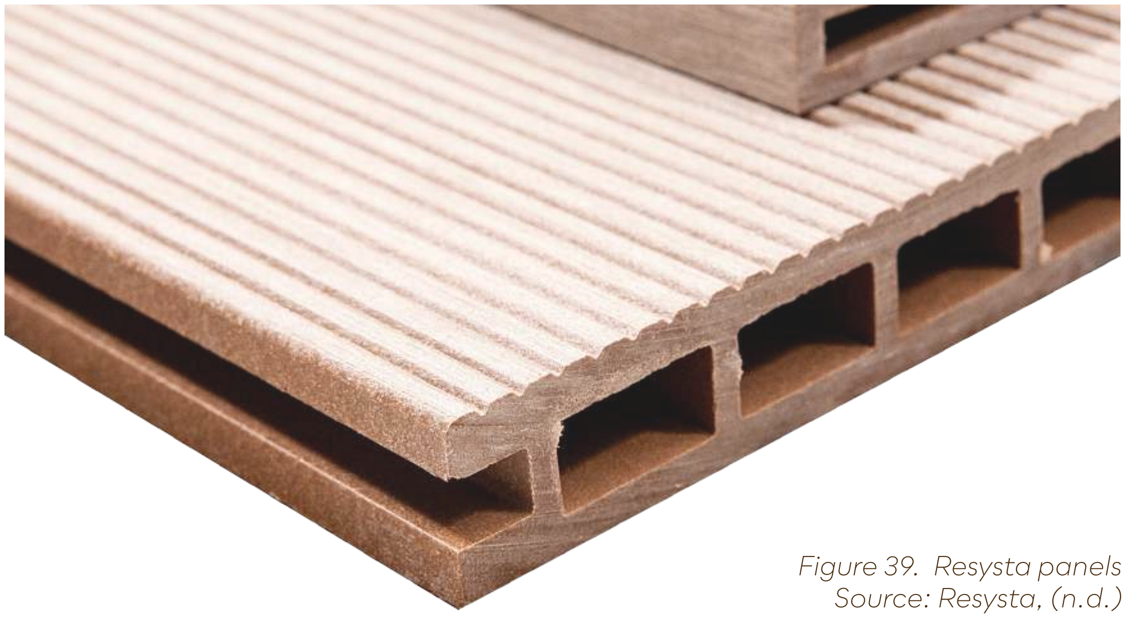


Figure 39. Resysta panels
Source: Resysta, (n.d.)

SUMMARY

Table 1 presents a comprehensive list and comparative analysis of the bio-based certified materials under examination, highlighting essential details such as the associated company, application areas, materials used, and the corresponding manufacturing processes employed.

With this summary and the established criteria for material selection firmly in mind, it becomes possible to deliberate on the subsequent steps to be taken. This involves conducting extensive literature research and exploring avenues for further enhancements in line with the identified objectives and requirements.

COMPANY	NAME	APPLICATION	MATERIALS	MANUFACTURING
NPSP (NL)	Nabasco 50s	INDOOR	NATURAL FIBERS, RESIN	VACUUM INFORMING (MouldING)
NPSP (NL)	Nabasco 80s	INDOOR AND OUTDOOR, FURNITURE, STREET SIGNS	NATURAL FIBERS, RESIN AND FILLER	HOT PRESSING (MouldING)
NPSP (NL)	Nabasco 100s	INDOOR AND OUTDOOR	NATURAL FIBERS, RESIN AND NATURAL FILLER	HOT PRESSING (MouldING)
BAM INFRACONSULT, NPSP, CHAIN CRAFT, AMS INSTITUTE, TU DELFT (NL)	RE-PLEX	NOT KNOWN YET	CELLULOSE FIBERS, BIOLOGICAL GLUE (KAUMERA)	HOT PRESSING (MouldING)
PAQUES, ORGAWORLD, AMS INSTITUTE, TU DELFT (NL)	PHBV-FABULOUS	NOT KNOWN YET	URBAN ORGANIC WASTE	HOT PRESSING (MouldING)
RESYSTA (DE)	RESYSTA	INDOOR AND OUTDOOR	60% RICE HUSKS, 22% SALT, 18% SOIL	CUTTING, DEFORMING, MACHINING AND THERMOFORMING

Table 1. Bio-based Materials Summary
own ill.

CONCLUSION

After analyzing the potential materials that can perform the requirements for further design, a choice has to be settled.

Having the chance to interview Willem Bottger from NPSP, who had developed - and collaborated on - most of the selected materials, the whole scenario was precise.

Unfortunately, Re-plex and Fabulous are still in the embryonic stages to be certainly provided in the market: they plan to sell them in at least one year. Therefore, these two options need to be excluded.

Considering the Nabasco products, instead, the criteria for choosing the most accurate material for the design are different. Therefore, they have all been tested and provided for different use.

As mentioned in the previous paragraphs, Nabasco 50s is a high-cost material since the shaping of the product can only be produced by manual cutting. Moreover, it is suitable for interior applications and, in case the potential design is intricate, and the details to be cut are too small, the finishing process becomes complicated.
Therefore, these aspects need to be considered while considering the best choice.

Nabasco 100s, instead, gives more circular solutions because of the 100% bio-resin. However, visually speaking, the selection of colors could be more substantial because the dark-brown natural resin gives color to the product. Moreover, the product state is still in process. Therefore, there is no certainty in the panel realization. Therefore, since the willingness is to provide a product into the construction market proposing a material still under research is quite controversial: Nabasco 100s has to be excluded.

Resysta and Nabasco 80s are the last materials to be analyzed.

Resysta is a peculiar solution that responds to the design criteria: it is easy to construct, it can be thermoformable - therefore, the three-dimensional shape can potentially succeed - and it offers numerous finishing colors.

Nabasco 80s, on the other hand, is easily assembled and disassembled; it is thermoset - therefore, the three-dimensionality can be realized as well - and, as mentioned before, the coloring change about the selected fibers.

In conclusion, the above considerations are vital in determining the most suitable material for the intended purpose. To gain a comprehensive understanding of the available options and fulfill the aspiration to create complex three-dimensional shapes, it is crucial to consider the manufacturing process.

As illustrated in Table 1, all the proposed materials are manufactured using different moulding processes (vacuum informing, hot pressing, thermoforming). Therefore, compiling a list of the most relevant moulding techniques is essential. This compilation will aid in finalizing the selection of the most effective materials, considering the established criteria and objectives.

Lastly, in addition to the material selection criteria, practical aspects of manufacturing feasibility must be considered when planning the realization of the prototype. This practical assessment considers factors such as resource availability, production complexity, and any potential constraints that may impact the successful execution of the prototype process.

2.5_ MOULDING PROCESSES

After analyzing the chosen bio-based materials, as mentioned in the last chapter, attention is given to the manufacturing process. As stated, moulding processes are generally the most used in bio-based materials (considering the certified ones taken into account). Therefore, the most relevant processes will be studied and listed.

Furthermore, the moulding process will be then used as an expedient for respecting a further circular design strategy - the *dematerialization* explained in chapter 2.2 - that will be further developed within the conceptual design and, therefore, in chapters 3 and 4.

Additionally, this process enables the creation of complex shapes and countors with high precision, making it an ideal choice for the realization of the envisioned design.

Having shown the context of interest, the most usual types of moulding will be described.

CAST-MOULDING

Cast-moulding is a piece-by-piece moulding in which liquid material is poured into a cavity in a mould that mimics the shape of the finished object. When the desired shape is achieved, the molten material cools while typically absorbing heat from the mould.

It is a straightforward procedure, and it can be done on each scale without using industrial machinery. However, the material is not perfectly compressed into the mould with this process. Therefore, the stiffness will be relatively low compared to other manufacturing processes.

The mould can either be opened or closed.

In the first case, a contre-form is made in which liquid can easily be poured. Therefore, the matter will be exposed to air on one side: in most cases, the hardening will happen thanks to evaporation or cooling.

In the second case, the mould comprises two halves - or more. The liquid material is poured into a cavity while the air inside the mould escapes through vent holes.

Lastly, slipcasting is another type of cast-moulding.

Slip is placed into the mould, which is typically formed of plaster. The substance hardens when it comes into touch with the walls, forming a nearly solid crust but still moist. The excess is removed. Shrinkage brought on by drying makes removing the component from the mould easier. The drying process is finished outside the mould (Kula et al., 2013).

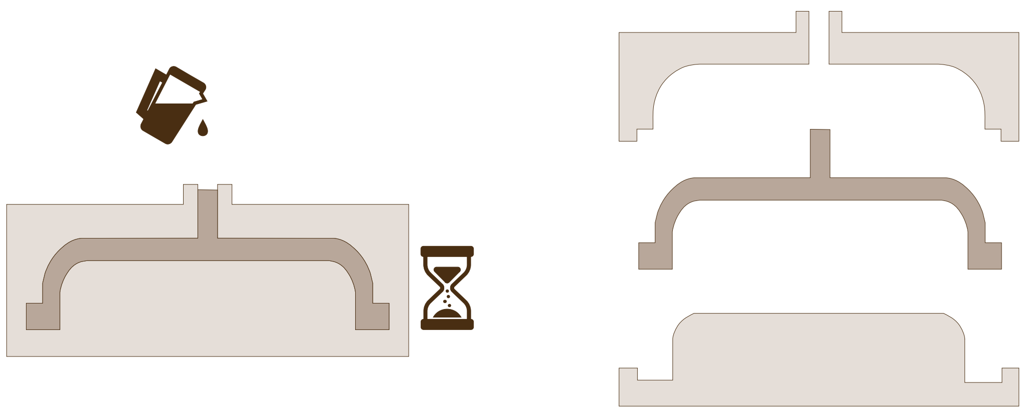


Figure 40. Cast moulding
Illustration adapted from Kula et al., (2013)

INJECTION MOULDING

Injection moulding is an industrial production process in which a melted material is injected at high pressure inside a closed mould, which is opened after the part has solidified: because of this, complex forms and precision can be achieved.
The mould dimensions can vary between a few millimeters to several meters; however, it is an expensive method.

PLASTIC INJECTION

In an injection screw, plastic grains are heated and friction-melted before being injected into a mould at high pressure and temperature, which is subsequently sealed by a hydraulic or motor system. The mould will feature a cooling system to ensure that the material solidifies evenly and has a clamping force of several hundred tonnes. Finally, the mould is opened, and the item is taken out.

Moulds are often precision-machined from specific, extremely resistant steels, being, therefore, expensive. Most moulds are constructed of two parts - one permanent and the other mobile - that is hollowed out to create a cavity that is the counter-form of the finished product.

Furthermore, production for injection moulding fluctuates between 100,000 and 1,000,000 pieces. Today, options for small-scale injection moulding are being developed, mainly to create prototypes (Kula et al., 2013).

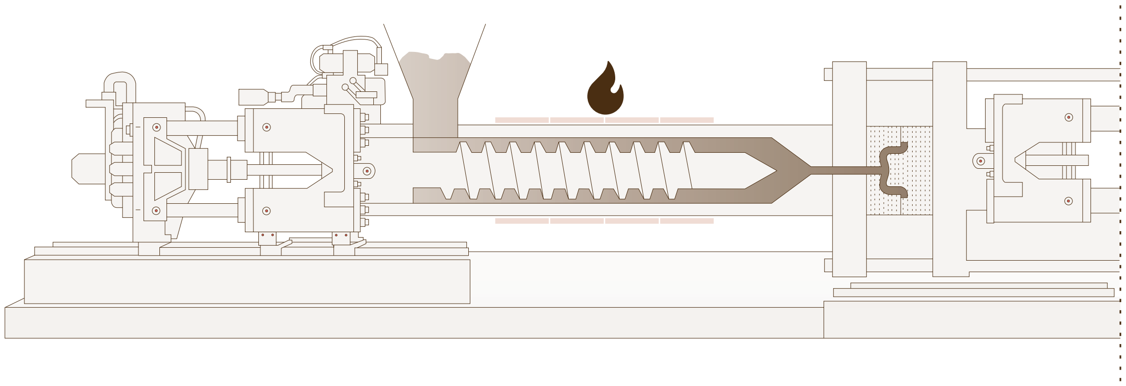


Figure 41. Injection moulding
Illustration adapted from Kula et al., (2013)

HOT PRESSING

Hot pressing is a densification process where a compound undergoes uniaxial pressure and sintering- meaning carefully heating a powder or a dough to a temperature slightly below its melting point (Cambier et al., 2021).

This controlled heat enables the particles to fuse, forming a solid, cohesive piece (Cambier et al., 2021) (Spriggs et al., 1967). By pressuring the compound at high values, the stress between the material particles vastly increases, causing an acceleration of the densification kinetics: during the process, the matrix of the composite spreads between the fibers filling the gaps (Bottger, 2023).

This process gives high performance to the material for several reasons. The hot-pressed process gives the product extremely low porosity, reaching almost the density theoretical value.
In addition, this process offers a high degree of flexibility and versatility in shaping, as it enables the material to be moulded into intricate and complex shapes with relative ease, thus allowing for greater creative freedom in the design and production of various products. The strength of the products generated by this procedure is one of the reasons why it is attractive to numerous sectors.

However, the hot pressing process can only produce one to a few products at a time since the used tools are simple to manufacture and have a quick production cycle, making them well-suited for single-piece or small-volume production needs.

Therefore, due to the high cost of manufacturing metal moulds, the process can be expensive, making it less suitable for large-scale production runs. This is because the costs incurred in creating the moulds are significant and are usually spread across a relatively low number of units. As a result, the cost per production unit can be prohibitively high, making the process less attractive for mass production.

Although the cost of the process is relatively high and its productivity is limited, it remains a valuable tool in the prototyping phase of product development (Bhatti et al., 2000).

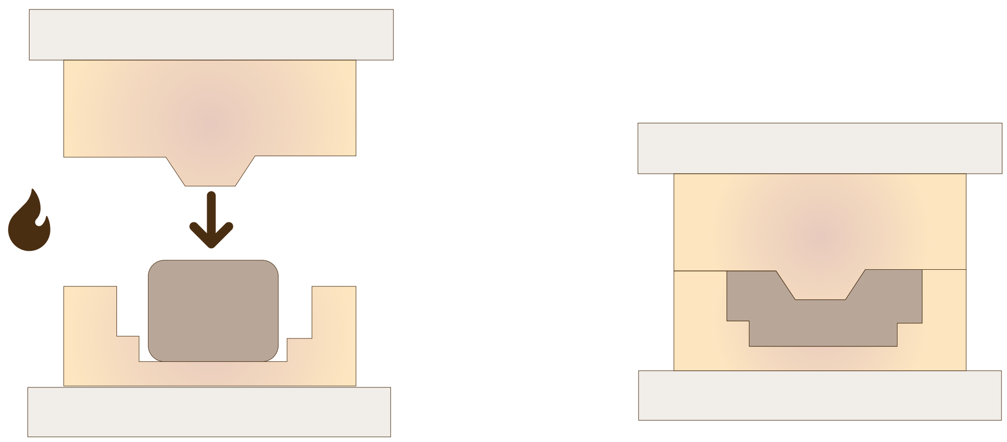


Figure 42. Hot pressing own ill.

THERMOFORMING

Thermoforming is a technique of hot moulding plastics from sheets or films under pressure or vacuum.

Very complex shapes can be made with this process, however, it can feature thickness variances, which might harm the object's overall strength. Moreover, the object's strength can be further afflicted since only one side of the product is in contact with the mould; therefore, the opposite side cannot be assured to be precise mechanically or aesthetically.

After all, it is a low-priced production technique - besides the trimming process - and adaptable to many shapes and dimensions - it can vary from a few centimeters to more than a meter (Kula et al., 2013).

PLASTIC THERMOFORMING

The thermoplastic sheet is heated until it becomes sufficiently soft before being clamped into a frame (blank holder). It is then cooled after being suction-pushed and distorted over a model. After removal, trimming is required to remove the edges (by sawing or punch cutting for thin films) - as a matter of fact, a considerable amount of material loss occurs.

In terms of production, thermoforming is viable for 1,000 to 10,000 pieces or more (Kula et al., 2013).

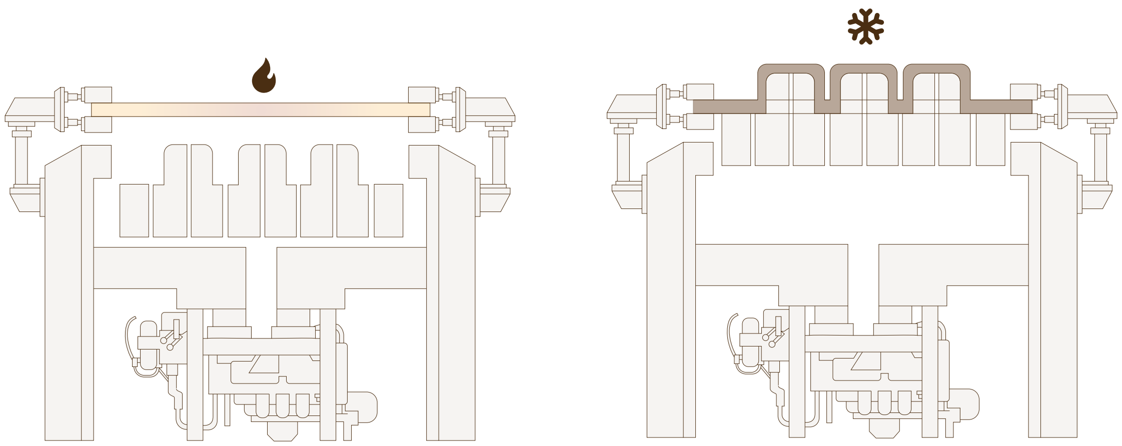


Figure 43. Thermoforming
Illustration adapted from Kula et al., (2013)

VACUUM INFUSION

The Vacuum Infusion Process (VIP) is a technique that utilizes vacuum pressure to drive resin into fibers.
The mould is gel-coated, and the fibers are laid on it: the fibers are usually long or weaves. While sealing the mould, a perforated release film covering the dry reinforcement has to be present.
The dry materials are compacted by applying vacuum pressure before introducing the resin.

Once the vacuum process is complete, the resin is infused within the mould through specific tubes.

Attention has to be paid to the resin viscosity. For instance, resins with very low viscosities may need to adequately infuse the entire material due to the high flow resistance of specific reinforcements. Therefore, even slight variations can lead to significantly different infusion flow rates. Storage conditions, particularly temperature changes, can impact resin viscosity. (Spasojevic, 2019).

Furthermore, the main disadvantage of this process is that the finishing layer on the surface may not be as refined as with the open mould process, primarily due to fabric print through. However, it is possible to enhance the finish by applying a barrier coat.

This is the typical manufacturing process for polyester fiber technologies, offering significant emissions reductions (Bleeker, 2023).

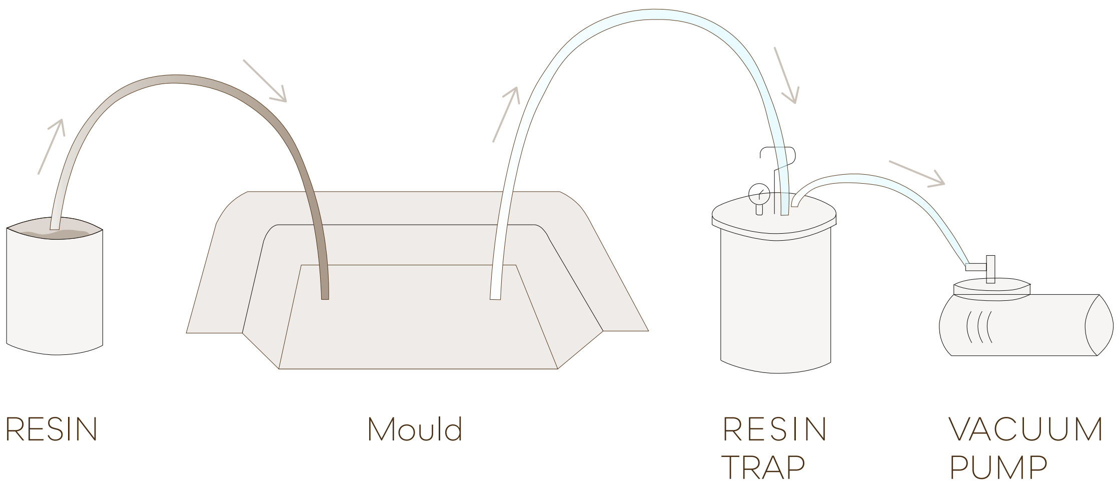


Figure 44. Vacuum infusion process (VIP)
Illustration adapted from Spasojevic, (2019)

ROTATIONAL MOULDING

Rotomoulding, or rotational moulding, is a special moulding technique dedicated almost exclusively to creating large hollow objects from plastic materials without welding or bonding. The created holes can reach considerable dimensions and large moulds dimensions are possible.

One of the main advantages of rotomoulding is that it is a low-cost process compared to injection moulding, which is often used for the production of smaller plastic objects.

Additionally, rotomoulding allows for the creation of large moulds and the production of hollow objects with considerable dimensions: this makes it an ideal choice for creating large, lightweight plastic products such as storage tanks, playground equipment, and outdoor furniture.

However, there are also some limitations to the rotomoulding process.
The inner surface of the finished product is often poor, which can impact the thickness and strength of the plastic piece. This can be problematic for applications where a high degree of structural strength is required.

In conclusion, rotomoulding is a unique manufacturing technique that is ideal for creating large, hollow plastic objects without the need for welding or bonding. While the process may have some limitations, it remains a cost-effective and practical solution for many applications in various industries (Kula et al., 2013).

THERMOPLASTIC ROTATIONAL MOULDING

The substance, either as a fine powder or a liquid, is put into a mould comprised of two components, often steel or aluminum. After that, this mould is mechanically rotated around two parallel axes. Under the influence of rotation, the substance disperses evenly over the inside surface of the mould.

Once the material is set by cooling, the entire assembly is heated in an oven until it hardens, finishing by taking the mould (Kula et al., 2013).

CENTRIFUGATION THERMOSET PLASTIC

The thermoset resin can be producedin a similar way.

In the manufacturing process utilizing short fiber reinforcements, these reinforcements are inserted in the form of reinforcements along with resin into a rotating mould. Through the application of robust centrifugal force, the resin and reinforcements are thoroughly mixed, ensuring a uniform distribution. To expedite the polymerization of the resin, heat is employed, facilitating the curing process (Kula et al., 2013).

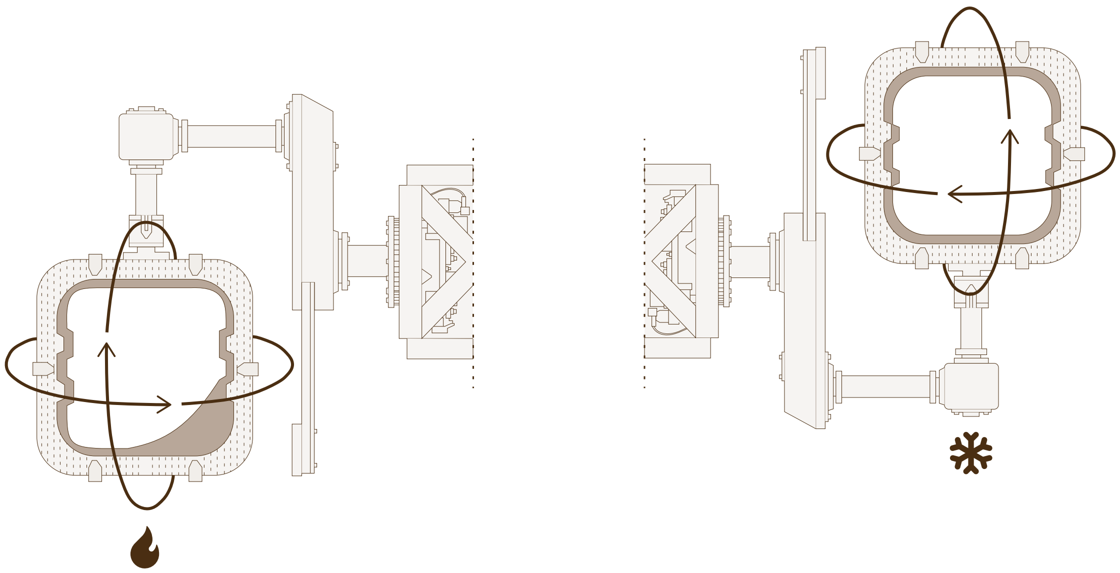


Figure 45. rotational moulding
Illustration adapted from Kula et al., (2013)

CONCLUSION

After analyzing the various common moulding processes, a decision needs to be taken. The research on both the material and moulding processes was conducted simultaneously, recognizing that whichever field was chosen first, would inevitably have influenced the other.

Through a thorough assessment of the complexity and advantages of each moulding process, the suitability for realizing the three-dimensional cladding, and the proximity of companies to facilitate direct observation of the process and prototype creation, the **Nabasco 80s** series is chosen, and, therefore, the **hot pressing** process.

2.6_ CONCLUSION

The shift towards a circular economy holds immense promise in tackling the environmental challenges associated with material extraction, energy production, and waste management. However, it is essential to recognize that transitioning from a linear economy to a circular model poses significant challenges, with various limits and barriers hindering a seamless shift. Nevertheless, design strategies emerge as crucial tools in mitigating the impact of these constraints and facilitating the transition towards a circular economy. By incorporating designing considerations for durability, reparability, modularity, and disassembly into product and system design, the environmental footprint can be substantially reduced while the circularity of resources is enhanced.

To realize complex three-dimensional cladding, parametric design is the primary tool for fast and efficient visualization of ideas.
Additionally, exploring rationalization and optimization tools enables an understanding of how fabrication restrictions can be incorporated into the design of intricate architectural geometry and whatever is the most efficient based on selected criteria.
The development of those mentioned above complex three-dimensional cladding must adhere to circular design principles. Among the prioritized principles is the selection and realization of a safer and more circular option, hence the choice of bio-based materials. In external cladding, the materials considered are existing and certified options. Of the listed and analyzed materials, particular attention is given to the Nabasco 80s series and Resysta. However, before finalizing the selection following the criteria outlined in Chapter 2.4, the manufacturing process, specifically moulding, is considered.

Through a thorough assessment of the complexity and advantages of each moulding process, the suitability for realizing the three-dimensional cladding, and the proximity of companies to facilitate direct observation of the process and prototype creation, the Nabasco 80s series is chosen, and, therefore, the hot pressing process.

Furthermore, the moulding process upholds another vital circular design strategy—dematerialization, as explained in Chapter 2.2. This principle is further explored in the conceptual design phase, which is detailed in Chapters 3 and 4.

In conclusion, the knowledge and insights gained from studying and comprehending circular principles and design strategies are paramount in successfully realising the three-dimensional cladding design.

_3 CONCEPTUAL DESIGN

3.1_ PANEL CONCEPT

The starting point of the conceptual design involves the objective of realizing a new design that follows circular principles and strategies, as largely explained in the chapter 2.

CIRCULAR DESIGN STRATEGIES

The first circular principle stated in the last chapter is ***safe and circular material selection***.

In terms of designing, ***modularity and flexibility*** in circular design was emphasized as crucial principle. This is because such an approach allows for the effortless replacement of individual components, which can help reduce costs. By adopting a modular design approach, significant savings can be achieved in mould realization. This means that a small number of moulds can produce many panels, resulting in ***dematerialization*** and minimizing material usage. Such an approach not only saves energy and resources by reducing material waste and energy required for production, but it also allows for efficient resource utilization by employing the same moulds for multiple components. Overall, the modular design approach presents an environmentally sustainable solution for manufacturing complex and customized products.

Furthermore, since the attention is given to modular - and therefore, easily replaced elements -the ***design for disassembly*** will be another aspect to be considered.

Therefore, during the conceptual design phase, the main objective is to develop a modular panel that offers flexibility and versatility for various designs and solutions. This modular panel will be designed to facilitate customization and adaptability to different applications, making it an incredibly versatile product suitable for diverse contexts while minimizing the number of panels needed. The panel's adaptability is achieved through its dry connections, which allow for effortless assembly and disassembly.

SEAMLESS TILING

To fulfill these premises, the *seamless tiling* concept has been established. Seamless tiling is a self-coined term that refers to the pattern continuity through the cladding panels. Hence, the aim is to realize a flexible standardized module that can be placed where preferred in the façade while the whole pattern will still match.

This concept came out after listening to a conference by Martha Tsigkari from Foster + Partners at TU Delft (Tsigkari, 2022), where she was explaining the concept and the parametric design of the UAE Pavilion Milan Expo (Fig.30, 31). Even if it has never been referred to as "seamless tiling", that pavilion follows the same principle: therefore, the pattern is continuous through all the panels, but just horizontally.

A step further that was intended to develop into my design concept, is the complete flexibility of the building product into the façade. Therefore, the continuous pattern does not have to respect just one axis - the horizontal, as in the case of the UAE Pavilion - but all three axes.

To do so, the panel will be designed, on the one hand, to be easily rotated and placed freely, while, on the other hand, to match different three-dimensionality within the facade - the process paragraph will further explain this concept.

THREE DIMENSIONALITY

The primary goal of the design concept is to introduce a groundbreaking product to the market.

Traditionally, bio-based claddings have been manufactured as flat or slightly three-dimensional, while sharp three-dimensional claddings have typically been associated with metal materials. In line with the principles of circular design, the new concept aims to challenge this norm by creating a sharp three-dimensional shape using circular materials.

To highlight the intention of breaking away from the traditional association of materiality with shape, the concept will incorporate a design inspired by the folding process commonly employed in metal product manufacturing. However, in this case, biobased materials and a moulding process will be utilized to bring the design to life.

Ultimately, this innovative design will introduce a product that has a two-fold impact. Firstly, it will contribute to the sustainability of the building industry by offering new options through the use of more circular materials and processes. Secondly, it will have a social impact by challenging conventional perceptions of three-dimensional cladding, providing a diverse, innovative, and more sustainable alternative.

DESIGN PROCESS

After showing the principles of interest, the design process can start.

The process begins with understanding the most promising shape to create a modular but flexible design.

Following research of various regular forms, it can be determined that the square is the optimal choice since its four equal edges allow easy rotational settlement and changing of location within the façade (fig.43). Moreover, a criterion must be established to comprehend how the pattern flows across the different panels. After a visual analysis, it became apparent that the pattern must intersect at specific points along the shared edges to align with the subsequent panels.

Therefore, the edges of the square are divided into segments, and each vertex - of the segment - becomes a connecting point of the pattern, as shown in Figure 44.

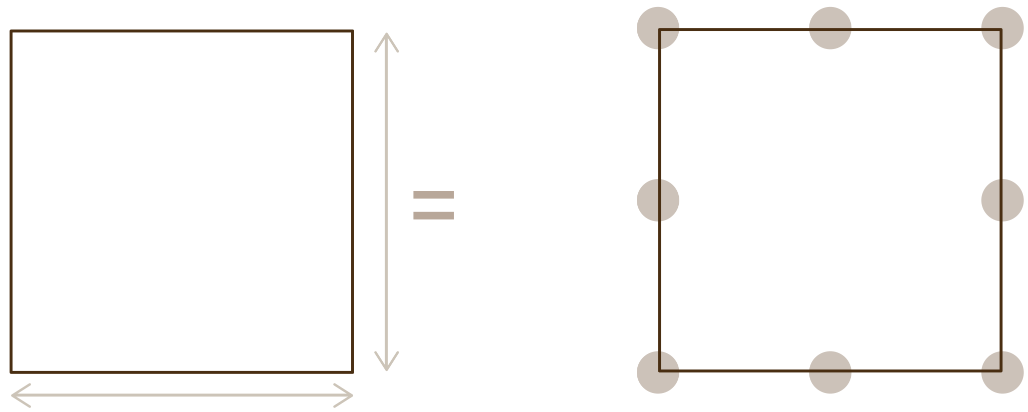


Figure 46,47. Square Shape Decision and Edges Division own ill.

To understand how the pattern can be shaped, the whole view of all the spacial possibilities has been created - as visualized in Fig. 48. Thus, every single vertex is now connected, creating a guideline from which the pattern can be formed: an example of how the pattern can be is shown in figure 49.

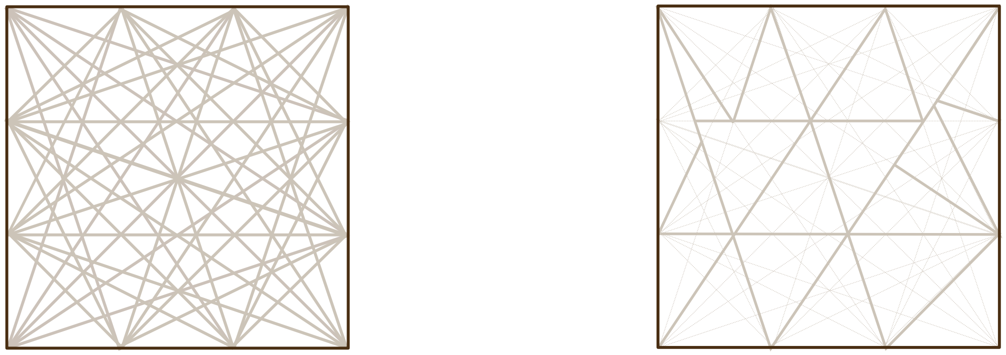


Figure 48,49. Pattern Guidelines and Pattern Example own ill.

However, the created guideline gives an infinite number of possibilities for the panel that creates a chaotic and nonregular facade: therefore, to moderate the panel aesthetic confusion, a constant must be included in the design.

Hence, a so-called *focal point* is inserted into the design, becoming the core where all the lines intersect. Thus, the panels now possess a higher degree of regularity and cleanliness while still adhering to the requirement of allowing the pattern to flow seamlessly through the points at the sharing edges (Fig. 50).

Furthermore, the focal point can be crucial for the three-dimensionality of the panel. Therefore, the focal point can be conceived as the panel's three-dimensional peak and the folding's resembling appearance. (Fig.51)

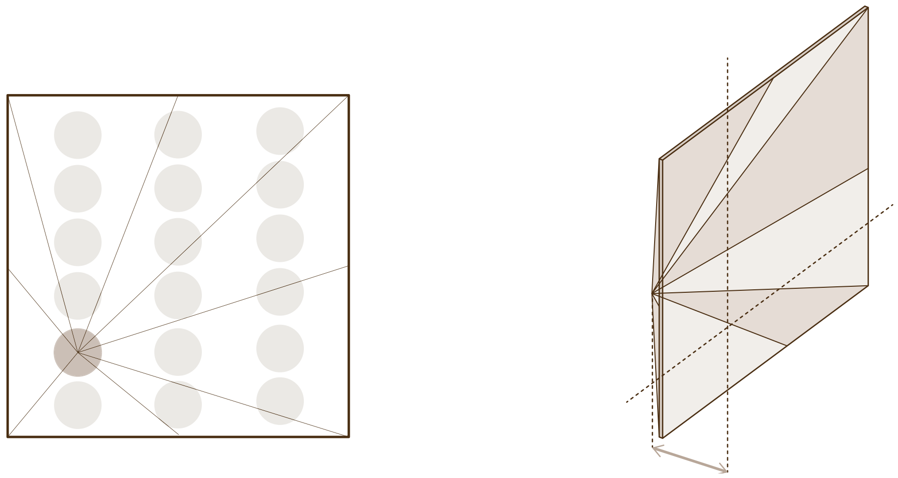


Figure 50,51. Focal Point Location and Focal Point Three-Dimensionality own ill.

From this state, the three-dimensional design can be more challenging, to emphasize the just mentioned folding appearance.
To do so, each vertex of the panel will be protruded towards the third axes, giving the panel a sharp looking.
However, the protrusion range needs to follow specific criteria. Therefore, as mentioned previously, the panel will be designed to be easily rotated on itself: thus, the point coordinates can not be random.
The mathematical rule to accomplish this aim is that the points located in the panel vertices do have the same z-coordinates and the same for the points located in the panel edges (Fig. 52), thus, by rotating the panel in each position (Fig.53), the pattern and configuration will still be precise.

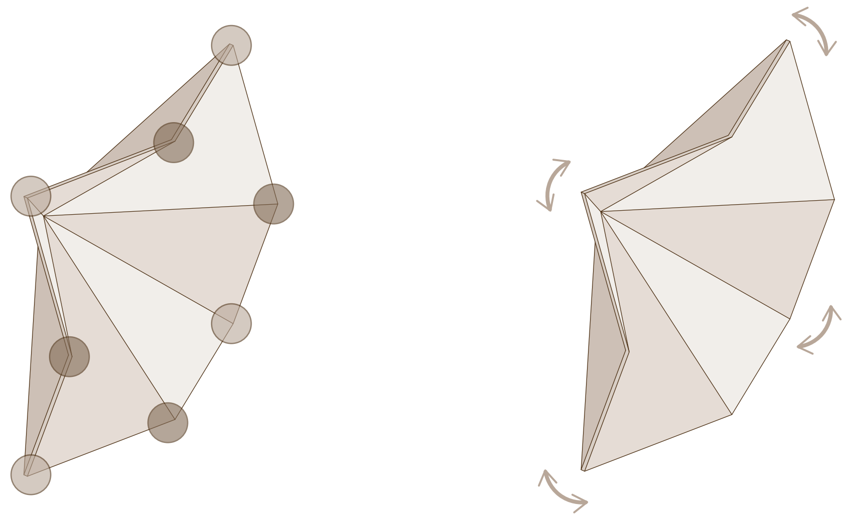


Figure 52,53. Vertices Protrusion and Panel Rotation Accomplishment own ill.

3.2_ CLADDING PRODUCTS

After understanding the concept of the modular and flexible panel, it is important to comprehend how this product can vary in terms of composing a whole façade.

The seamless tiling concept has been explained in terms of how the pattern spreads through the façade, but not yet in terms of its three-dimensionality.
Three-dimensionality can be effective to recreate infinite aims and geometrical solutions, however, this peculiarity could be influenced by the building's context and scale.

Therefore, the coined concept can be expedient to vary the depth of the façade while still maintaining the same language within it.

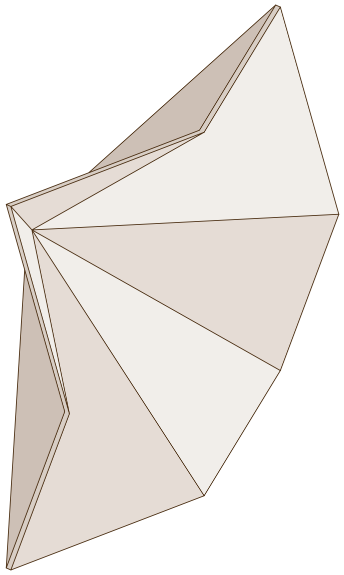
Following the mentioned process, three panels have been developed: the *complex*, the *bridge* and the *flat* panels.

The complex panel is shown in Fig. 54, which is the peak of the sharp three-dimensionality: by rotating and duplicating it through the façade, the designer will obtain a modular and symmetrical three-dimensional appearance - this design process will be further explained in the paragraph "one-panel configuration" in chapter 3.3.

The other provided panels will give the chance to soften the façade and let it flow from a three-dimensional scenario to a bi-dimensional one - as will be explained in the paragraph "all-panels configuration" in chapter 3.3.
For obtaining this transition, some "hybrid" panels will be needed: the so-called bridge panels.

The bridge panels are cladding products that have the same design principles as the complex ones, however, they vary by having from one to three flat edges for "bridging" the complex and the flat just-mentioned way, depending on the designer's purpose, it is possible to find areas where three-dimensionality prevails (for performances such as sun shading, wind loads, and geometrical) and others where softening and two-dimensionality are desired.

The illustration of all the developed panels will be graphically shown:

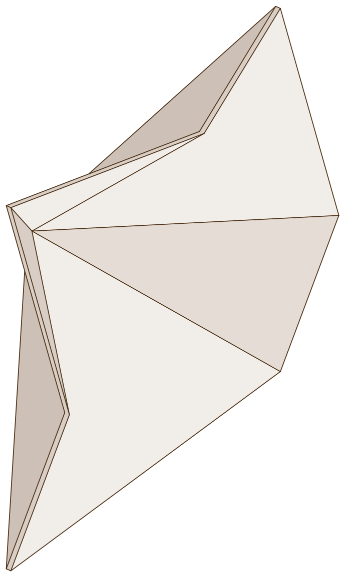


COMPLEX PANEL

4 3D EDGES

0 2D EDGES

Figure 54. Complex Panel Illustration
own ill.

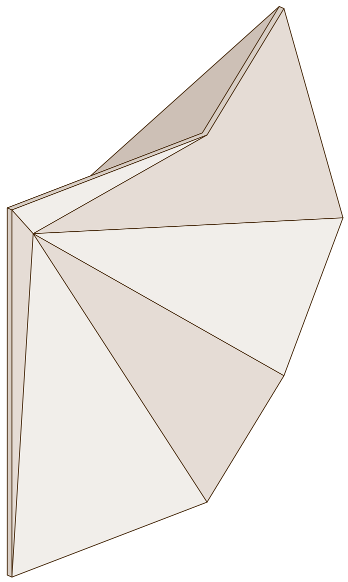


BRIDGE 1 PANEL

3 3D EDGES

1 2D EDGES

Figure 55. Bridge 1 Panel Illustration
own ill.

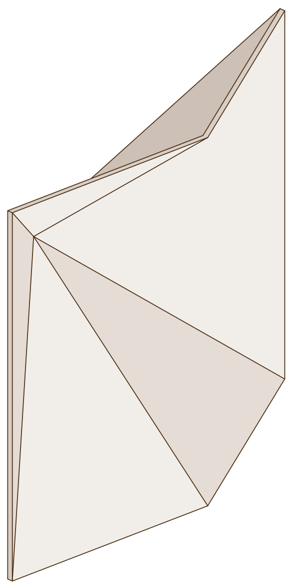


BRIDGE 2 PANEL
ADJACENT

2 3D EDGES

2 2D EDGES

Figure 56. Bridge 2 with Adjacent Complex Edges Panel Illustration
own ill.

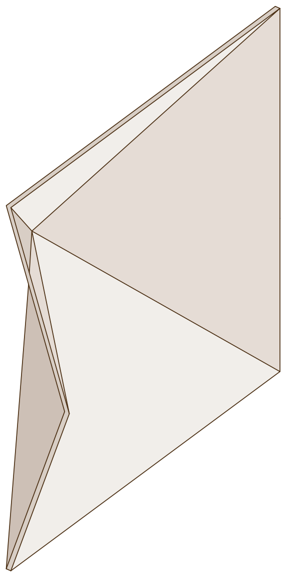


BRIDGE 2 PANEL
OPPOSITE

2 3D EDGES

2 2D EDGES

Figure 57. Bridge 2 with Opposite Complex Edges Panel Illustration
own ill.

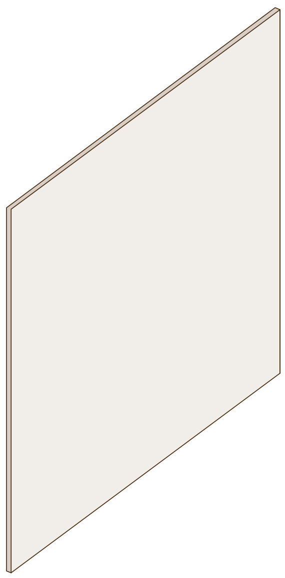


BRIDGE 3 PANEL

1 3D EDGES

3 2D EDGES

Figure 58. Bridge 3 Panel Illustration
own ill.



FLAT PANEL

0 3D EDGES

4 2D EDGES

Figure 59. Flat Panel Illustration
own ill.

3.3_ SYSTEM CONFIGURATIONS

As mentioned, the façade configuration varies in terms of how and which panels are selected and located.

The 6 panels just shown are designed to be placed one close to the other, taking into account specific constraints: the complex panel can match with itself and the three-dimensional edge of each of the bridge panels; the bridge panel can potentially match with all the others, depending on which edge is facing; the flat panel can match with itself and the bi-dimensional edge of the bridge panels. The visual configurations (considering just which panels are placed and not where) are displayed in Figures 60, 61, 62, 63, 64 and 65.
Having explained this reasonable rule, the designer is "free to play" composing the puzzle.
Two configurations will be shown to suggest how to proceed to compose the façade.

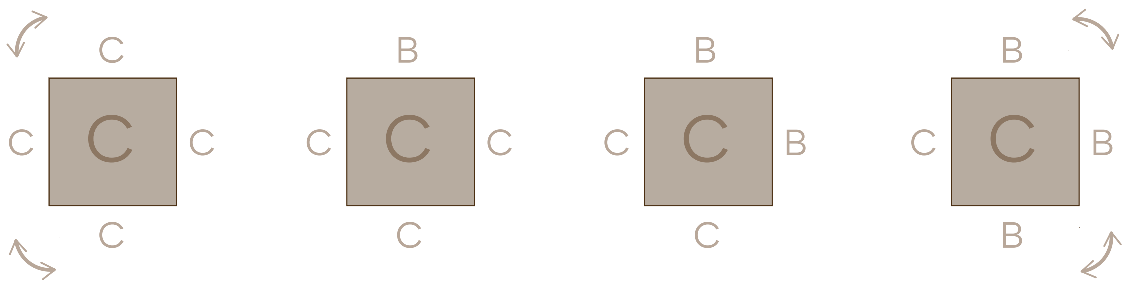


Figure 60. Complex Panel Configurations
own ill.

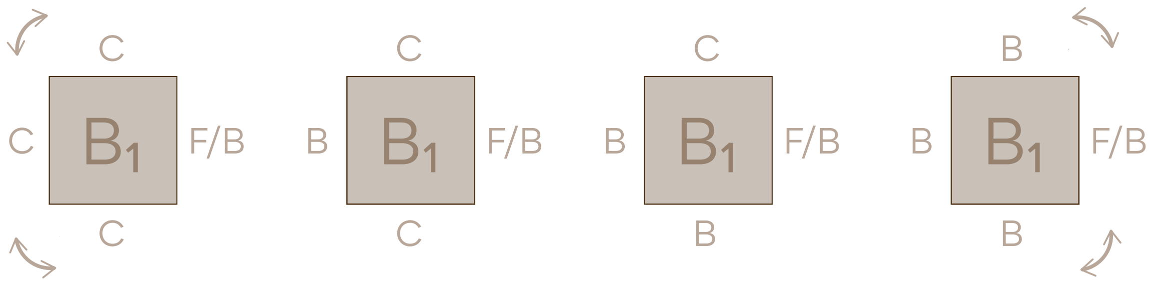


Figure 61. Bridge 1 Panel Configurations
own ill.

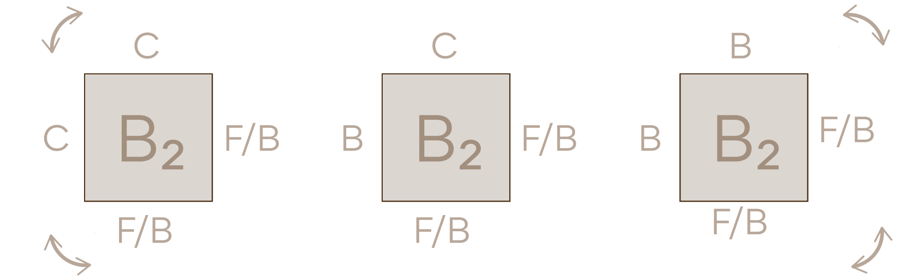


Figure 62. Bridge 2 Panel Configurations
own ill.

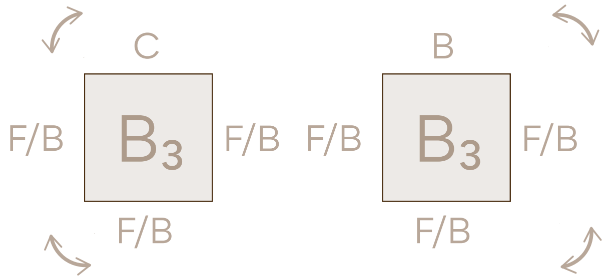


Figure 63. Bridge 3 Panel Configurations
own ill.

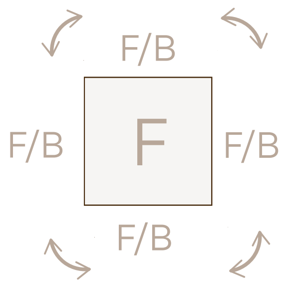


Figure 64. Flat Panel Configurations
own ill.

ONE PANEL CONFIGURATION

The most conventional method of constructing a tiled surface involves the rotation and manipulation of symmetrical panels that can be duplicated or reflected. By rotating a single element, a wide range of compositions can be created, resulting in enhanced versatility in the final design (Fig. 65). This approach has been a long-standing practice in tile design, and it continues to be a popular choice due to its simplicity and flexibility in generating diverse patterns and configurations.
An example of a hypothetical one-panel configuration façade is shown in Fig. 66 67.

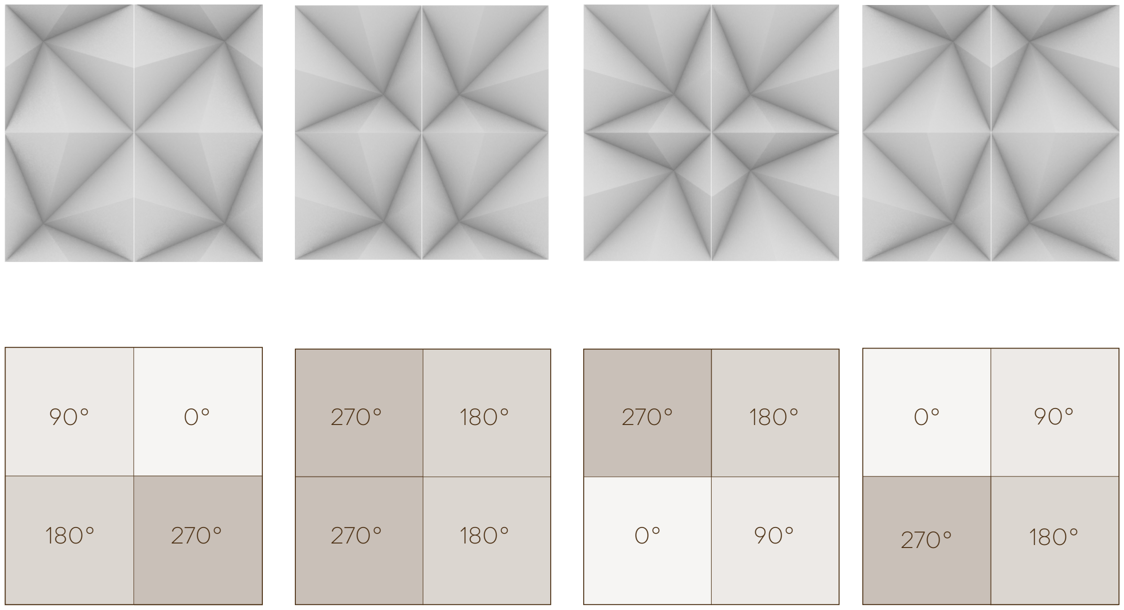


Figure 65. Different Modular Configurations due to the panel rotation
own ill.

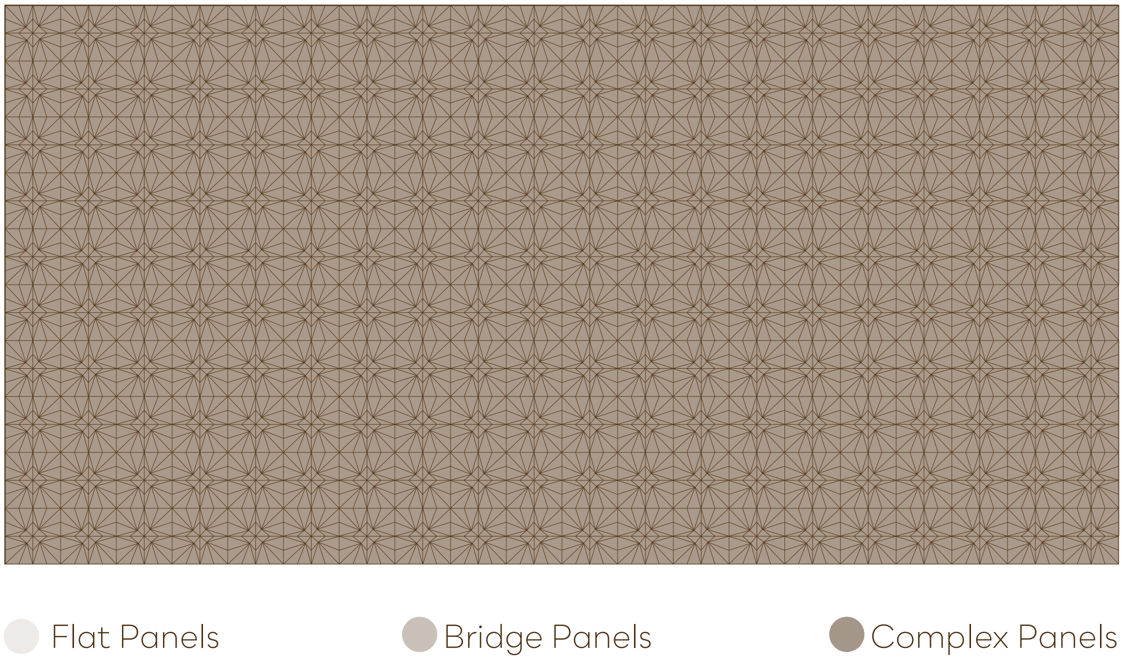


Figure 66. Complex Panel Façade Example
own ill.

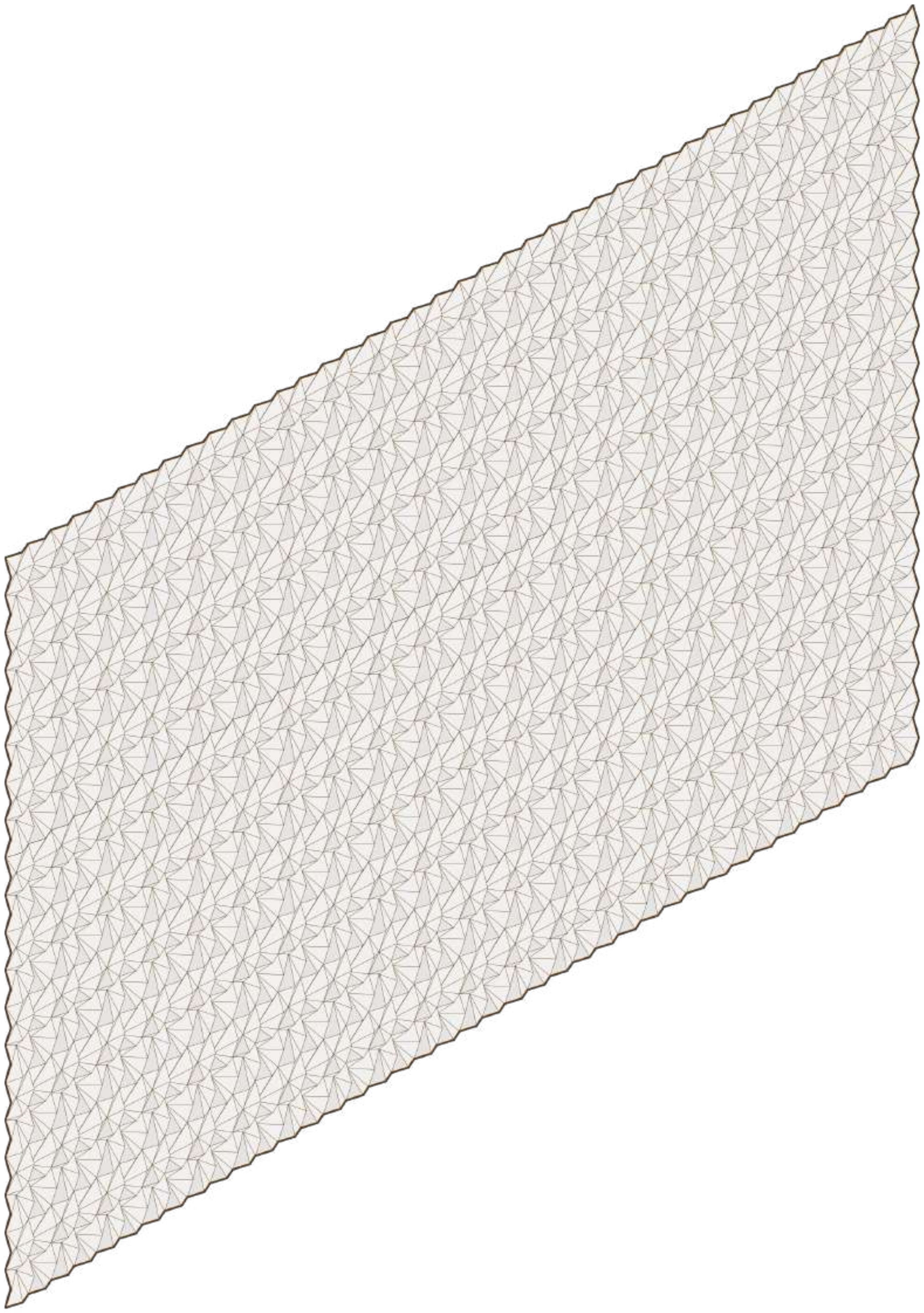


Figure 67. Complex Panel 3D Façade Example
own ill.

ALL PANEL CONFIGURATION

To encompass all the aforementioned panels, an innovative and distinctive approach can be explored.

By adhering to the concept of seamless tiling in all directions, the façade can seamlessly transition from sharp three-dimensional geometry to a flat surface and vice versa.

However, in order to effectively compose a façade with these elements, a design principle must be established, and the proposed principle is the representation of macro-geometry.

The presented concept stands in contrast to the traditional single-panel configuration, as it shifts the focus from a repetitive arrangement to placing the macro-geometry as the central element of the façade. Thus, the same panels that can be arranged to achieve symmetry and repetition can also be strategically positioned to represent a geometry that transcends conventional rules and instead conveys the desired aesthetic and performance envisioned by the designer.

There are no limitations on the form of the geometry representation, although the less organic it appears, the more approximate the reproduction may be. Additionally, unless the geometry exceeds the dimensions of the façade frame, there are no restrictions on the number of geometries that can be employed. As illustrated in Figure 70, a single geometry can be dispersed across the façade, which is the result of the step-by-step process that will be further explained in Chapter 4, while Figure 73 demonstrates a pattern composed of four equidistant and identical geometries.

Therefore, the façade is initially composed of a desired macro-geometry (as seen in Fig. 68 and 71). Then, through the use of a parametric script explained in Chapter 4, the complex panels will come together to form the macro-geometry, while the flat panels will serve as the background for the entire composition. To connect these two elements seamlessly, bridges will be placed in between (as depicted in Fig. 69 and 72).

CONCLUSION

In conclusion, the exploration of the seamless tiling concept for the façade design offers a vast array of configurations while remaining aligned with key circular design principles. Throughout the process, considerations such as modularity, material selection, design for disassembly, and dematerialization have been integrated.

The concept allows for the creation of diverse configurations, each representing a unique expression of the macro-geometry. It is important to note that the configurations presented are not final products but rather demonstrations of the versatility and flexibility inherent in the proposed system. The possibilities are expansive, and the chosen configurations are indicative of the wide range of aesthetic and functional options that can be achieved.

To fully comprehend the rules and principles utilized in the design, a comprehensive explanation will be provided in the upcoming chapter. It is within this chapter that all aspects of the design process will be thoroughly elucidated.

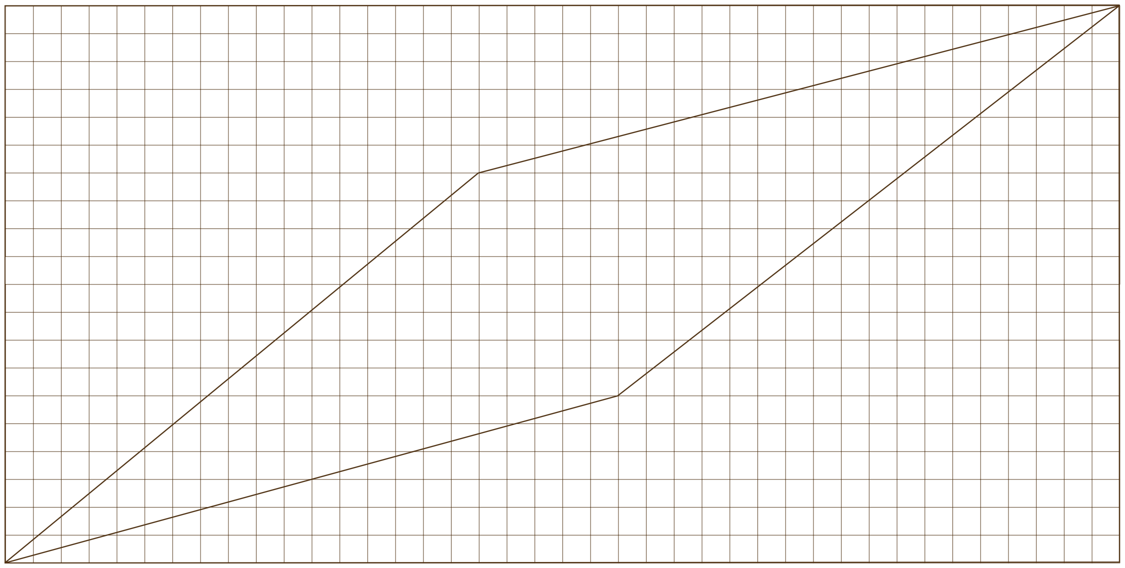


Figure 68. Macro-Geometry Example Representation
own ill.

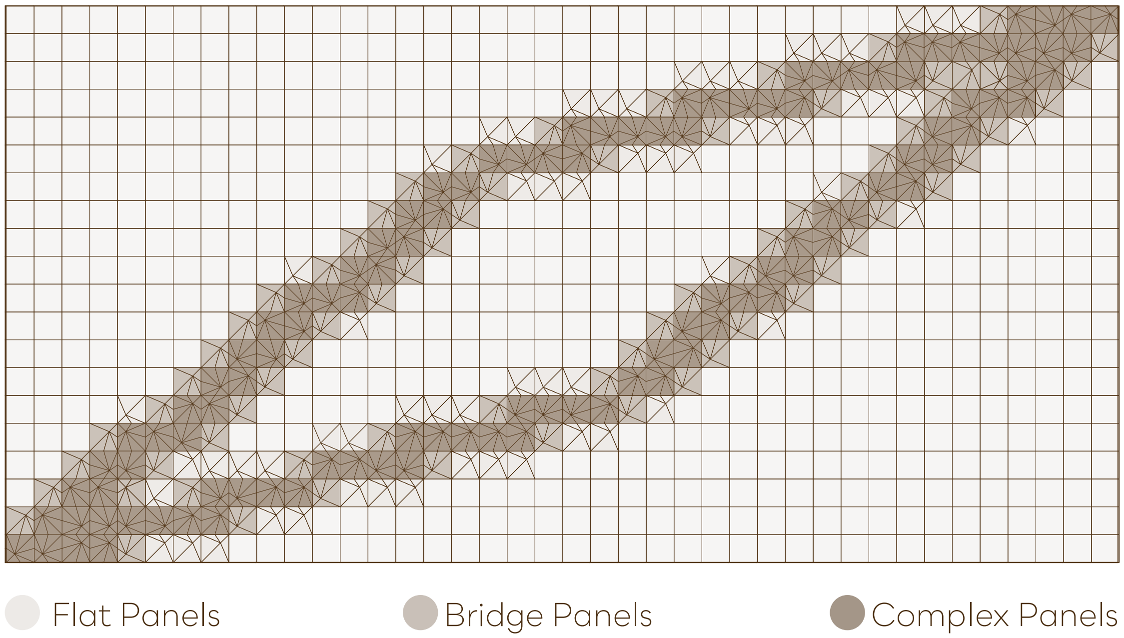


Figure 69. Macro-Geomtry Example Representation with the Panels
own ill.

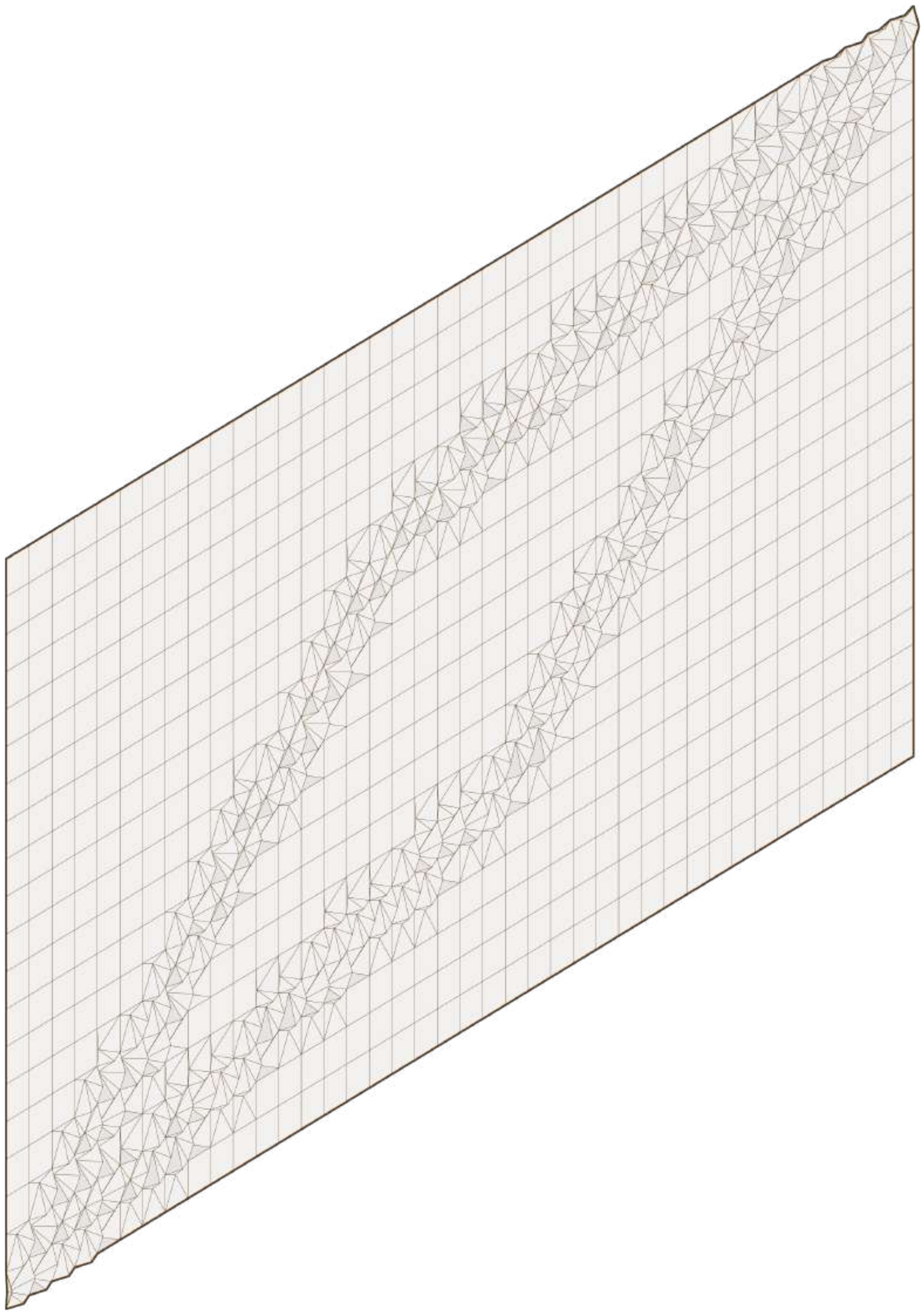


Figure 70. 3D Macro-Geomtry Example Representation with the Panels
own ill.

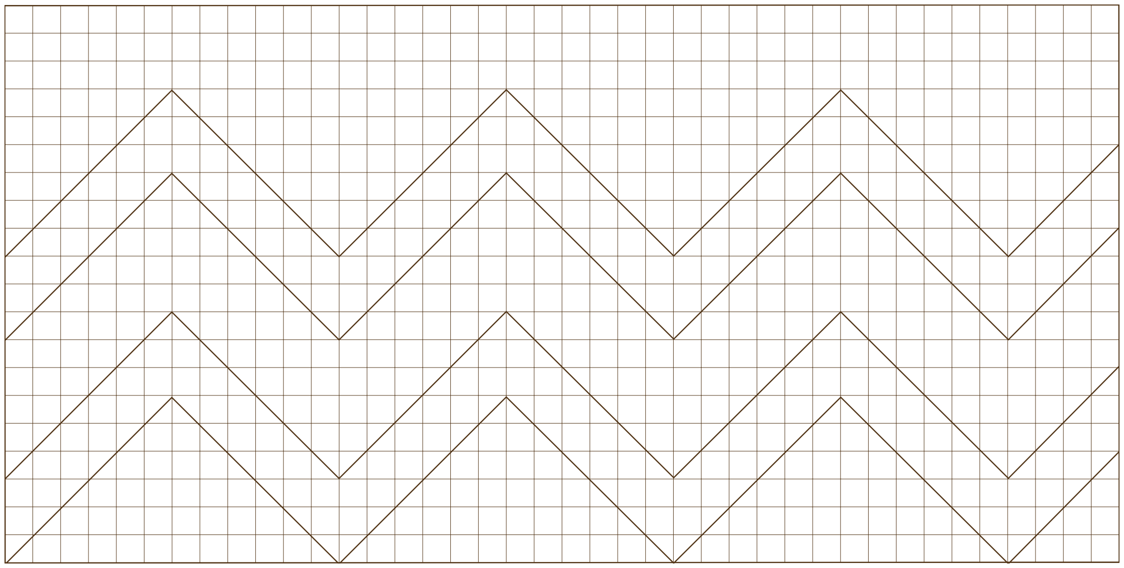
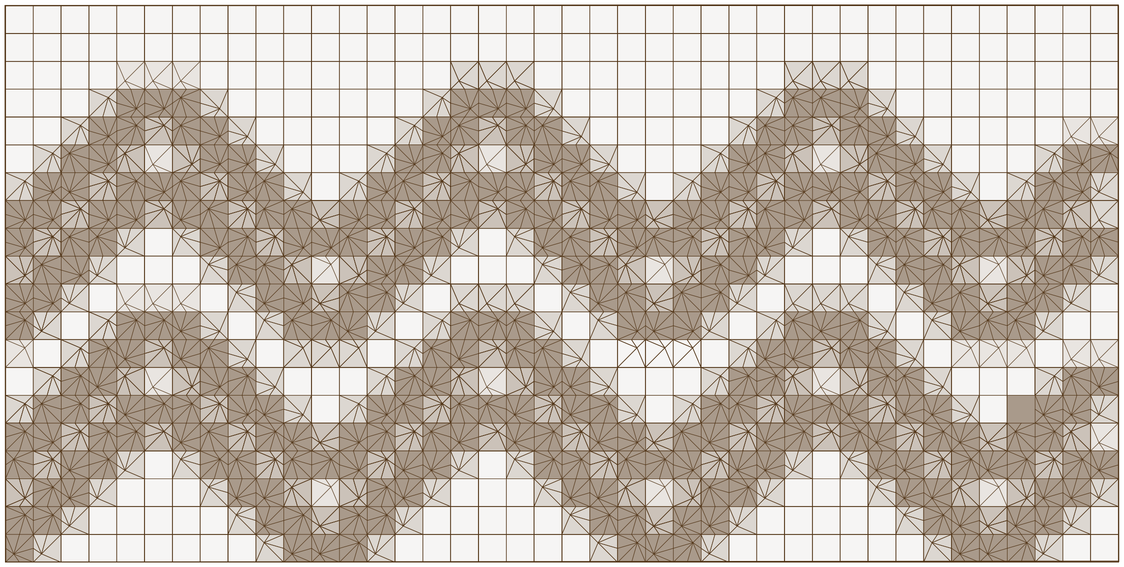


Figure 71. Macro-Geometry Example Representation
own ill.



Flat Panels Bridge Panels Complex Panels

Figure 72. Macro-Geomtry Example Representation with the Panels
own ill.

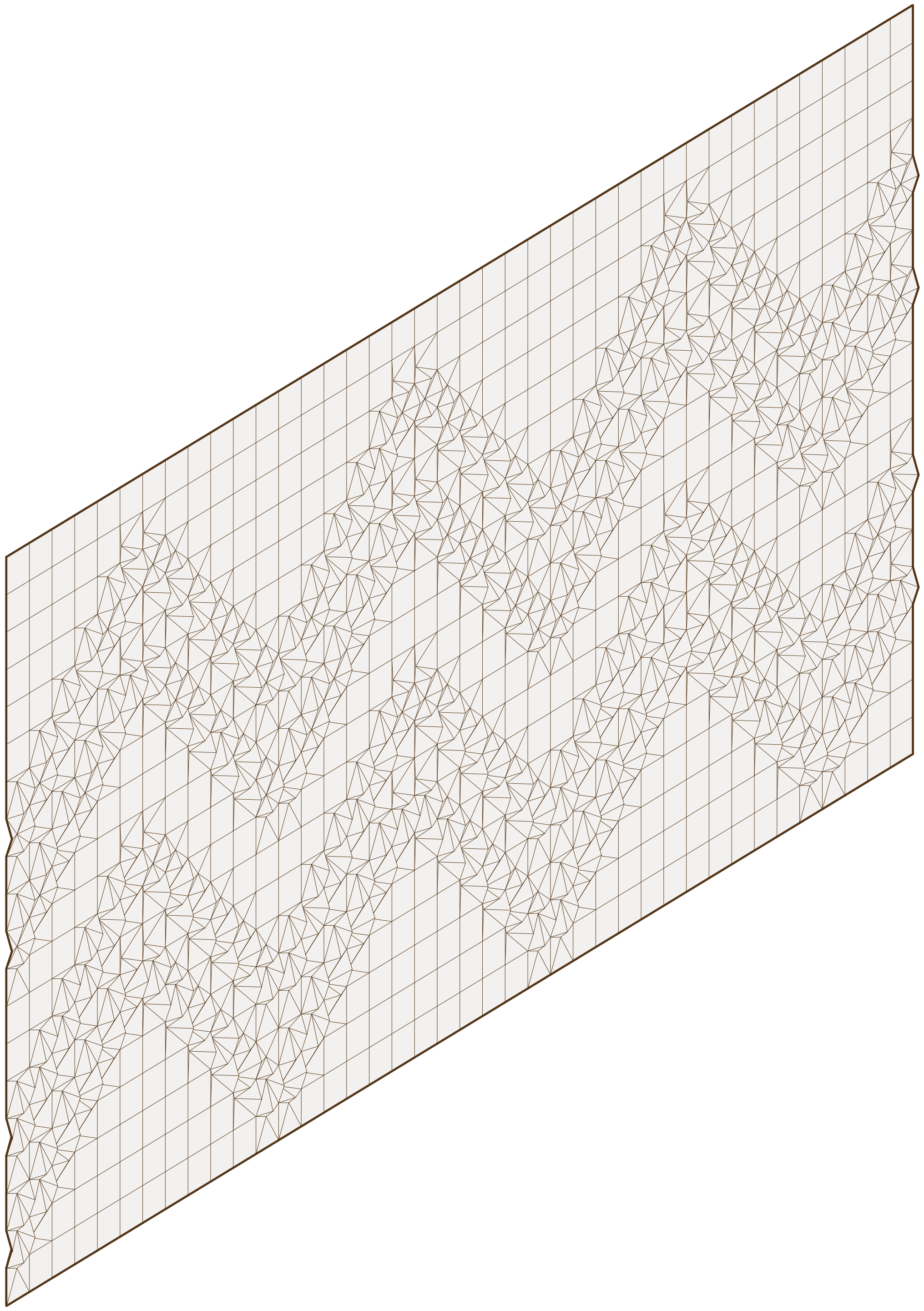


Figure 73. 3D Macro-Geomtry Example Representation with the Panels
own ill.

_4 COMPUTATIONAL DESIGN

4.1_ PANEL PARAMETRIZATION

The concept panels are now undergoing the process of parametrization. This technique offers a multitude of solutions based on the desired outcome, taking into account the scale and context of the building.

The entire panelization process is done with Grasshopper, a programming language integrated into the Rhinoceros 3D software. The knowledge acquired about parametrization and additional tools such as rationalization and optimization has informed the conceptual design. The aim was to represent a minimum number of panels to cover all dimensional possibilities.

A rationalization mindset was adopted during the development of the panels - which will be explained better in this chapter - to ensure they fit together seamlessly, eliminating the need for excessive panels. The focus was on achieving an efficient arrangement while maintaining the desired aesthetic and functional goals.

As for optimization, the six developed panels allow for comprehensive exploration in all directions, eliminating the need for either minimizing or maximizing. Therefore, the actual process has not been used, but the process to come out with a minimized number of panels.

Therefore, the computational process will be executed through parametric design, utilizing data management techniques for the hierarchical structure that has been developed. By manipulating and organizing the data effectively, it has been possible to precisely control and adjust the parameters to achieve the desired outcome.

The complex panel serves as the initial prototype, setting the foundation for the subsequent bridge panels that will follow the same principle. Each panel will be refined and realized through this iterative process, ensuring coherence and consistency throughout the design.

DESIGN VARIABLES

The first step to correctly settle is the design variables understanding, therefore, those values can easily change by the horizontal movement of a slider (Fig. 77).

As discussed in the design process, the panel has a squared shape. The edges dimension can parametrically change since the final dimension of the tiles is still unknown (Fig.74).

Moreover, as also mentioned in the previous chapter, another parameter is the division of the edges, from which the pattern will be created: through this variable, the appearance and three-dimensionality of the panel can largely change concerning the sharing points each side has (Fig.75).

This is where the rationalization mindset starts, because, by giving this constraint, the panels will be developed in such a way to minimize the range possibilities while maintaining the pattern continuity.

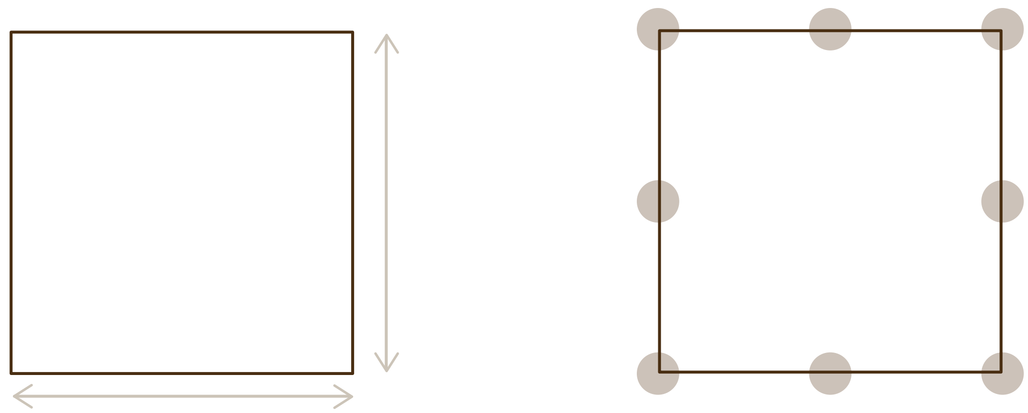


Figure 74, 75. Square Shape Decision and Edges Division Variables
own ill.

The third slider is about the panel thickness: since the material responses are still unknown, it is important to let the design freely change in terms of potential changes, aiming for the most challenging case with the most performing results (Fig.76).

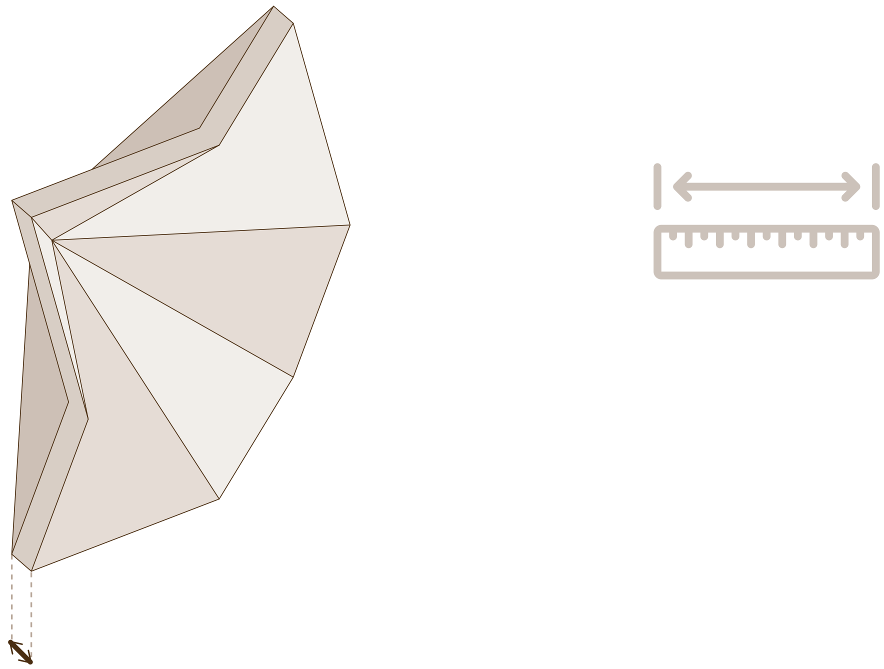


Figure 76. Panel Thickess Variable
own ill.

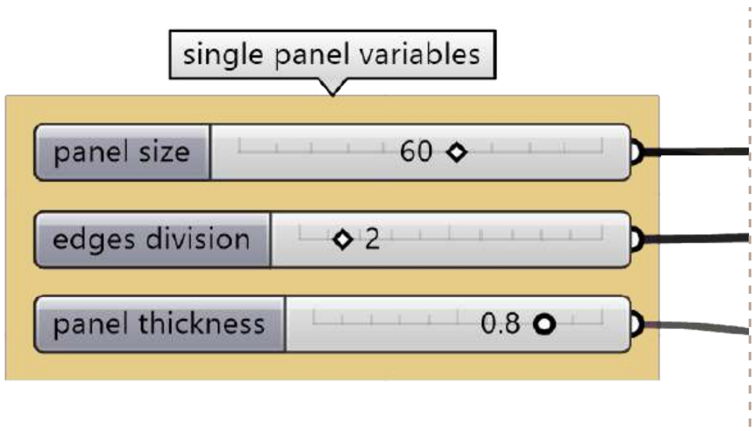


Figure 77. Single Panel Variables
own ill.

Having stated the usual slider, the other two variables behave slightly differently than the just mentioned one.

An MD slider is chosen to parametrize the location of the *focal point* since by using that tool the spacial bi-dimensional location within the panel façade is better understood (Fig.78).

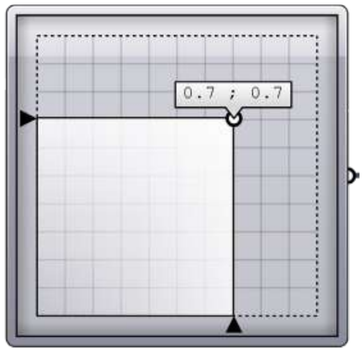


Figure 78. MD Slider for Focal Point Variable own ill.

Finally, the last variable is a "dependent" one since it is scripted to be directly influenced by the panel dimension. This variable is the range of extrusion of the panel perimeter points, which are valued inscribed between 0 and the panel dimension divided by three (x/3): therefore, if the panel dimension is 60, the maximum extrusion will be 20 (Fig. 79).

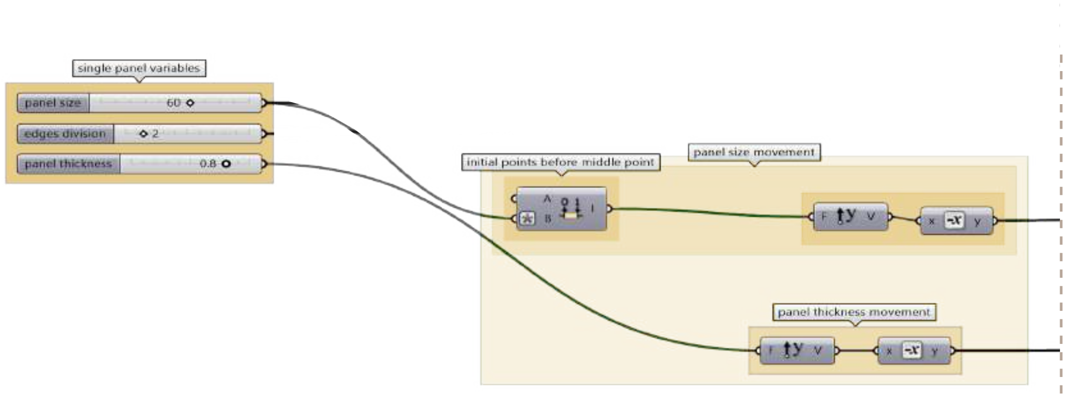


Figure 79. Extrusion Panel Variable own ill.

COMPLEX PANEL PROCESS

Having listed the “pillars” of the script, the process will now be explained. A rectangle composed of the panel size parameter (Fig. 77) has been created, considering that all the tools will be used, considering that the panel lays on the xz plane.
The rectangle will be exploded and then divided into the variable number of segments mentioned in the previous paragraph. Moreover, the culling duplicates and shifting list tools have been used to clean and sort the data by letting them start from the point (0;0;0).

PATTERN CREATION

As explained in the design concept chapter, the coordinates of the sharing points of the panels are essential for goal fulfillment.
To accomplish the constraint of having interrelation between the points laying on the edges and those in the corner, an adjustment of the grasshopper script is needed: for reorganizing the list, dispatch will be used, aiming to have the corner points in the 1s and the edge points in the 0s outputs.
To do so, a guideline pattern has to be created that considers the potential changing of the design variables, in particular the edge division parameter: therefore, when the edge division number increases, the 0s in the list increase, and vice versa; when 0s are less or more, the location of 1s in the list will be different.

After analyzing the data, it has been understood that, in one edge, the 0s do correspond to the (n-1) value, where n is the number of edge divisions: for instance, when the edge is divided by 3, the 0s will be 2 (Fig. 80, 81).

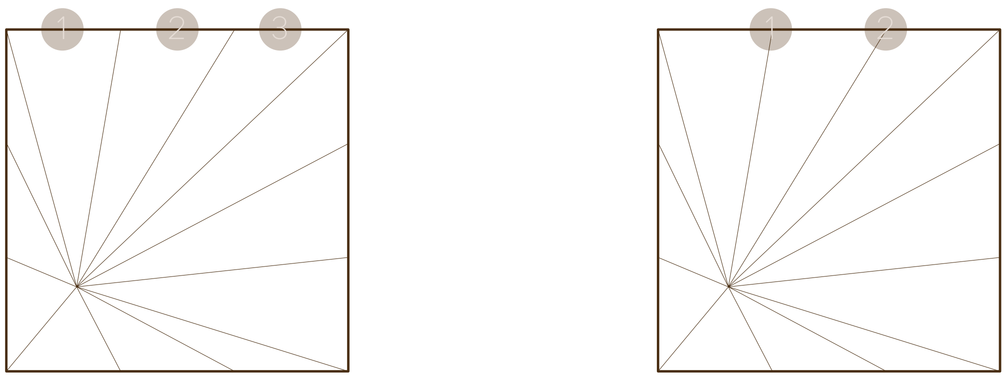


Figure 80, 81.Edge Division Changing Example own ill.

Furthermore, in this sequence of 0s, the corner points need to be included. A panel representing 1 will be inserted in the parametric list, and, finally, to include all the four edges of the square, this new list will be again duplicated by 4: the pattern is now complete and the points dispatched (Fig.82).

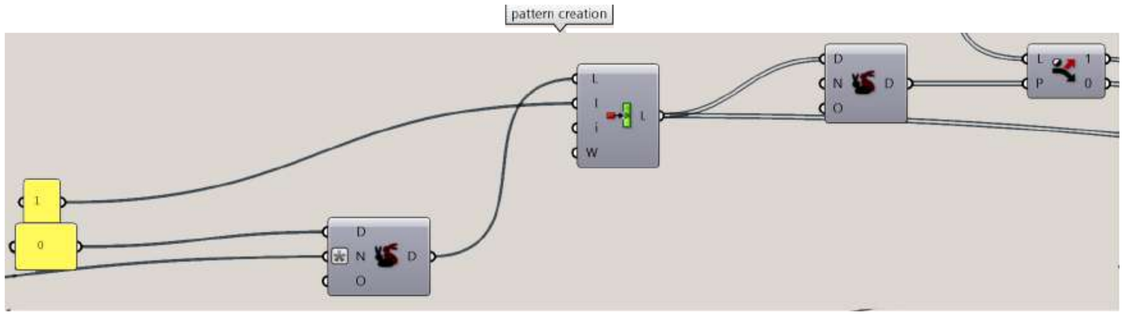


Figure 82. Pattern Panel Completion
own ill.

The corner and the edge points can now be separately moved toward the y-direction, giving the panel the peculiar sharp shape shown in the design concept paragraph.

These data need to be collected together for continuing the script, however, the merge tool does not work properly because it will merge the data without following a specific order. For this reason, the tool weave will be used, in which the pattern created in the "insert list" tool will be respected by taking the new 1s and 0s points that have been just moved (Fig.83).

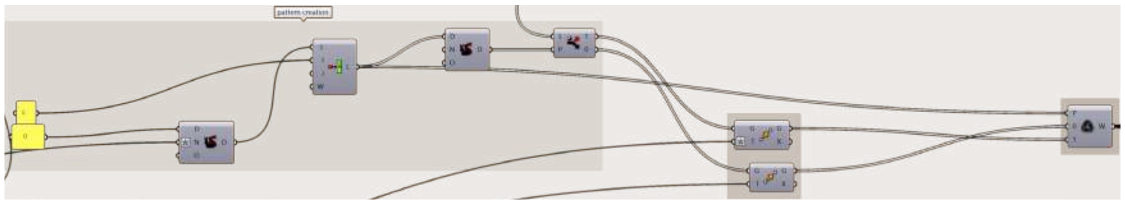


Figure 83. Moving of corner and edge points
own ill.

Having created the correct pattern, it is possible to connect the sorted data. As mentioned in the design concept, all the perimeter points are connected to the *focal point*, therefore, the next step is parametrizing it.

From the initial rectangle, a boundary surface and an evaluation of it have been settled. By evaluating it, it is possible to choose the decimal position of the focal point within the panel shape by using the MD slider (Fig. 78). Having created all the needed data, the next step is connecting these points to create polylines and then, surfaces, and finally the volume.

From the weave tool, a polyline can be settled that represents the perimeter of the panel. Moreover, to represent the thickness of the panel, the just mentioned perimeter will be moved in the y-direction by the panel thickness design variable: a line will be created by connecting these two tools.

The first sweep1 surface will be created by considering the rail as the perimeter of the panel, while the section will be the line that connects the panel points to the focal point.

Furthermore, to create three-dimensionality, the sweep2 command has been used. The first and the second rail will be the two-panel polylines: the initial one and the one moved towards the y-direction previously mentioned. In this case, the section is the lines that connect the two rails.

Finally, all the created surfaces will be merged, by concluding the script with the boundary volume command: the complex panel is parametrically complete (Fig. 84).

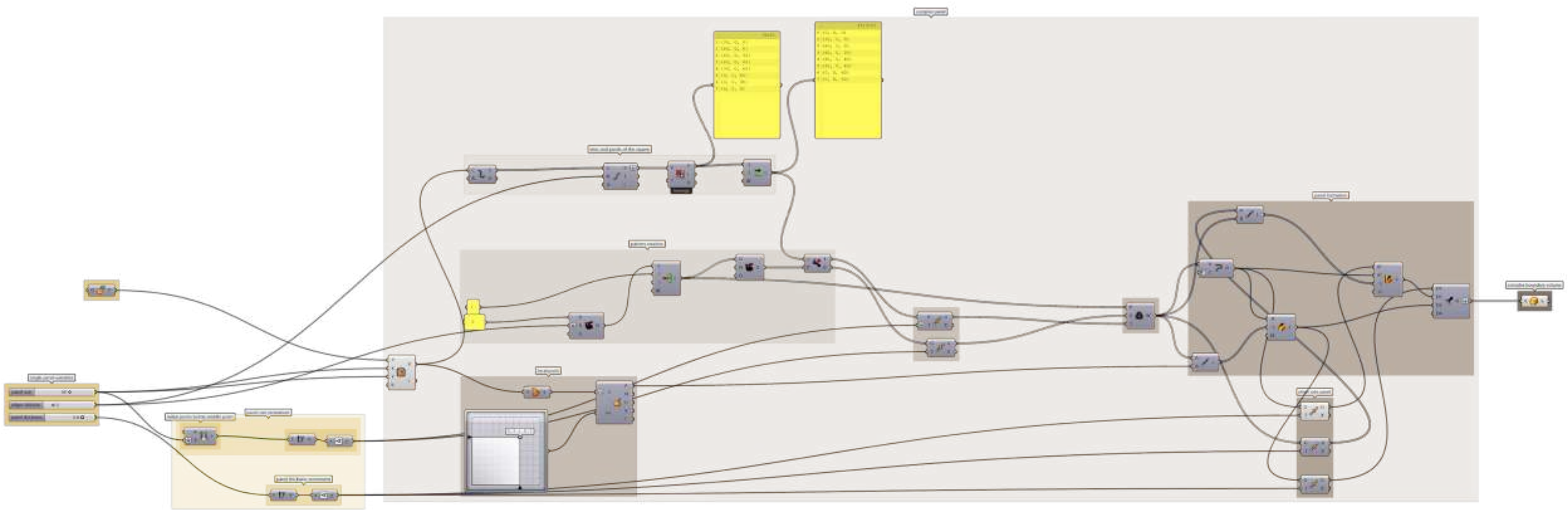


Figure 84. Comple Panel Scripting
own ill.

BRIDGE PANELS PROCESS

What parametrically differs between each bridge panel with the complex one is the y-direction location of specific edge points: for instance, in the case of bridge 1 panel (fig. 55), one edge will have the edge points with the same y-coordinates as the corner points; in the case of bridge 2panel (fig. 56, 57) the edge points laying in two edges will behave in this way; finally, the points laying in three edges will have the same y-coordinates for bridge 3 panel (fig. 58).

Therefore, the 0s output of the command dispatch previously mentioned, - in which the corner points are listed - needs to be sorted: the list will be divided between those points that will behave as in the complex panels and those that will create the wanted flat appearance.
Thus, the split list tool will be used, by changing the expression concerning the considered bridge panel.

As just explained, bridge panel 1 does have one flat edge. Hence, in the list of edge points, just one data will have the same y-coordinates as the corner points. Considering the way the data is sorted, to create a flat edge on the bottom side of the square, the list has to be split by x-1, where x is the edge division parameter (Fig. 77). Finally, by assigning each point to the desired value, the weave component will sort the data and the script will follow the same path as for creating the complex panel (Fig.85).

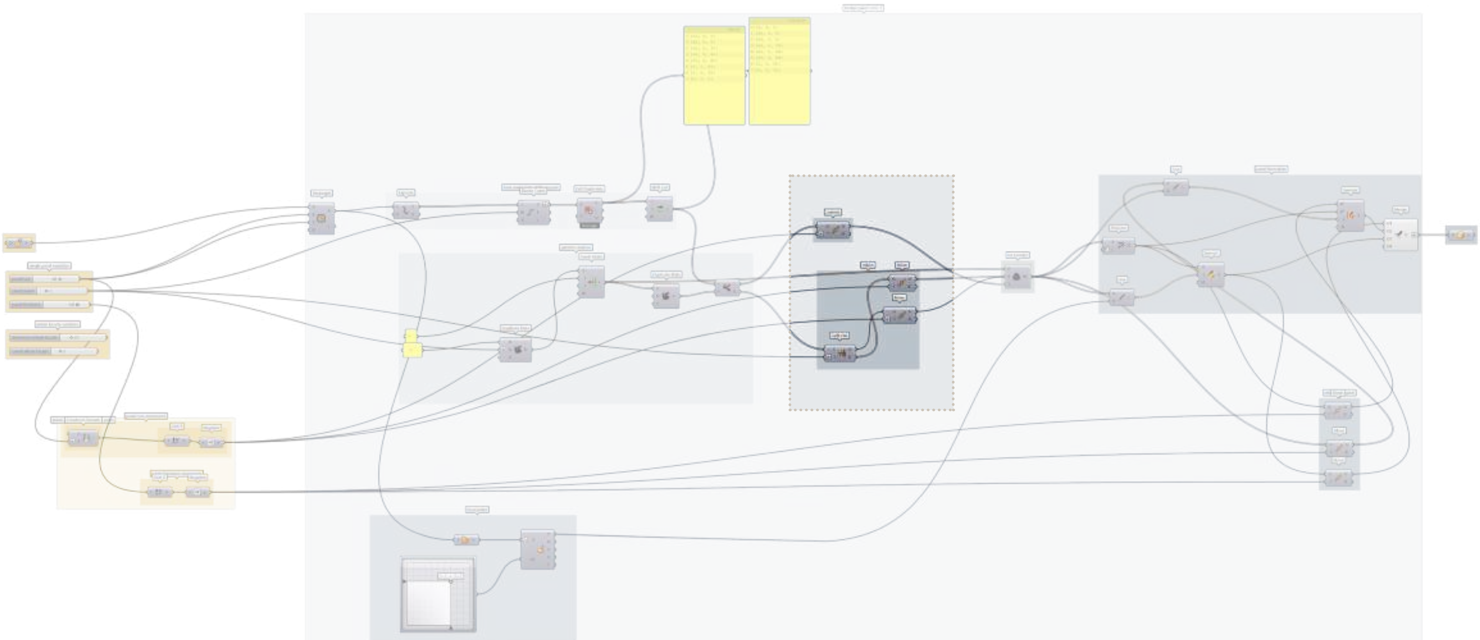


Figure 85. Bridge 1 Panel Scripting
own ill.

Furthermore, creating the script for bridge panel 3 can be parametrically thought of as the bridge panel 1 inverse: therefore, the output and inputs of move coordinates direction are the opposite. Therefore, the points laying on three edges will have the same coordinates as the corner points, while the points laying on the last edge will be moved as they were complex panels (Fig. 86).

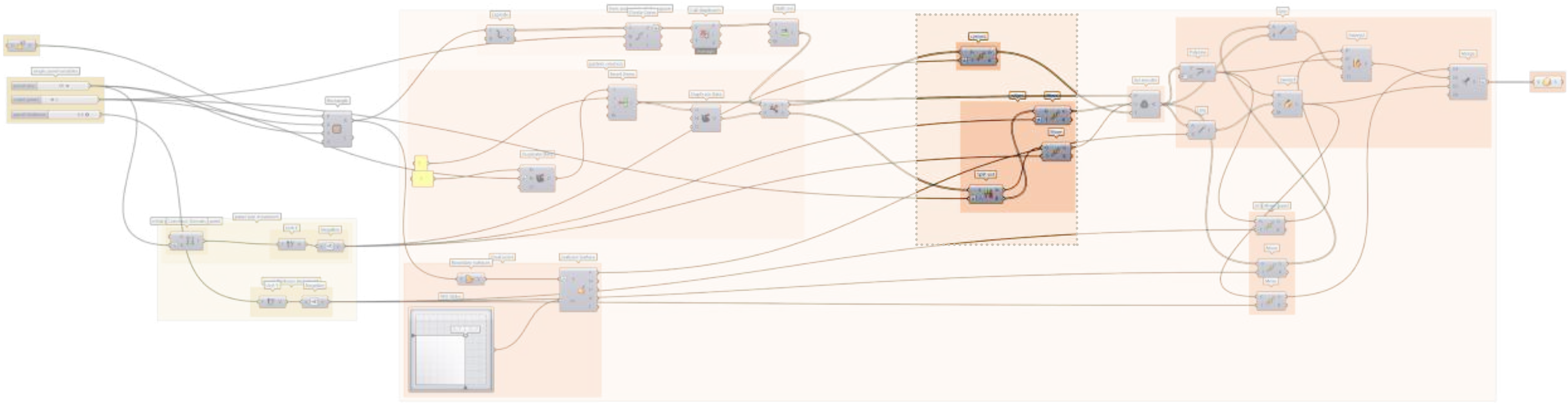


Figure 86. Bridge 3 Panel Scripting
own ill.

To design the script of bridge panel 2, a differentiation has to be done between the bridge panel 2 that has adjacent three-dimensional edges, and the one that has opposite three-dimensional edges.

Considering the first configuration, the process will be similar to the just explained panels. However, the list will be split by (x*2 - 2) where x is the edge division parameter: therefore, the points laying in two edges will be treated as flat points.
As in the previous case, the script will now proceed like the complex panel (Fig. 87).

In the case of the second configuration, the script will slightly differ.

Therefore, splitting list cut the list into a specific index, while in this case, it is important to separate the items in a true/false procedure.
For this reason, the partition list tool will be used to create specific sub-lists: on one side, the first and the third branch has been collected, while on the other side the second and fourth ones. In this way, the data has been sorted to manage the opposite edge points. Therefore, they will be moved to create two parallel flat and three-dimensional edges. In conclusion, the data will be sorted and merged to continue the script for all the other panels (Figure 88).

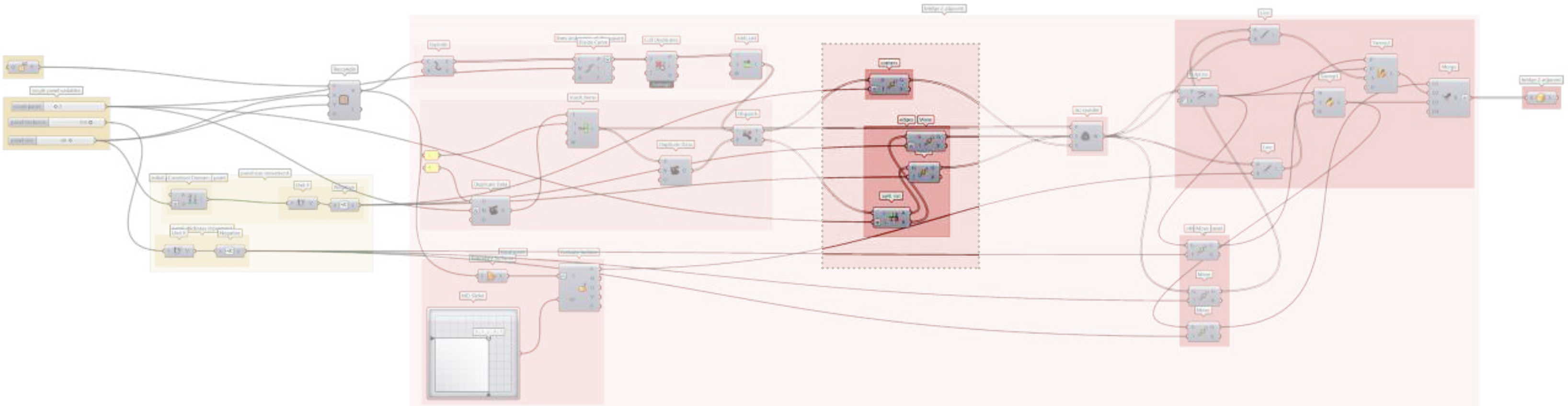


Figure 87. Bridge 2 Adjacent Panel Scripting
own ill.

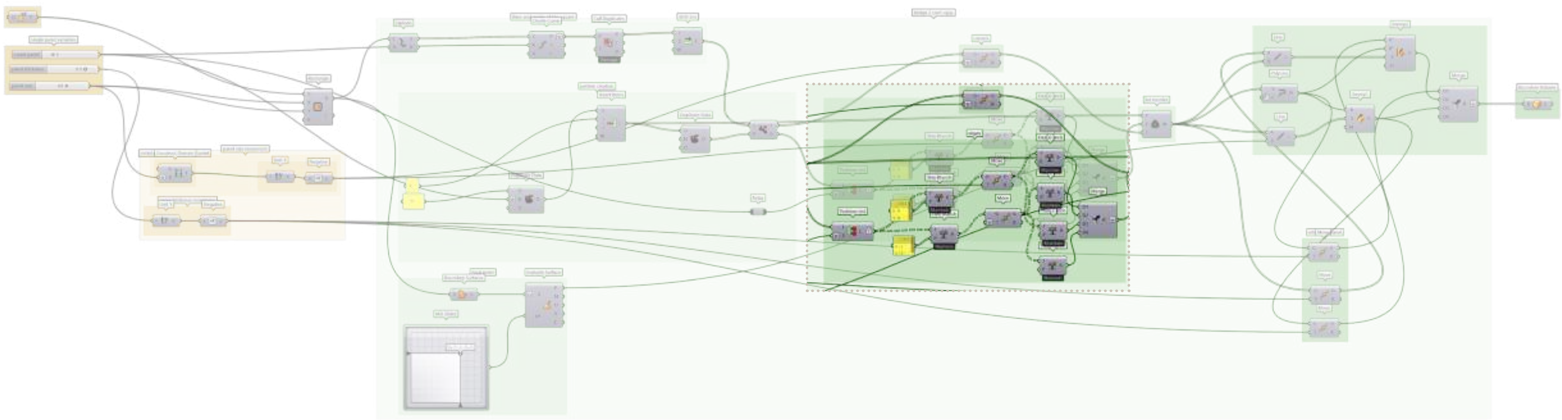


Figure 88. Bridge 2 Parallel Panel Scripting
own ill.

FLAT PANELS PROCESS

Finally, the flat panel is easily scripted by the boundary surface tool created by the rectangle - mentioned in the initial paragraph of panel parametrization - concluding by its extrusion.

In conclusion, the panel is moved in the y-direction by the same coordinates as the flat points of the other panels, hence it will match the other bridge panels: all the panels are parametrized (Fig. 89)

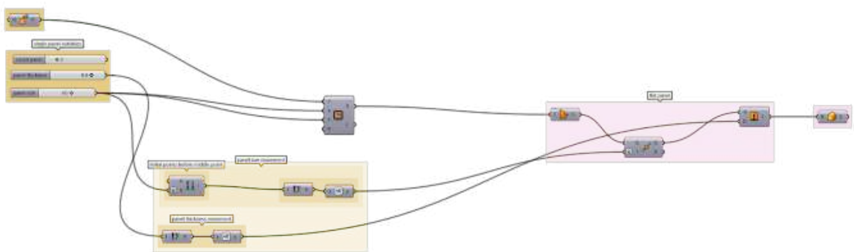


Figure 89. Flat Panel Scripting
own ill.

4.2_ COMPUTATIONAL CONFIGURATIONS

The designed products can be assembled in terms of the designer's preferences considering, however, the geometrical constraints of each panel, as explained in Chapter 3.3 (Fig.60 - 64) .

In this chapter, the two configurations mentioned in the conceptual design chapter - one-panel and all-panel configuration - will be shown computationally, for understanding the parametric versatility of the panels throughout a whole façade.

4.2.1_ONE-PANEL PARAMETRIC CONFIGURATION

The one-panel parametric configuration has been settled with the complex panel, which is the representation of the whole design concept.

After scripting the single panel design, it is appropriate to place it in a building's façade.
Before starting with the script, it is important to understand how to rotate the panels throughout the whole façade.

Following a visual examination by rotating the panel in various configurations (fig. 53), it has been observed that regular geometric designs are achieved by alternating the rotational patterns in every other row and within the row (fig. 90). Therefore, the following script needs to be analyzed considering this data order.

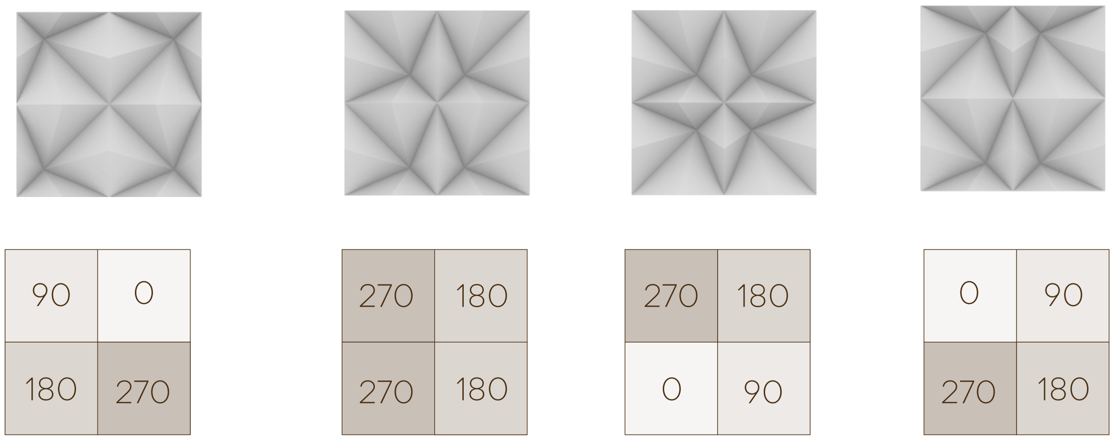


Figure 90. Rotational Complex Patterns
own ill.

As a starting point, a square grid having respectively as size and plane the panel dimension and xz plane needs to be created. To sort the data to respect the alternate geometrical mechanism split tree has been used having as the mask the respective alternate expression.
Since this pattern must also be scripted within each row, the dispatch tool has divided the two split trees into two: therefore, the alternated rows will have alternated elements. Having all the data sorted, the geometry can be placed in specific locations thanks to the vector 2 pt that lets the geometry coincide in the desired location within the square grid - the façade.

Finally, the collected geometries follow the wanted rotation that varies in terms of the designer's preferences, as shown in Fig. 91, to create a configuration such as the one shown in Fig. 92.

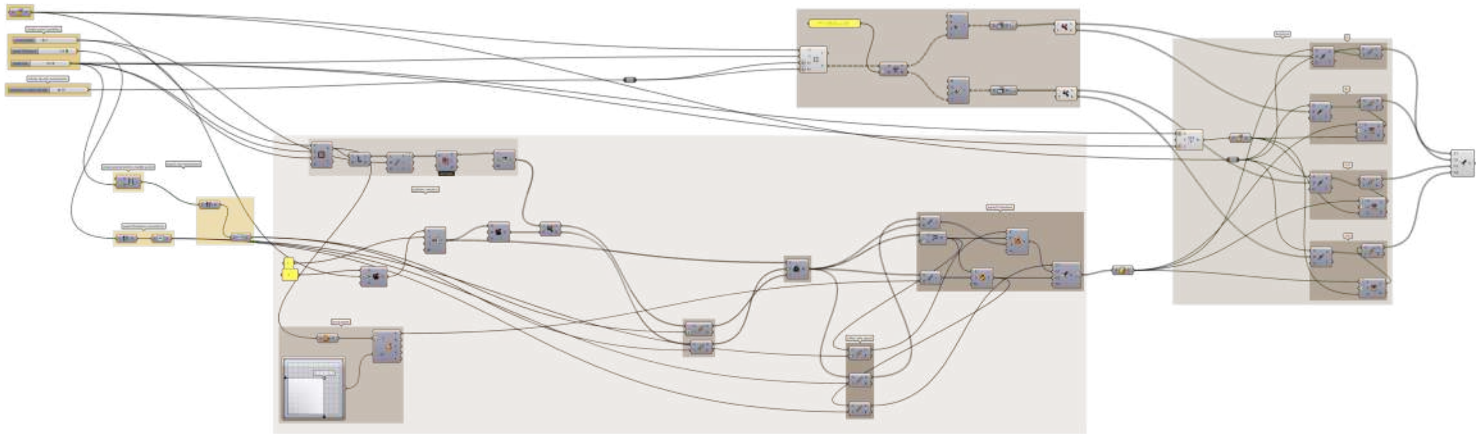


Figure 91. One-Panel Configuration Scripting
own ill.

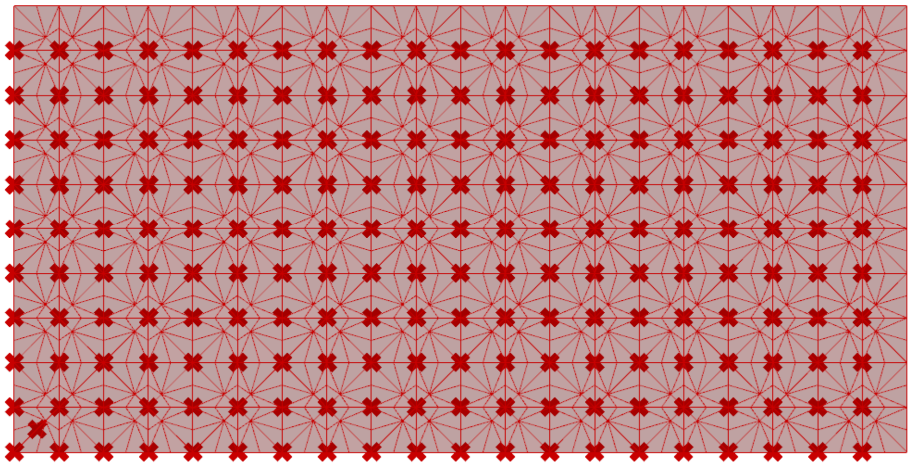


Figure 92. One-Panel Configuration Grasshopper 2D View
own ill.

4.2.2_ALL-PANEL PARAMETRIC CONFIGURATION

The concept from which all-panel configuration will be developed follows a geometrical reason on how to assemble the panels through the façade. The referred reason is about resembling a macro-geometry throughout the façade by placing and rotating the developed products.

To do so, whatever curve and facade can potentially be taken into account, therefore an easy geometry would be shown as a basis for the process understanding.

After realizing the bi-dimensional curves in Rhino, these will be set in Grasshopper: the next process is to settle a rule of how the parametric panels will be placed to compose the macro-geometry. Therefore, the complex panels will be the main character of the macro-geometry: thus, they will shape it through their sharp form and rotation.

The flat panels, instead, will be the background of the frame. Hence, to connect the complex to the flat panels, the bridge panels are needed: they will vary from bridge 1 to bridge 3 concerning how the complex and flat panels are placed in the façade (Fig. 69, 72).

SCRIPTING PROCESS

After describing the concept of the example configuration, the script can be settled.

The mentioned whole façade will be shaped by a square grid, considering the size panel and the size of the façade previously determined by parameters.

By having the façade division and the parametric macro-geometry, the tool curve | curve will create their intersection. By creating a panel, it will be visualized that each branch is composed of two indices, which represent the corresponding sorted panel and curve of the macro-geometry (Fig. 93).

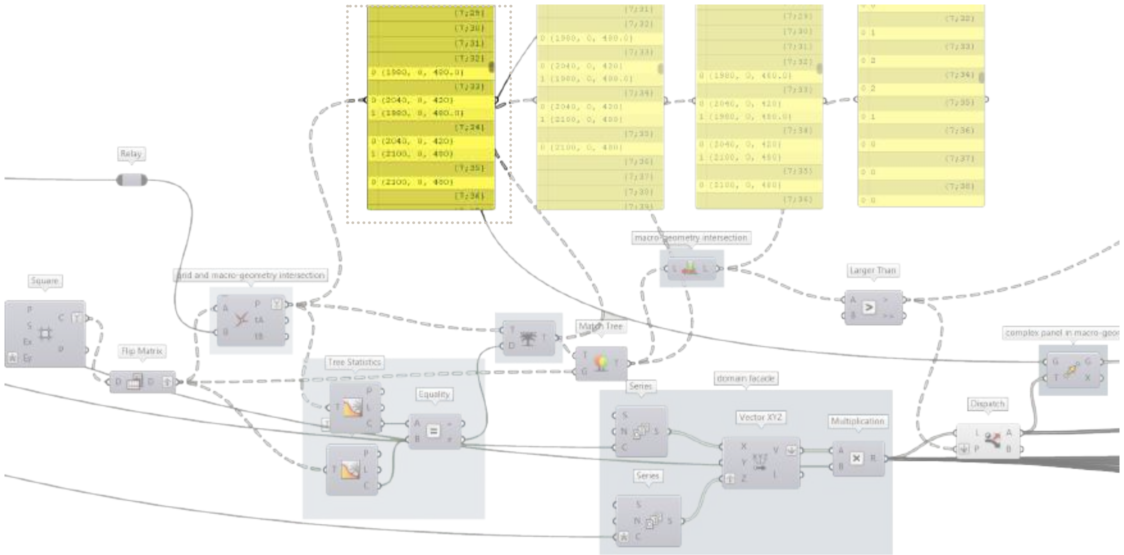


Figure 93. Intersection of curve and facade and data structure own ill.

Moreover, each branch will have the coordinates of the intersection between the indices as data. However, for further sorting the lists, it is more important to know which panel has the intersection rather than the correlation between the panel and the macro geometry: therefore, the points output will then follow the tree trim. Thus, by having a list, it will be now clear which panel has been considered and which coordinate points are present within the panel.

Furthermore, the tree will be "matched" with the square grid geometry, to represent each panel as indices. Finally, list length will help to visualize the number of intersections for each panel (Fig. 84).

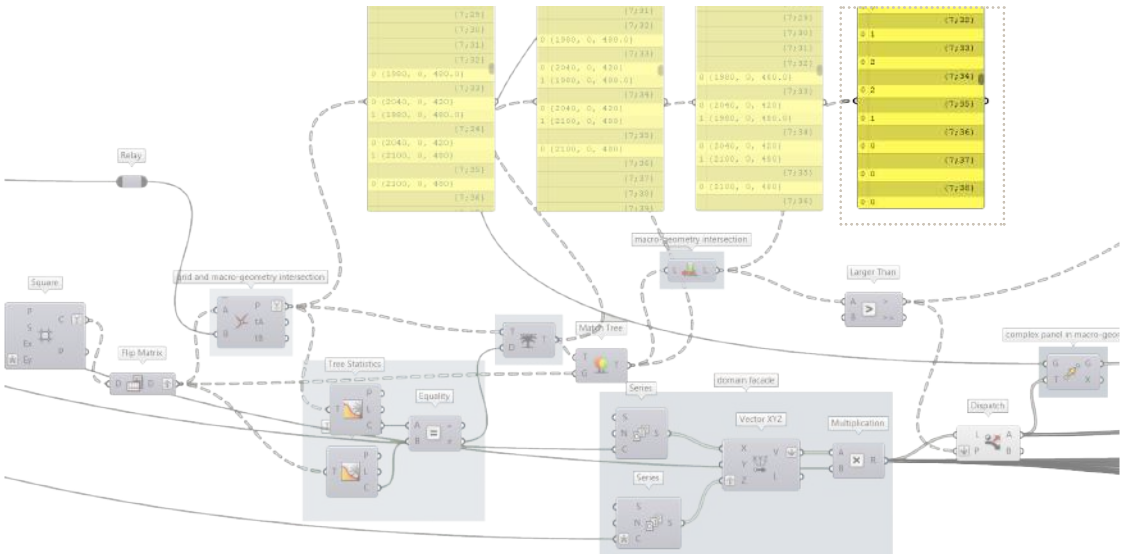


Figure 94. Manipulation of data structure for visualizing number of inteserction, own ill.

However, there are some panels in which grasshopper recognizes one intersection even though a real intersection is not present: for instance, in panel (7;32) (Fig. 95) the panel shows one intersection, however, the point is located in the corner between two panels. In this situation, Grasshopper recognizes an intersection in both the touching panels even though, physically speaking, the intersection can be considered in just one of the two sharing panels.

To avoid this data duplication, the larger than tool has been used, considering therefore just those data that are larger than 1.

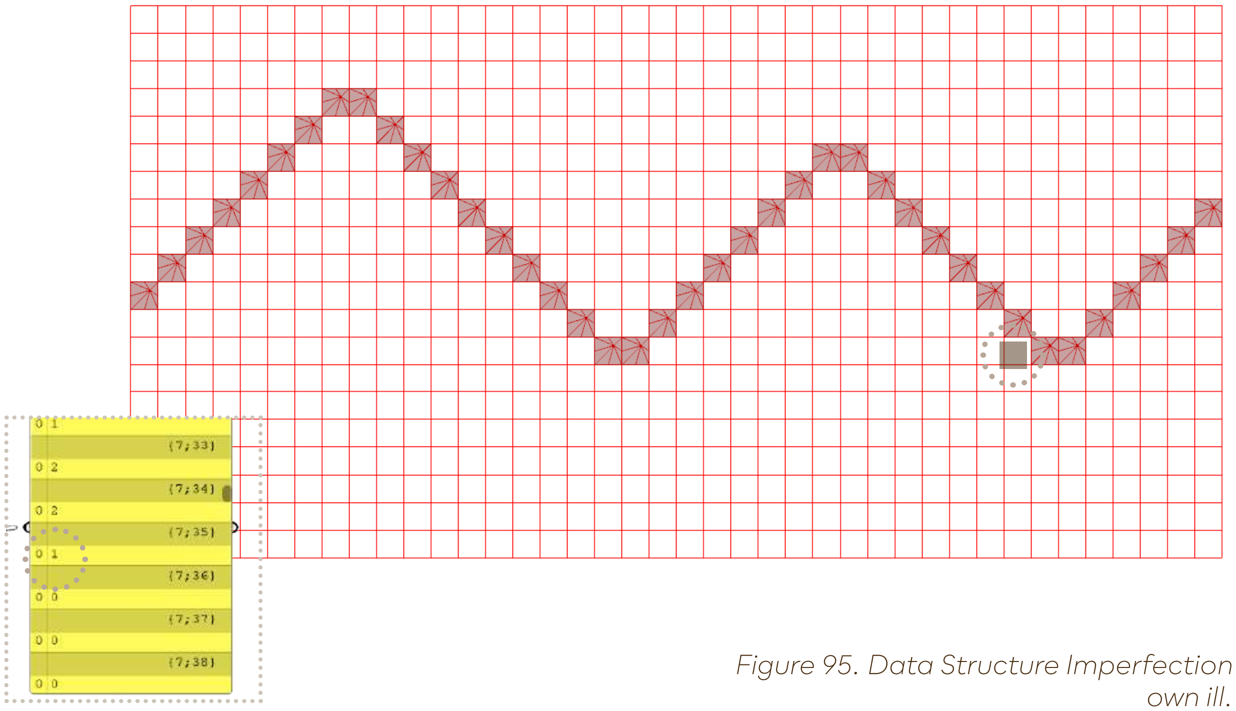


Figure 95. Data Structure Imperfection
own ill.

All sorted data need to be located within a domain: the façade dimension will be composed of a series of squares that will have the same dimension as the panel size.
This will be the list of the dispatch tool, from which the squares where the double intersection is present will be extrapolated.

Finally, to represent the complex panels within the created path, the move component will be used by considering as a geometry the complex panel and the translation vector the A output from the dispatch tool (Fig. 96).

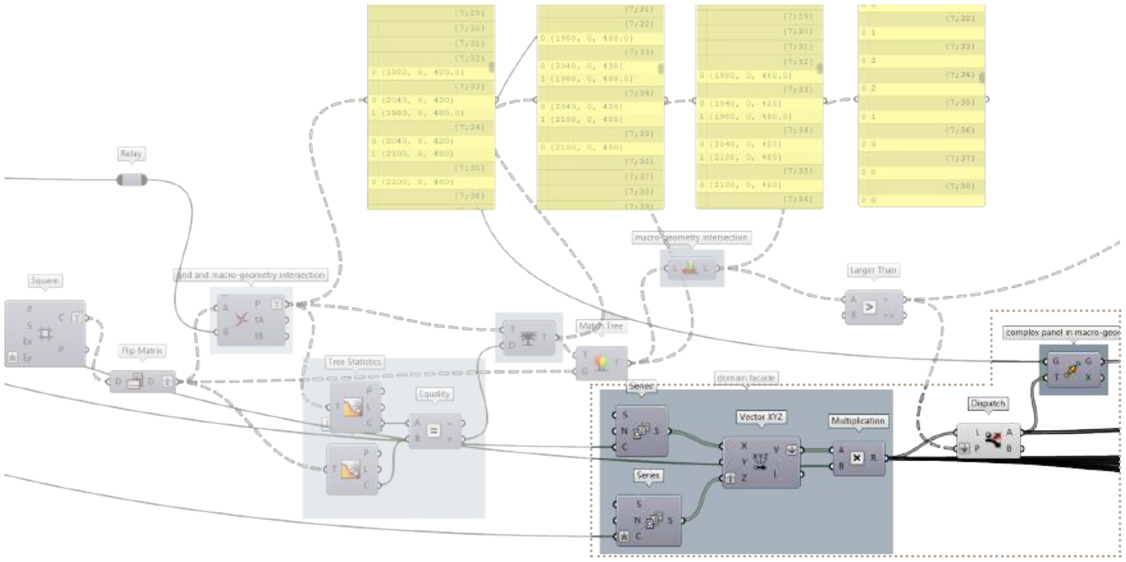


Figure 96. Complex Panels Placement considering the Macro-Geometry
own ill.

BRIDGE PANELS DATA MANAGEMENT

Having dispatched the list and collected the complex panels, now it is important to sort the data correctly for the accurate location of the bridge panels within the façade.
The outputs of the “larger than” tool is “translated” to numbers, where 1 corresponds to the complex and 0 to the bridge panels (Fig.97). Moreover, the tree with single branches has been trimmed to reorder the data as preferred.

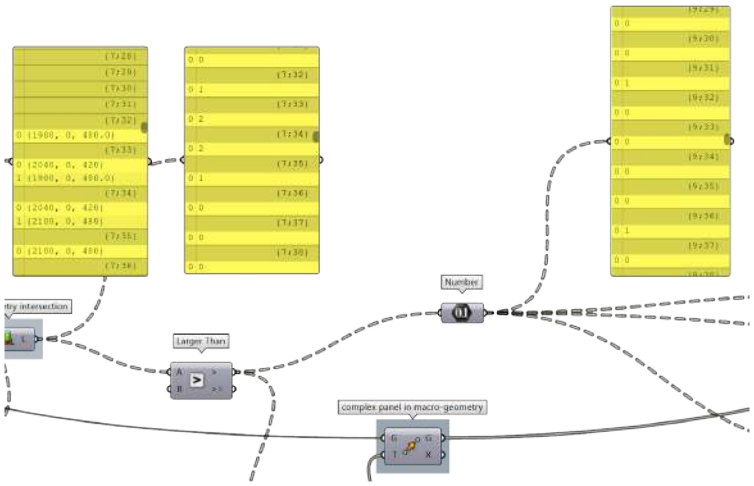


Figure 97. Labeling comple and bridge panels through data management
own ill.

As mentioned in the design process, the bridge panels are those that are adjacent to the complex ones. Therefore, it is important to computationally understand that the bridge panels can be placed either above, below, to the right, or the left of the complex ones. To create a parametric translation of this concept, the shifting list will be used for each direction separately.

RIGHT SIDE SHIFTING BUT LEFT SIDE BRIDGING

To locate the bridge panels situated to the left side of the complex panels, a shift list has been established with an offset of 1 toward the right. Thanks to the explicative panels, it is clear from Fig. 98 how 1 is identifying the complex panels and the bridge ones on their left side.

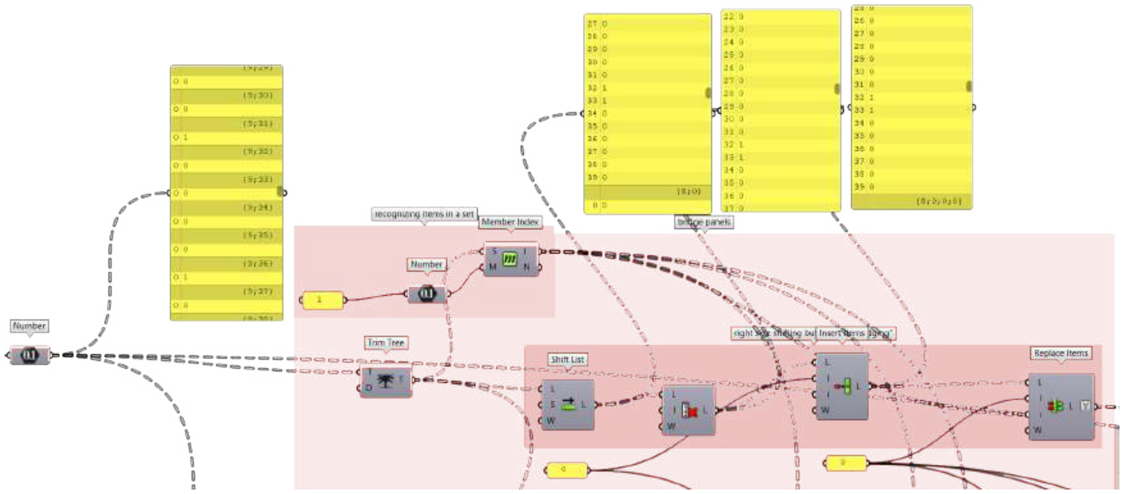


Figure 98. Labeling Bridge Panels located to the Complex Panels left own ill.

However, attention has to be paid to the last and the first elements of each row since the façade is a finite element although Grasshopper defines it as a loop and infinite set. Therefore, it is not obvious that a 1 element that has been shifted from the last panel of the row corresponds to the wanted panel at the beginning of the row.

To avoid this type of miscalculation in data management, cull index will be used by removing the -1 index, and a 0 will be inserted for matching the initial amount of data in the list.

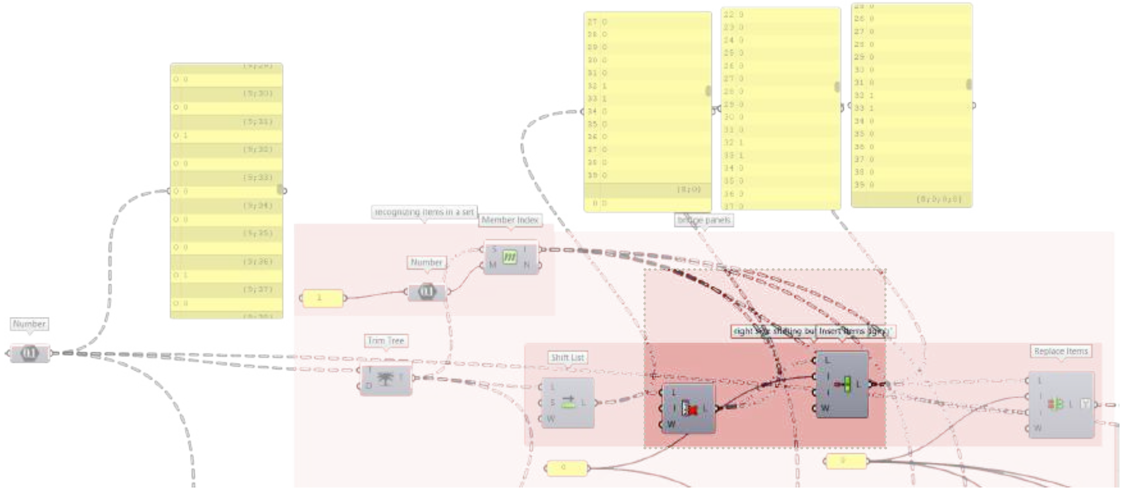


Figure 99. Manipulation of data for avoiding loops
own ill.

The correlation between the complex panels and the "right side" bridge panel is set. However, as mentioned before, they are both defined as 1. Therefore, for differentiating them, the complex panels will be then replaced by labeling with 0. To do so, the data in the previously mentioned tree trim has been collected - in which complex and other panels were defined respectively with 1 and 0 - and - by using the member index tool - 1s elements have been recognized in a set, and then replaced it with 0 in the replace items tool, by having as the shifted list as the main list, 0 as the index and finally, the member index output as the replacement index. Thus, the bridge panels have been isolated by labeling them as "1" (Fig.100).

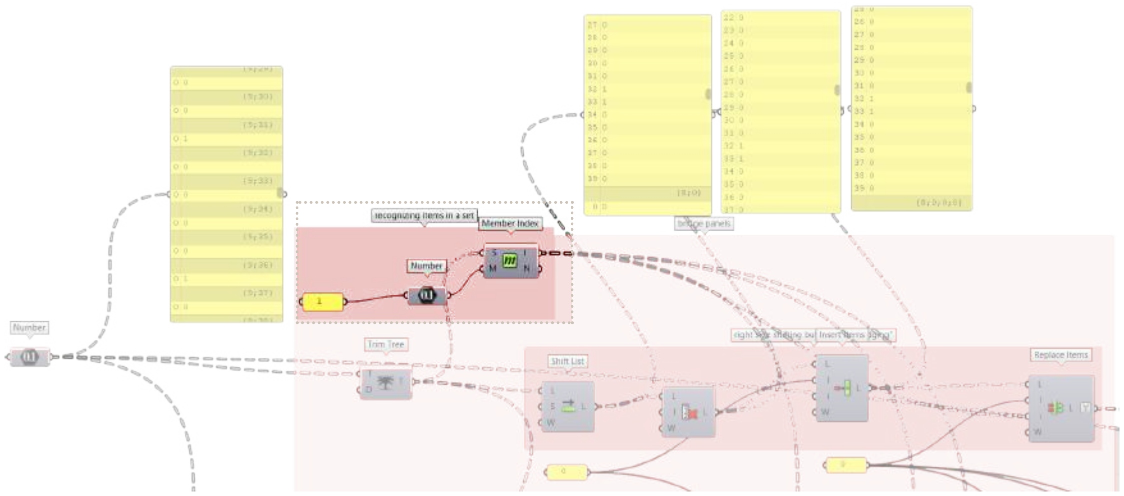


Figure 100. Manipulation of data for avoiding mislabel
own ill.

LEFT SIDE SHIFTING BUT RIGHT SIDE BRIDGING

To identify and isolate the bridge panels on the right side of the complex, the same process is employed. However, in this case, the shift list offset is set to -1, causing the list to shift toward the left.

TOP SIDE SHIFTING BUT BOTTOM SIDE BRIDGING

To reorganize data and determine the bridge panels on the bottom side, a flip matrix has been used between the trim tree and the shift list tool (Fig.101). In this way, the same process as before could be used even for columns, by concluding, before replacing the member index item, with a flip matrix again to restore the initial situation.

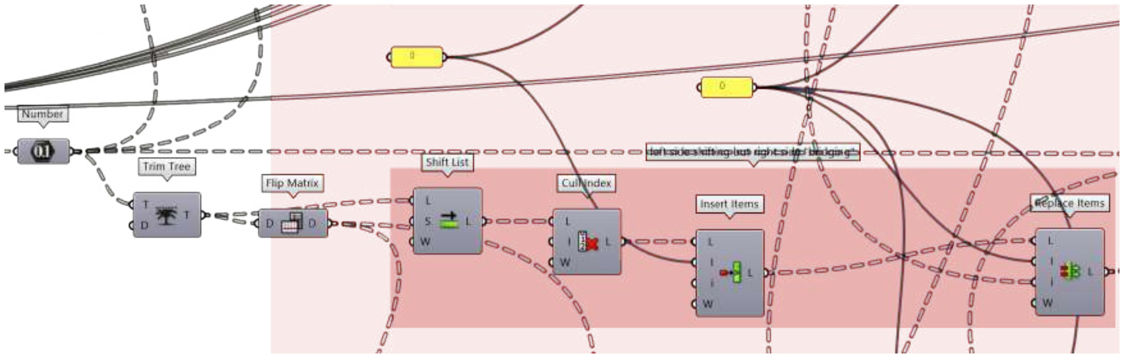


Figure 101. Manipulation of data for using same process when data were inverted own ill.

BOTTOM SIDE SHIFTING BUT TOP SIDE BRIDGING

To identify and isolate the bridge panels on the right side of the complex, the same process is employed. However, in this case, the shift list offset is set to -1, causing the list to shift toward the left, therefore to the bottom.

Therefore, having all the different scenarios, the addition of each result will be placed. In this way, it will be possible to understand which panel is a bridge and how many three-dimensional and bi-dimensional edges does have, as shown in Fig. 102 : thus, complex and flat panels will be labeled as 0 - since they are not the focus of this script part - while 1 corresponds to bridge 1 panel, 2 corresponds to bridge panel 2, and, finally, 3 corresponds to bridge panel 3.

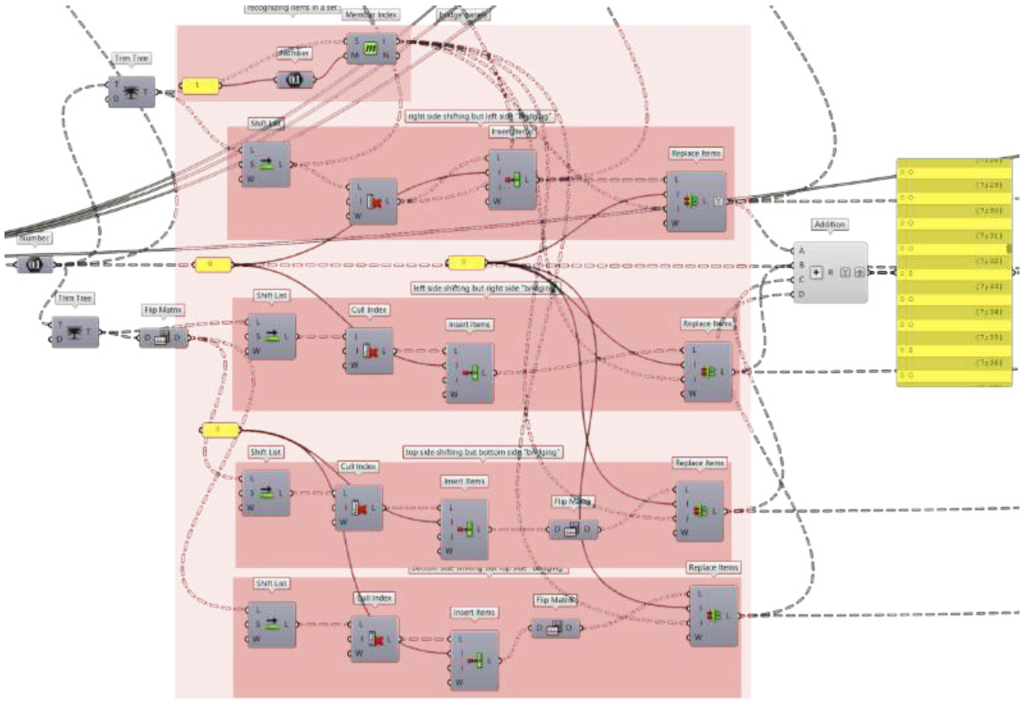


Figure 102. Manipulation of data for labeling complex, bridge1, 2, 3 panel own ill.

COMPLEX PANELS ROTATIONAL PLACEMENT

Before placing the actual bridge panels in the façade, it is important to set rules on how to locate the complex panels. Therefore, the desired constraint is that the panel does not have to be repeated, but each time has to be rotated compared to the narrow panels.
To do so, the data list needs to be ordered: it will be sorted taking into account the x-coordinates values.

The panels will be rotated based on the façade macro-geometry, meaning that whenever the curve will change the angle, a rotation will be taken into account - as schematically shown in Fig. 103.

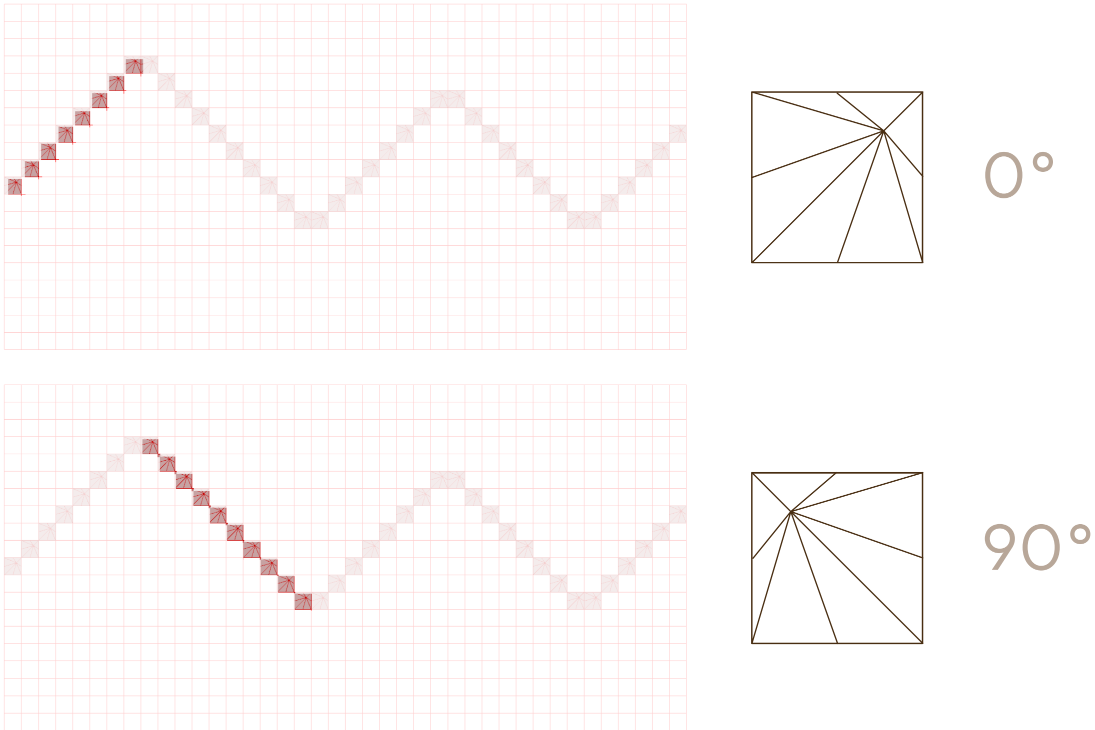


Figure 103. Geometrical Constraint for Complex Panel location within the façade own ill.

To let Grasshopper understand when this happens, shift list and subtraction will be used.
Therefore, there will be a subtraction between the z-coordinates of the front panel - on the right - and the back panel - on the left: if the subtraction is positive, the value will be false, thus the panel will stay the same having the diagonal from bottom left to top right; if the subtraction is either equal to 0 or negative, the value will be true, thus the panel will be rotated by 90 degrees and it will follow that rotation until the curve will not change the angle again.

However, in some cases whenever the subtraction is equal to 0, the solution is not precise, therefore an if statement is needed: if the subtraction is equal to 0 and the panel to their left is labeled as true, then the panel is surely true, therefore it will be rotated in the same direction. To combine the if statements with the premise mentioned before, a boolean disjunction is needed.
Therefore, if either the boolean conjunction occurs or the subtraction is negative, then that panel will be true: thus, by translating the output

datas to number, it is possible to notice how the panels are collected with 0 and 1 based on the curvature angle.
The panels can now be rotated considering as the angle, the number pattern just mentioned, and as the plane, the xz plane having as a rotational axis the middle point of each panel - as shown in Fig.104

However, the final intention is that, within both the 0s and 1s data, each panel differs from the other by rotating by 180 degrees, thus, there will not be an identical panel to the following one. To do so, the rotated geometries will be collected in list length, the data amount will be divided by two while the duplicate data will be used by having 1 and 0 as data to duplicate by half of the list.
In this way, the pattern will now be displayed as 1 and 0, but still taking care of the rotational panels influenced by the selected curve that has been previously settled. Therefore, within the segment of the curve, the panels are alternatively rotated by 180 degrees until the beginning of the other curve segment.

In the next segment, a new rotation of the first panel is present, following the same rotational principle of the curve segment just mentioned.

Finally, cull index is also taken into account whenever the macro-geometry is creating an odd amount of panels: whenever this happens, the -1 index will delete the last panel avoiding a duplicate miscalculation: the complex panels are placed (Fig. 105).

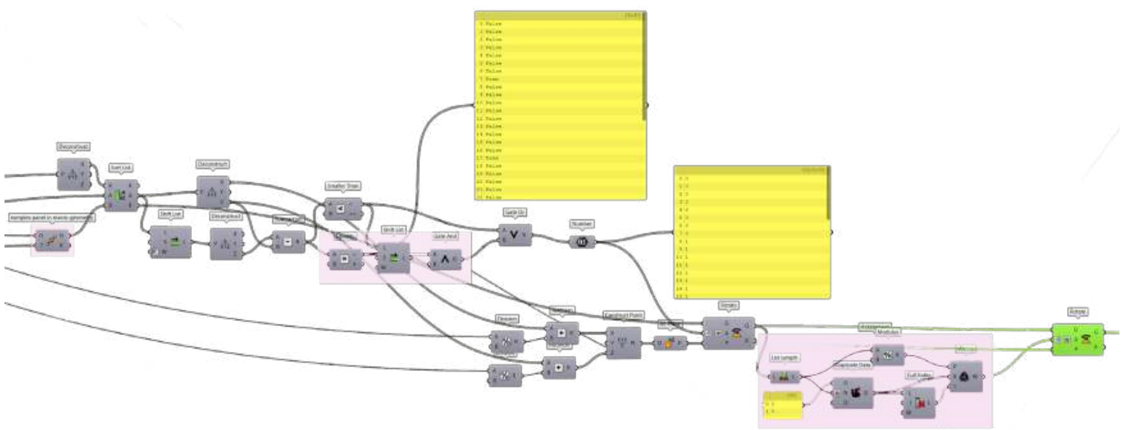


Figure 104. Manipulation of Data for respecting constraints and placing panels own ill.

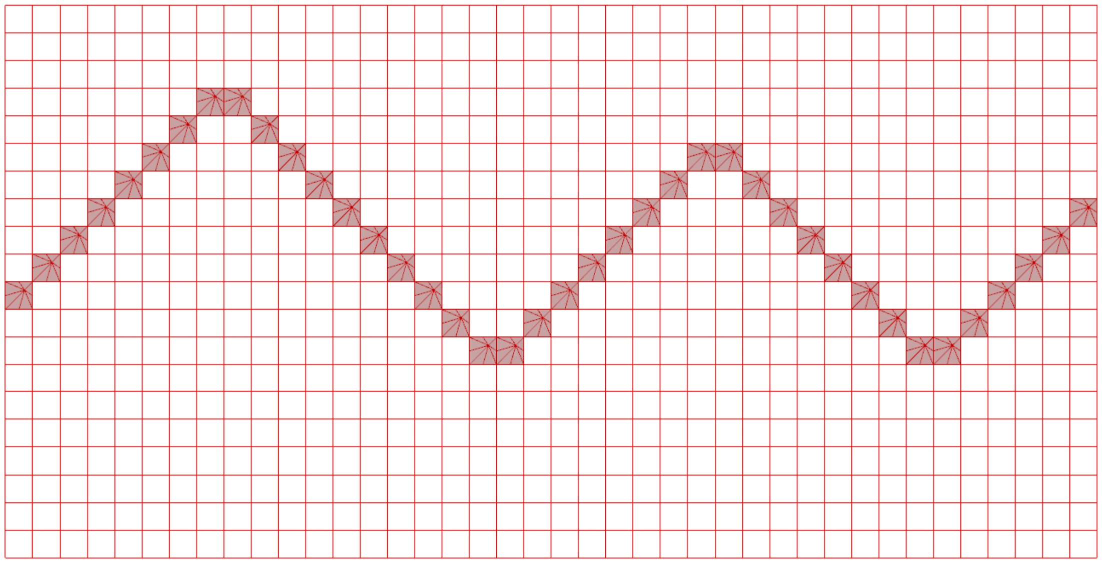


Figure 105. Complex Panels placement following the selected constraints own ill.

BRIDGE PANELS ROTATIONAL PLACEMENT

Having placed the complex panels correctly, bridge panels can be consequently located taking care of their three-dimensionality. Every bridge panel will be analyzed and scripted, taking into account each direction towards the complex panel - left, right, bottom, and top - collecting those data sorted in the previous management data paragraph. To precisely locate the bridge panel 1, each potential panel rotation needs to be differentiated.

The inputs of this part of the script will be the output of each bridge panel of the management data paragraph. Every output will be then translated into a number, from where the script can be shaped by performing boolean conjunctions in relation to the needs.

To understand how to compose the script, it is important to analyze for each rotational scenario, the orientation of each edge relative to the initial parametric panel, and determine whether it has a flat or complex shape - as explained in Fig. 106.
This mechanical process will start with the elaboration of the script of bridge panel 1 without any rotation.

The bridge panel 1 has been designed in such a way that the three-dimensional edges are located everywhere but the bottom side.

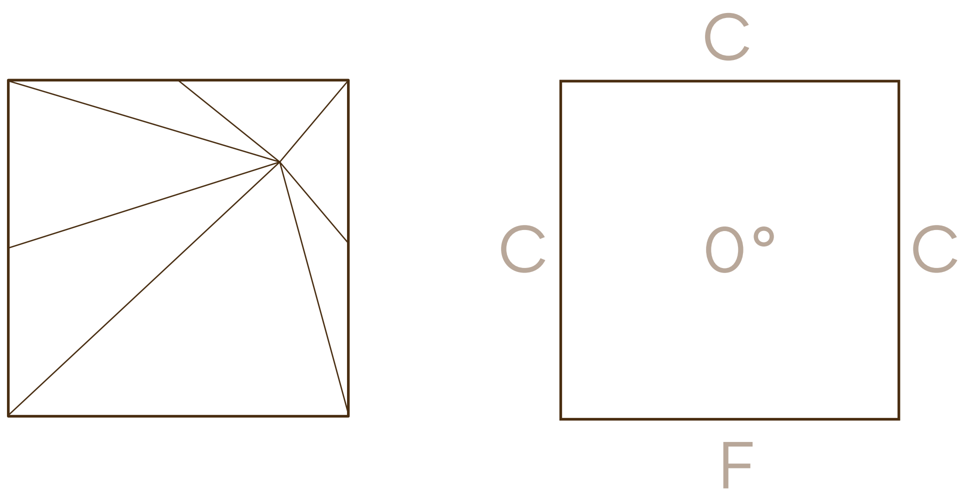


Figure 106. Bridge Panel 1 with 0° rotational scenario
own ill.

Therefore, each number output previously mentioned can be combined except that list that refers to the bottom side “bridging”. On that side, it is important to neglect that data since there is a flat edge, by using gate not as the last input of the gate and tool.
The resulting values will then be dispatched taking into account just those values that do respect the premises: that output will be the translation vector of the geometry in the façade. Therefore, those bridge 1 panels that will be needed in the façade without any rotation will not be shown in the Rhino viewport.
This process will now be repeated for each rotational side - 90, 180, and 270 degrees.
In the case of bridge panel 1 which has been rotated by 90 degrees, the only flat edge will be present only on the right side of the panel: therefore, the only number output that will be neglected is the second one, referring to the “right side bridging” (Fig. 107).

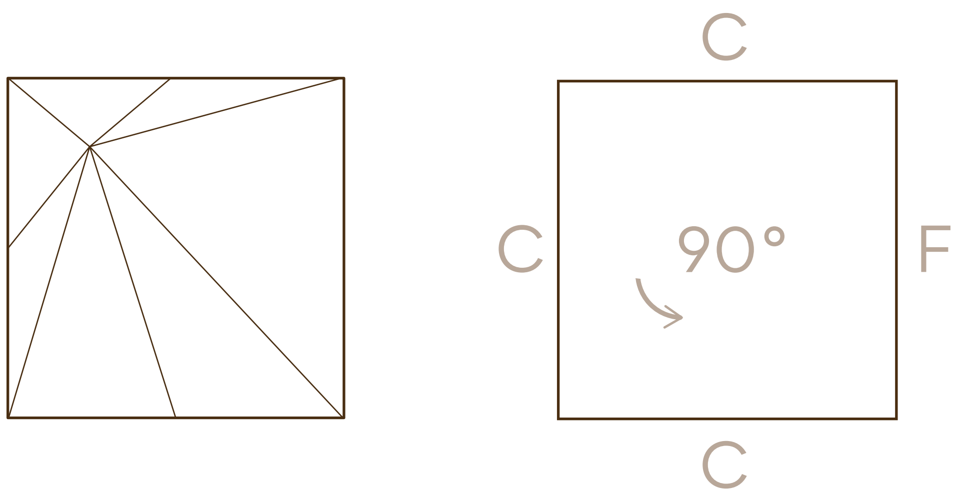


Figure 107. Bridge Panel 1 with 90° rotational scenario
own ill.

Having now the correct data, it is important to effectively rotate the panel by 90 degrees, taking the geometry just moved, and as a plane the xz one having as a rotational axis the middle point of each panel.

The same process will be taken for each rotation and each bridge panel, taking always into account where the three and bi-dimensional edges are supposed to be located and managing the data in relation to that (Fig. 108, 109).

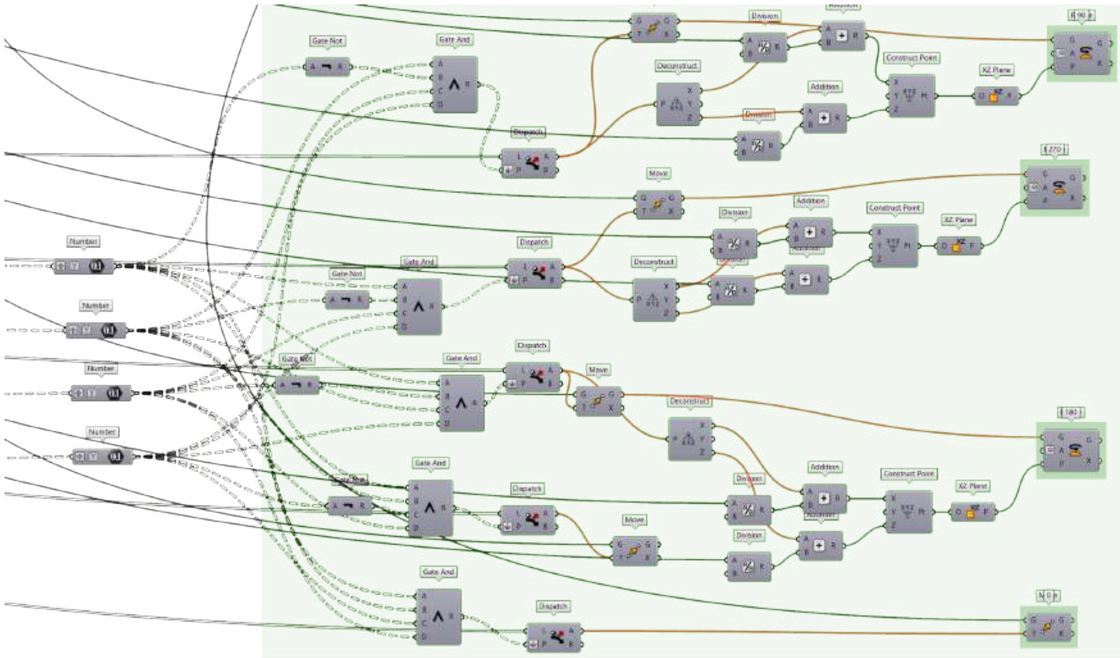


Figure 108. Bridge Panels with all rotational scenarios own ill.

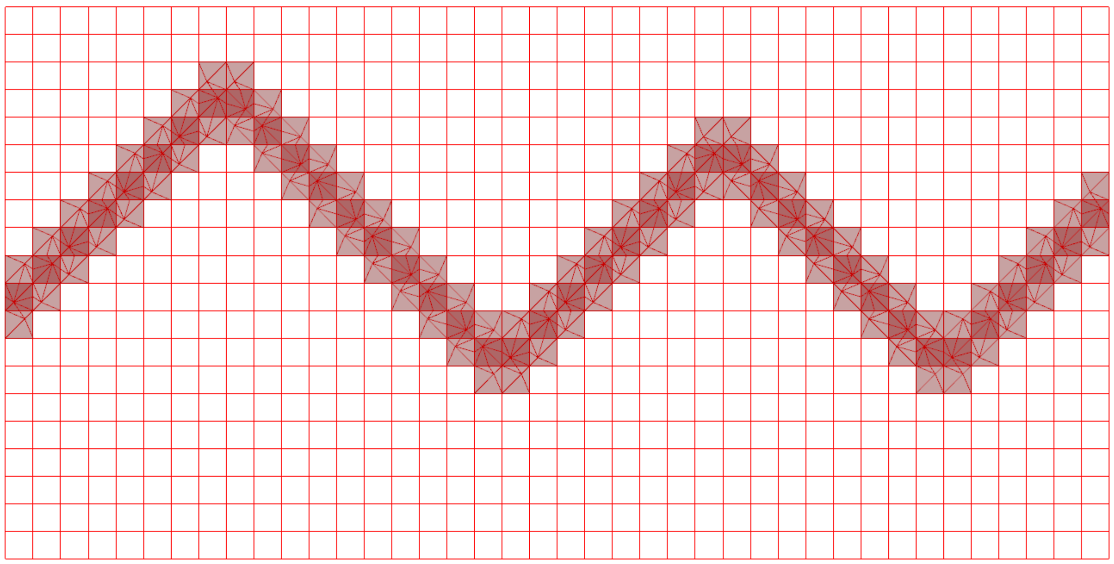


Figure 109. Bridge Panels placement following the selected constraints own ill.

FLAT PANELS ROTATIONAL PLACEMENT

Last, the flat panels will be isolated and collected by an if statement. Therefore, if the addition between the number output of the curve intersection in the façade and the number of bridge panel complex edges is equal to 0, then there is certainty the panels will be flat. The needed data will be dispatched which output will be the translation vector of the move tool (Fig.110).
Finally, all the final outputs will be merged by having the whole desired façade (Fig. 111).

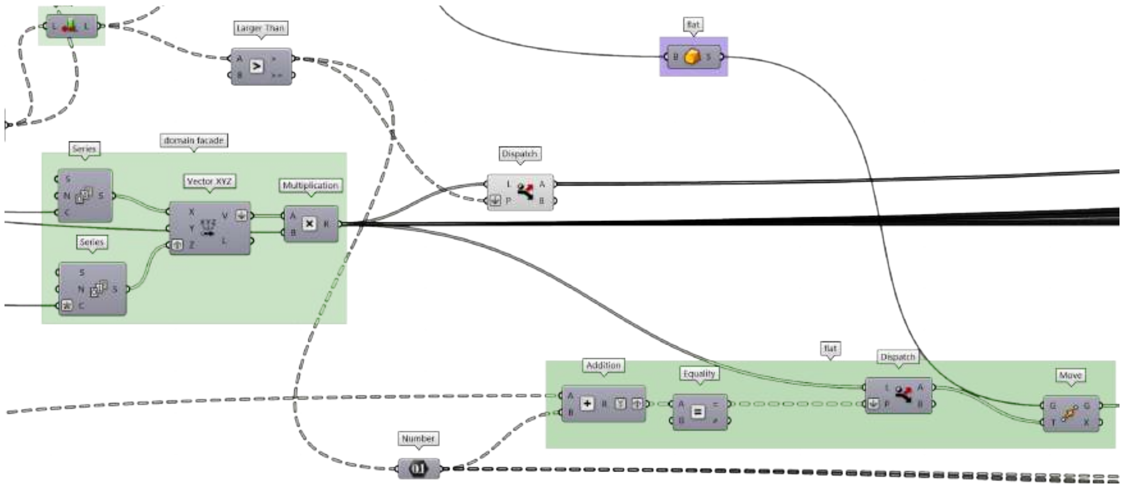


Figure 110. If statement for placing flat panels within the façade own ill.

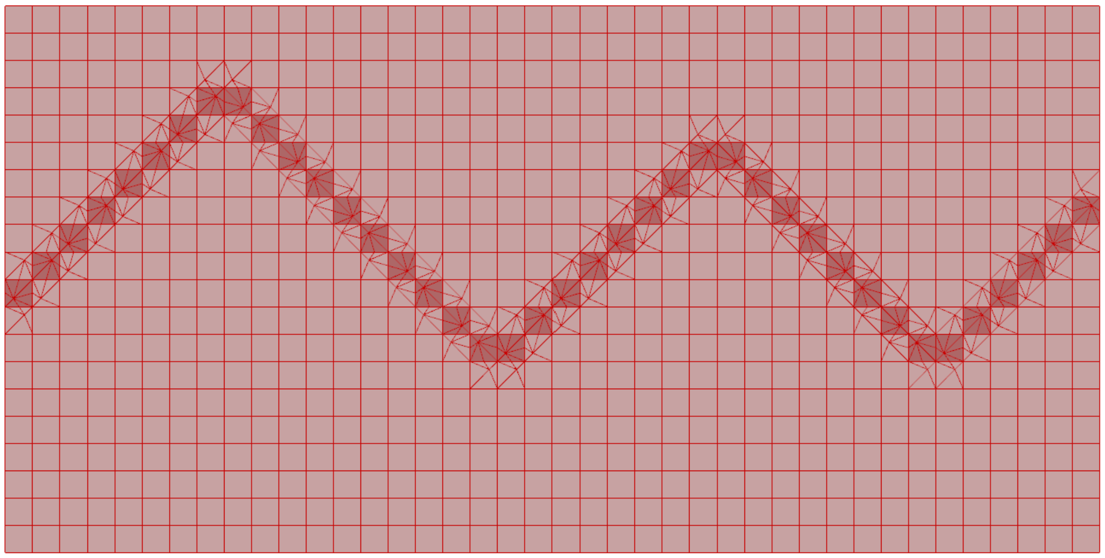


Figure 111. Façade Panelization following the selected constraints own ill.

CONCLUSION

In conclusion, the computational model used in this design process serves as a tool for showcasing a dynamic system rather than a final product.

By introducing various variables and parameters, flexibility is embedded within the design, allowing for a multitude of possibilities. Each variable represents an opportunity to explore and understand the underlying rules of the system, revealing its inherent characteristics.

The presentation of different configurations provides designers with the flexibility to realize their preferred outcomes. The emphasis is placed on offering choices and options, empowering the designer to make informed decisions based on their unique vision and preferences. This approach highlights the innovative nature of the panel configuration system, which maintains a predetermined amount of panels - shown in Chapter 3 - while enabling diverse and creative outcomes.

Moreover, the possibilities for realizing façade configurations are vast, encompassing the circular design principles of minimizing the material, and the circular strategy of *rethinking* (Fig.22) a model to maximize flexibility while minimizing waste (mould materials). This opens up a realm of opportunities to create environmentally conscious and aesthetically pleasing designs.

In summary, the computational model serves as a platform for showcasing the inherent flexibility of the design system. The presentation of various configurations highlights the innovative and dynamic nature of the panel configuration approach. With a focus on circular design principles, numerous possibilities arise for creating façade configurations that are both aesthetically captivating and environmentally sustainable.
By embracing this approach, designers can push the boundaries of architectural design while making conscious choices that contribute to a more sustainable future.

_5 FINAL DESIGN

5.1_ PRODUCT REALIZATION

Having shown the conceptual and computational concepts and explorations, the actual final design will be now explored. Therefore, the parametric variables wil now be established for the proposed design.

DESIGN

The final panel dimension is 60 x 60cm, which has been selected by the hot presses' maximum dimensions available at NPSP.
The final thickness will be 8mm - which is one of the most common dimensions for this material panels given its properties - except for the four cornerback side panels, in which thicker protrusions have been designed (Fig.112).
These elements are designed to facilitate a planar connection with the substructure behind to avoid complications from connecting the panels at sharp angles.
Moreover, these four thicker corners have the same depth, facilitating the connection between the panel and the substructure even when the façade design entails a rotational variation of the product itself.

To achieve the desired connections, a dry connection method with a mechanical secret fixing system has been chosen (Plasterstrips n.d.). This system involves a wooden substructure attached to the traditional wall system, which includes masonry walls and an insulation layer. An aluminum alloy horizontal channel is screwed to the substructure, while the vertical fastener is bolted to an aluminum spacer and screwed to the façade. Finally, the panels with the screwed and bolted elements will be slid into the horizontal channel, as shown in Fig. 114-117.
The explained connections have been designed being inspired by the SFS NV3 Subframe System (SFS n.d.).

This system has been meticulously selected and developed to ensure that the production of the mould remains unaffected, allowing for flexibility in the designer's choices.

Having stated the system on which the panels will be placed, the developed design can be assembled considering the panels' constraints - as mentioned in the previous chapters.
Therefore, a six panel-configuration will be displayed (Fig. 113).

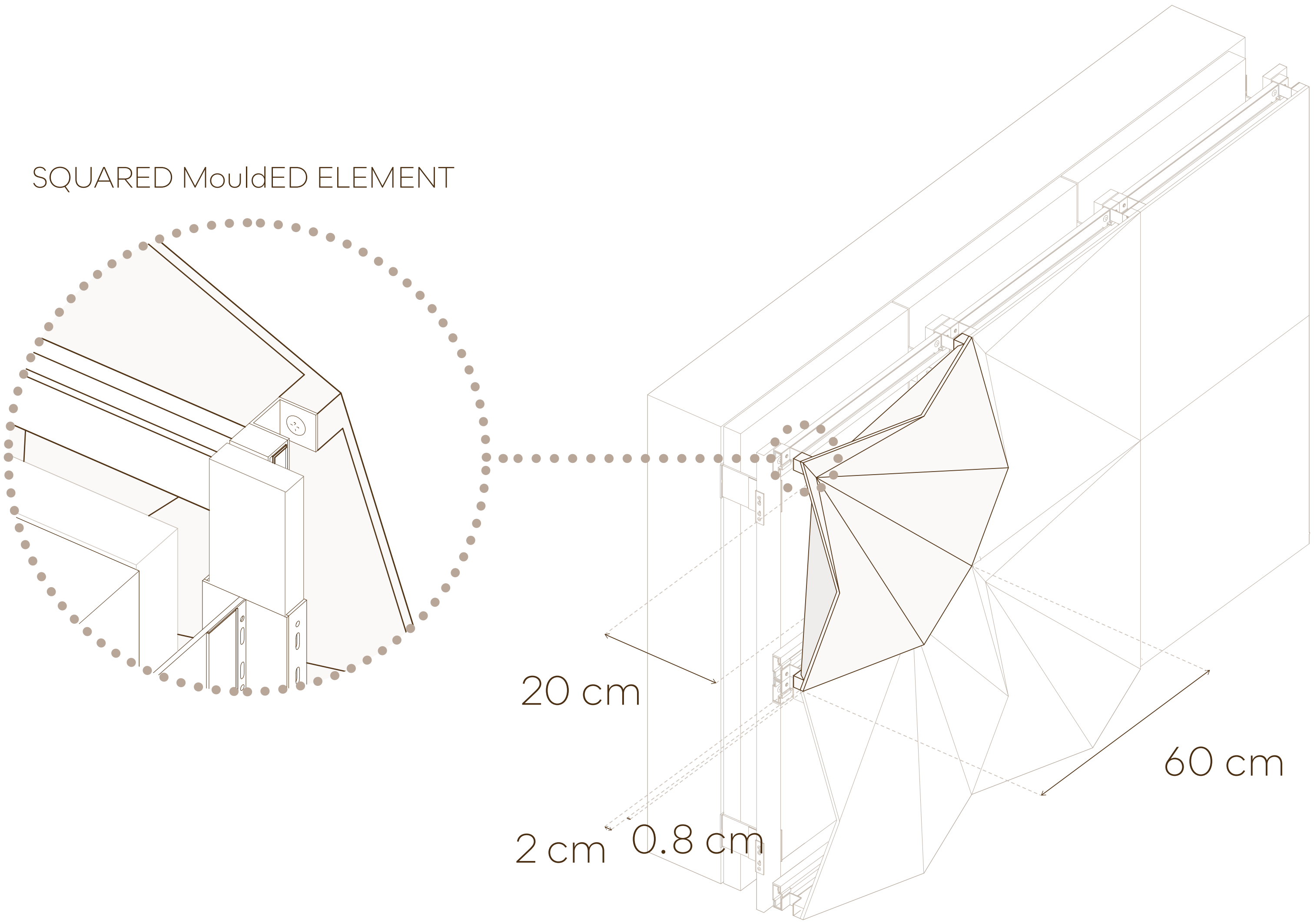


Figure 112. Final Panel dimensions and peculiarities
own ill.

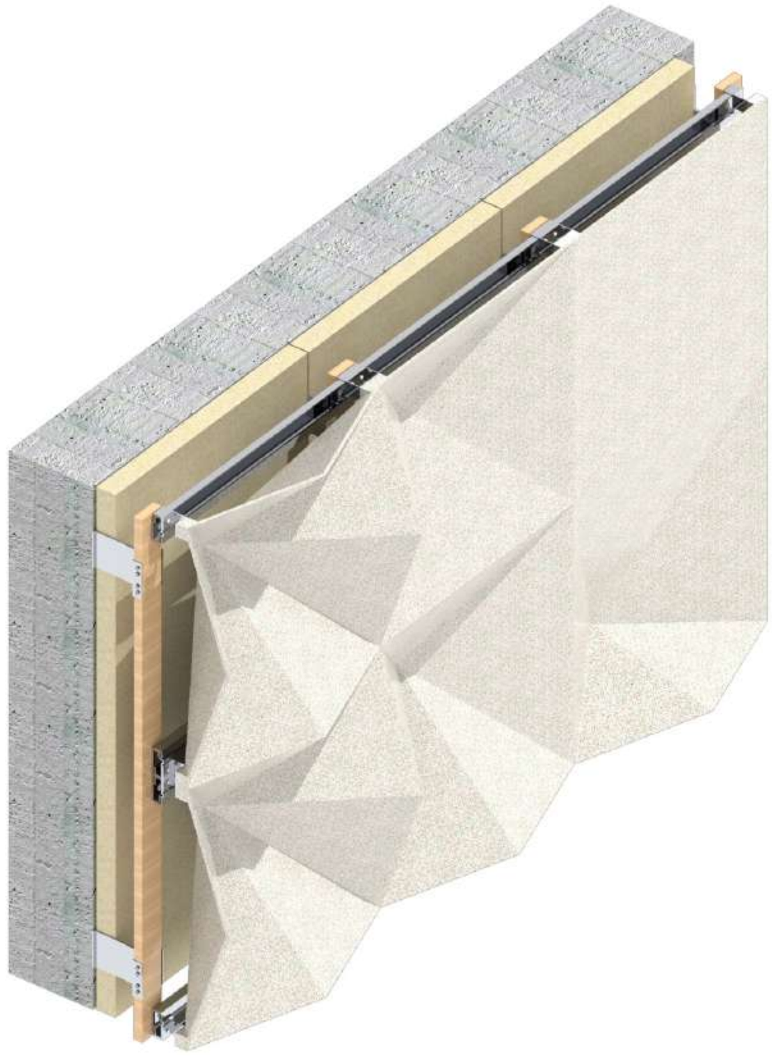
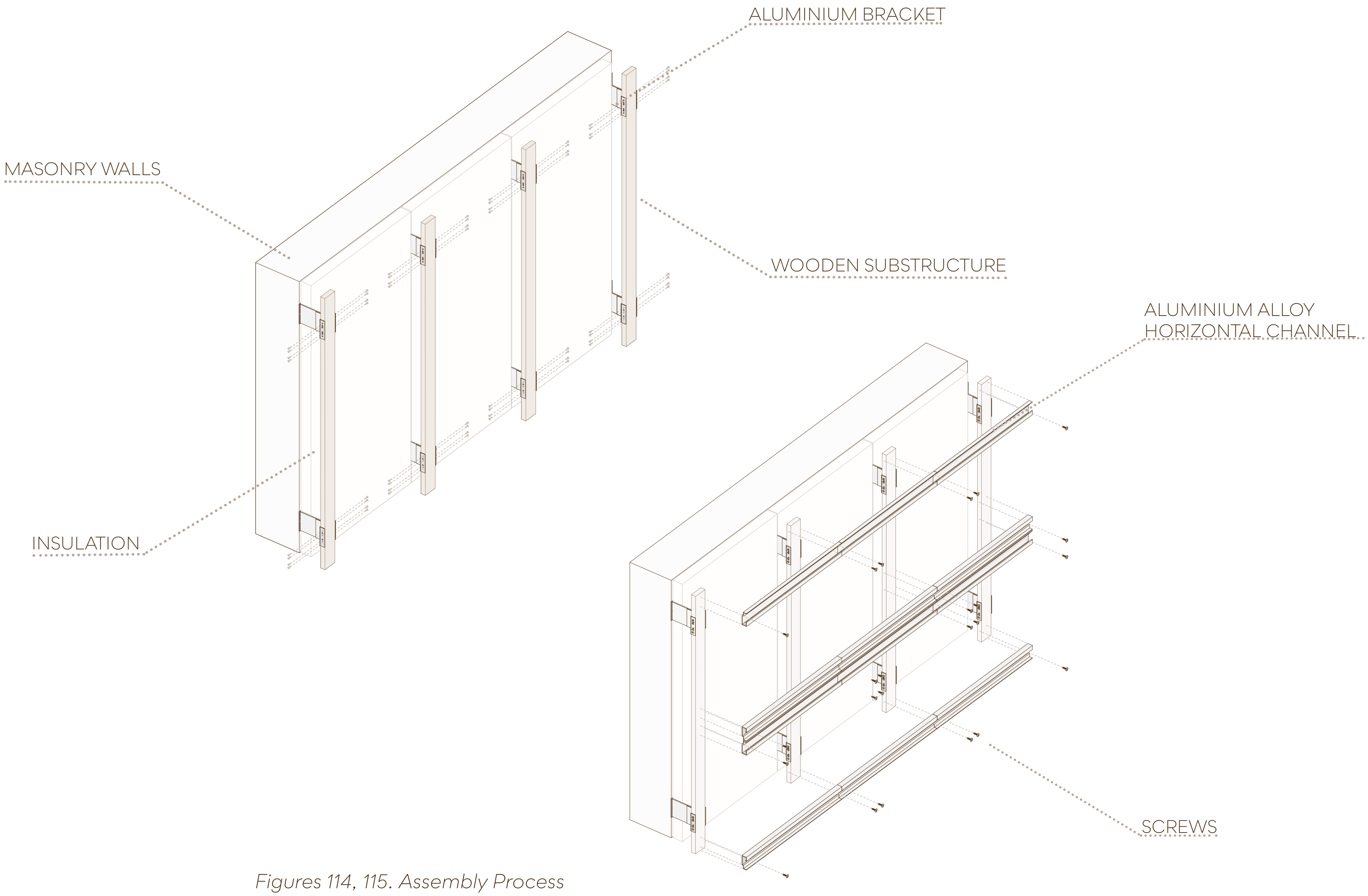


Figure 113. Final Six Panel Configuration
own ill.

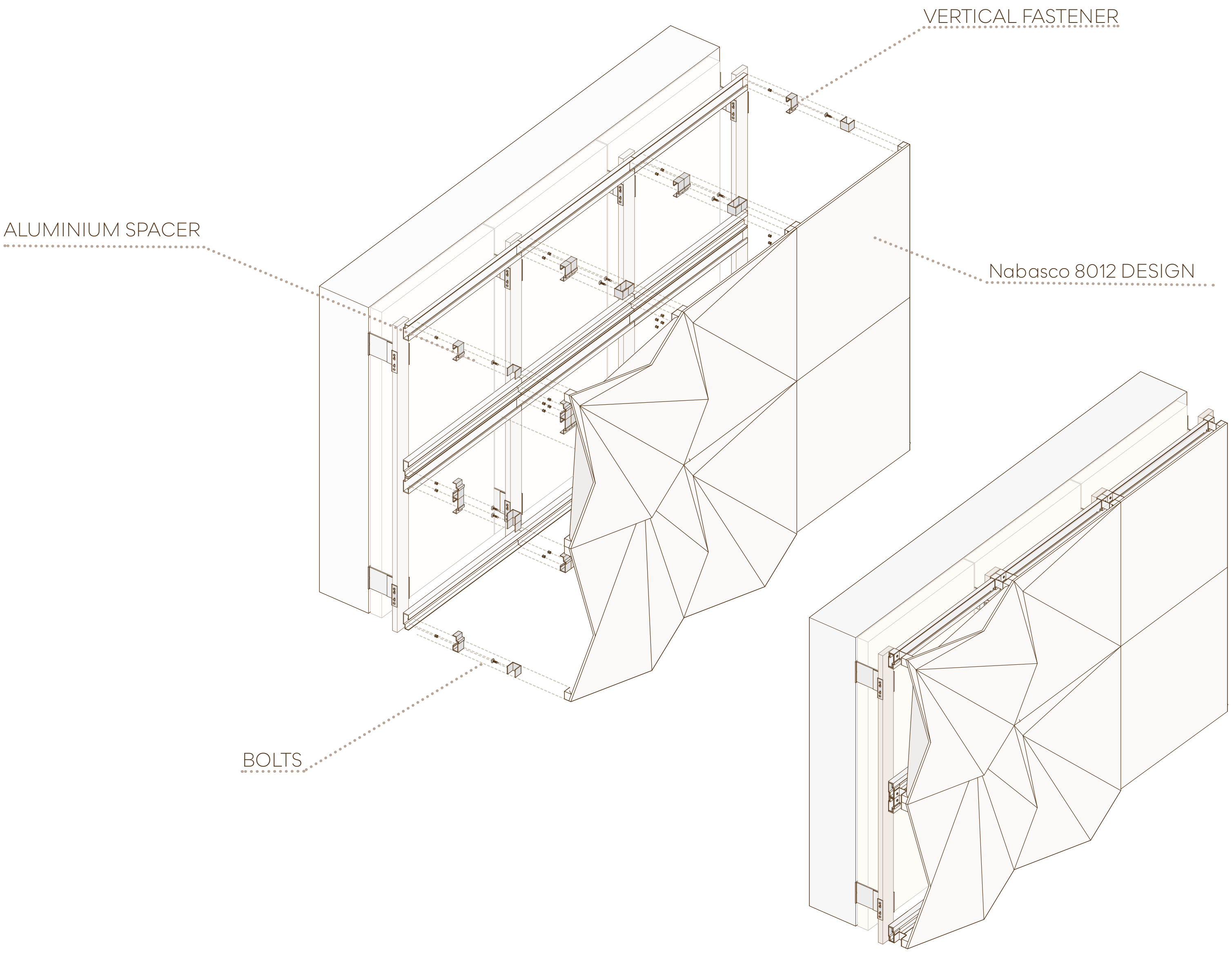
DESIGN FOR DISASSEMBLY

Besides their non-invasive impact on the production process, the selected connections also satisfy the criteria of easy assembly and disassembly - as shown in Figures 114 - 117; however, this does not provide the possibility of replacing just a single central panel at a time. This decision was intentionally made to align with the project's vision of being a system that can evolve and grow, rather than a fixed and final product. Therefore, not affecting the mould design has been prioritized compared to the single panel replacement.



Figures 114, 115. Assembly Process

Furthermore, the selected system permits to avoidance of interruptions to let the three-dimensionality freely spread throughout the whole façade. This consideration further influenced the decision-making process regarding the connections to be utilized

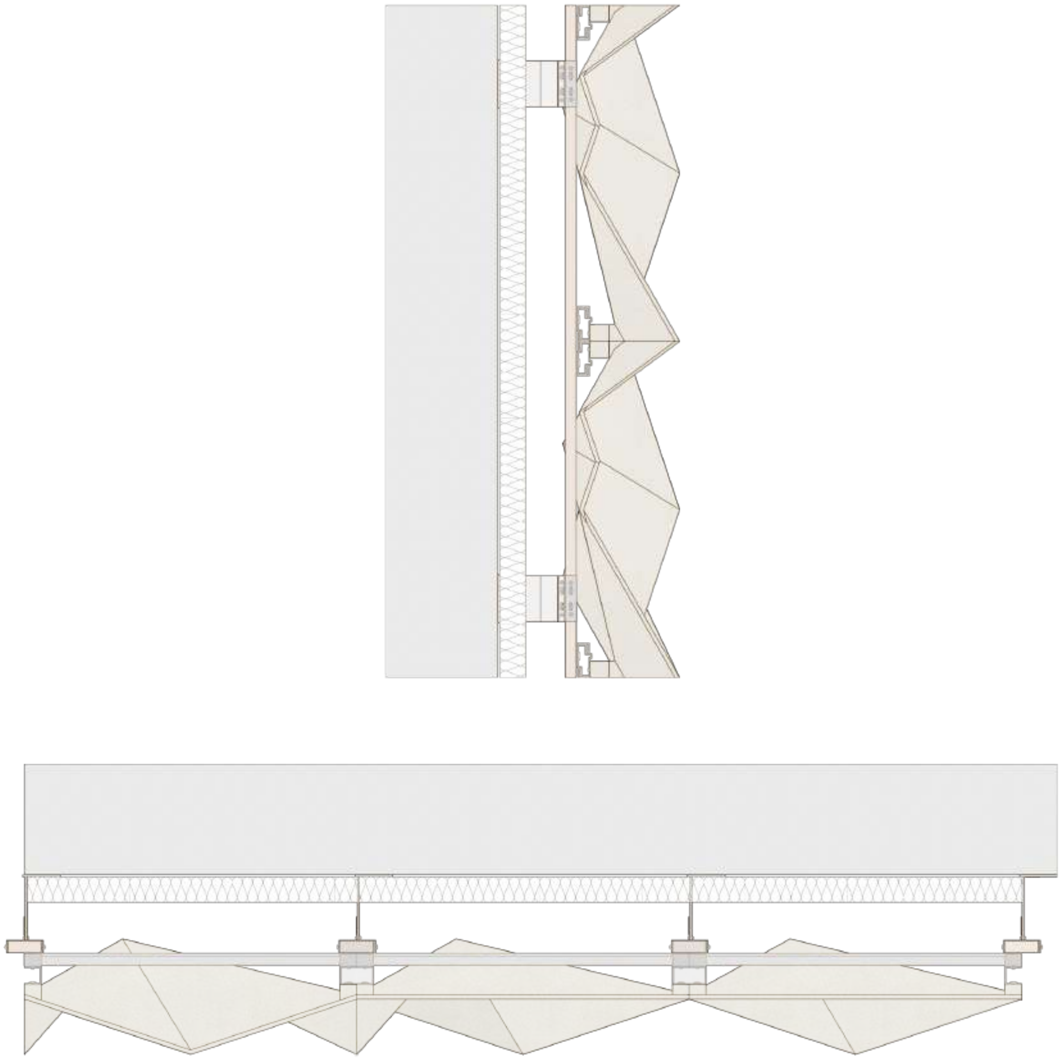


Figures 116, 117. Assembly Process

DETAILED SECTIONS

A comprehensive vertical and horizontal section provides a technical illustration of connections and panels. As previously mentioned, the four corner backside panels are attached to an aluminum spacer through screws and then secured with bolts to the vertical fastener. Including the aluminum, spacer is necessary to prevent any collision between the vertical fastener and the panel, as depicted in the top and bottom portions of the section.

Once all the components are securely connected, the entire element will be smoothly slid into the horizontal aluminum channel (Fig. 118,119).

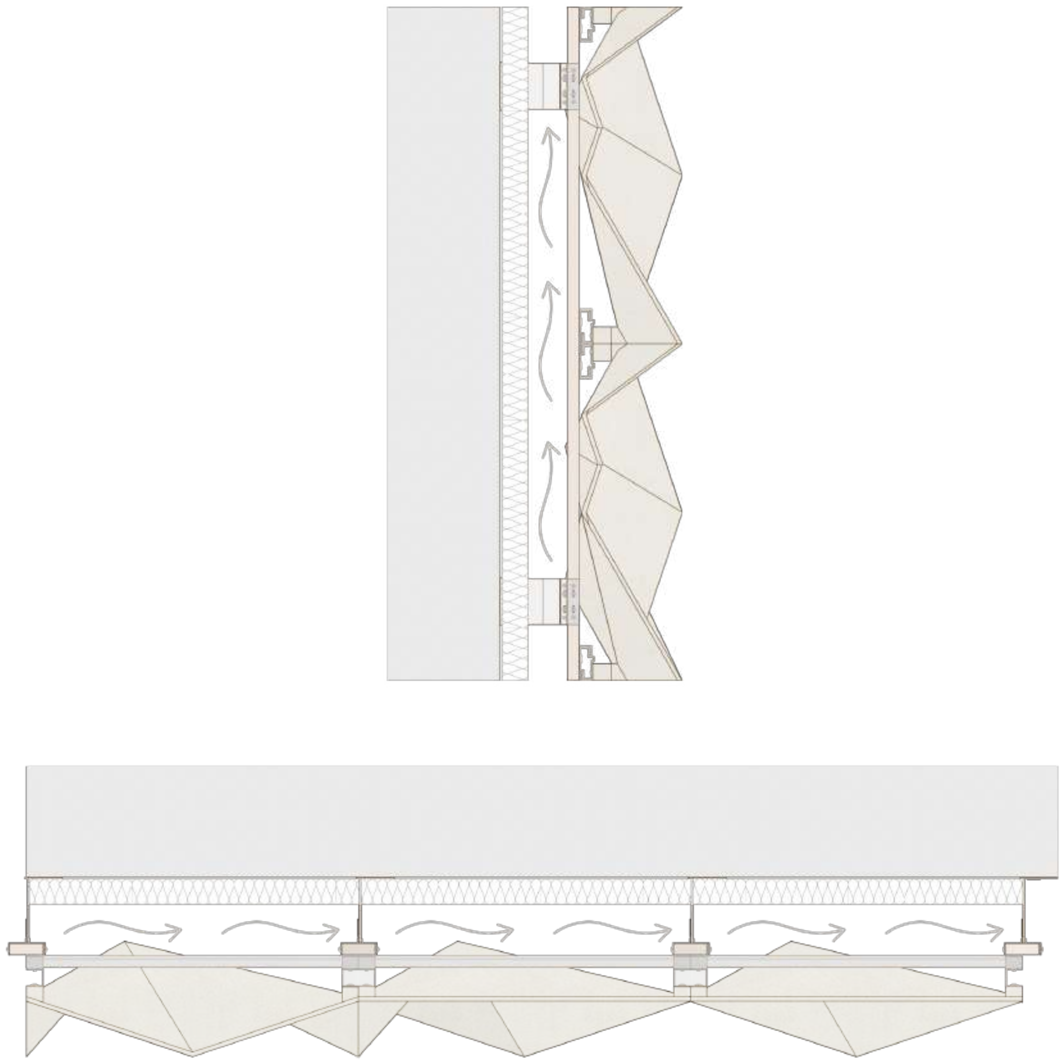


Figures 118, 119. Vertical and Horizontal Section own ill.

CLIMATE BENEFITS

Moreover, the arrangement of the three-dimensional panels, which extend inward from the façade, offers advantages from a climatic perspective. In order to avoid any collision between the façade and the underlying layers, the connection system requires a bracket with sufficient length to accommodate the panel.

This geometric constraint contributes to the creation of a ventilated façade, effectively preventing the transfer of heat and moisture from the exterior to the interior of the building. This beneficial feature is illustrated in Fig. 120 and 121.



Figures 120, 121. Vertical and Horizontal Section of a Ventilated Façade own ill.

MATERIAL

A final material has yet to be selected, but a series, which will be the Nabasco 80s. The Nabasco 80s are all composed of natural fibers, a resin, and a filler, usually calcite ($CACO_3$).

NPSP offers a diverse range of configurations for the Nabasco 80s, which are currently being researched and developed. Each configuration differs in terms of the type of fibers, resin, and fillers used, resulting in slightly varied mechanical properties and, more importantly, different environmental impacts.

For the purpose of analysis and comparison, one specific series will be considered, namely the Nabasco 8012. This choice was made because the other products are still in the developmental stage, requiring further information for a comprehensive comparison. Additionally, the selection of Nabasco 8012 was influenced by NPSP's collaboration with a factory capable of providing a substantial quantity of panels made from reed waste. Since the objective is to introduce a new product to the building market, a material was chosen that not only meets the necessary cladding requirements but also offers the potential for large-scale production.

Nabasco 8012 is comprised of reed fibers obtained from waste in roof constructions, a partly bio-polyester resin, and a calcite filler derived from waste produced by a drinking water company.

With the known fiber density and panel volume (1700 kg/m3 and 0.00288 m3, respectively) (Fig. A_4), it can be determined that each individual panel weighs approximately 4.76 kg.

As a result, it is evident that the assembly of these panels does not require specialized or heavy machinery, making the process faster and more sustainable.

MANUFACTURING

The manufacturing process will be the hot press process, in which the double-side moulds will be heated at 140°C and matched under 100 bar pressure for 35 minutes: the specification of the timing differs concerning the panel thickness, which is 8mm for all the sides, and 27mm more for the four-squared corner.

There is actual research on manufacturing the Nabasco 80s at 40 bars, drastically reducing the energy used: however, it has yet to be standardized; therefore, it will be neglected.

Given the laboratories-scaled types of machinery that NPSP provides, to cure 1mm of material 1 minute is needed: however, in case the product is standardized and manufactured in a factory, the curing time - and therefore the energy demand - will be less (41 sec per mm).

Furthermore, the double-sided moulds need to be made of a metal material since they need to, on the one hand, not deform or melt at high temperatures and, on the other hand, conduct heat for transmitting it to the bulk mounding compound.

As mentioned in Chapter 2, the usual mould materials for hot presses are steel and aluminium. Usually, aluminium moulds are mainly used for small-scale projects or prototypes since the cycles that these can handle are around 5000. In contrast, steel moulds - which are way more expensive and durable - are usually used for large-scale projects (Bottger, 2023).

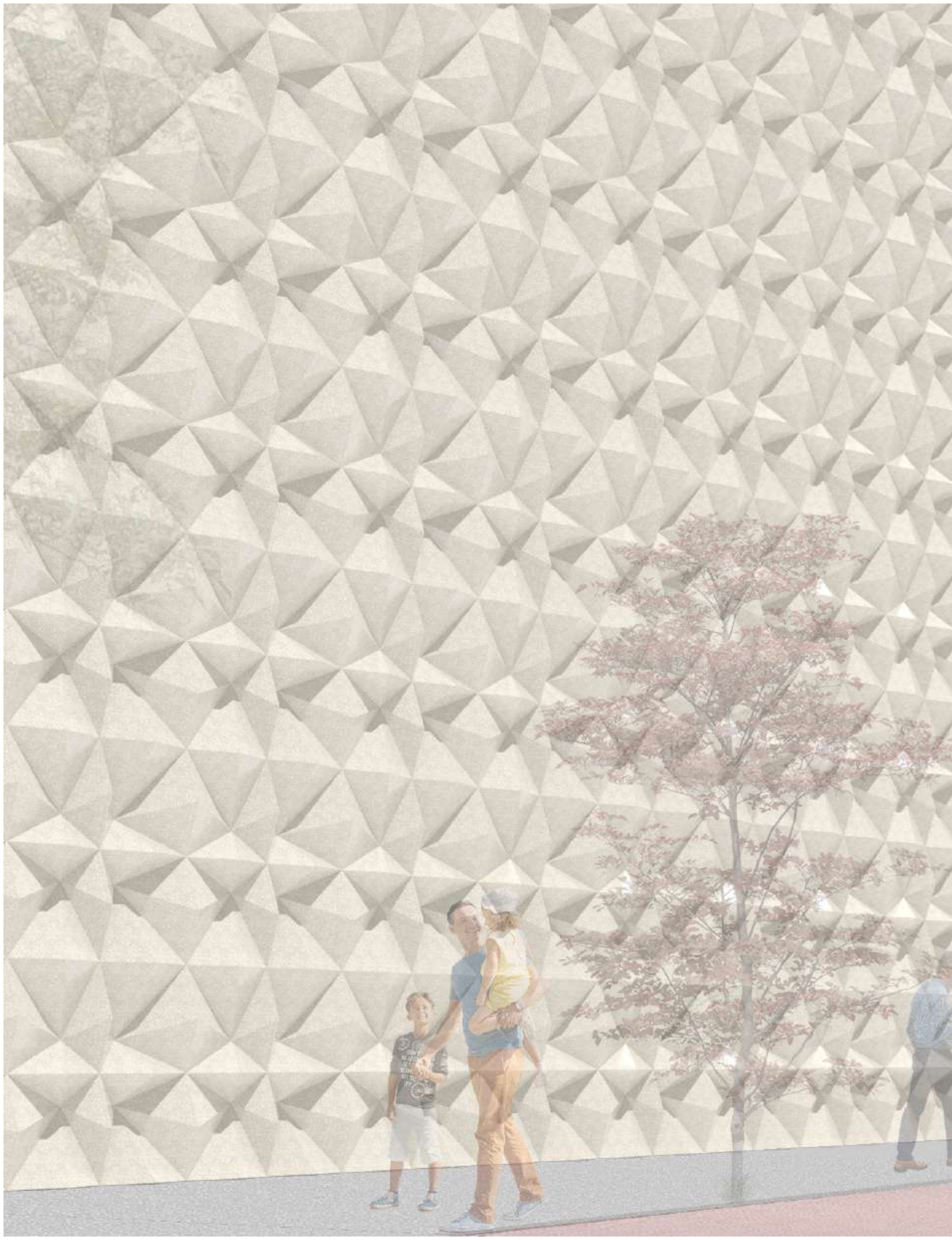
In the present scenario, the material selection was primarily based on the availability and cost offered by various companies. After thorough consideration and evaluation, it was decided that aluminium would be the most suitable material for the intended purpose.

CONCLUSION

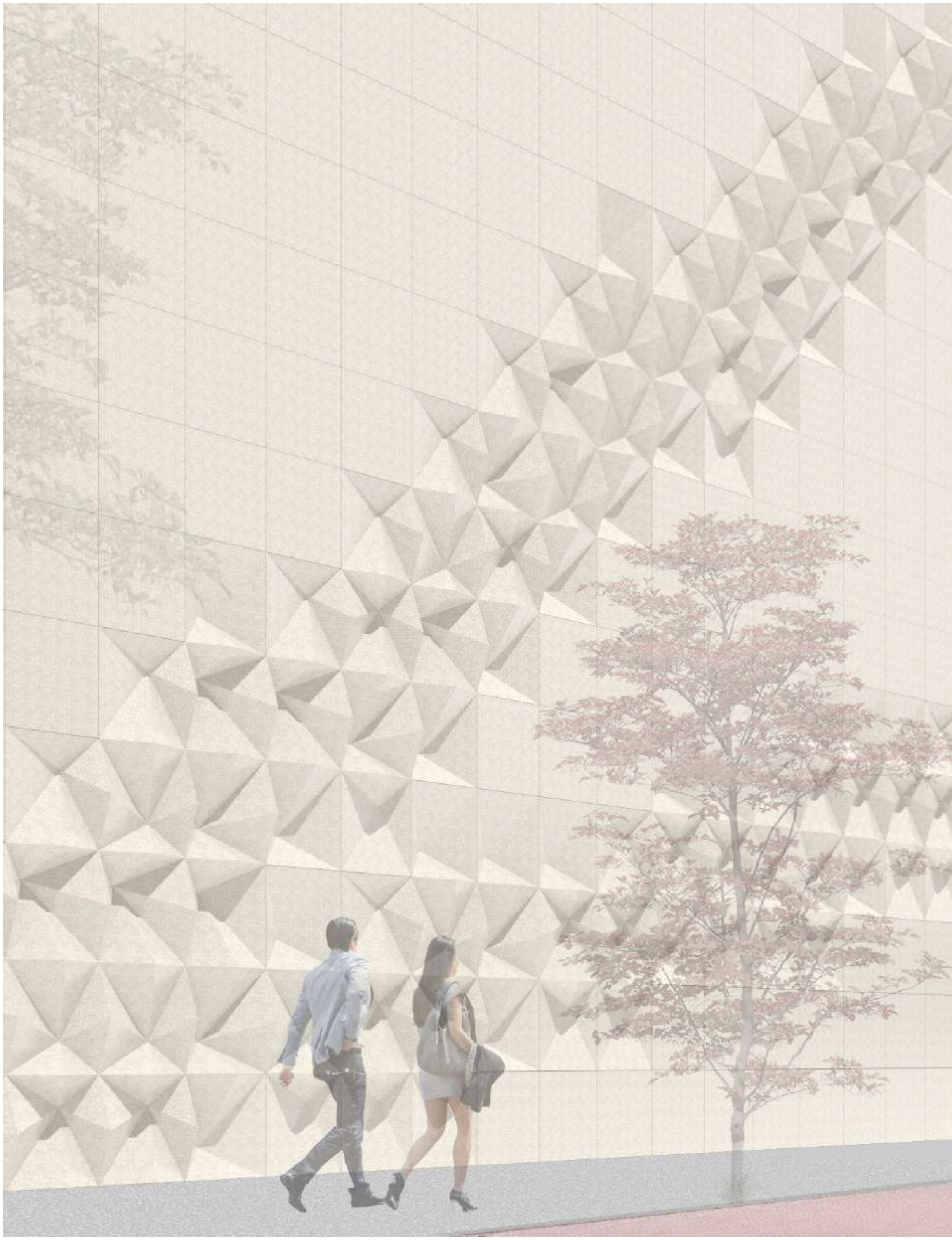
In summary, the proposed product is a 60cm x 60cm panel made of Nabasco 8012, created through the conceptual and computational design process.

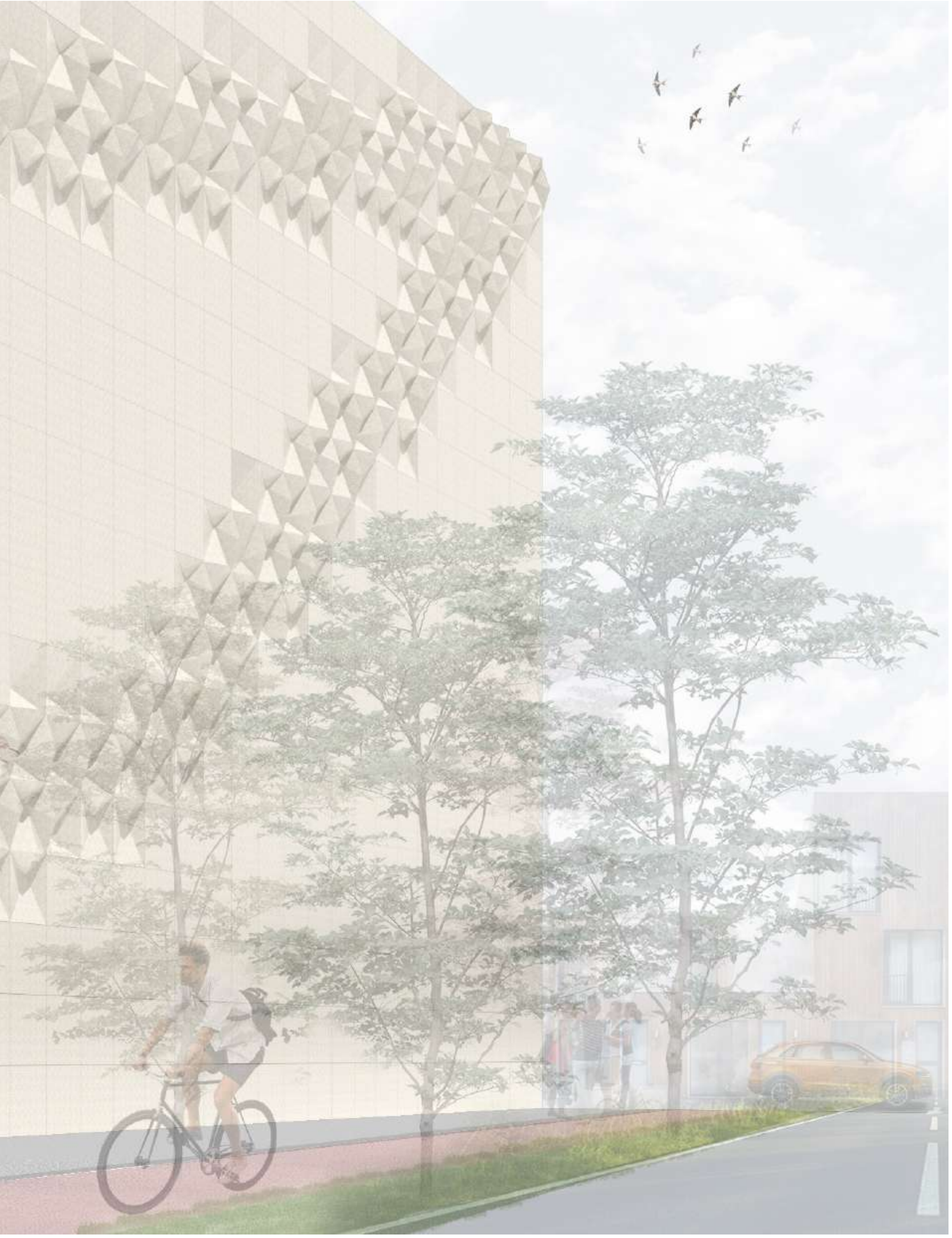
These hot-pressed panels utilize mostly waste materials such as reed fibers from the roof construction industry, partly bio-polyester resin, and calcite filler from drinking water company waste. The integration of these panels into the substructure is facilitated by thoughtful design and connection systems, offering a sustainable and efficient cladding solution with improved energy efficiency and ventilation.

The realistic visualizations of the final product is shown in the following three figures (Fig.122-124), showing how they rely on the computational configurations explained in Chapters 3 and 4.

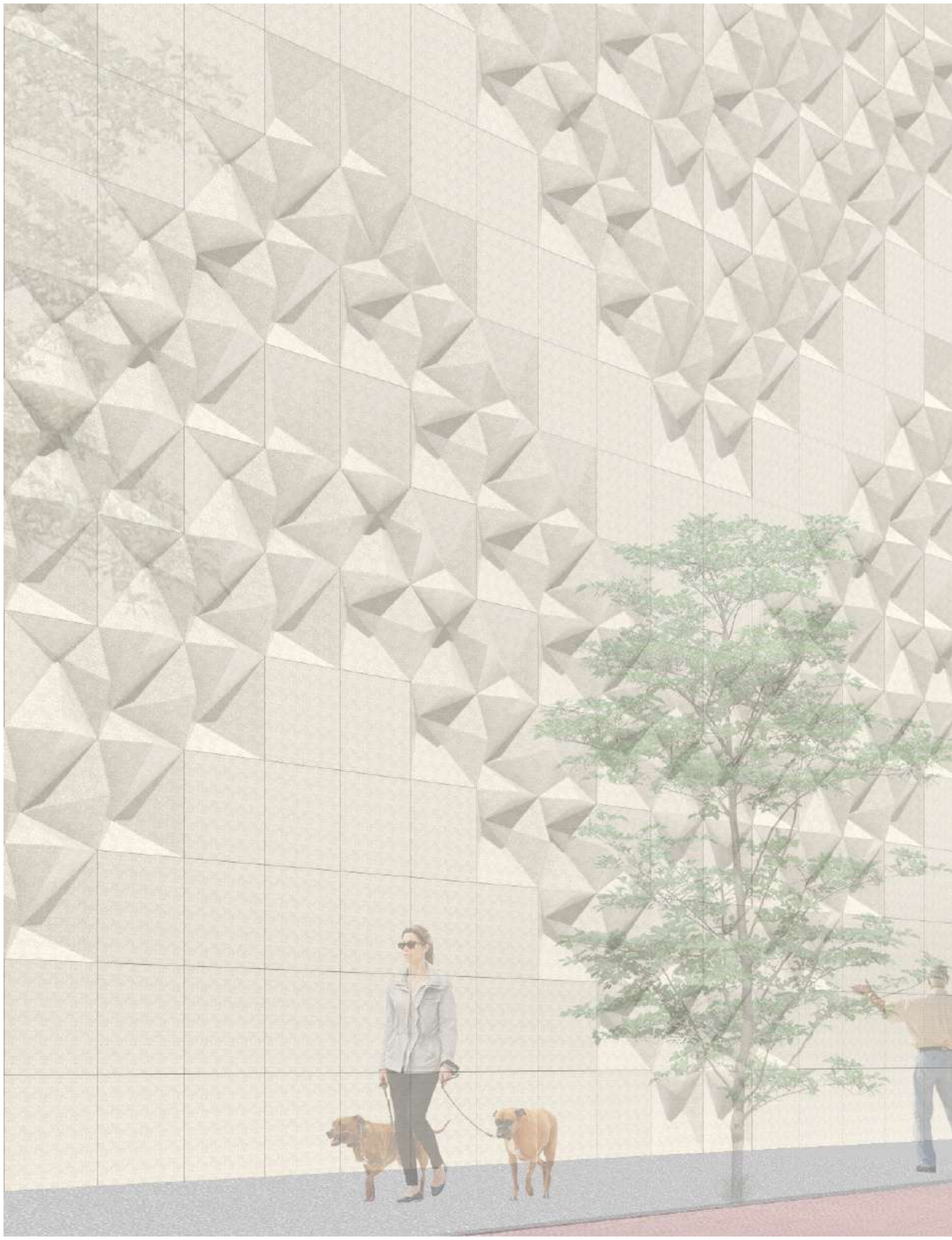


Figures 122. One-Panel configuration three-dimensional visualization own ill.





Figures 123. All-Panel Configuration₁ three-dimensional visualization own ill.



Figures 124. All-Panel Configuration$_2$ three-dimensional visualization own ill.

_6 PROTOTYPE

6.1_ PROTOTYPE ACKNOWLEDGEMENT

The final design will be prototyped.
The prototype will be realized in a scale 1.33, therefore realizing a panel of 20x20cm: this choice has been settled mainly for cost reasons.

The prototype will be realized thanks to a collaboration with Deltavorm for the mould realization, and with NPSP for the materials provision and hot pressing production.
The mould and panel realization will separately be explained and shown.

6.2_ MOULD PROTOTYPING PROCESS

The process of prototyping mould designs comprises several distinct stages that must be followed. The initial stage involves digital modeling, where modifications are made to the initial Rhino model in order to create a model suitable for pressing.

Once the final model has been established, CNC Programming becomes necessary. This step is essential because the ultimate model will be produced through CNC Machining. CNC programming involves the conversion of a 3D CAD model into a series of machine-readable instructions. These instructions specify which cutting tools to employ, the desired feed rate, and the precise tool movements required to fabricate the final component. In essence, CNC programming is the procedure of generating instructions for cutting tools (De Vries, 2023).

With the instructions in hand, the machining phase commences. Each component is milled individually to fabricate the various final components that will eventually be assembled together to have the final mould.

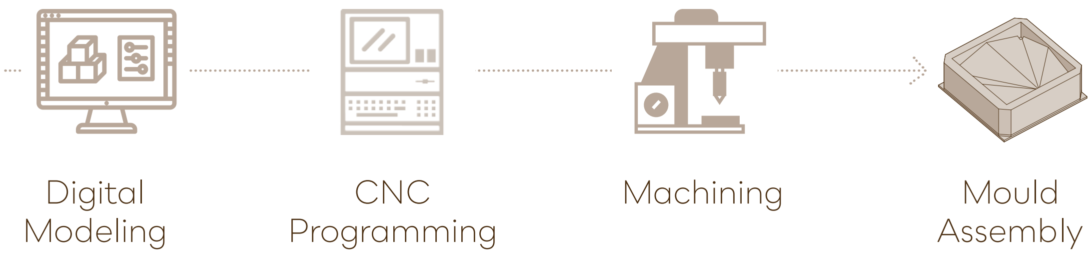


Figure 125. Moulding PrototypingProcess own ill.

MODELING

The process of mould design initiates with the scaling of the Rhino model to the specified dimensions. Once the accurate sizing is achieved, the finalized .step file is sent to Tjomme de Vries from Deltavorm, marking the commencement of the double-sided mould modeling.
For realizing the final model for both the mould and panel manufacturing processes, an iterative exchange of adjustments and advice took place between Deltavorm, myself, and NPSP.

Prior to commencing the modeling stage, Frank Bleeker from NPSP outlined several essential requirements that the final model needed to fulfill.
Firstly, to ensure efficient heat conduction and proper alignment, each opposing edge of the moulds was made flat, resulting in a configuration resembling a metal box when the moulds are joined together (Fig. 127). To ensure a precise fit, four guide pin locations were designed on the corners of the positive mould, corresponding to four holes on the negative mould for their proper placement.

Furthermore, a critical consideration in mould design is the incorporation of a draft angle. Both moulds have to be designed with a draft angle of 96° towards the openings, facilitating the smooth release of the panel. Insufficient draft angle could lead to the panel becoming stuck in the moulds, necessitating their destruction.
To achieve compatibility with the draft angle, the panel itself required modification. Figure 126 illustrate the initial design of the draft angle for the panel, which served as the basis for subsequent mould design. Additionally, the panel's perimeter was designed with rounded angles to accommodate the limitations of CNC milling, which struggles with accurately reproducing small sharp angles.

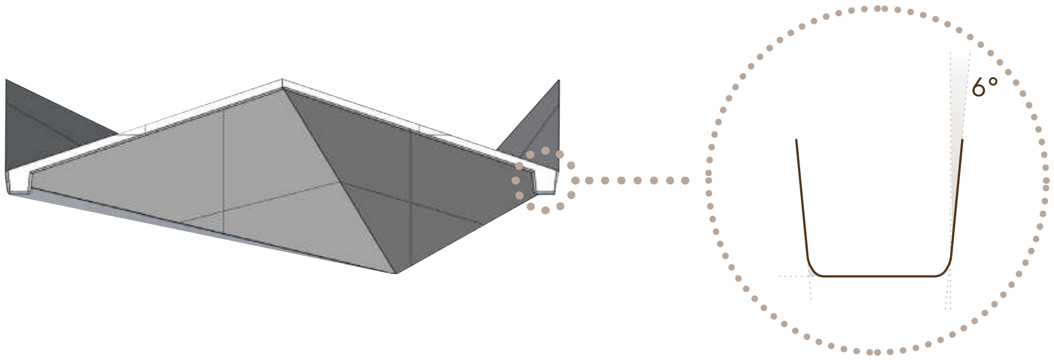
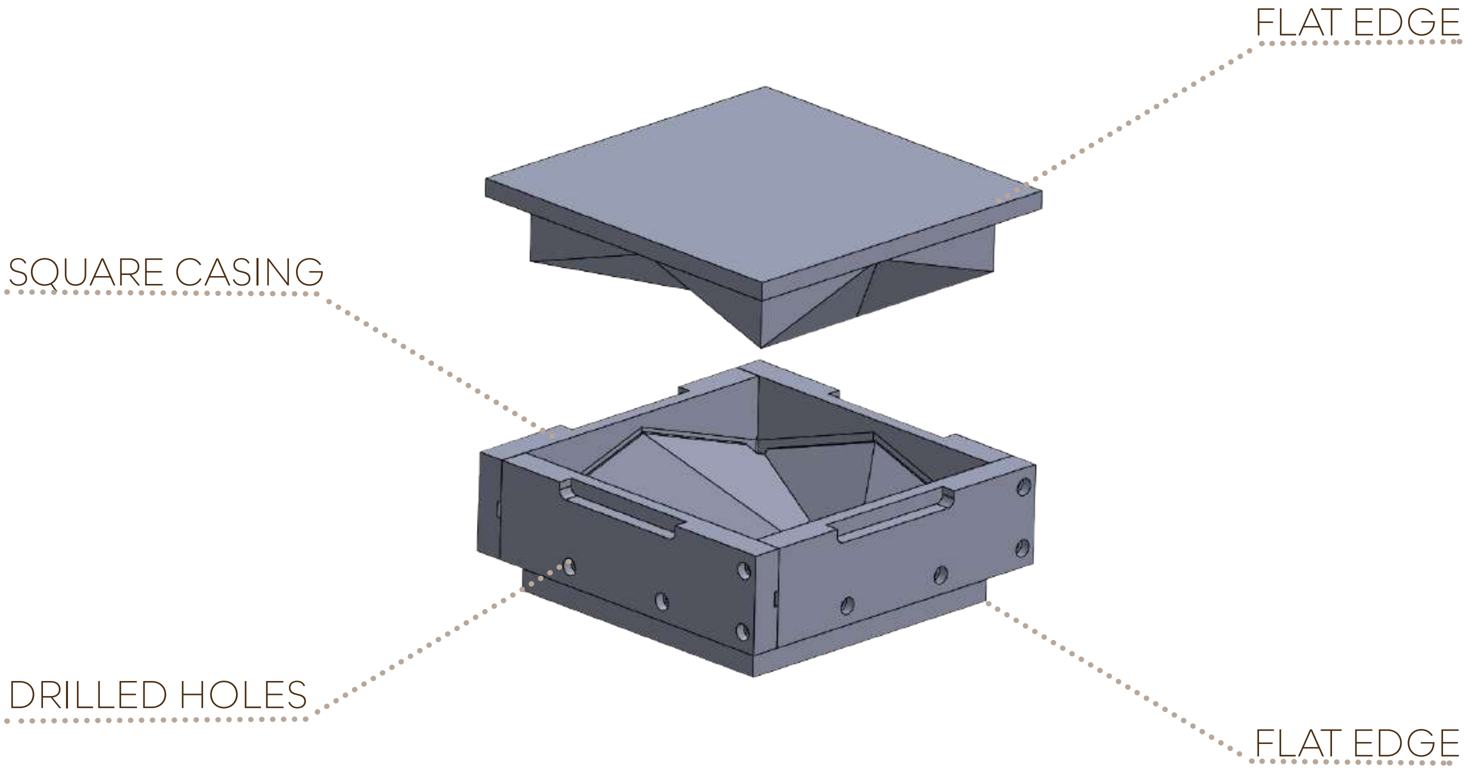


Figure 126. Panel draft angle visualization
own ill.

An additional modification made to the updated version of the mould design was the inclusion of an independent *square casing* surrounding the entire mould (Fig. 127). This addition served two purposes: expediting the process and preventing the material from flowing outside the mould, thereby ensuring proper compaction within the panel's shape. Hence, this supplementary element was incorporated into the composition of the mould avoiding the need of guide pins.

However, the introduction of this element resulted in an incorrect draft angle. The draft angle had been modeled solely on the bottom part of the bottom mould, without considering the design of the entire square casing. Consequently, the model required rectification. Unfortunately, Deltavorm lacked the necessary equipment for such modifications, and time was of the essence.

To address this challenge, Tjomme proposed the idea of employing a detachable square casing that could be unbolted when the panel needed to be released (Fig. 127). This solution struck the right balance and was chosen as a suitable compromise, considering the aforementioned considerations. With the model prepared, the subsequent step involved initiating CNC Programming.



Figures 127, Final mould model
Source: De Vries (2023)

PROGRAMMING

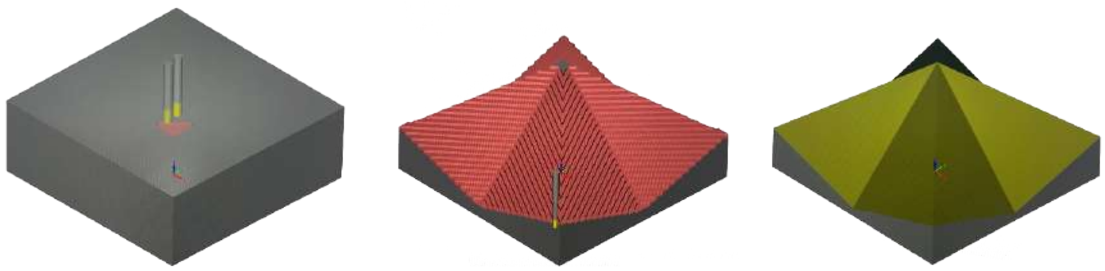
Prior to CNC programming, a thorough analysis of the final shape is conducted to identify the initial stages of shape formation from a solid block. Factors such as material thickness are carefully considered. In this particular case, the intended thickness for the bottom and top moulds was 85mm and 75mm, respectively. However, since Deltavorm did not provide components of these specific dimensions, plates were assembled together to achieve the desired thickness. Specifically, three elements measuring 25mm, 25mm, and 35mm were drilled and bolted together for the bottom mould (Fig. A7). Similarly, the top mould was composed of three 25mm plates.

Consequently, specific holes were designed within the mould to facilitate the connection between each plate (Fig. A7, A9, A10). Once the practical constraints were addressed, the solid aluminum volumes (Fig. 128) were successfully prepared, signifying that the programming phase could commence.

The programming process involved three main stages. The first stage encompassed *roughing*, where the block began to take shape, resulting in a crinkled appearance (Fig. 129). Subsequently, the model underwent the *first finishing* phase, where the roughed surface was smoothed using a spherical Ø4 mm tool, with the process being carried out in increments of 0.2mm.

To achieve a clear and flat panel (Fig. 130), the *second finishing* phase was implemented. This phase involved the use of a smaller spherical tool (Fig. A13) to address the finishing of inner corners.

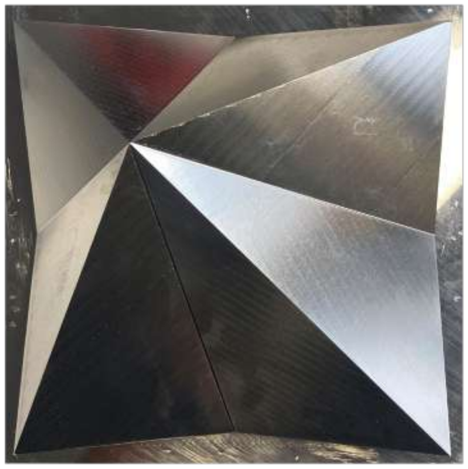
With the completion of CNC programming, the machining process was ready to commence.



Figures 128, 129. 130. CNC Programming Processes
Source: De Vries (2023)

MACHINING

Following the successful completion of CNC programming, the next step involves the machining and realization of the mould components, which includes the bottom and top moulds, as well as the square casing. These components will undergo the three aforementioned stages: roughing (Fig. 131), first finishing, and second finishing (Fig.132).



Figures 131, 132. Top Mould Roughing and Finishing Stages
Source: De Vries (2023)

However, an unforeseen inconvenience occurred during the placement of the plates for the bottom mould. One of the plates was inadvertently twisted by 90°, resulting in a milling mishap where a section was inadvertently milled and a drilling hole was created. To rectify this mistake, the drilled holes were welded using stainless steel material (Fig. A8). Consequently, the affected area of the back panel may exhibit slight imperfections, but it will still be viable for the moulding process. Fortunately, this imperfection does not have any significant impact on the final appearance of the panel, as it pertains solely to the back-side panel.

With the completion of the necessary adjustments, the components are now prepared for assembly and ready to be utilized for pressing at NPSP (Fig. 133 and 134).

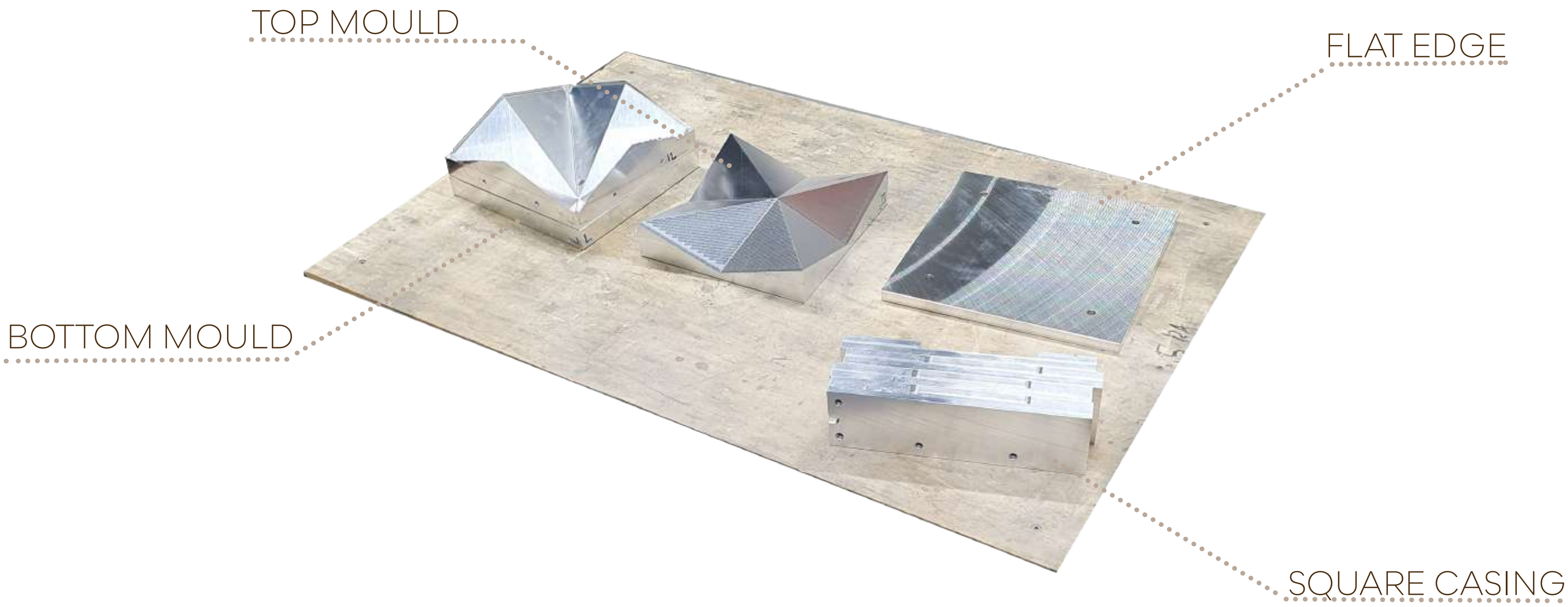


Figure 133. Mould Components
Source: De Vries (2023)

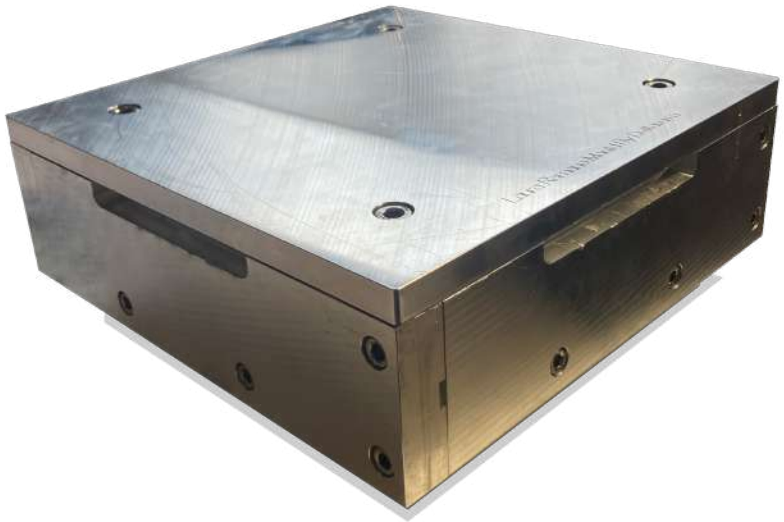


Figure 134. Assembled Mould

6.3_ PANEL PROTOTYPING PROCESS

The panel prototyping process consists of several sequential steps that are essential for its successful completion.

To begin with, NPSP initiates the process by mixing reed fibers, polyester resin, and calcite filler to create the final material. In this prototyping process, reed fibers repurposed from the roof construction industry are utilized in one material, while pigmented virgin reed fibers are employed for another. Consequently, the realization of the four panels will be composed of two slightly distinct materials (Fig. 138).

Once the material mixture is prepared, the mould is delivered to NPSP, marking the commencement of the process (Fig. 135). Following comprehensive instructions and adhering to safety precautions provided by NPSP, the mould undergoes a thorough cleaning using a chemlease mould cleaner. This step eliminates any dark particles that may have accumulated on the mould surface.

With the completion of the cleaning phase, a three-layering procedure begins, involving the application of Chemlease sealer with alternating 20-minute drying intervals. The sealer plays a crucial role in filling small material particles and preventing the formation of minute cavities.

Subsequently, the mould surfaces are coated with a releaser three times, each time followed by a 15-minute drying period. This component facilitates the subsequent release of the final panel from the mould.

Furthermore, upon the completion of the pre-settlement process (A18), the mould is gradually heated. During this heating process, the bottom mould is maintained at a temperature 10 degrees higher than the top mould (155°C and 145°C). It is essential to maintain a temperature difference

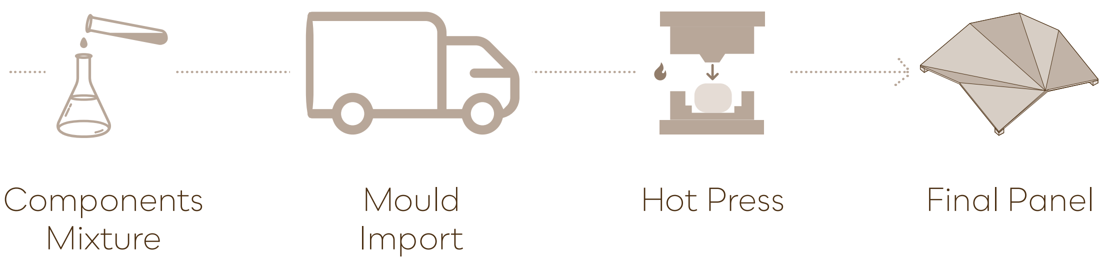


Figure 135. Panel Prototyping Process own ill.

between the two mould components to facilitate efficient heat transfer. While a temperature difference of approximately 5 degrees is typically adequate, in this case, considering that the aluminum slightly expands when heated and the absence of significant draft angles in the bottom moulds, Mark Lepelaar decided to increase the temperature difference by an additional 5 degrees. This allows for more expansion during the heating process, providing ample space for the panel to be released.

Meanwhile, while waiting for the moulds to heat up, the bulk moulding compound is rolled and shaped into a flat and uniform dough-like consistency (Fig. A20). To further enhance the panel's release, the dough is coated with a powder of bio-based wax fat. When the moulds reach the desired temperature, the temperature of the top mould has been slightly increased (159°C), while the one of the bottom mould has been decreased (143°C). This process has been done for let the top mould expands, and facilitating even more the release of the panel.

When the temperature has been stabilized, the just mentioned powder is also applied to both moulds. Finally, the prepared dough is placed within the mould, and the pressing process commences (Fig. 136).

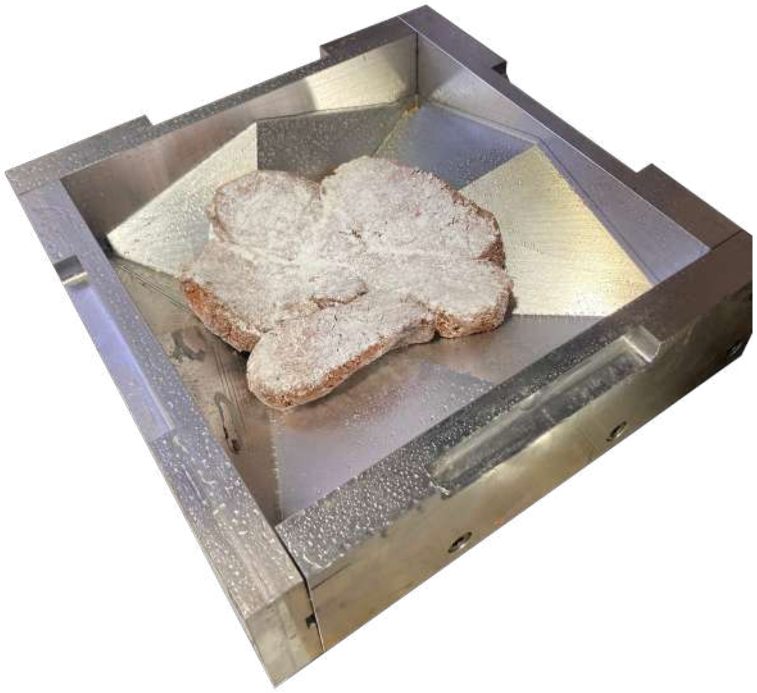


Figure 136. Dough within the Bottom Mould

The pressing process is carried out for a duration of 6 minutes, after which the release phase (A21) follows.
Once the pressing is completed, the hot mould is carefully placed on a flat surface, and the disassembly process begins. By removing the square casing bolts, the top mould can be detached.

However, it was observed that the mould still had some residual adhesion. To address this, caution was exercised, and small sticks were strategically placed at the edges where the panel was not stuck. Gradually and delicately, the panel was detached from the mould. Subsequently, the panel was placed within a frame to facilitate the cooling process (A22).

A total of four panels were prototyped, with half of them composed of repurposed reed fibers and the other half consisting of pigmented fibers. The mechanical properties of the panels are identical, although there is a slight variation in color: the pigmented panels exhibit a brighter red hue, while the other material presents eventually black spots due to the aluminium mould dark particles release. (Fig. 140).

The first and last prototypes encountered some issues due to a leakage within the mould, which caused the dough to seep out. As a result, there was insufficient dough during the pressing process. In the first prototype, the corners could not be adequately formed (A23, A24, A25), while in the last prototype, cracks appeared, and one of the corners detached.

On the other hand, the second and third prototypes were successfully produced using pigmented reed and repurposed reed materials, respectively (Fig. 137, 138, 139). When the prototypes are aligned and rotated together, it is evident that the edges match seamlessly (Fig. 138).

However, In the aftermath of producing these four prototypes, it became evident that the mould had sustained some damage due to the applied heat and pressure. Specifically, one of the bolts used in the pressing process bent under the immense pressure. Additionally, the sides of the mould, where the aluminum thickness was only 1mm, exhibited slight deformation, resulting in some minor damage to the final products.

These observations emphasize the importance of avoiding excessively thin sections in the aluminum mould design to prevent such issues from occurring in the future.

Figures 137 and 138. Final Prototyped Panel

Figure139. Four Panel Configuration

6.4_ CONCLUSION

In conclusion, the prototyping process undertaken by both companies involved a significant absorption of knowledge, particularly in the manufacturing of the aluminum mould and the subsequent production of the panel. The intricate steps involved in this process added complexity to the prototype development, necessitating meticulous attention to detail and precision to meet the specified requirements.

The prototyping journey revealed the paramount importance of each step, from the careful analysis of the shape formation to the programming of CNC machines, assembly of mould components, and the pressing process itself. These steps required expertise and meticulous execution to address challenges such as the accidental twisting of plates, welding of holes, cleaning and layering of the mould, and managing temperature differentials during heating.

The resulting prototype showcases the remarkable potential of the chosen material. By successfully fulfilling the sharp design requirements, and the learnt technical details from the prototyping process, the prototype demonstrates that a more circular material, such as the Nabasco bio-composite used, has the capability to serve as a viable substitute for traditional materials like metals and concrete. This highlights the shift from mere assumptions to tangible evidence, indicating the material's potential for wider applications in various industries.

The success of this prototyping process reinforces the importance of precise execution and attention to detail in material selection, mould design, and manufacturing techniques.

_7 CONCLUSION

7.1_ RESEARCH QUESTIONS

The aim of this research is to explore the possibilities of developing a design system that enables the creation of complex designs in the construction industry. This system will prioritize three-dimensionality while upholding circular principles and strategies.

In conclusion, the study aims to provide a comprehensive understanding of the system by addressing the research question through the examination of sub-questions and obtaining a holistic perspective to answer the main question.

"What is the relevance of three-dimensionality in external claddings?

In general, incorporating three-dimensionality in external cladding offers numerous benefits to a project. As demonstrated in Chapter 2.1, the versatility of three-dimensionality allows for the attainment of various performance goals, including thermal efficiency, acoustic enhancement, shading capabilities, and structural integrity.

The examples presented in the chapter provide a glimpse of how three-dimensionality can enhance external cladding. They were a guideline for developing my concept of three-dimensionality and its role in my design.

While the research and subsequent design exploration of three-dimensionality extend beyond performance aspects, it does not disregard their importance. The primary focus lies in testing new materials and their mechanical properties through research by design. This is why the realized three-dimensionality is that sharp: to convince and demonstrate to be a valid alternative present alternative options to conventional metals and cement, aligning with a more circular approach.

Furthermore, the three-dimensionality is also relevant for achieving geometrical versatility within the facade. The thesis showcased different configurations and applications of three-dimensionality, ranging from modular and repetitive cladding to the reassembly of macro-geometries.

The exploration of geometry encompasses not only the three-dimensional aspect but also delves into understanding how three-dimensionality can be achieved and dissolved harmoniously.

Hence, in this research, three-dimensionality offers a means of expression, flexibility combined with modularity, and serves as a tool to showcase the research results.

“How does circularity affects the final product realization?

Chapter 2.2 provided a comprehensive list and explanation of circular design strategies, which served as the foundation for the subsequent design process.

Throughout the conceptual design phase, careful consideration was given to these strategies to guide the final realization. As a result, specific strategies were selected and incorporated into the overall design, encompassing rules, constraints, and the design concept itself.

Modularity and flexibility emerged as the primary strategy, leading to the introduction of the seamless tiling concept. The final design consists of six modular panels designed to be flexible and easily placed anywhere within the facade. This modularity allows for customized assembly while adhering to the geometric constraints outlined in Chapter 3.3.

Furthermore, the emphasis on safe and circular choices played a significant role in the research from the outset. Consequently, a bio-based material was chosen, although its properties did not directly impact the final product realization.

Additionally, dematerialization was another key strategy considered, integrating circular principles into the design process. Therefore, considering that the moulding has been selected, the design has been realized in such a way to minimize material use by producing only six panels, minimizing therefore, material, energy and waste of further moulds.

Lastly, the design for disassembly strategy was taken into account. To facilitate easy assembly and disassembly of the panels while retaining the desired flexibility, the backside of the final product was slightly modified. Square moulding elements were incorporated into the four-corner backside panels, allowing for seamless assembly-disassembly and rotational placement, as discussed in Chapter 5.1.

In summary, the circular design strategies listed in Chapter 2.2 guided the design process, contributing to the development of a more sustainable and adaptable design solution.

"What are the available bio-based materials that can be used for external cladding?"

There are plenty of bio-based materials: starting from the well-known wooden types to more innovative ones such as bio-plastics and bio-composites.
As mentioned in chapter 2.4, the main experimenting focus was the design while the materiality has been conceived as the tool for the realization, therefore, certified bio-based materials have been selected for the analysis.

Several criteria were considered when choosing which materials to compare. First and foremost, their suitability for three-dimensional cladding was crucial. The aim was to demonstrate that three-dimensionality can be achieved using sustainable materials like bio-based options.

Another important factor was the reusability of waste streams, considering the construction industry's significant waste generation. The ability of a material to be treated in a manner that extends its lifespan and aligns with the principles of the R-s-strategies was also taken into account.

Water and fire resistance were additional criteria, as the panels needed to meet the regulatory requirements for external cladding.

Lastly, proximity to the companies supplying the materials was considered, as it facilitated information gathering, testing, and prototyping of the material within the developed design.

Based on these criteria, a list of certified bio-based materials was compiled for comparison. This included various Nabasco materials such as Nabasco50s, Nabasco80s, and Nabasco100s. The Resysta material was also considered, along with more experimental options like Re-Plex and PHBV Fabulous.

"What are the relevant moulding processes for such bio-based materials?"

Moulding processes play a significant role in shaping materials, wherein a substance in the form of a fluid, liquid, or powder is moulded using a rigid frame called a mould and subsequently solidified. These processes offer a wide range of flexibility and variety since the mould dictates the final form.

Among the numerous moulding processes available, several commonly used ones include cast moulding, injection moulding, hot pressing, thermoforming, vacuum infusion, and rotational moulding. While these processes fall within distinct categories, subtle variations exist. For instance, thermoplastic rotational moulding and centrifugation thermoset plastic involve rotation but differ in terms of material state and process characteristics.

Within the bio-based material selection outlined in Chapter 2.4, various moulding processes have been employed, including hot pressing, thermoforming, and vacuum infusion. Hot pressing involves the use of preheated double-sided moulds, which subject the material to high temperatures and pressures, resulting in a highly flexible and versatile process. Hot pressing has been utilized for the production of Nabasco80s, Nabasco100s, Re-Plex, and PHBV Fabulous.

Thermoforming, on the other hand, is a technique that employs heat to mould bio-plastics from sheets or films under pressure or vacuum. This process has been utilized for the production of Resysta.

Lastly, vacuum forming is a similar process to thermoforming, but it does not involve the application of heat. It primarily creates sheets or films under pressure or vacuum. Vacuum forming also offers a degree of flexibility in realizing complex shapes. Nabasco50s has been moulded using this method.

By employing these moulding processes, the desired forms and properties of the bio-based materials have been achieved in the research.

"How can external ***three-dimensional*** *cladding be realized using* ***circular strategies****,* ***bio-based materials*** *and being manufactured with* ***moulding****?"*

The realization of external three-dimensional cladding using circular strategies, bio-based materials, and moulding involves a systematic approach that combines various design strategies and manufacturing techniques. By following these principles, it is possible to create such an external three-dimensional cladding with alternative materiality.

Incorporating circular design strategies is fundamental to the process.

Strategies such as modularity and flexibility, dematerialization, safe and circular materials, and design for disassembly shape the overall design concept. These strategies ensure that the cladding system is adaptable, minimizes resource consumption, utilizes sustainable materials, and enables easy disassembly for potential reuse or recycling.

The choice of a bio-based material is crucial for realizing the desired three-dimensional shape, still respecting one of the just mentioned stratgies. The selected material is Nabasco 8012, which is composed of reed fibers taken from the roof construction waste, a bio-polyester resin, and a calcite filler taken from the drinking water companies waste. This bio-based composition aligns with circular principles by utilizing waste resources and giving a new life to it. Nabasco 8012 provides the necessary flexibility and structural integrity required for complex three-dimensional forms.

To manufacture the cladding panels, moulding techniques, specifically hot pressing, are employed. Hot pressing involves using double-sided moulds that have been preheated to shape the material under high temperature and pressure. This technique allows for the creation of intricate three-dimensional shapes, while also optimizing material usage and minimizing waste. The moulding process further supports the circular principles by enabling efficient production and reducing the environmental impact associated with conventional manufacturing methods.

By combining circular design strategies, the utilization of bio-based material Nabasco 8012, and the application of moulding techniques, it becomes possible to realize external three-dimensional cladding that is both geometrically flexible and environmentally more sustainable. This approach demonstrates a holistic integration of design, materiality, and manufacturing, highlighting the potential for innovative and sustainable solutions in the field of architecture and construction.

7.2_ DESIGN QUESTIONS

Given the answers to all the research questions, to have a whole idea of the design process, the design and sub-design questions will be answered.

"Which will be the design variables that allow flexibility in different façade configurations?"

The design variables discussed in Chapter 4.1 offer significant flexibility in the panel design, enabling the creation of diverse and adaptable cladding configurations. These variables include the panel size, edge division, panel thickness, and the location of the focal point in both two and three dimensions.
The panel size parameter allows for customization and scalability, accommodating different project requirements and aesthetic preferences. By adjusting the size, the cladding system can be tailored to fit specific architectural contexts.

The edge division variable offers a range of possibilities for achieving various levels of intricacy in the three-dimensional form of the panels. This flexibility allows for the creation of visually dynamic and captivating facades. Panel thickness is another design variable that influences the overall appearance and structural performance of the cladding system. By varying the thickness, the design can optimize the balance between aesthetics and functionality, considering factors such as material strength and weight.

Furthermore, the location of the focal point, both in two and three dimensions, adds another layer of flexibility to the system. This parameter allows for emphasizing or softening the panel extrusion, enhancing visual interest and potential performance solutions.
By combining these design variables, the façade configurations can be tailored to meet specific project requirements and design intentions, resulting in a highly flexible and versatile cladding system.

"What are the limitations and opportunities of the final product?"

The final product offers significant opportunities due to its design flexibility. The system can effectively represent a given macro-geometry, allowing for various design possibilities. However, reproducing more organic shapes precisely poses challenges due to the sharp panel geometry. Another opportunity lies in achieving varying degrees of smoothness or sharpness in the configurations by adjusting the design variables as desired. This flexibility extends to the representation of geometry and the relationship between three-dimensional and two-dimensional elements.

Furthermore, it is essential to note that there are limitations when considering the Nabasco 8012 material and the use of NPSP machinery. One such limitation is the maximum size constraint, currently 60cm. However, once the cladding product enters the construction market, manufacturing factories could produce larger sizes, expanding the possibilities in scale.

These opportunities highlight the adaptability and potential for customization offered by the flexible design of the cladding system. While there are some limitations, the system presents a versatile solution that can be tailored to meet various design requirements and accommodate different architectural contexts.

*“How can the external three-dimensional cladding be **parametrically** designed to **minimize** the number of **modular** moulds while allowing **flexibility** in diverse façade configurations?”*

To minimize the number of modular moulds while allowing flexibility in diverse façade configurations, the seamless tiling concept has been introduced. Seamless tiling enables the creation of a flexible system where the panel configurations can be adjusted parametrically to achieve various three-dimensional and bi-dimensional forms.

This approach maintains pattern continuity while using a limited number of six panels. By carefully arranging and shifting the panel configurations, diverse façade designs can be achieved, considering both the geometry to represent and the shift between three-dimensional and bi-dimensional configurations.

The advantage of this approach is that it offers flexibility in the overall design while minimizing the number of modular moulds required. Utilizing only six panels allows for a more efficient manufacturing process and reduces material waste.

The seamless tiling technique ensures the panels connect easily, creating a cohesive and visually appealing façade. This approach provides design flexibility and maintains a consistent pattern throughout the cladding system.

Overall, by incorporating parametric design principles and seamless tiling, the external three-dimensional cladding can be designed with minimum modular moulds while offering flexibility in diverse façade configurations.

_8 REFLECTION

8.1_ GRADUATION PROCESS

This thesis aims to explore and provide a new three-dimensional design system that takes care of innovation while respecting and enhancing circular strategies.

This research started by following a case studies observation of three-dimensional claddings and their usually used materials.
From this observation, the goal was to understand the actual environmental impact of realizing such designs and the possible beneficial impact that the thesis could have on the building market.

Following the information obtained regarding the impact that usual materials used for three-dimensional cladding are causing on the environment, the analysis of how to create a more circular option began. Therefore, the thesis principle is innovation through design and materiality.

As the first step for the design concept, an attempt has been made to analyze three-dimensional case studies that start from a bio-based material to compose the design. However, results have yet to appear. In fact, from the personal experience absorbed with the literature research, either performative designs or circular experimental materials are usually developed. Consequently, finding references to understand the proper method of approach has been complicated.
Nevertheless, this shows the innovation in considering design, materials, and manufacturing process simultaneously with a circular point of view.

In realizing this thesis, a method was implemented that combined two simultaneous kinds of research: on one side, the research by design, and on the other, the material understanding. This method has been slightly changed from the usual correlation between research by design and experimentation since, given the timing of a master thesis and the initially set objectives - which were developing both design and material- there was no possibility of concluding in time.

Consequently, the aim moved to configure the design by looking for a material already certified in the building market that could reflect the given requirements, explained in Chapter 2.4.
The research-by-design approach and the theoretical understanding of potential materials and manufacturing processes have led to qualitative results. However, sometimes the concomitance could throw off the balance of the two topics and therefore develop one more than the other: this was a thread that could have continued throughout the drafting of

the thesis, but which fortunately did not happen.
Once the concept design was established, this thread was no longer present; on the contrary, simultaneity gave the opportunity to fully understand the benefits and disadvantages of each topic, creating a product that is the summary and balance of what has been learned.

Therefore, the peak in the relationship between research and design occurs following the concept design. Constraints, parameters, and variables were closely related to the choice of material and - subsequently, to the manufacturing process - the circular design strategies explained in Chapter 2.2 and then pre-settled and validated in Chapter 3.1.

Following this concurrency, it was possible to create a design that responded to circular principles without abandoning the versatility given by the computational configuration created.

8.2_ GRADUATION RELEVANCE

The proposed design system presented in this study holds significant social, professional, and scientific relevance.

First and foremost, the primary objective of this thesis is to offer a viable design system that can be directly implemented as a product. Consequently, it operates within the cognitive framework and fosters innovation based on real-life aspects rather than experimental ones. By prioritizing the objective of “connecting the dots” instead of experimentation, the potential for social and professional impacts is heightened.

The central focus of this research is to discover a suitable and certified alternative for materials that, as discussed in Chapter 2, negatively impact the environment due to material extraction, production processes, energy consumption, and waste generation. This thesis convincingly demonstrates that it is feasible to transition to new material, thereby adding value to three-dimensional geometries.

Therefore, this new vision contributes to shifting the construction market towards the circular economy by proposing a new application system that can substitute those more traditional materials that consume the material, energy, and waste, impacting the environment.

To comprehensively evaluate each facet of the research and product realization, a detailed analysis will be conducted, considering the four domains of circularity: *design*, *material*, *manufacturing*, and *management*.

FOUR DOMAIN OF CIRCULARITY

DESIGN

The panel design consists of a squared-modular panel composed of sharp three-dimensional angles ending in a protruded core called a focal point.

As explained in Chapter 3.1, this concept is to break the traditional way of associating design with materiality by incorporating a design inspired by the folding process commonly employed in metal product manufacturing. As a matter of fact, this design highlights the material's ability to withstand complex shapes, making it an optimal alternative to the aforementioned materials.

Furthermore, this innovative design has been developed to promote sustainability. Design strategies that facilitate circularity in the outcome have been employed. Modularity and flexibility are the primary and fundamental principles considered during the design process. As a solution, the seamless tiling approach was devised by maximizing versatility and creativity while respecting the environment and minimizing energy consumption, waste generation, and costs. As extensively explained, this approach offers significant flexibility in composing the panel and the façade.To implement such strategy, Parametric design has been used as a primary tool, enabling freedom of expression and establishing a new foundation for future applications. Besides that, other circular strategies such as dematerialization, design for disassembly and material choice have been applied: the latter will be explained in the next section.

After showing the system, a final product has been realized. Therefore, the panel freedom has been stabilized while showing the flexibility of the actual product for the realization of different façades. The individual elements for composing the flexible façade are panels measuring 60cm x 60cm and weighing 4.7 kg each. These panels can be easily assembled and disassembled without requiring specialized machinery. Moreover, because of the weight and the limited size, there is no need for extravagant and impacting transportation.

Because of how it has been assembled and the chosen components, the façade is ventilated. Therefore, the arrangement of such three-dimensional panels, which extend inward from the façade, requires a gap between the panel and the wall system, functioning eventually as a natural ventilation chamber.

However, it is essential to acknowledge a primary limitation concerning the representation of complex geometries. As explained in Chapter 7, given the sharp nature of the design, reproducing more organic macro-geometries becomes challenging unless the parametric panel variables are distorted to realize a smoother configuration.

MATERIAL

The material choice, extensively discussed in Chapter 2 and 5, is the Nabasco 80s series, specifically Nabasco 8012.
Nabasco 8012 is a certified material which has been largely tested in different configurations and functionalities.
Composed of reed fibers obtained from the waste generated by the roof construction industry, calcite sourced from the waste produced by drinking water companies, and a partially bio-based resin, Nabasco 8012 exemplifies the utilization of by-products in its composition. By incorporating these waste materials, a significant portion of the final material is derived from repurposed sources.

Furthermore, Nabasco 8012 is a bulk-mounding compound that exhibits a dough-like consistency. This fluid yet dense state allows for substantial flexibility in realizing the end product, which was a primary criterion for selecting this material.

However, it is important to note that the resin, as previously mentioned, is only partially bio-based, as it is derived from leftover biofuel resources. Nevertheless, efforts are already underway at NPSP to explore more circular options that rely on fully bio-based materials possessing similar mechanical properties. These alternatives, because more experimental, have not yet obtained certification.

Therefore, given the criteria of the graduation research, the material decision was made to prioritize a certified product over a more experimental but potentially more circular material. This choice ensures the fulfillment of academic requirements while still acknowledging the ongoing exploration of circular options by NPSP.

MANUFACTURING

The manufacturing process employed for creating the panel made of Nabasco 8012, as discussed in Chapters 2.5 and 2.6, is the hot-press process. As noted by Kula et al. (2013), this process offers a high degree of flexibility and versatility in shaping the material. It enables the material to be easily moulded into intricate and complex shapes. As explained earlier, the combination of this process with the material's unique properties grants the freedom to explore and challenge three-dimensionality in design.

In the research context, where design, material, and manufacturing processes are interconnected, the manufacturing process does not represent an innovative aspect. Instead, together with the material, it serves as a tool for realizing the desired innovation.

However, it is essential to acknowledge that the hot-press process needs metals for the moulds. As explained in Chapter 5, the mould material must possess high-temperature and pressure resistance while facilitating heat transfer to the material without deformation.

Consequently, producing aluminum required for the moulds becomes an unavoidable environmental impact associated with manufacturing. The aluminum will undergo further processing through CNC machining to create the moulds.

To mitigate this impact, a dematerialization strategy has been implemented as extensively explained.
The overall environmental footprint is reduced by creating only six moulds capable of producing various configurations.
This strategic approach minimizes the need for additional mould production, mitigating the environmental consequences of raw material extraction and aluminum production.

MANAGEMENT

While the management domain was not a primary focus of this research, it is important to consider certain aspects in order to provide a comprehensive understanding.

The design system and resulting product have a significant impact on management practices. Analyzing the R-strategies presented in Figure 22, it becomes apparent that the final product aligns with both the upper part macro-group, which - *by rethinking* - emphasizes resource efficiency and minimizing environmental impact, and the middle part, which extends the lifespan of by-products such as the Nabasco 8012 components by *repurposing* with a new function.

This shift in design and product approach also necessitates a change in resource management and related policies. The realization of the design's potential leads to a broader understanding of resources and their value not only during their initial use but throughout their entire life cycle. This holistic perspective influences the way materials are valued and how resources are managed and allocated.

Furthermore, recognizing the significance of waste and the potential to create strong and flexible materials from it, waste management policies should be prioritized to transition towards more effective and appropriate waste management practices. This highlights the importance of developing policies that emphasize proper waste handling and utilization, taking into account the potential of waste as a valuable resource.

COMPARISON

After conducting a comprehensive analysis of the product based on the four domains of circularity, a comparative evaluation will be conducted to assess its performance against existing products. However, it is important to note that the management aspect was not included in the literature research and, therefore, will be omitted from the evaluation.

DESIGN

The developed system presented in this study introduces new approaches and possibilities for the building market.

Through its design - and the consequent prototype realization - the system showcases the potential of bio-based materials to be shaped in unconventional ways, departing from the typically offered flat façade designs. The accompanying images below depict some examples of the façades created using bio-based materials, demonstrating both flat compositions and, in the case of The Exploded View Beyond Building project utilizing Nabasco 8010 (Fig. 142), bas-relief designs.

Therefore, until now, the prevailing focus has primarily been on the materiality of these circular panels, with limited exploration of their geometric possibilities. Thus, the developed system unveils the potential of simultaneously exploring both materiality and geometry while encompassing all the aforementioned domains of circularity.

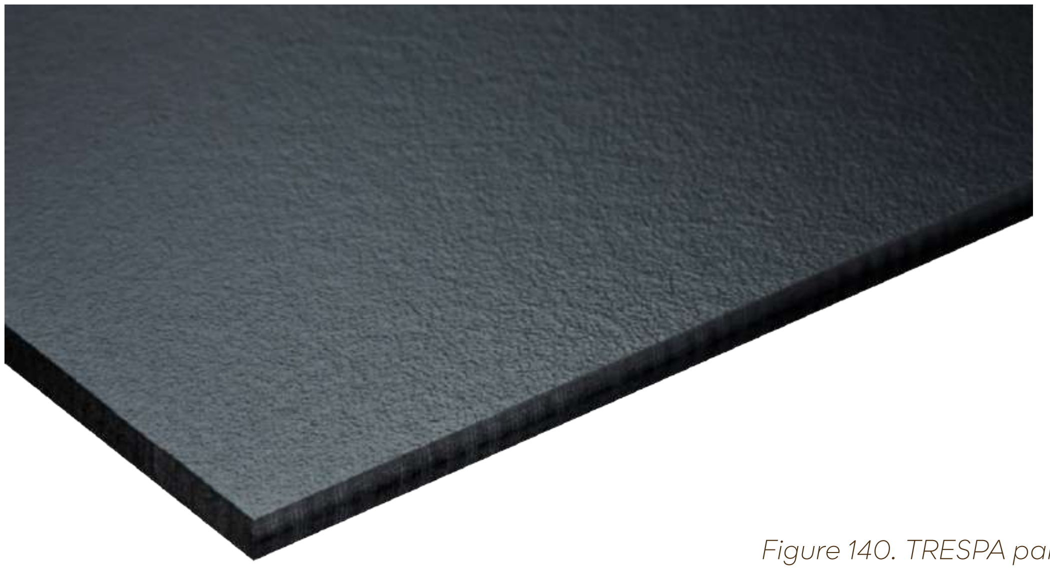


Figure 140. TRESPA panel
Source: TRESPA (n.d.)

Figure 141. RESYSTA panel
Source: RESYSTA (n.d.)

Figure 142. Nabasco 8010 panel in The Exploded View Beyond Building
Source: NPSP (n.d.)

MATERIAL

To adequately assess the potential of the developed panel's three-dimensionality, a comparison with conventional three-dimensional cladding materials is conducted. In order to ensure a comprehensive material comparison, it is necessary to assume that the developed panel incorporates all the materials examined in the case studies presented in Chapter 2. It should be noted that for the purpose of this analysis, an equal volume is considered for all the cases, which will be the volume of the final product (0.00288 m3).

The materials included in the comparison are as follows:

- Aluminium with Bronze Coat
- Aluminium Composite (Aluminium foils + plastic core)
- Laminated Glass
- Glass Fiber Reinforced Concrete (GFRC)
- Nabasco 8012

The lifespan of a material is an important consideration when evaluating its suitability for a particular application. Metals such as aluminium and steel are favored due to their long-lasting nature, which reduces the frequency of replacements. Comparing this innovative material to traditional ones is crucial to assess its practicality and determine if it offers advantages in terms of lifespan, thereby minimizing material usage, energy consumption, and waste generation.

In many cases, it was not possible to find exact matches for the materials used in the case studies. Therefore, the comparison will be based on the general macro-group of materials, and alternative sources will be used to provide insights. This is because the lifespan of a material depends on various factors such as quantity, exposure, and climate conditions. The aim is to gain a generalized understanding of whether the lifespan of Nabasco 8012 can be comparable to that of traditional materials.

For example, Northeastern University's cladding utilizes aluminium coated with bronze, but since the bronze layer is thin, it will not be considered. Aluminium, known for its considerable lifespan, typically exceeds 75 years (Reynaers, 2022). In contrast, the internal cladding at Theatre Zuidplein, consisting of 5mm of plastics and 1mm of aluminium, may last only around 5 years before requiring replacement, which is relatively short (Alutech, n.d.).

In the case of laminated glass, specifically the manufacturer Harpa Concert Hall, it is expected to last approximately 30 years (Schollglas, n.d.). As for Glass Fiber Reinforced Concrete, the lifespan range generally extends to 50 years or more (Rieder, n.d).

Regarding Nabasco 8012, it is important to acknowledge that laboratory tests have indicated a projected lifespan ranging from 50 to 100 years (Bottger, 2023). However, it should be noted that these values have not been validated under real-world conditions, and there is inherent uncertainty regarding its performance in specific situations.

From a theoretical standpoint, the lifespan of Nabasco 8012 demonstrates promising results - as shown in Fig. 143 - , positioning it favorably in comparison to traditional materials. It is essential, though, to exercise caution when drawing conclusions, as further testing and validation in real-world applications would be necessary to confirm its long-term durability and performance.

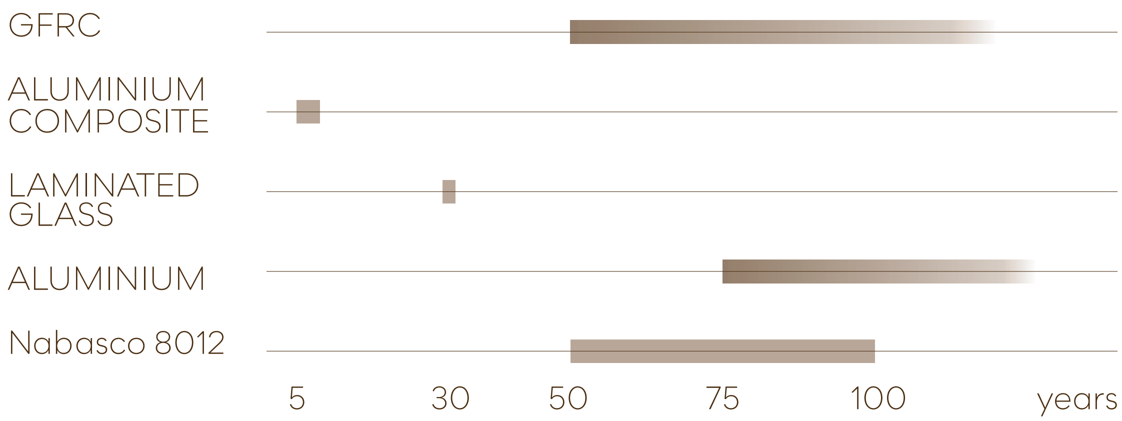


Figure 143. Life span Selected materials own ill.

Another crucial aspect that warrants careful consideration in the analysis is the carbon footprint associated with the production of these materials. However, despite the efforts, obtaining precise carbon footprint values for the specific case studies examined has proven challenging, necessitating the adoption of a similar approach as previously described.

Based on the available information, as depicted in Figure 144, both laminated glass and aluminium composites exhibit comparable carbon footprint values, averaging around 7 $kgCO_2eq/kg$ - respectively 7.61 and 6.56 $KgCO_2eq/Kg$ - (Schollglas, n.d.) (Alcotek, 2020). Conversely, aluminium demonstrates a higher carbon footprint, with values reaching 14.78 $KgCO_2eq/Kg$ (Alupro, n.d.). In contrast, NPSP has conducted a comprehensive evaluation of Nabasco 8012's carbon footprint, which encompasses both material production and the manufacturing process, resulting in a carbon footprint below 1 $kgCO_2eq/kg$ (Bottger, 2023). Regrettably, specific carbon footprint values for glass reinforced concrete were not identified during the research.

In conclusion, although precise carbon footprint values for all the materials examined were not readily available, it is evident that Nabasco 8012 possesses a comparatively lower carbon footprint. This conclusion is supported by the findings presented by Bottger (2023), which indicate that the carbon footprint values for Nabasco 8012 include not only the material production but also the associated manufacturing process.

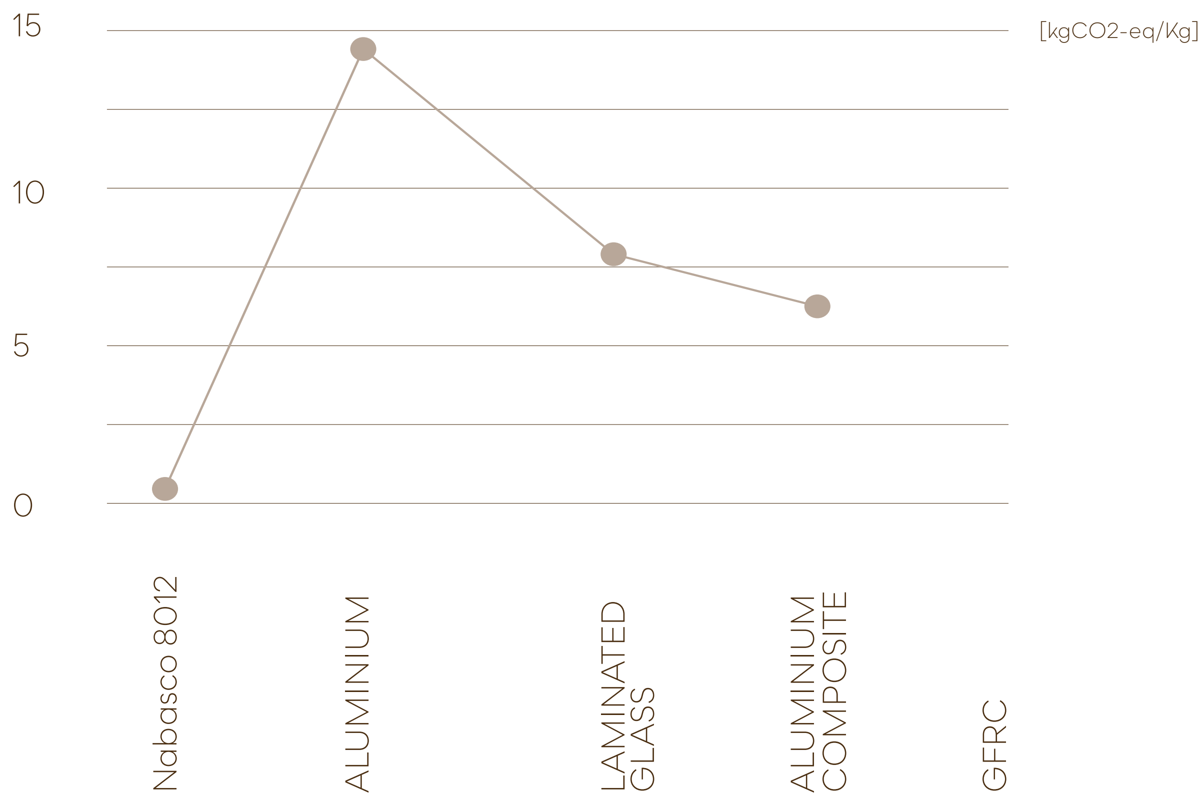


Figure 144.Carbonfootprint felected materials own ill.

In evaluating the overall sustainability of Nabasco 8012, it is imperative to consider the end-of-life aspect and gain a comprehensive understanding of how this material performs throughout its life cycle. While all the mentioned materials are recyclable, Nabasco 8012 offers a distinct advantage by providing the opportunity for repurposing.

As discussed in detail in Chapter 2.4, when Nabasco 8012 reaches the end of its useful life, it can be efficiently shredded and repurposed as filler material for the production of new panels. This innovative approach not only extends the material's lifespan but also contributes to a significant reduction in waste generation. By transforming the panel into a valuable by-product, the utilization of Nabasco 8012 promotes the principles of a circular economy, emphasizing resource efficiency and minimizing environmental impact, as explained in Fig. 22.

MANUFACTURING

The hot press manufacturing process employed for the production of Nabasco 8012 panels is not considered an innovative process in itself. However, it is important to note that certain energy-intensive processes are still involved in this manufacturing technique. Comparing the hot press process to other manufacturing processes is challenging due to the complexity and diversity of processes employed to produce a final panel. Attempting to assess and evaluate each process comprehensively would result in a generalized and complicated analysis.

Nevertheless, the development of Nabasco 8012 panels incorporates a positive aspect in terms of manufacturing. By approaching the design *rethinking* method, careful consideration has been given to reducing the number of manufactured panels, which consequently minimizes the amount of material and energy required. To illustrate this point a contrasting scenario will be considered. In the case of the project "The Broad" discussed in Chapter 2.1 (Fig. 14), a staggering 380 moulds were necessary to produce 2500 panels. In contrast, with the developed design using Nabasco 8012,taking into account the reusability of aluminum moulds for at least 500 cycles - as mentioned by Bottger in 2023 - it becomes apparent that by employing this method, it would be possible to achieve the same number of panels with a reduction of 374 moulds.

This example highlights the significant reduction in the number of moulds and associated energy-intensive processes achieved through the innovative design approach. By streamlining the manufacturing process, the environmental impact in terms of material usage and energy consumption can be considerably mitigated.

CONCLUSION

In conclusion, the development of the final product presents significant opportunities within the four domains of circularity. Through its own inherent properties and by comparison to traditional materials, it demonstrates the potential for enhanced sustainability and resource efficiency. While further research is warranted, given the relative novelty of this material and the only scaled prototyping test for the design realization, it is clear that the design system in combination with Nabasco 8012, has the potential to contribute significantly to sustainable practices, fostering a circular economy and minimizing environmental impact.

8.3_ FUTURE RESEARCH

As this study progressed, numerous potential further steps emerged, each intended to explore the different aspects involved in this thesis.

MATERIAL EXPLORATION

Considering the chosen certified material as a product non-completely bio-based because of the resin, a material test and exploration could be assessed. Consequently, considering the fundamental principles of this thesis, it would be intriguing to contribute to developing and providing a bio-based resin while still maintaining the efficient mechanical properties of the chosen material.

Mould MATERIAL EXPERIMENTATION

The material realization needs a metal that withstands high temperatures and can conduct heat. Metals are the most appropriate ones; however, as explained in the previous chapters, the energy required and the carbon footprint emitted are impacting mainly the environment.
Further research could be studying a new material that could replace the aluminum or steel moulds that withstand the same requirements.

PANEL DESIGN ADAPTABILITY

The design systems propose a panel design. However, given the scenario, infinite configurations can be created by respecting the seamless tiling concept.
Potential further steps could be creating different designs and, eventually, tools for letting the user choose which configuration suits their preference the best.

PANEL DESIGN ADAPTABILITY

As explained in Chapter 7, the design is related chiefly to sharp-looking three-dimensionality. Further research by design could be handled to understand how to include more organic shapes in this flexibly developed rule.

DIGITAL DESIGN

The suggested workflow for generating the façade's geometry has the potential for further refinement, aiming to evolve into a comprehensive parametric design tool that architects and engineers can readily employ. The tool could incorporate parameters tailored explicitly to the moulding process to expand its functionality.

STRUCTURAL OPTIMIZATION

Attention is given to the material use of moulds. Thanks to the parametric design of the developed panels, just six moulds have been shaped, offering the chance to have infinite design configurations.
Since the project covers the material amount for resources and energy demand, a structural optimization for minimizing the material used within the panel and the mould could be implemented in a thesis storyline.

CIRCULAR SUBSTRUCTURE AND STRUCTURE

In conclusion, considering the focus on altering conventional materials to create three-dimensional claddings, it would be prudent to apply the same level of precision in comprehending how to adopt circular principles in the elements behind the façade, such as the substructure, structure and wall components.
The substructure in the proposed design heavily relies on metal connections. As discussed in Chapter 5, this decision was made to preserve the integrity of mould production while offering designers flexibility in their choices. Additionally, it catalyzes future advancements in connection techniques, given a flat surface that does not impede other design possibilities.

Therefore, new connection systems can be designed to respond to both the rotational and mass of the panel (4.7kg) by reducing impacting materials or using less impacting materials than conventional connections.

THERMAL PERFORMANCE

Since the final shape permits the ventilated façade implementation, thermal simulations and analysis can be made to understand the design's thermal performances and optimize it.

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INTERVIEWS

Peter Mooij (AMS), 7th of February 2023, Questions regarding Re-Plex and Fabulous

Nick Tossings (Scheldebouw), 13th of February 2023, Questions regarding Northeastern University Manufacturing

Willem Bottger (NPSP), 17th of March 2023, Questions regarding Nabasco materials and manufacturing process

Nils Dogger (Deltavorm), Tjomme de Vries (Deltavorm), 01st of April 2023, Questions regarding aluminium moulds

Willem Bottger (NPSP), Mark Lepelaar (NPSP), Frank Bleeker (NPSP), 11th of April 2023, Questions regarding hot press process and how to design a mould

Nils Dogger (Deltavorm), Tjomme de Vries (Deltavorm), 01st April 2023, Questions regarding aluminium moulds

Rob Henderson (Etcetera), Ariane Stracke-Henderson (Etcetera), bi-weekly meeting, Design Consulations

Marcel Bilow (TU Delft), 10th May 2023, Questions regarding design connections

Frank Bleeker (NPSP), 15th of May 2023, Questions regarding material availability

Jeroen Rietvelt (Deltavorm), 06th of June 2023, Interview for a Linkedin Article

CONFERENCE

Tsigkari M. (27th October 2022), *Design Perspectives*. The New Open (Mind) Talks, Delft, The Netherlands.

_APPENDIX

Figure A1.Concept Maquette Initial Idea

Figure A2.Concept Maquette Initial Idea

	CALENDARING	CUTTING	STAMPING	EXTRUSION	FOUNDING	FORGING	SINTERING	PRINTING	INJECTION	CAST MOULDING	INJ. MOULDING	FOLDING	NUMERICALLY CONTROLLED PROCESS	ROTATIONAL MOULDING	THERMO-FORMING	MACHINING	HOT PRESSING
CERAMIC	●	●		●			●	●	●	●			●			●	●
COMPOSITE		●						●			●		●			●	●
CONCRETE		●						●		●			●			●	
GLASS	●	●		●				●		●		●	●		●	●	●
LEATHER	●	●	●					●				●	●			●	
METAL	●	●	●	●	●	●	●	●	●	●		●	●			●	●
PAPER	●	●	●					●				●	●			●	
PLASTIC	●	●		●			●	●	●	●	●	●	●	●	●	●	●
STONE		●						●					●			●	
TEXTILE	●	●						●				●	●			●	
WOOD		●						●			●		●			●	

Figure A3.Concept Maquette Initial Idea

		FLAX	REED	TEXTILE	SISAL	JUTE	FIRE REED	
characteristics	unit value	value	value	value	value	value	value	norm.
DENSITY	g/cm³	1.7	1.71	1.7	1.65	1.65	1.86	ISO-1183
FLEXURAL STRENGTH	MPa	40.0	40.0	50.0	40.0	40.0	30.0	ISO-178
BENDING STIFFNESS	GPa	8.0	8.0	8.0	7.8	7.8	10.0	ISO-178
IMPACT RESISTANCE	kJ/m²	6.0	6.0	6.0	6.0	6.0	6.0	ISO-179
MOISTURE ABSORPTION	%	1.2	0.9	0.5	1.8	1.3	0.7	ISO-62
% BIOCIRCULAR	%	85.0	85.0	85.0	85.0	85.0	66.0	na
FLAMMABILITY MEETS	mm	-	-	-	-	-	1.0	UL94-V0
FIRE SAFETY	class	B-S1-DO EN 13501	B-S1-DO EN 13501	B-S1-DO EN 13501	B-S1-DO EN 13501	B-S1-DO EN 13501	B-S1-DO EN 13501	-B-S1-DO EN 13501

Figure A4.Most common fibers for Nabasco 80s

	NABASCO 8012	ALUMINIUM	LAMINATED GLASS	ALUMINIUM COMPOSITE	GFRC
DENSITY	1700 kg/m³	2710 kg/m³	2480 kg/m³	960 kg/m³ + 2710 kg/m³	2100 kg/m³

Figure A5.Referred Density for Material Comparison

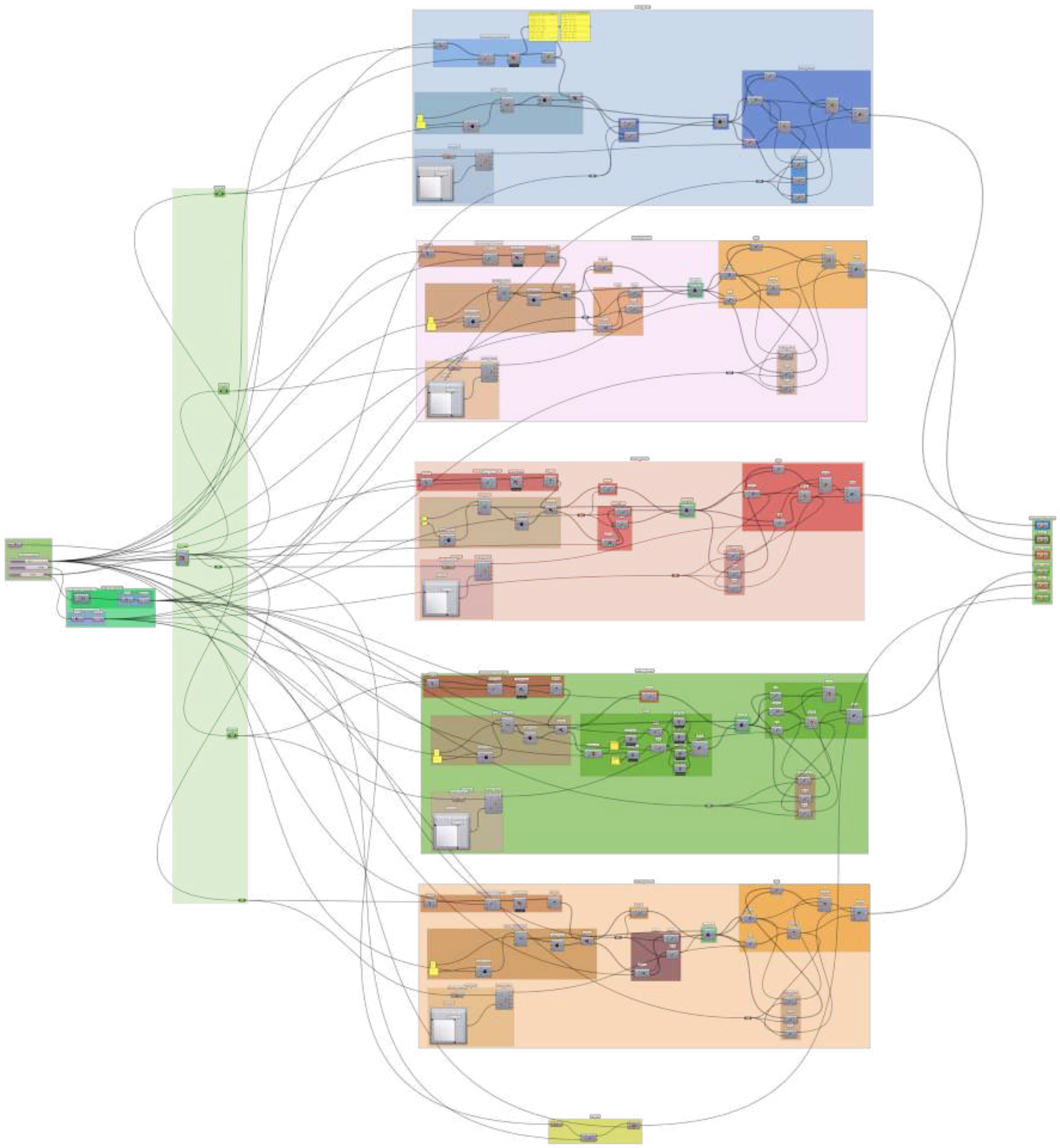


Figure A6. All panel parametrization

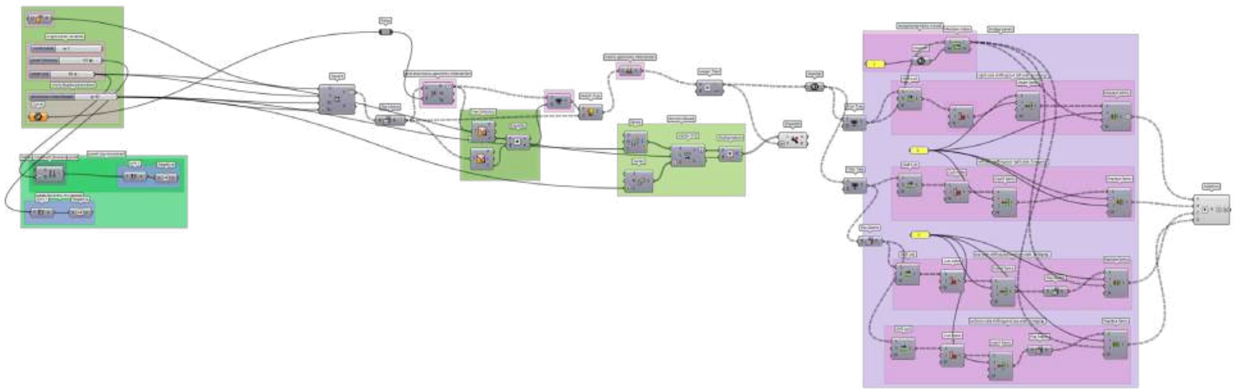


Figure A7.Bridge panels data management

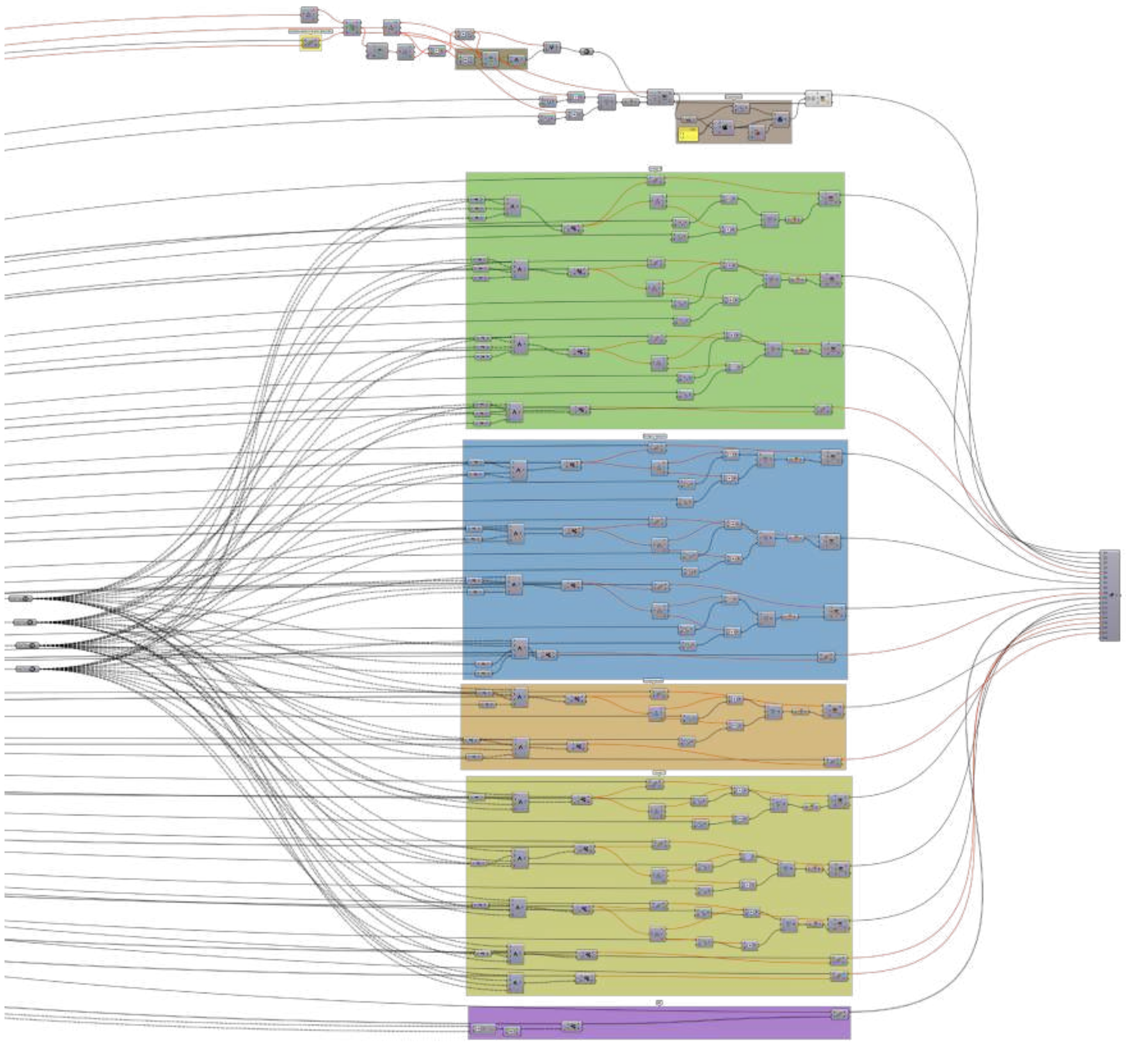


Figure A8.Panels rotational displacement

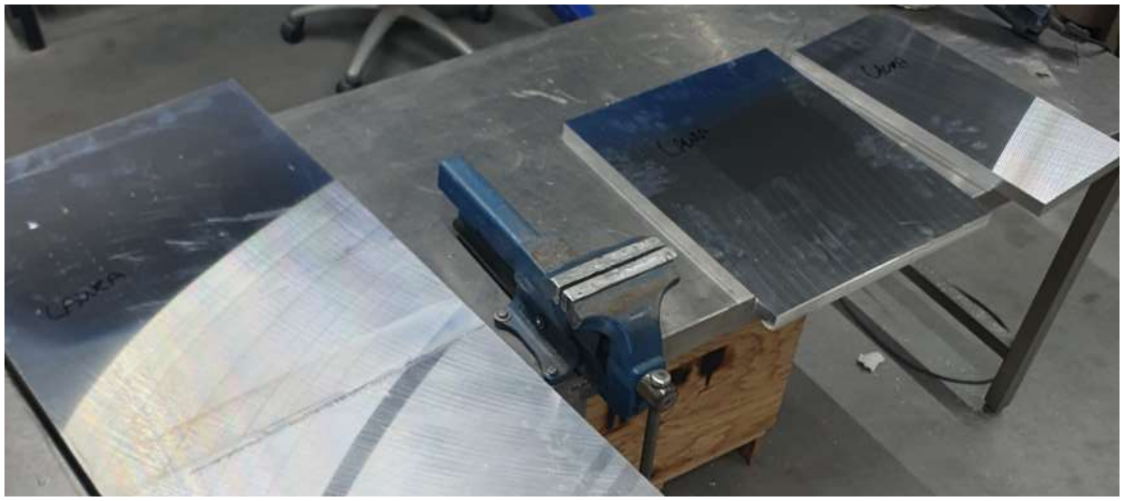


Figure A9. Aluminium Plates for Mould Production
Source: De Vries (2023)

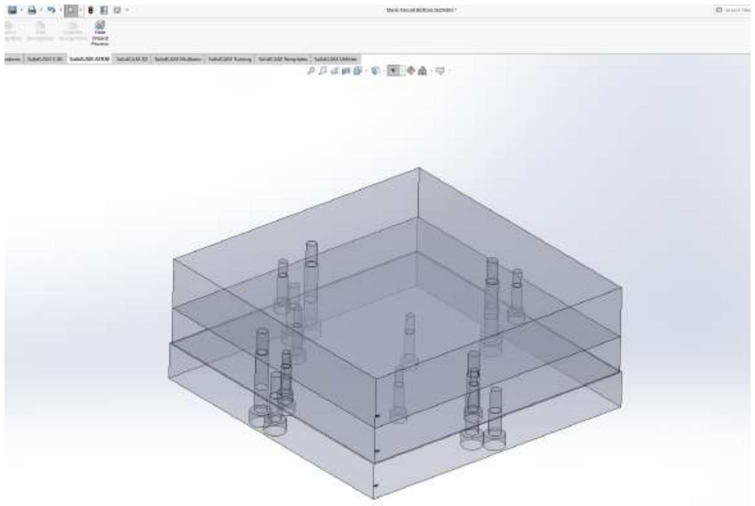
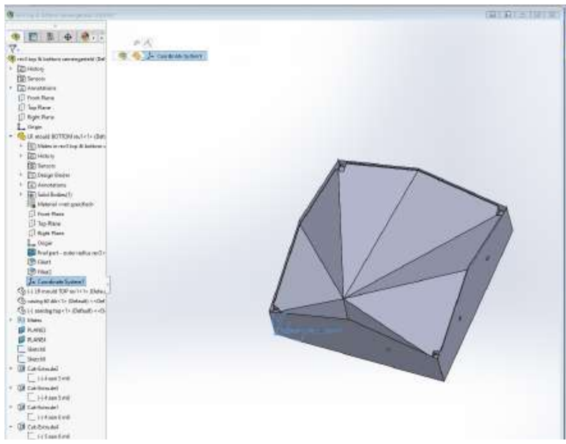


Figure A10, A11.SolidWorks Display for Drilling Holes and welded mistake
Source: De Vries (2023)



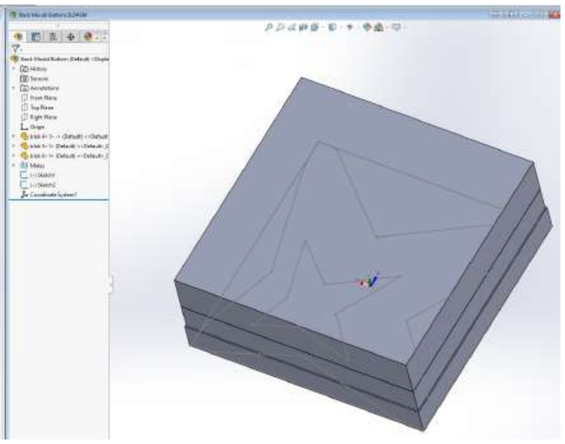


Figure A12, A13.SolidWorks Display for Layers Cut
Source: De Vries (2023)

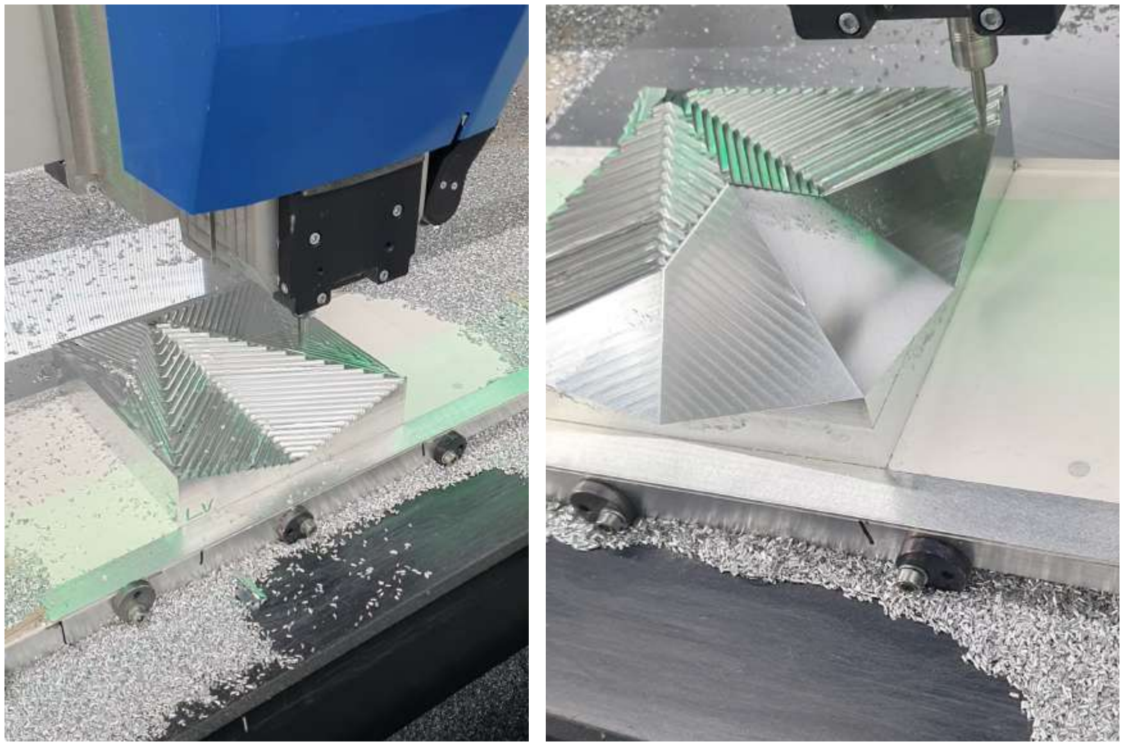


Figure A14, A15.Roughing and Finishing Machining
Source: De Vries (2023)

Figure A16, A17.Finishing Machining and Zoom In
Source: De Vries (2023)

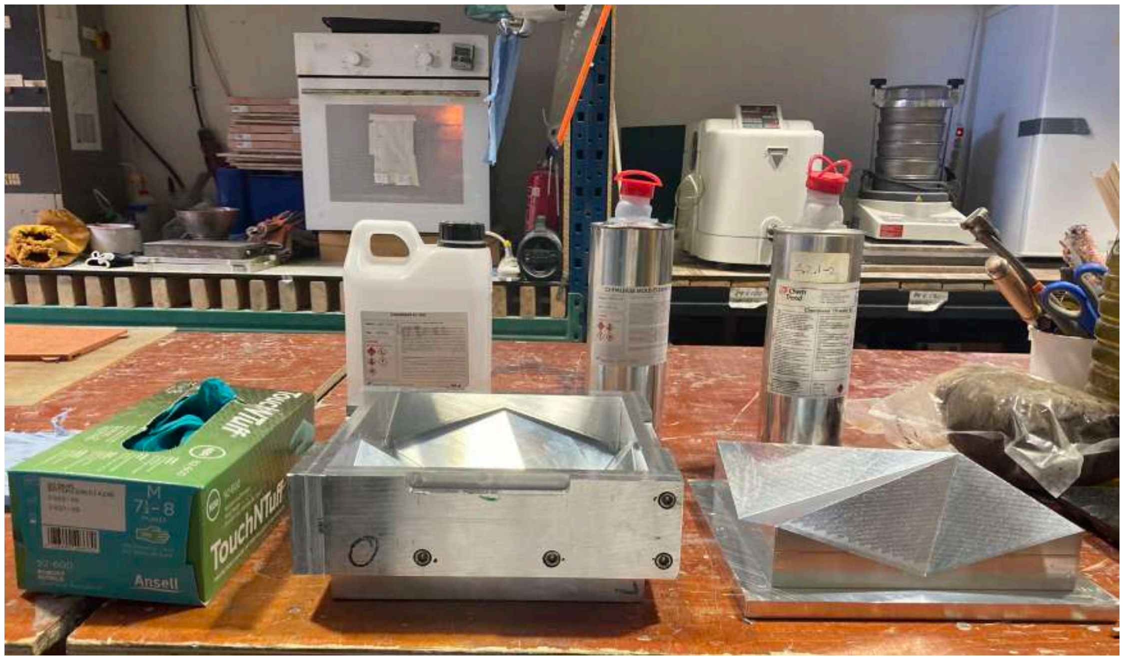


Figure A18. Pre-Setting for Pressing Process

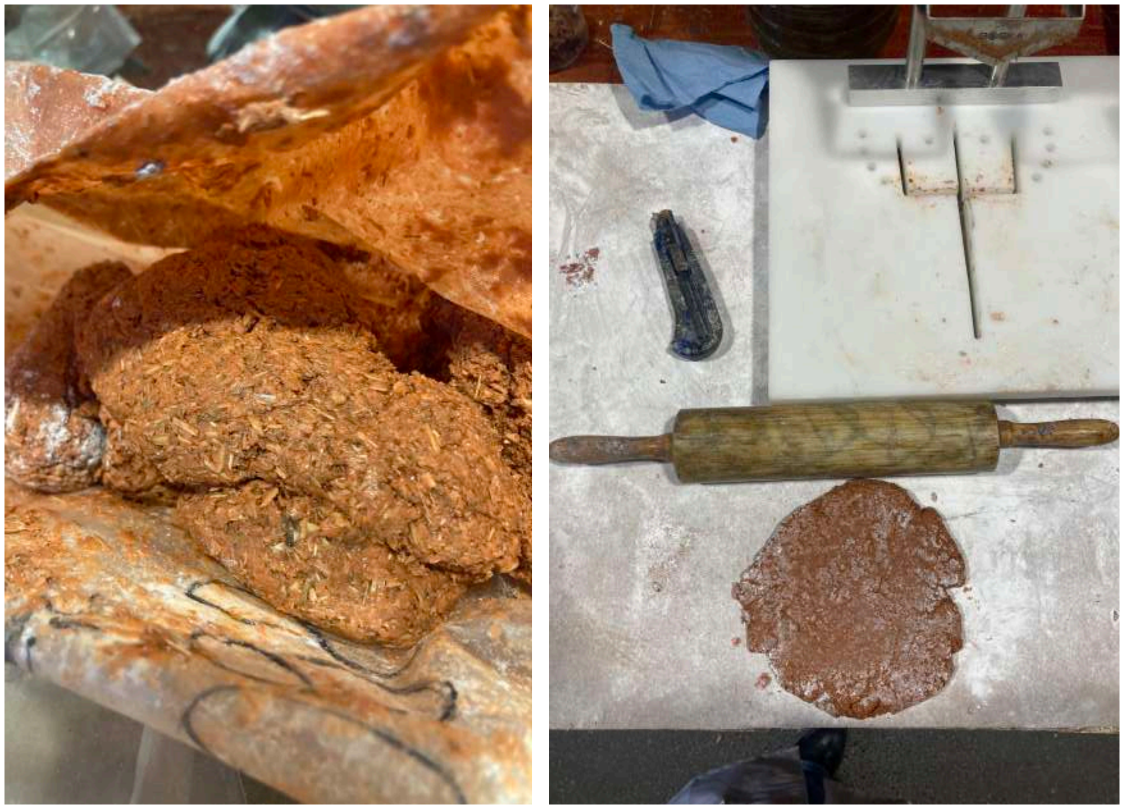


Figure A19, A20. 8012 Dough and pre-placement within the mould


Figure A21, A22. Dough placed within the mould, and cooling process



Figure A23, A24, A25, First try pressing