Master Thesis

Designing the Facade of the Future

A Regenerative Solution for Urban Areas

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TU Delft
npsp

Colophon

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A Regenerative Solution for Urban Areas

March 2025

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Executive Summary

This project aims to design the facade of the future in collaboration with NPSP, which provided material N-8040, a biocomposite developed by them.

The project starts with a literature review, focusing on the challenges that cities are currently experiencing and those they are expected to face in the future. One proposed solution to the reliance on unsustainable construction resources is the use of N-8040, which is composed primarily of bio-based and waste-derived materials.
Following a brief analysis of facade trends over recent decades, a vision emerges in which future buildings coexist symbiotically with their ecosystems rather than existing in isolation.

As the project starts with the material, it follows the Material Driven Design Method established by E. Karana and B. Barati (2015). This approach emphasizes an initial analysis of the material itself. So, N-8040 was evaluated on both a technical and experiential level, revealing its potential to support the growth of organisms in moist environments. This potential, when combined with urban challenges, offers a pathway to integrate rainwater and vegetation effectively.
User tests focused on experiential characterization were conducted to enhance the original N-8040, resulting in a more positive experience with the material.

The design draws inspiration from several concepts: the More-than-Human Design approach, regenerative approaches and biomimicry. The design employs surface geometry to facilitate controlled vegetation growth, thereby transforming public perceptions. What was once regarded as a weed or a sign of decay can be changed into appreciation. Among various plant options, moss emerges as the most suitable choice owing to its low-maintenance nature and resilience.

To achieve the necessary bio-receptivity for moss, a series of experiments were carried out to create a facade panel that meets specific requirements. By utilizing biomimicry to emulate leaf morphology for effective rainwater channelling and drainage, along with a pattern of grooves on the surface, the facade panel establishes ideal conditions for moss growth. Ensuring the panels fit together seamlessly in all rotational orientations, leads to dynamic line formations and the flexibility to create diverse patterns.

The result is the facade panel *REVI*.

Preface

This project is not only a presentation of a product but also a discovery of me, both personally but also as a designer. I must honestly say that in the bachelor's I (often) went on full of energy and motivation and, on the contrary, often lost it in the master's. Maybe because I didn't know very well what I wanted to do, and if I knew, the subjects didn't really match that.
By choosing a subject in this project that suits me and realizing that taking the lead in this is actually really fun, I found this energy again during this project. Being able to pick exactly what I love made a huge difference for me. The fact that I found this motivation and enthusiasm again is perhaps the most valuable thing about this project for me.

There are a number of people I would like to thank.

First of all, NPSP, Willem and Mark, thank you for being so open and supportive. I am extremely happy that you wanted to work with me for my graduation project. To be honest, I was quite nervous about starting this project with you, but this disappeared quite quickly when I saw how involved you were and your willingness to think along and help me out. And Frank, thanks for helping me every time I had a 'little problem' with Solidworks.

Then my supervisors, Stefano and Joost, you are totally different, but you make a great team together. I could always count on you. Stefano, I really appreciate you as my chair, you are incredibly involved. And Joost, thanks for reminding me to trust myself, especially when I was stressing too much about my schedule. You both got some really inspiring ideas and often helped steer me back on track when I got lost. Thank you for your trust and time.

Then I would really like to thank Marijn, thank you for all your help and support throughout this project, without you I would have had endless frustrations with Onshape and I wouldn't have been able to bring my ideas to life without you. I would also like to thank my parents who were always there for me to help me out, especially in the last weeks. And my friends, thank you for the distractions and good times.

I'm really proud to present this project. I know it's a bit long, but hang in there, I hope you enjoy it!

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1. Introduction

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1.1 Setting the Scene

As urbanisation increases, metropolitan areas face critical environmental problems that threaten the health and well-being of their populations. In the Netherlands, urban centres struggle with problems such as declining air quality, the heat island effect and increased vulnerability to extreme weather events, all intensified by climate change. The scarcity of green spaces in these urban environments magnify these challenges by trapping heat, reducing biodiversity and hindering rainwater infiltration, increasing the risk of flooding. Addressing these problems requires innovative designs that effectively integrate urban development with ecological systems.

This project aims at sustainable urban design by developing a façade panel made from N-8040, an advanced biocomposite material developed by NPSP and Nabasco. As a carbon-negative material, N-8040 reflects a strong commitment to environmental sustainability. This façade panel goes beyond conventional architectural applications by integrating water and moss to create a regenerative system that actively supports urban ecosystems. By promoting biodiversity, reducing urban heat, improving air quality and enabling rainwater management, this façade design offers a solution to pressing urban challenges by designing with and for the environment. Besides environmental benefits, the integration of green elements contributes to human well-being, which are associated with reduced stress.

By merging architecture and ecology, this project aims to promote a sustainable future in which urban areas blend harmoniously with the natural environment.

1.2 Three Pillars: Environment, Facade, Material

This project is structured around three fundamental pillars: the environment, building facades, and materials. Every aspect within this project can be traced back to one of these core focus areas, which serve as the foundation of the project. The goal is to harmonize these pillars into a meaningful design that addresses the urgent need for sustainable cities, offering a solution to the critical question: **What will the facade of the future look like?**

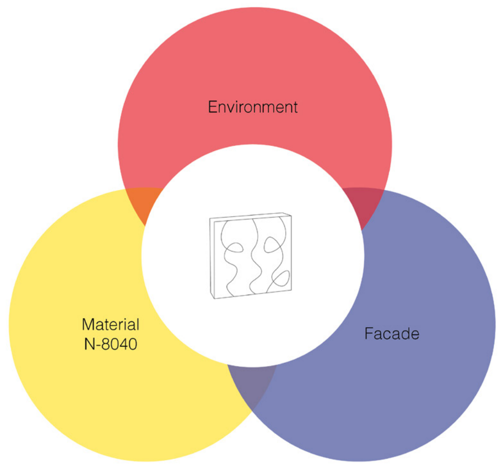


Figure 1. Core focus areas

2. Project Stakeholder: NPSP

This project is a collaboration with NPSP, a company that specializes in creating sustainable, bio-based composite materials and products. This project assists NPSP in converting the material into an attractive facade panel that aligns with their product portfolio. NPSP is supplying all the materials for the project, along with their expertise in the material and its production process.

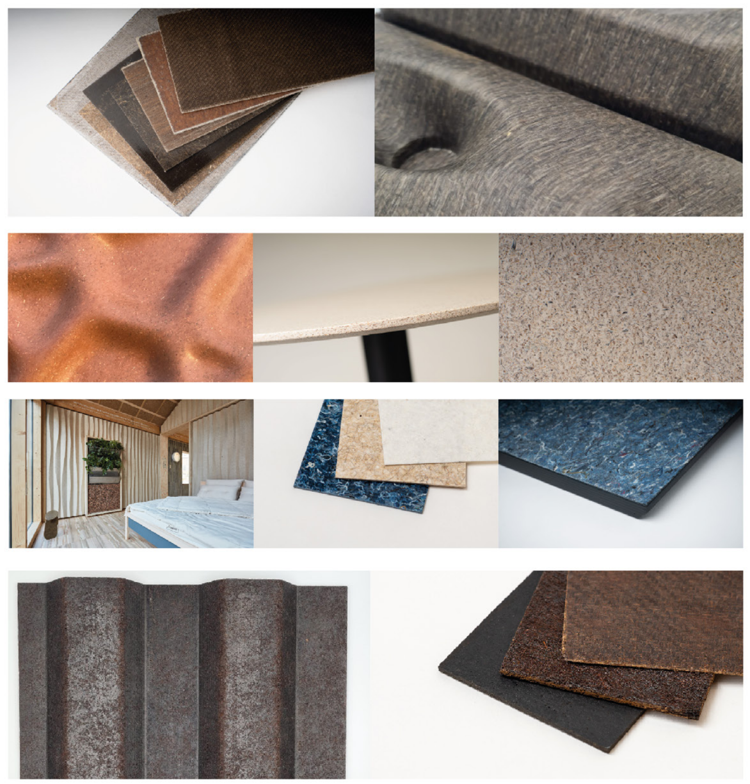
By harnessing renewable resources such as bio-based, circular and waste-based materials, the company offers innovative alternatives to traditional plastics and synthetic composites from 1998 on.

2.1 Nabasco

The Nabasco brand is established by NPSP, which oversees product and project development, while Nabasco focuses on the material development of biocomposites.
The biocomposites created by Nabasco incorporate bio-based, circular, or renewable materials, utilizing resources such as flax, hemp, and various residual materials, including recycled toilet paper, lime filtered from drinking water, and resins derived from the byproducts of paper, sugar, and biodiesel production. Additionally, Nabasco is actively experimenting with new materials.
At the end of their life cycle, NPSP's materials can be ground down and completely recycled to serve as filler for new composites (NPSP, n.d.).

Alongside ongoing material development, Nabasco currently produces a variety of biocomposites, as illustrated in Figure 2. The variations among these composites arise from differences in raw materials, including fibers, fillers, and resin types, which result in distinct properties. Another key distinction lies in the degree to which the materials are bio-based and waste-based.

Recently, Nabasco has introduced an innovative biocomposite, N-8040, which is composed of 98% bio- and waste-based materials.



N-5010
44% - 73% biobased

N-8010
natural fibres, filler from waste streams and a largely biobased resin
> 80% biobased and recycled

N-9010
natural and/or recycled fibres with a biobased plastic
up to 100% biobased

N-10010
natural fibres with 100% natural resource-based resin
100% biobased and 100% waste-based

Figure 2. Nabasco's biocomposites (NPSP, 2024)

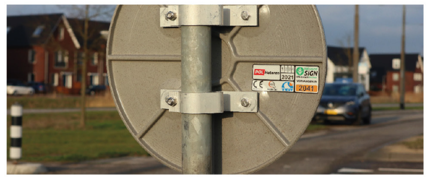
2.2 NPSP

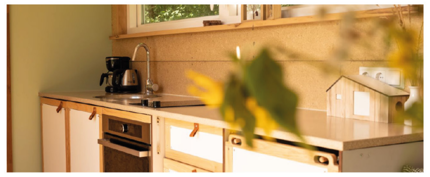
NPSP transforms the materials from Nabasco into products for public spaces, transportation, construction, and design, for example facade panels, furniture and traffic signs. Figure 3 presents a concise overview of NPSP's portfolio. The product batch sizes range from a few units to thousands. While smaller products are manufactured in-house, larger projects are outsourced.

Over the past year, NPSP has concentrated its focus on facade cladding, as these products are proving to do well in the market. Panels have also been identified as an ideal application for NPSP's manufacturing process. Quoting NPSP:

> *"We have been getting an incredible number of requests for facade panels lately, so that is what we are focusing on now." - NPSP, 2024*

Currently, Nabasco and NPSP have identified facade panels as the only application for their newly developed material, N-8040. They are exploring the right purpose, appearance, shape, and function for this material, which is in alignment with this project's objective.

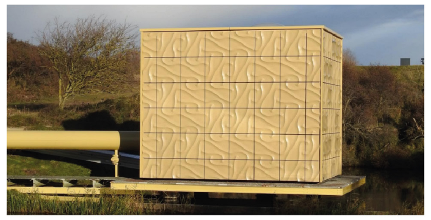

Traffic signs


Kitchen furniture


BioFold, interior and acoustic panels (in collaboration with Samira Boon, Wolck and Dofactory)

Facade panels with residual streams from water authorities

Facade panels for Enexis energy office, Zwolle


Facade panels for pumping station in the Amsterdam water supply dunes


Facade panels with built-in insect and nesting boxes in collaboration with Studio Marco Vermeulen, Amsterdam

Figure 3. Selection of the product offering of NPSP (NPSP, 2024)

3. Methodology and Approaches

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3.1 Material Driven Design Method

The method used for this project is the Material Driven Design method (MDD). The method created by E. Karana and B. Barati is a facilitation to use when the starting point of the design process is the material or material proposal. The goal is to end with a product or further developed material. This method is chosen, because the starting point of this project is the material, the biocomposite N-8040.
The method is based on the principle of moving from the tangible to the abstract, namely starting from the material to a materials experience vision. To then again express this abstract vision in the tangible further developed material or product. This process is reflected in the following four steps the method consists of, see figure 4 (Karana, E., Barati, B., Rognoli, V. et al, 2015):

1. **Understanding the material**: technical and experiential characterization.
2. Creating a **materials experience vision**.
3. Manifesting **materials experience patterns**.
4. Designing the **material** or **product concept(s)**.

What is meant by material experience? Materials are not only functional, they also trigger reactions and emotions, evoke associations and appeal to our senses. Not only the design and styling, but also the material offers the user a certain experience. This material experience is caused by both technical and experiential properties, and, according to Karana and Giaccardi (2015), consists of four levels that are strongly intertwined. The four levels are:

- **Sensory level**: This experience takes place through touch, sight, smell, sound and taste. Descriptions such as *smooth* or *sticky*, fall under the sensory level.
- **Interpretive level**: This involves how we interpret and judge materials. What meaning and description do we give the material after the first sensory experience? This includes descriptions such as *modern, old-fashioned* or *contemporary*.
- **Affective level**: The affective level entails how the materials make us feel, what emotion does it evoke? Descriptions such as *surprising, bored* or *fascinated* fit this level.
- **Performative level**: This level is influenced by the three levels above and describes the actions the material triggers in the user.

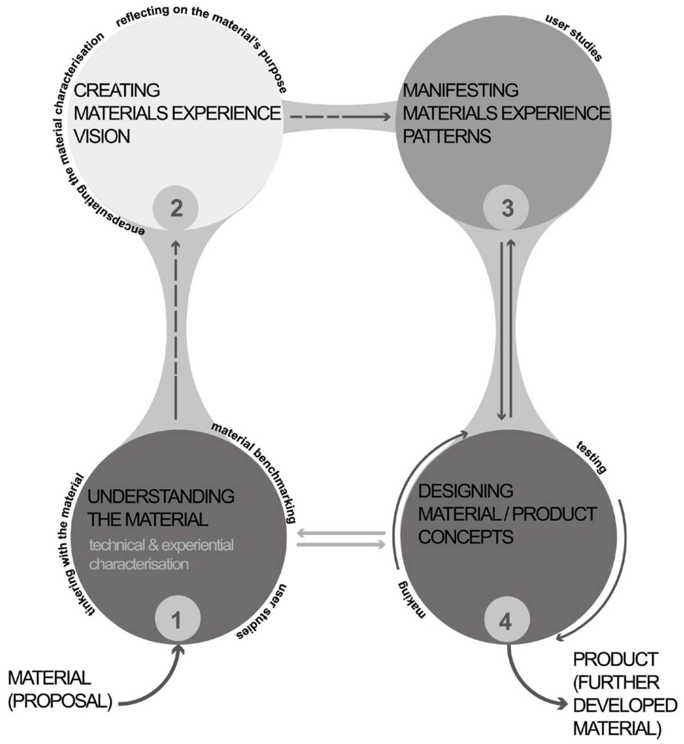

Figure 4. The Material Driven Design Method (Karana, E., Barati, B., Rognoli, V. et al, 2015)

Back to the steps of the Material-Driven Design Method. These four steps can be adapted to the designer's needs. Steps can be skipped or redone depending on the designer's needs and in the best interest of the project.
In this project, steps one, two, and four have been implemented.

Examples of where the MDD method is applied are Waste-coffee Grounds (Karana, E., Barati, B., Rognoli, V. et al, 2015), Living Media including Mycelium-based Composites (Parisi, S., Ayala Garcia, C. & Rognoli, V., 2016) and 3D Printing Waste Recycling (Teixeira, L.F., de Vilhena Rodrigues, J., Cohen, L.A.F.P. et al., 2021).

3.2 Approaches

The project was carried out in three phases: research, design, and reflect. Each phase necessitates a distinct approach. Below is an overview of how each phase was addressed.

Additionally, the review portrays biocomposites, exploring their composition, their environmental and economic advantages and disadvantages, and societal perceptions.

For this literature research, an exploratory approach was adopted, resulting in a snowball effect. Both backward citation searches (examining relevant publications referenced in the article in question) and forward citation searches (investigating publications that cite the articles in question) were utilized. Furthermore, **examples from practice** were researched and analyzed, similarly using an exploratory approach.

Next to the literature research, several **experts were interviewed**. These experts come from diverse fields that could be relevant to this project. Referring back to the three core principles of this project - Environment, Facades, and Materials - these were used as a guideline to ensure that at least one expert was interviewed in each area, allowing for a combination of knowledge and perspectives. The

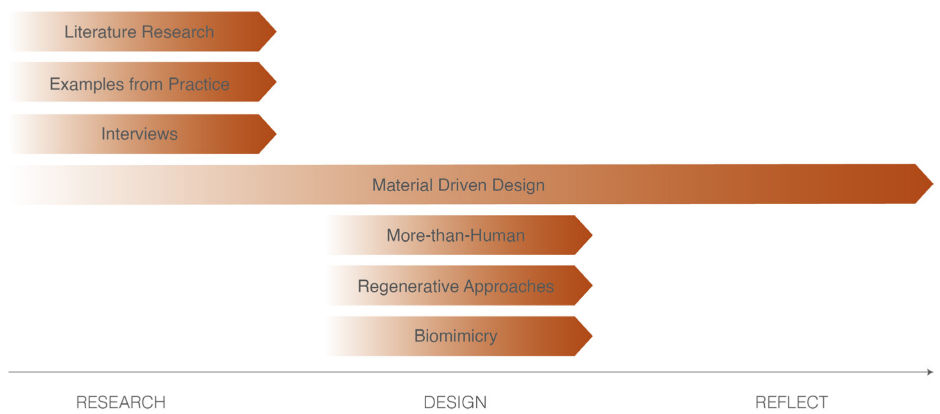

Figure 5. Project approach

3.2.1 Research Approaches

To start, a **literature review** was conducted on the contextual problem. A review that focused on the threats posed by climate change in urban areas, the role of the construction industry in worsening these issues and the impact of materials and their utilization. The research also examined the evolution of facade design over the past century and anticipated future trends in facade design.

interviews were conducted in a semi-structured format, where each expert was asked the same questions, followed by deeper exploration based on their responses. The interviews focused on their vision for the future of facades, particularly regarding innovation, sustainability, and challenges in the field. Some experts have been consulted multiple times, again during the design or reflection phase.The questions are provided in Appendix B.

The experts interviewed are:

- *Willem Bottger* and *Mark Lepelaar* - Founders of NPSP and Nabasco
- *Marco Vermeulen* - Architect at Studio Marco Vermeulen (designed the nature-inclusive panels for NPSP, see figure FIXME)
- *Wouter* - Biology student (participated in monitoring the ecological aspects of the nature-inclusive panels and completed his graduation project on integrating nature into urban construction)
- *Olga Ioannou* - Assistant Professor in Building Innovation and Circular Built Environment, Faculty of Architecture and the Built Environment
- *Laura Lee Stevens* - Professor of Biomimicry Design Education at The Hague University of Applied Sciences
- *Bas Adib* - Founder of Into the Wild (supporting companies to innovate with nature-based design)
- *Jos de Krieger* - Architect at Superuse
- *Ward Groutars* - PhD Candidate TU Delft (involved in multiple projects on bio-receptivity)
- *Auke Bleij* - Founder Respyre
- *Peter Mooij* - AMS Institute

As part of the research, a **material analysis** of the material in question N-8040, was carried out that depicts both the technical and experiential properties of the material. The method followed for this purpose is the Material Driven Design Method.

3.2.2 Design Approaches

In the next phase, designing, there are three approaches that are used or are inspired by:

- More-than-Human Design Approach
- Regenerative Approaches
- Bio-inspiration

More-than-Human Design

The conventional human-centered design approach, where human needs and desires are the highest value in design, is increasingly viewed as insufficient for tackling today's global challenges. There is a rising acknowledgment for the need of a more widespread perspective that includes the "more-than-human" realm, considering all forms of life and systems. The more-than-human concept acknowledges that human life and society are deeply connected in a web with non-human entities, such as plants, animals, technologies and natural systems. When designing with the More-than-Human Design approach in mind, you shift from designing *for* humans to designing *with and within* ecosystems, ensuring that all life forms and systems are considered in the process (Giaccardi, E., Redström, J., & Nicenboim, I., 2024).
Figure 6 envisions the shift from human-centered approach to a more-than-human centered approach.

Regenerative Approaches

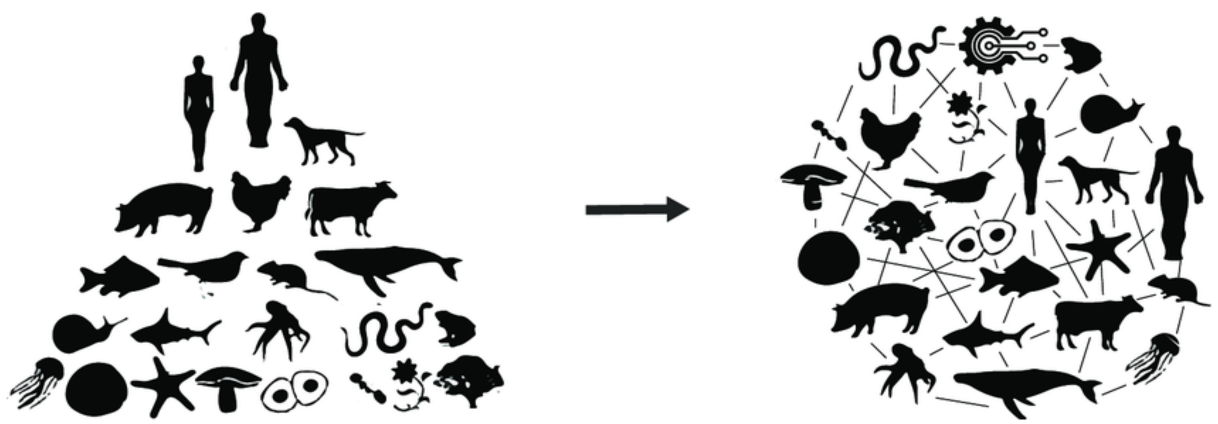

Figure 6. Human-centered approach to a More-than-Human approach (Lehmann, 2019)

Regenerative approaches focus on enhancing the health of ecosystems. Rather than adhering to the principles of *"recycle, reduce, and reuse"*, these approaches emphasize *"restore, renew, and replenish*". As the destructive effects of climate change become increasingly apparent, regenerative designs are one of the solutions to take measures to protect our planet. They not only minimize harm to the environment and communities, but also actively contribute to restoring the environment (The Global Institute of Regenerative Design, n.d.).
In regenerative ecosystems the relationship between humans and nature goes beyond just being separate. Instead, they work together as one system, which shows the relation of the More-than-Human approach and regenerative approaches (Karana, E., McQuillan, H., Rognoli, V., et al., 2023).

Biomimicry

"Biomimicry is basically taking a design challenge and then finding an ecosystem that's already solved that challenge, and literally trying to emulate what you learn." - Janine Benyus

Biomimicry serves as a tool for drawing inspiration from the solutions that nature has developed through natural selection. These solutions are applied to human engineering and design. All in all, it focuses on abstracting and adopting the functions of living organisms.
The rationale behind utilizing bio-inspiration for design solutions is that nature has undergone millions of years of evolution, demonstrating that these strategies and mechanisms are often more effective at working in harmony with the rest of the natural world than many human-developed approaches (Biomimicry Institute, n.d.).

Figure 7. Human-centered approach to a More-than-Human approach (Lehmann, 2019)

Research

The first phase of the project focuses on research. This chapter outlines the investigation based on the three foundational pillars of the project: environment (section 2), materials (sections 3 and 4), and facades (section 5).

The project addresses the challenges currently faced by urban areas and those anticipated in the future. These challenges, along with the environmental impact of the construction industry and its materials, are discussed in the environment section.
The solution to the problems posed by these conventional, polluting building materials lies in the adoption of eco-friendly alternatives, with NPSP's biocomposites representing an optimal choice. These materials are carbon-negative, made from natural resources, and provide additional economic advantages. Section 3 presents NPSP as a company, while section 4 dives into the details of biocomposite materials.
The final pillar focuses on facades, discussed in section 5. This section explores the evolution of facades over the last decade, revealing insights not only about architectural design but also about the zeitgeist, technology, culture, and society. These factors are considered in the project's design to ensure it resonates with contemporary trends while also being timeless.
The section concludes with insights from interviewed experts regarding the vision for the future of facades and their key characteristics. Several case studies are presented to illustrate this vision.

The research is followed with an analysis of the material in question, N-8040, which is considered the initial step in the Material Driven Design Method, aimed at understanding the material. This understanding involved examining its composition and technical properties, conceptualizing the production process, and comparing it with other biocomposites and materials designed for the same use, facade cladding. User tests were conducted to evaluate the material's experiential qualities, using the Experiential Characterization Toolbox created by E. Karana and B. Barati in 2018.
Lastly, a brand analysis of NPSP was carried out through a SWOT analysis to identify the company's strengths, weaknesses, opportunities, and threats.
By the end of this research, insights have been gathered to shape a vision for designing the facade panel.

4. Environment

4

4.1 Call for Action

Around the world, temperatures are rising, glaciers are melting, and weather patterns are becoming unpredictable. Each heatwave, flood, and wildfire highlights that small, incremental changes are no longer sufficient. Climate change is one of the main challenges of this century. Over the past 65 years significant global shifts have developed (Abbass, K., Qasim, M.Z., Song, H. et al. 2022), meaning that climate change may be one of the biggest dangers to humanity, if we do not act.

To indicate the urgency for action, the framework of planetary boundaries is presented (Figure 9). This framework helps to understand the relationship between humans and the planetary ecosystems that sustain us. It presents the limits for humanity to sustainably coexist with the planet, based on nine critical processes on the earth. These nine boundaries include: ozone layer depletion, the health of the biosphere, chemical contamination, climate change, ocean acidification, the use of freshwater, changes in land systems, disruptions to nitrogen and phosphorus cycles, and the presence of aerosols in the atmosphere. The framework updated in 2023 shows us that we have crossed six of the nine boundaries.

This call for action is reflected in the Sustainable Development Goals (SDGs) that the United Nations adopted in 2015. It is a universal call to protect people and the planet. This framework represents 17 goals that serve as a guide to conserve and improve our economies, environments and societies focused on equity, resilience and sustainability.

4.2 Sustainable Cities

The Sustainable Development Goals are designed for a global context, but if we zoom in on Dutch cities, we can see that several of these goals are relevant here. Dutch cities, renowned for their culture, architecture and often forward-thinking perspective are increasingly facing climate-related challenges. This project focuses on a few of the urban challenges that are related to the following Sustainable Development Goals:

SDG 11: **Sustainable Cities and Communities**
SDG 12: **Responsible Consumption and Production**
SDG 13: **Climate Action**
SDG 15: **Life on Land**

Urban Heat Island Effect (SDG 11, SDG 13)

Besides the global effect of climate warming, this process is amplified in cities. Dutch cities, like many other urban areas worldwide, face the Urban Heat Island (UHI) effect. A phenomenon in which cities are significantly warmer than surrounding rural areas due to dense buildings, asphalt and a lack of greenery. Unlike vegetation and other natural surfaces, modern building materials absorb heat instead of reflecting it (Heaviside, C., Macintyre, H., & Vardoulakis, S., 2017).
The map in Figure 8 shows the UHI effect in the Netherlands in 2020. The figures on the map are averages for the summer season (June, July, August). The temperature difference between city and surrounding area remains maximum 3 degrees over this period. On some summer days, the difference can be as high as 7 or 8 degrees Celsius (RIVM, 2020).

This phenomenon leads to several hazards, such as increased demand for cooling, which leads to higher energy requirements and greenhouse gas emissions. Also, living organisms in urban areas face challenges due to changing conditions (Heaviside, C., Macintyre, H., & Vardoulakis, S., 2017).

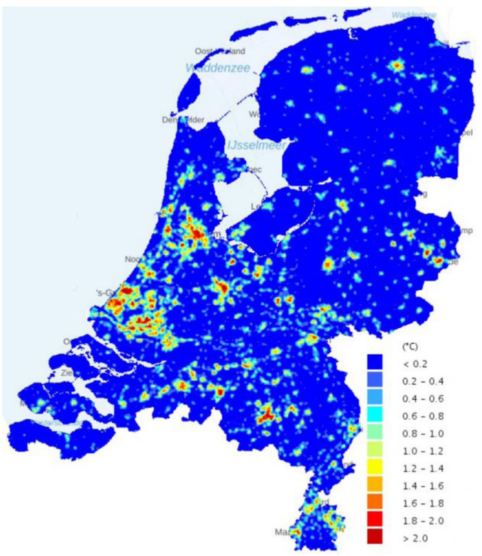

Figure 8. Urban Heat Island Effect in the Netherlands, 2020 (RIVM, 2020)

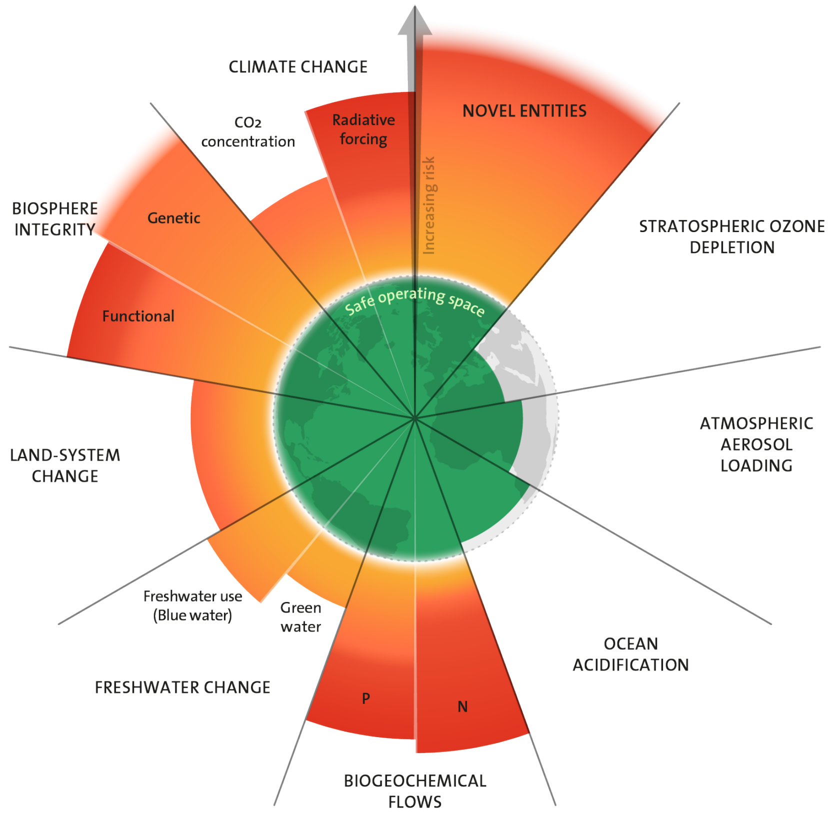

Figure 9. Planetary Boundaries in 2023 (Stockholm University, 2023)

Figure 10. UN Sustainable Development Goals (UN, 2015)

Extreme Rainfall and Danger of Flooding (SDG 11, SDG 13)

As climate change intensifies , Dutch cities face more and more extreme rainfall events. Urban areas covered in impermeable surfaces such as concrete and asphalt increase the risk of flooding.
Extreme precipitation events in the Netherlands have increased sharply. Most striking is the increase in the number of days with heavy precipitation, i.e. days with more than 50 mm of precipitation. This number has increased by 85% since 1951.
Besides extreme precipitation, the annual precipitation amount in the Netherlands rose uniformly from 694 to 875 millimetres over the period 1910-2022. This is an increase of 26% in 113 years, see figure 11. This is mainly due to the rise in temperature (Compendium for the Living Environment, 2023).

"Cities receive significantly more rainfall than surrounding areas"- NRC, 2024

Next to encountering more extreme rainfall overall, cities receive more rainfall than the surrounding areas. This phenomenon is related to the UHI effect. Heat in cities promotes the formation of rain clouds. And tall buildings can influence wind patterns and delay storms, which can lead to more intense rainfall over cities. In addition, exhaust fumes and pollution contribute to cloud formation (Niyogi, D., Lei, M., Kishtawal, C., et al, 2017).

The danger of extreme rainfall events can overload drainage systems and increase the risk of flooding and water contamination from overwhelmed wastewater systems.

Loss of Urban Biodiversity (SDG 15, SDG 11)

Urbanization poses significant challenges to biodiversity, particularly in densely populated regions. In cities green spaces are shrinking, leaving limited room for biodiversity to thrive.
In a UN report published in 2019, scientists warned that one million species, out of an estimated total of 8 million, are on the verge of extinction, many of them already within a few decades. One of the major causes is habitat change, including urbanization (European Parliament, 2021).

The related dangers are the reduction of biodiversity in cities, which reduces air quality and ecological health of cities. Another danger is the reduced mental and physical well-being of city dwellers, who rely on green spaces for recreation and stress relief (Tzoulas, K., Korpela, K., Venn, S., et al, 2007).

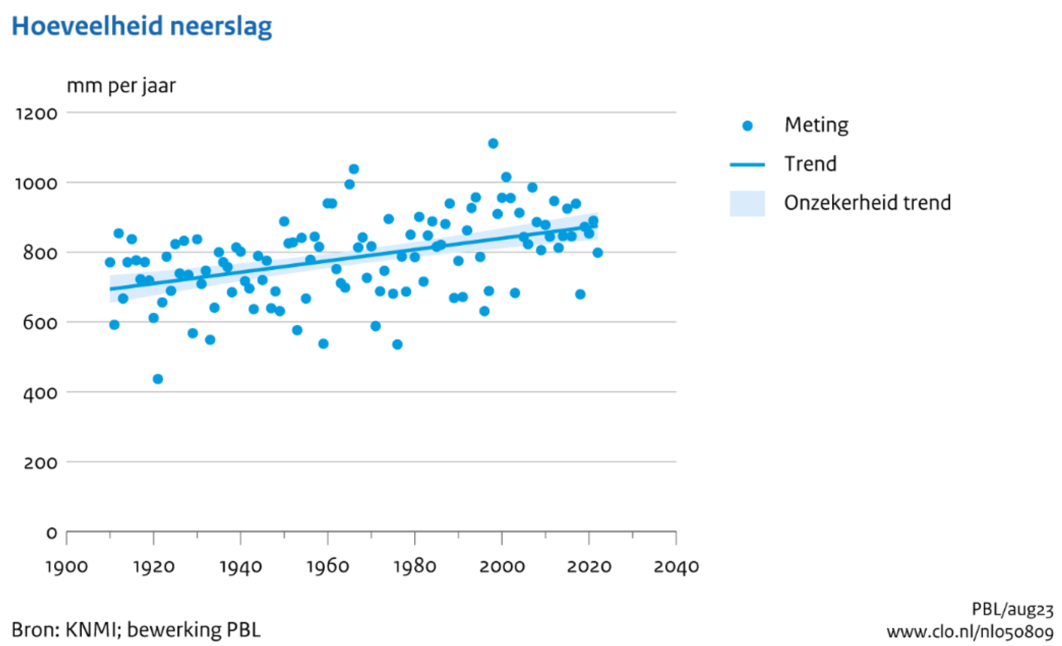

Figure 11. Amount of rainfall from 1910-2022 in the Netherlands (CLO, 2023)

Unsustainable Resource Use (SDG 12, SDG 13)

Cities encounter significant challenges in adopting circular economies. The construction industry is one of the extensive contributors to climate change. The construction and use of the built environment has led to high levels of CO2 emissions (IEA, 2019). As urbanization continues, there is more and more demand for living and working facilities.
The construction sector encompasses a diverse range of activities and phases, including the production of building materials, construction practices, building operation, and decommissioning. Its expansion has a profound direct and indirect impact on the environment, making it one of the largest consumers of natural resources and significant generators of waste (Bilal, M., Khan, K.I.A., Thaheem, M.J. et al., 2020).

4.3 Impact of the Construction Industry

To gain insight into the construction industry and its material usage, as well as the potential role of new sustainable materials, it is essential to first analyze the impacts and effects associated with this sector. This analysis will clarify the implications and opportunities for the adoption of innovative materials. Starting with portraying the (in)direct impacts of the construction industry. These can be categorized in three categories:

The first category of environmental impact of the construction sector is the **impact on ecosystems**. The construction sector is responsible for significant energy consumption and emissions of greenhouse gasses such as CO2, particulates, carbon monoxide, sulfur dioxide and nitrogen oxides. The high energy consumption in this sector causes an increase in the concentration of CO2 in the atmosphere and accounts for approximately 39% of global CO2 emissions in 2019 (IEA, 2019), see figure 12. One of the main sources of the emissions in this sector is the disposal of waste and consumption in the production of the raw materials (Ahmed Ali, K., Ahmad, M.I., Yusup, Y., 2020).

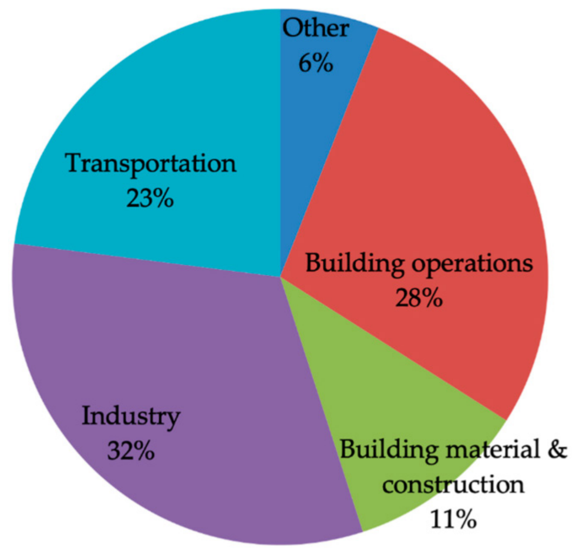

Figure 12. Global CO2 emissions by sectors (Ahmed Ali, K., Ahmad, M.I., Yusup, Y., 2020)

The second category is the **impact on public health**. Pollution poses not only a threat to the climate but also to human well-being. The release of pollutants contributes to air pollution, which can be harmful to humans and other living organisms when present in high concentrations. Areas with dense populations, particularly cities, tend to have the poorest air quality (Wieser, A.A., Scherz, M., Passer, A. et al., 2021). Figure FIXME illustrates air quality in the Netherlands, specifically focusing on nitrogen dioxide and particulate matter. The data reveals that these pollutants are most concentrated in urban centers and along major roadways. Additionally, livestock and extensive industrial activities also contribute to particulate matter.

The ongoing trend of urbanization is likely to result in an increasingly unhealthy urban environment for a growing number of people. According to the United Nations, by 2050, approximately 68% of the global population is expected to reside in cities or urban areas (WHO, 2028).

The third and final category of environmental **impact is on natural resources**. The construction industry consumes a large proportion of non-renewable raw materials. This industry is responsible for 40% of the global consumption of raw materials in 2017 (UN Global Alliance for Buildings and Construction, 2017).

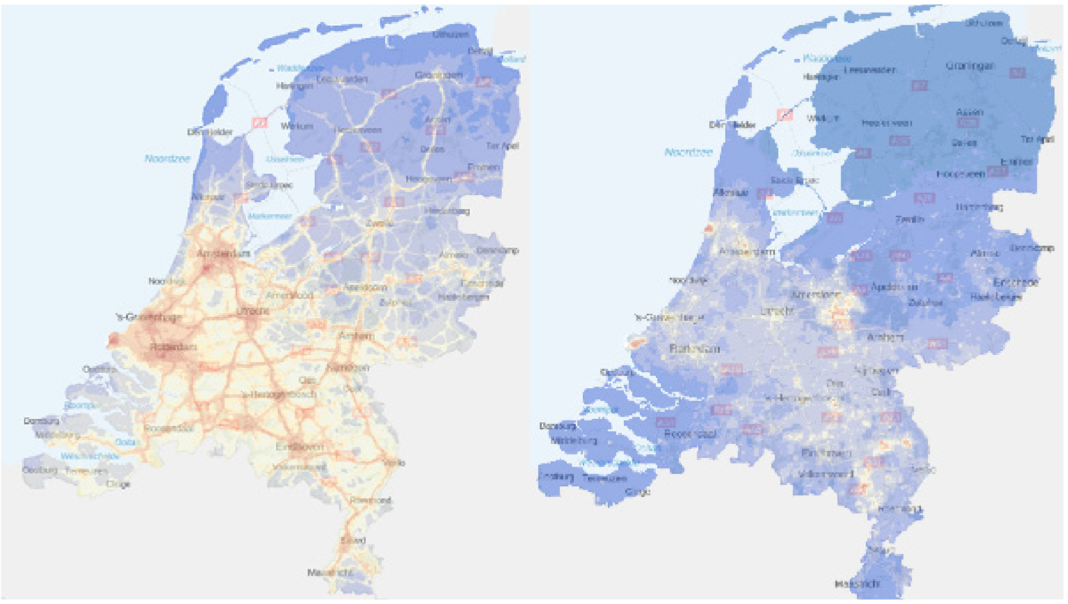

Figure 13. Concentration of nitrogen dioxide (left) and particulate matter (right) in the Netherlands in 2017 (Atlas Leefomgeving, 2017)

4.4 Material Effect

We narrow our focus from the broader industry to the specific stage of material production. The manufacturing of these materials involves a series of distinct steps and activities, each of which holds its own environmental impact.

A full life cycle stage of building materials include the following: extraction of raw materials, processing and production of these raw materials, transportation, construction and adaptation, use and maintenance, demolition and waste management, disposal and circular processing through reuse, recycling and recovery (Huang, B., Gao, X., Xu, X. et al, 2020). See figure 14.

Each activity in this material life cycle requires an input (energy, raw materials) and releases an output (pollutants, waste). The Life Cycle Assessment (LCA) is a method to display and assess the environmental impacts of a material or product. In short, The LCA represents the environmental impact per stage. Figure FIXME presents these key environmental impacts during the life cycle of building materials.

In terms of the input, the production of building

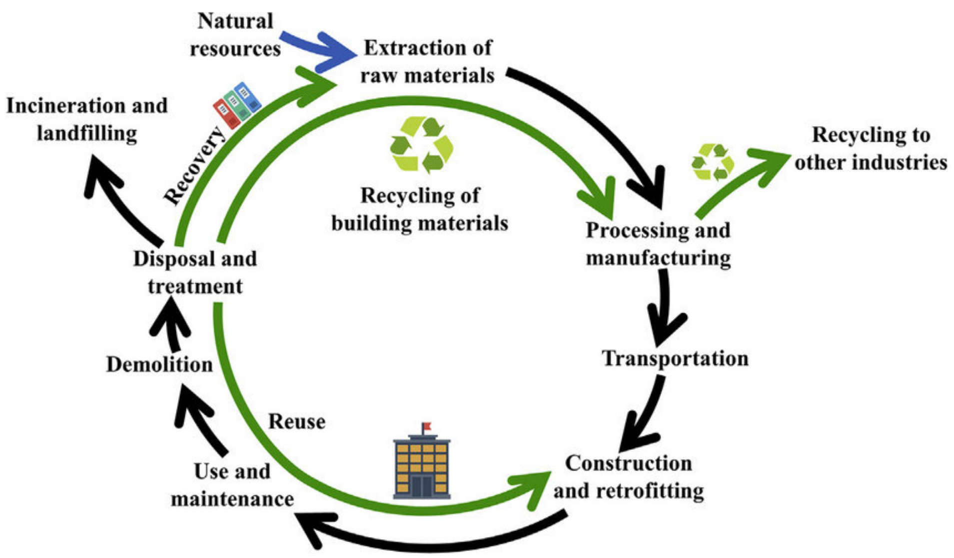

Figure 14. Building Material Life Cycle (Huang, B., Gao, X., Xu, X. et al, 2020)

materials leads to the depletion of non-renewable resources. Resources for both the raw material and used as energy source. Figure 15 also shows that multiple activities consume water, which is often drinking water. Besides, harmful chemicals are used to process or recycle most construction materials (Sharma, N.K., 2020).
In terms of output, 90% of the pollutants released in the life cycle come from the extraction and production of construction materials. The other 10% is caused by transport, construction and treatment of construction waste. Another output of the different stages is the amount of waste generated in landfills (Huang, B., Gao, X., Xu, X. et al, 2020).
These outputs can have various harmful impacts on the environment:

- Climate change
- Acidification: acidification of soils and waters can damage ecosystems, especially plants.
- Eutrophication: an increase in nutrient concentration in ecosystems, which can lead to imbalances such as desertification or super fertilization.
- Ozone depletion
- Human health damage
- Other environmental impact

The impact of construction materials can vary significantly depending on the material in question. Figure 16 gives an indication of the ecological impact of individual construction materials. This impact is shown in Global Warming Potential (GWP). The GWP reflects the carbon footprint of the material, it calculates how much heat a given amount of gas (released by 1m^3 of the material in question) can retain in the atmosphere, compared to the same mass as CO2 (Souza, E. 2022). The figure shows that metals, paint, PVC and ceramic tiles have the highest carbon footprint and wood, on the other side, absorbs CO2, resulting in a negative carbon footprint.

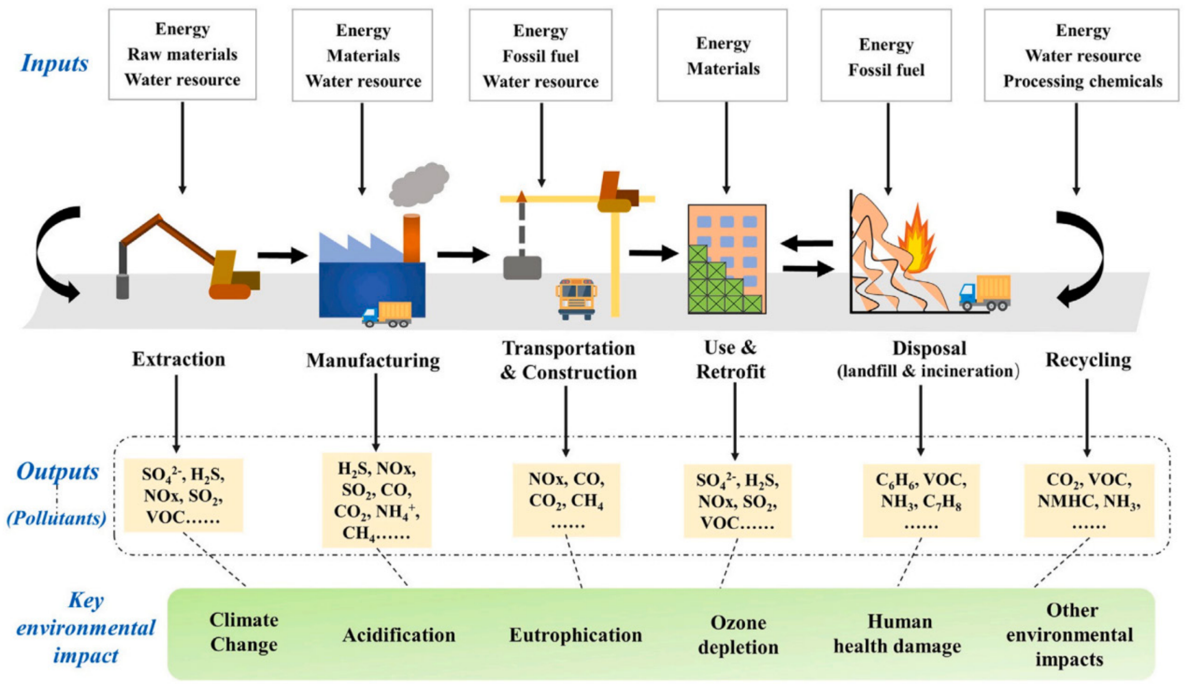

Figure 15. Key environmental impacts during the Life Cycle of Building Materials (Huang, B., Gao, X., Xu, X. et al, 2020)

Figure 16. Carbon Footprint per construction material (Souza, E. 2022)

4.5 What does this mean for Design?

In conclusion, the need for eco-friendly building materials is evident, driving innovation in the development of sustainable alternatives that not only minimize environmental harm but also conserve resources and reduce costs. These materials should not compromise on performance, and are required to meet the needs for durability, reliability, and functionality of conventional building materials. Therefore, these eco-friendly materials should fulfill the following criteria (Yahia, A. K. M., Rahman, D. M. M., Shahjalal, M., et al, 2024):

- **Renewable sources**: These materials are sourced from renewable origins, such as biobased materials derived from plant or animal biomass. Another category of eco-friendly materials includes those made from waste. Increasing amounts of waste are being repurposed as valuable input materials. The key focus with waste-based materials is to transform them into usable and non-toxic products through the application of efficient and environmentally friendly processes. Ideally, a material should be entirely biobased and/or waste-based, rather than partially so.
- **CO2-neutral or negative**: Some materials have a negative carbon footprint, acting as a 'carbon sink'. They store a certain amount of CO2, and so contributes to clean our air. This often occurs with materials derived from plant biomass.
- **Smart and efficient production processes**: To minimize waste, smart production processes are introduced with minimal or no waste produced. An example is the process of 3D-printing.
- **Circularity**: At the end of its life cycle, a material should ideally possess one or more of the following qualities: reusability, recyclability, or biodegradability. In cases of reuse or recycling, Closed Loop Recycling is the preferred method. This approach involves returning all materials after their lifetime, along with those generated during the production process, back into the manufacturing cycle as raw materials for new products. As illustrated in figure 14, this method closes the loop of the Material Life Cycle while also reducing production steps.

5. Facades

In this section we dive into the second foundational pillar of the project, facades. A facade involves much more than just the material, it also incorporates various elements such as functionality, aesthetics, and cultural significance.

This chapter reflects on the evolution of facades over the past century. What have been the key developments in facade design over the last 100 years? How has the role of the facade and the priorities of architects shifted during this period? Today, the focus continues to evolve; what are the current trends, and what will be the defining features of facades in the years to come?

5.1 Short history on Facades of the last Century

Facades play a fundamental role in architectural design, it's the first thing to notice when approaching a building. A facade bridges technological values, artistic aspirations and cultural values. A facade acts as the outer skin of a building that stays in contact with both environmental forces and public perception.
From the ancient temples to modern skyscrapers, each era redefines the purpose and potential of building exteriors and reflects a pursuit of beauty, function, and innovation. Over centuries, architects evolved their approaches, based on social, technological and environmental developments.

This chapter will shortly describe the history of facades over the last century, reflecting the mindset and developments of facade design.

Figure 17. Chrysler Building, New York, William van Alen, 1930 (archdaily, 2019)

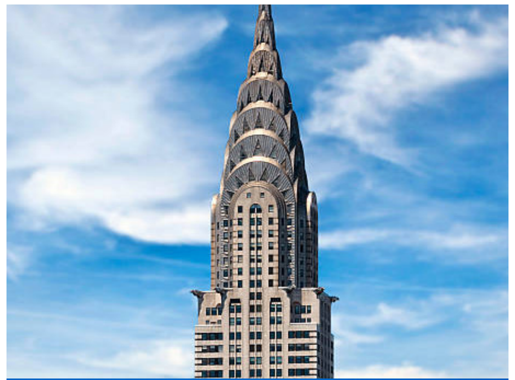

Figure 18. Villa Savoye, Poissy, Le Corbusier, 1928 (wikipedia, n.d.)

1920s–1930s: Decorative (Art Deco), Simplicity and Functionalism (Early Modernism)

The 1920s and 1930s marked the emergence of the Art Deco movement, which emphasized decorative yet sleek facades. This style featured geometric shapes, striking lines, and decorative motifs, an example is the Chrysler Building in New York.
In contrast, Early Modernism was initiated by architects such as Le Corbusier and Walter Gropius. This era prioritized simplicity and functionality, with facades designed to showcase clean lines and minimal ornamentation. Architects used materials like concrete and steel to imitate an architectural language of industrial aesthetics.

Figure 19. Central Post, Rotterdam, Kraaijvanger, 1959 (CBRE, n.d.)

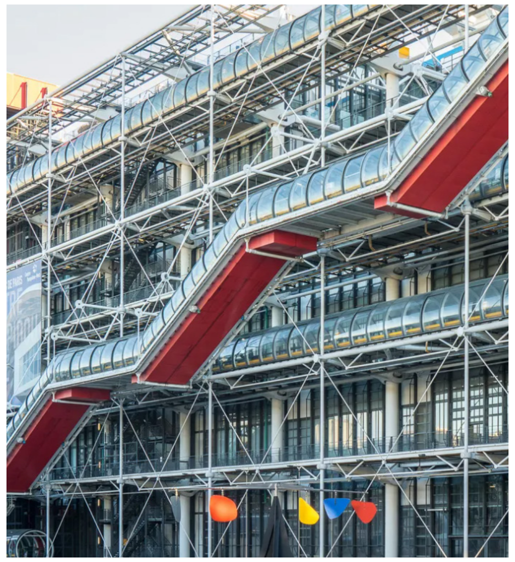

Figure 20. Centre Pompidou, Paris, Renzo Piano et al, 1977 (tiqets, n.d.)

Figure 21. Haas Haus, Vienna, Hans Hollein, 1990 (mixed materials) (wikipedia, n.d.)

1940s–1950s: Functionalism and cost efficiency (Post-war)

After the Second World War, architecture shifted its focus toward functionalism and economic efficiency. Facades from this era were often simple and utilitarian, typically featuring straightforward brickwork or concrete. The priority was on cost-effective construction to address the demands for housing and infrastructure.
The style of Brutalism was introduced during this era. It is characterized by its massive, block-like forms and the use of raw concrete.

1960s–1970s: Introduction of advanced technology

In the late 1970s the high-tech movement was introduced, which emphasized the visibility of a building's structural and mechanical systems in its facades. Designers like Richard Rogers and Norman Foster present exposed frameworks and modular elements, for example in the Centre Pompidou in Paris. Additionally, curtain wall systems were introduced in high-rise buildings. A curtain wall is a non-load-bearing facade, allowing it to consist of light materials such as glass. These glass-and-steel facades represented a shift towards transparency and a modern aesthetic.

1980s–1990s: Postmodernism, Energy efficiency and New materials

In the 1980s and early 1990s, facades were shaped by postmodernism, shifting away from the functionalism and minimalism of modernism. Technological advancements continued, and the energy crisis of the 1970s had a huge impact on architectural priorities throughout the 1980s and 1990s. Facades began to incorporate energy-efficient strategies such as enhanced insulation, solar shading, and energy-efficient glazing. Although environmental concerns were on the rise, they had not yet become a main focus they are nowadays. The development of new materials grew, innovations like composite panels, high-performance concrete, and advanced polymers enabled more possibilities and greater creativity in facade design.
Architects started to experiment with mixed-material facades, blending traditional elements such as brick with contemporary materials to create distinctive aesthetics, an example is Haas Haus in Vienna.

Figure 22. Institut du Monde Arabe, Paris, Jean Nouvel, 1987 (energy efficiency) (imagoDens, 2022)

Figure 23. Bosco Verticale, Milan, Boeri Studio, 2009 (archdaily, n.d.)

Figure 24. Heydar Aliyev Centre, Baku (Azerbaijan), Zaha Hadid, 2012 (BEGA, n.d.)

2000s–2010s: Sustainability and Innovation

Facade desivgns increasingly prioritized sustainability, incorporating elements such as double-skin facades, green walls and continued on the development of energy-efficiency. Cladding materials help regulate indoor temperatures and lower energy consumption.
Advanced materials played a crucial role during this time, enhancing both aesthetics and functionality; for instance smart glass that can modify its transparency. Designers also began to create facades that respond to their surroundings, including kinetic facades that alter shape and light-filtering systems that adjust to varying sunlight levels.

2020s–Present: Algorithms and Adaptive design

Modern facades started to utilize parametric design to produce distinctive patterns, resulting in complex and efficient facades. Parametric design is a computational method that uses algorithms to create and modify architectural shapes.

Current facade design emphasizes environmental performance, incorporating solar panels into building exteriors and employing bioclimatic principles to enhance natural ventilation. Recent facades prioritize integrating adaptive technologies, where the facade responds to the environmental conditions. Think of photovoltaic cells (solar cells) and responsive shading systems that adjust to weather conditions, which maximizes energy efficiency and increases comfort inside the building.

5.2 Facade of the Future

“I think nature should become an integral part of the facade.” - Marco Vermeulen

In an interview with architect *Marco Vermeulen*, he emphasized his vision of the future where facades are nature-inclusive. Reflecting this perspective, Vermeulen together with NPSP designed a facade panel incorporating nesting boxes for insects and birds, aiming to enhance the biodiversity. Similarly, architect *Jos de Krieger* from Superuse and nature-based design expert *Bas Adib* agree that a modern facade should not exist in isolation but is part of the surrounding ecosystem and actively participates in and contributes to it.

“Buildings of the future serve the ecosystem in the future” - Bas Adib

Facades and its focus have transformed over time. Primarily it served from technical purposes as structural integrity to adding aesthetic value. However, as climate change and urban sustainability concerns increase, the role of facades is undergoing a profound transformation. Facade design is increasingly shifting from a passive role to one that actively contributes to environmental resilience. Traditional facades are adapting to new sustainability standards, focusing on the development of materials, technology and structural configurations to improve energy performance and integrate climate-adaptive functions.
Overall, facades are shifting to multifunctional systems that are built in symbiosis with its surroundings.

Qualities of the facade of the future can be defined as: modular, resilient and responsive to both environmental and social demands. These evolving facades are not only expected to protect and insulate buildings, but also to change the way people experience architecture, bridge the gap between functionality and aesthetics and ultimately reflect our vision of a sustainable world.

The benefits of these future facades go beyond environmental gains. They offer social and economic benefits and align with the following Sustainable Development Goals (SDGs); *SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).* Through innovative designs, facades can play a role in shaping more sustainable, liveable and resilient cities for the future.

5.3 Facade Cladding Case Studies

To illustrate the vision of the development where facades harmoniously integrate with the surrounding ecosystem, some recent examples that embody this principle are highlighted.

Figure 25. Nature-inclusive panels (NPSP, 2024)

Facade panels - NPSP & Marco Vermeulen, 2023

An interesting example of innovative design that merges nature with architecture is a project by NPSP in collaboration with Marco Vermeulen, that is already mentioned above. These nature-inclusive panels feature openings that form fly-in openings for birds and insects, with wooden nesting boxes positioned behind the panels. The primary goal of this design is to enhance urban biodiversity, a significant challenge in recent years. A forward-thinking design like this demonstrates how the built environment can integrate with and actively support the surrounding ecosystem.

Elephant Skin - bioSEA, 2024

The Elephant Skin by bioSEA is a facade tile designed to enhance sustainability by integrating environmental principles into its structure. The Elephant Skin Tile is established by mimicking the fractal-like bumps and cracks of elephant skins. These natural characteristics allow the elephant to remain cool by providing shade, capturing cool air, and expanding the surface area for water evaporation. As a result of the biomimicry, the tile enhances passive cooling by facilitating airflow, minimizes heat absorption and captures and channels rainwater.

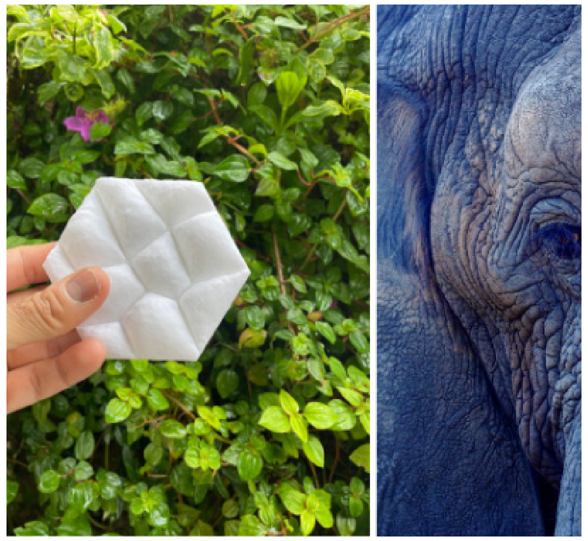

Figure 26. Elephant Skin Tile (bioSEA, 2024)

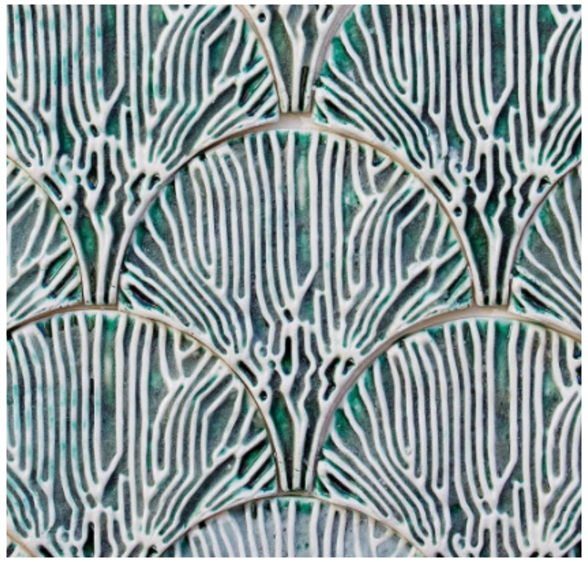

Figure 27. Algae Tiles (Bio-ID Lab, 2019)

Algae Tiles - Bio-ID Lab, 2019

The Algae Tiles developed by Bio-ID Lab exemplify a bio-receptive design that promotes sustainability by harnessing nature’s capabilities. Shaped like fans with vein-like channels, these tiles mimic the structure of leaves, effectively distributing water evenly across the surface. They are infused with a seaweed-based hydrogel and microalgae that remove pollutants from the water flowing over. Once collected at the bottom, the water is filtered to clean drinking water. This integration of living organisms into architectural design highlights the potential for buildings to benefit and coexist with nature while addressing ecological challenges.

Cellular - Vivian Tamm, 2023

Cellular is a water-storing green facade tile. The hollow ceramic panels act as rainwater reservoirs, ensuring a humid environment that provides an ideal habitat for vegetation. This effective water retention capacity addresses the challenges posed by (heavy) rainfall. The presence of stored rainwater offers natural cooling, while the layer of algae actively absorbs, breaks down, and eliminates airborne pollutants and serves as a habitat for various small organisms.

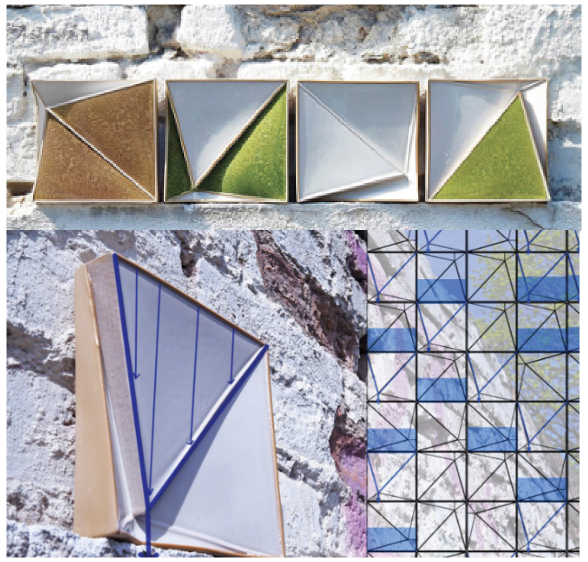

Figure 28. Cellular Tile (Vivian Tamm, 2023)

6. Material: Introduction of Biocomposites

6

Drawing from the key insights in Chapter 4.5, “What Does This Mean for Design?” this section emphasizes the necessity for eco-friendly building materials within the construction industry. This section concludes that eco-friendly materials should be derived from renewable sources, have a CO2-negative or neutral impact, be produced through smart and efficient processes, and be circular in nature. A material that fulfills all these criteria is biocomposite.This chapter explains why and provides an introduction to bio-composites, outlining their composition, environmental and economic benefits, and offers an overview of human perceptions regarding these materials.

6.1 Composition of Biocomposites

A bio-composite material consists of three primary components: the matrix, fillers, and fibers, mainly or entirely biobased. Table 1 clarifies the function, composition and properties of each ingredient. By selecting specific materials for each component and adjusting their relative proportions, it is possible to tailor the bio-composite’s functional and mechanical properties. The elements within a bio-composite form durable chemical and mechanical bonds, which influence both the strength and longevity of the material (Murawski et al., 2019).

6.2 Environmental Promise

The choice of the raw materials for each component plays a significant role in the composite’s environmental impact. Bio-based materials can capture and store CO during their lifecycle. This enables certain organic materials - especially those with minimal emissions during cultivation or sourced from bio-based waste - to achieve a low or even negative carbon footprint (Correa et al., 2019).
An 2012 analysis of 44 life cycle assessments on bio-based materials found that producing one metric tonne of bio-based material saves 55±34 gigajoules of primary energy and reduces greenhouse gas emissions by 3±1 metric tonnes of CO equivalents.

Bio-composite

	Matrix	Fibre	Filler
Function	The matrix is the primary bonding element; holding the fillers and fibers together.	Fibers reinforce the bio-composite. It enhances its strength, stiffness, and load-bearing capacity.	Fillers serve multiple purposes, such as reducing the overall cost of the bio-composite and enhancing certain mechanical properties. They can also modify the bio-composite’s weight, density, and thermal conductivity.
Composition	Bio-based polymers or resins.	Bio-based fibers can vary a lot. Commonly used fibers are flax, hemp, jute and bamboo, which offer high strength-to-weight ratios.	Bio-based fillers often include agricultural or industrial waste material.
Properties	The matrix provides ductility, impact resistance, and environmental protection for the fibers.	The fibers improve tensile strength and rigidity.	Fillers can increase compressive strength, modify stiffness, and sometimes contribute to biodegradability.

Table 1. The function, composition and properties of the components of a biocomposite (Murawski et al., 2019).

However, bio-based materials were associated with higher levels of eutrophication and ozone depletion compared to fossil-based alternatives, primarily due to the use of pesticides and fertilizers in industrial biomass cultivation. The study did not account for land-use impacts such as biodiversity loss, soil carbon depletion, erosion, deforestation or greenhouse gas emissions resulting from indirect land-use changes (Weiss et al., 2012).
There are several biobased materials that can be used for biocomposites. One option is using organic waste and forest or agricultural residues. There are numerous innovative developments taking place in the field of waste-based materials. For example, waste from feedstocks, such as chalk filtered from our drinking water or agricultural byproducts. Using waste biobased materials as raw materials also counteracts eutrophication, as no new plant or animal biomass needs to be cultivated.

Biocomposites are regarded as circular materials to a certain extent, depending on their composition and end-of-life management. Factors such as whether they are made from renewable sources, feature biodegradable matrices, and allow for the recycling of natural fibers play a significant role. Concluding that biocomposites can play an important role in the transition towards environmental sustainability and circular economy (Mikola, 2024).

The common production processes for biocomposites utilize molds, which helps minimize waste material:

- *Resin Transfer Molding (RTM)*: Resin is injected into a mold filled with natural fibers.
- *Compression Molding:* A pre-impregnated fiber-resin mixture is placed in a heated mold and pressed into shape.
- *Extrusion Molding*: The heated material is forced through a shaped die.

6.3 Economic Values

Bio-composites offer potential economic advantages, especially through the use of plant-based materials. While additional processing steps may be necessary, bio-based materials often cost less than their synthetic alternatives. Biological fillers or fibers can significantly lower the production costs of bio-composites. Natural fiber-based composites require 17% less energy compared to synthetic fiber-based composites (Akter et al., 2022).

The inclusion of waste materials offers even greater potential for cost reduction. Waste materials are often available at low prices from processing industries. This not only lowers raw material expenses but also supports waste valorization, turning industrial by-products into high-value materials. Developing and producing bio-based composites can create mutual economic benefits, fostering benefits for material producers and industries that generate waste (Rodríguez et al., 2018).

By combining natural ingredients, lower production costs and waste utilization, bio-composites represent an economic and sustainable alternative to traditional materials.

6.4 Perception of Biocomposites

Biocomposites can exhibit a variety of appearances and textures depending on their ingredients, production methods, and the preferences of the client or manufacturing company.

Despite a growing awareness of environmental issues, the demand for biocomposites in the market did not see significant growth until 2022. This limited interest can primarily be attributed to two factors: the perception that biocomposites possess lower functional properties compared to traditional materials, and the belief that they lack desirability (Manu, T., Nazmi, A. R., Shahri B. et al., 2022).

To overcome these perceptual barriers, it is essential to enhance the attractiveness and distinctiveness of biocomposites. Important factors that could improve perceptions include natural aesthetics and the unique sensory experiences that biocomposites can provide. By highlighting these attributes, the market appeal of biocomposites may increase, aligning them more closely with consumer values and the growing demand for sustainable and aesthetically pleasing materials (Manu, T., Nazmi, A. R., Shahri B. et al., 2022).

The broad adoption of biobased composites in product design encounters challenges owing to perception-related constraints. Thundathil et al. (2023) conducted a research on the visual and tactile perception of biobased composites, which examines how sensory evaluation, combining both visual and tactile assessments, affects perceptions of these materials. The biocomposite and natural samples that have been assessed are displayed in figure 29.

The findings of the research indicate various correlations among perceptual attributes, which can be summarized as follows:

- *Complexity x Unusualness x Interesting*
- *Smoothness x Worth x Simplicity x Strong*
- *Simplicity x Artificiality x Strength x Ordinary x Boring*
- *Naturality x Roughness*
- *New x Boring*
- *Beauty x Worth x Naturality*

Attributes such as *natural, beautiful*, and *valuable* exhibit positive interconnections, influenced by a combination of visual and tactile qualities. Attributes like *complex, interesting*, and *unusual* also show a positive correlation, but are primarily shaped by visual stimuli. Visual elements, like the presence of fibers and the perceived complexity of the material significantly enhance the perception of being natural. Materials that appeared '*simple*' (characterized by minimal surface variation, patterns, or features) were generally viewed as *stronger*, which in turn elevated their overall valuation. In terms of patterns, rhythmic patterns contributed to perceptions of increased beauty. These correlations and findings have been brought together in a framework, illustrated in figure 30, regarding the ideal biocomposite based on their visual-tactile analysis.

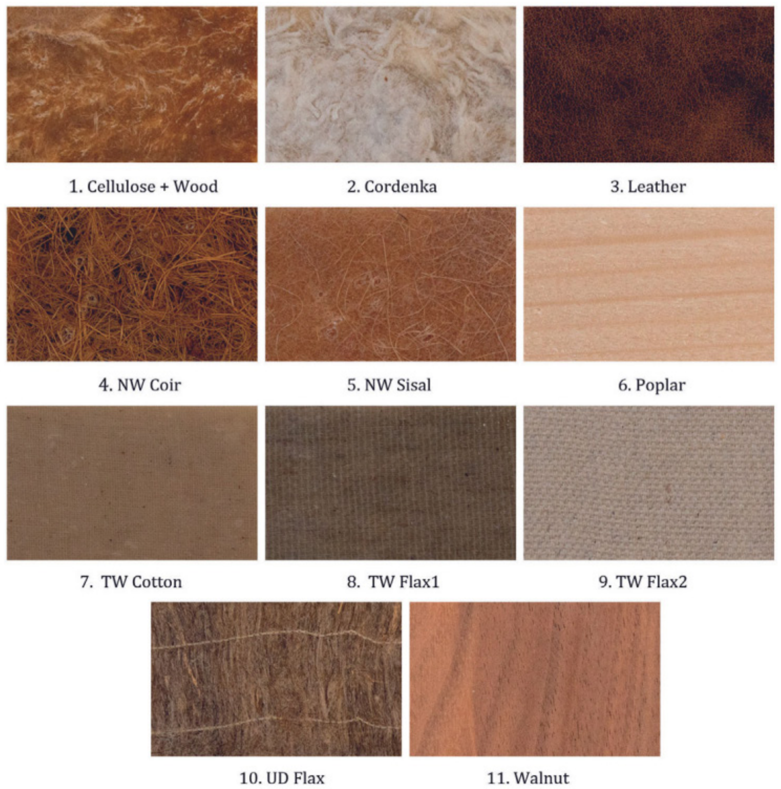

Figure 29. The samples used in the study of Thundathil, et al. (2023)

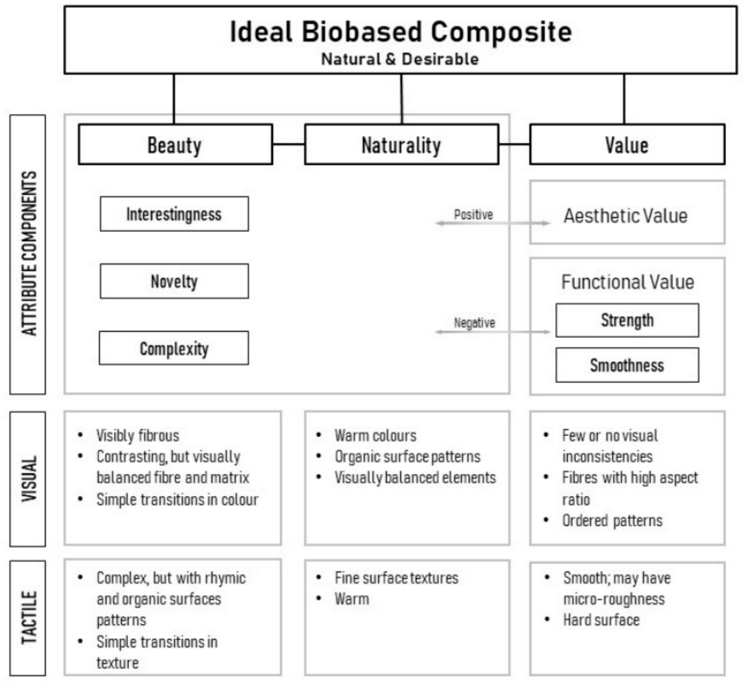

Figure 30. Theory of Thundathil et al. (2023) on the Ideal Biocomposite

In summary, the framework suggests that the key visual elements contributing to a perception of biobased composites as natural and desirable include:

- A visually prominent **fiber presence** that indicates natural origins, though this should remain subtle and involve fine fibers.
- Some type of **patterning**, with a preference for organic patterns over geometric ones. Fiber patterns should possess complexity, but this complexity should not hinder cognitive understanding (Thundathil, M., Nazmi, A. R., Shahri, B. et al., 2023).

7. Material: Analysis of N-8040

7

Figure 31. The material N-8040

7.1 Composition of N-8040

Nabasco-8040 (N-8040) is a biocomposite developed by NPSP, which has now reached a stage of full development and testing to validate its desired characteristics. To further refine the material, ongoing testing is being conducted to assess its properties such as fire safety and recyclability, among others. Figure 31 shows the material in an old design.

The composition of N-8040 deviates from the traditional biocomposite formula of resin, filler, and fiber. While a typical biocomposite typically incorporates all three components, N-8040's composition is composed of resin and filler, with a minimal amount of plasticizer and bonding agent. Experimental trials revealed that the removal of fiber from the material actually improved its properties. Although the exact reason for this phenomenon is unclear, NPSP and Nabasco have chosen to omit fiber from the final composition of N-8040, a decision that also offers financial benefits.

The resin presents the most significant drawbacks and limitations in N-8040's formulation. Its dark brown hue not only turns the panel a black color but also restricts the ability to incorporate any dyes. Moreover, the resin is the primary contributor to environmental pollutants, with substantial human toxicity and global warming potential arising mainly from its use.

Overall, 98% of N-8040's ingredients are biobased or derived from waste. While the percentage of these sustainable components is nearly 100%, it falls short of complete sustainability due to the specific requirements needed for the bonding agent. Currently, a fully biobased and waste-based bonding agent that meets the necessary performance standards is not available.
Consider it as ordering an alcohol-free beer; although it is labeled as such, it typically contains a small percentage of alcohol due to the brewing process, an amount that is largely negligible when experienced by the body. In the same way, N-8040 is marketed as 100% biobased and waste-based, despite the minor percentage that prevent it from reaching the full 100%.

As discussed in chapter 6.2, while biobased materials can contribute to eutrophication, the waste-based nature of N-8040's ingredients offers a distinct advantage against the process of eutrophication. Eutrophication is a process that concerns an increase in nutrient concentration in ecosystems leading to imbalances, mostly due to runoff from agriculture. When using waste-based materials, no new plant or animal biomass needs to be cultivated.

Finally, it is important to note that N-8040 is relatively new, and tests are currently ongoing to assess its fire, weather, and UV resistance. Should any test results fall short, adjustments can be made to the ingredient composition to improve the material's overall performance.

7.2 Production Process

The production process of N-8040 is known as compression molding. The entire process must be completed within 48 hours.

When NPSP created test products, it revealed the limits of the N-8040 dough's consistency. Figure 32 demonstrates one of the test products of N-8040. It is important to avoid corners and edges too sharp or small, as the material's flow during pressing cannot manage such complexity. Figure 33 illustrates the consequences of this issue where the material fails to fully flow out and come together at the corner. Additionally, if the mixture is dehydrated for too long, resulting in excessive dryness, the material will also exhibit poor flow, leading to production failures.

Figure 32. Test product of N-8040

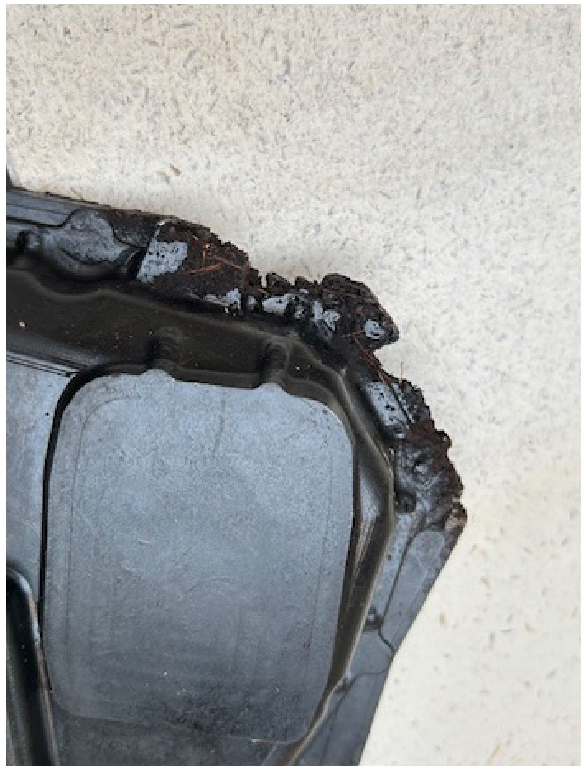

Figure 33. Failure of N-8040

7.3 Technical Characterization

The combination of ingredients and the production process employed for N-8040 yields a unique technical characterization for the material. Mechanical tests on N-8040 were performed by NPSP, who provided the technical data. To effectively convey its performance and technical attributes, a comparison is drawn between N-8040 and several commonly used conventional building materials; aluminium, wood, and glass fiber, relying on data from CES EduPack (2024). This comparison serves to highlight the distinct properties and characteristics of N-8040.

The data is visualized in figure FIXME, which demonstrates that N-8040 exhibits excellent strength and rigidity, qualifying it as a hufterproof and strong alternative to traditional materials. In terms of sustainability, N-8040 performs well, with a high percentage of biobased composition, low global warming potential (currently under testing but anticipated to be low), and strong end-of-life potential when compared to aluminium, wood, and fiberglass.

Wood is the primary competitor among materials, also boasting a negative carbon footprint, as it sequesters approximately 1 to 2 kg of CO per kg. In contrast, N-8040 sequesters 5.42 kg of CO per m^2 because it is derived from vegetable biomass. While wood offers notable strength, stiffness, and durability, a significant difference is that the components of N-8040 can be quickly cultivated and processed, whereas wood requires much longer to grow to a suitable size for construction use.

However, one drawback of N-8040 is its weight, measuring 9 kg/m^2, which is largely attributed to the high amount of fillers used and the absence of fibers.

The lifespan of 30 to 50 years is a goal and has not been tested yet, just like the fire resistance. To meet fire resistance certification, flame retardants may need to be incorporated, but the effects of these additives on the properties of unprocessed N-8040 remain unknown. Furthermore, weather and UV resistance are currently under evaluation.

	Aluminium	Wood	Fiberglass Composite	N-8040
Tensile Strength (MPa)	+/- 90	+/- 40-150	+/- 300-900	+/- 87
Elastic Modulus (Stiffness) (GPa)	+/- 70	+/- 8-16	+/- 20-50	+/- 5,5
GWP (Global Warming Potential) (kg CO2 eq /kg)	+/- 8-16	+/- -2-1	+/- 5-10	+/- -2,2
Density (kg/dm3)	+/- 2,7	+/- 0,4-0,8	+/- 1,5-2,0	1,4
% biobased	0%	100%	0%	98%
Life Span (years)	+/- 40-80+	+/- 25-50+	+/- 20-50	+/- 30-40
End of life potential	Medium	Medium/Good	Low	Good
Weather proof	Good	Medium	Good	Medium/Good

Table 2. N-8040 compared to Aluminium, Wood and Fiber Fiberglass (CES, 2024)

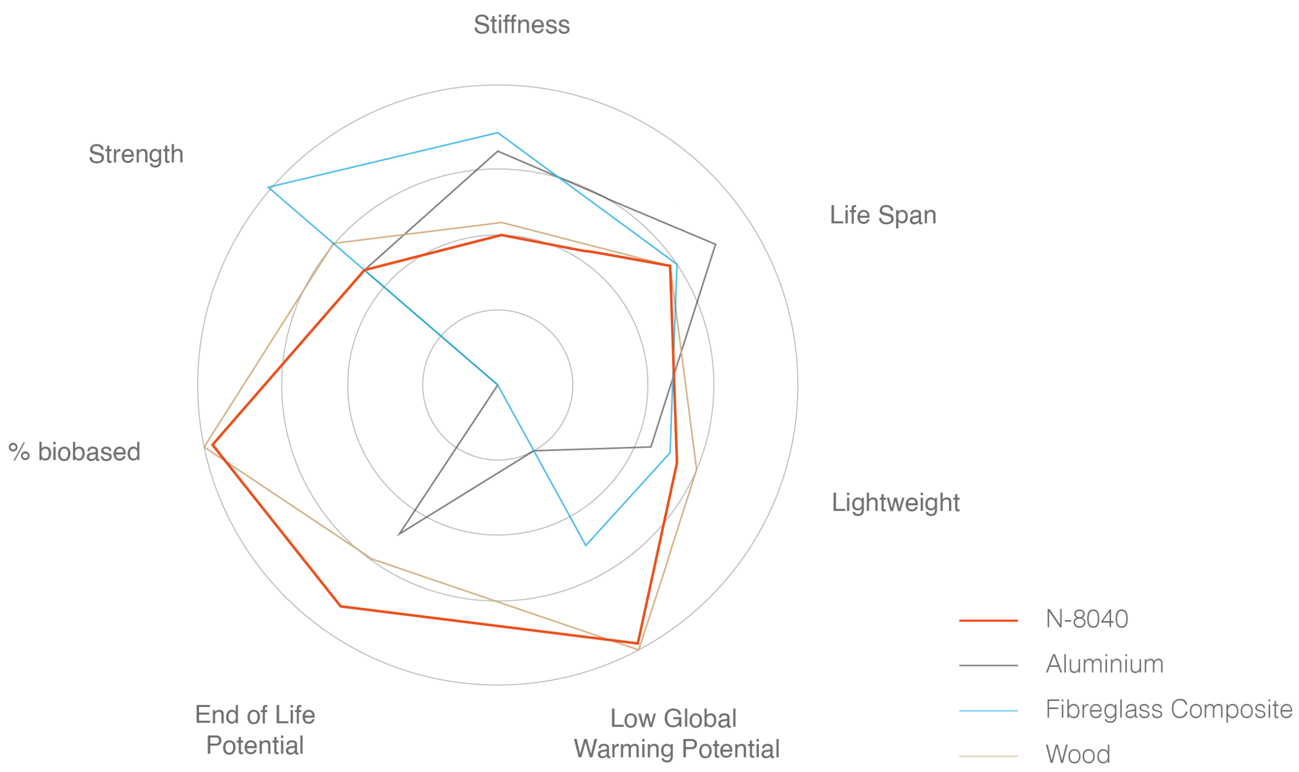

Figure 34. Overview of N-8040 compared to Aluminium, Wood and Fiber Fiberglass

7.4 Weather Resistance

Some weather tests have been completed, with more required tests ongoing. The recent weather resistance tests of the material N-8040 has demonstrated relevant behaviour when it comes into contact with natural elements, providing valuable insights into its long-term interactions with ecosystems.

UV Discoloration

When exposed to an extended exposure to UV radiation, N-8040 exhibits slight discoloration, likely resulting from the degradation of resin in its composition. Although this aesthetic change does not significantly compromise its structural integrity, the question can be asked to embrace this discoloration or to add additional UV stabilizers or coatings to preserve its visual appeal in outdoor settings.

Attachment of Organisms in Water

A study by NPSP involved N-8040 samples suspended in a lake for four months demonstrating the attachment of green growth, including algae and aquatic microorganisms (figure 35). In a separate experiment by NPSP, a less dense N-8040 sample was suspended in Het IJ, in Amsterdam, for an unknown period of time. Again, this sample attracted a diverse array of organisms, such as small shells and aquatic invertebrates. See figure 37.
This phenomenon suggests that the material has the potential to support the growth of organisms in wet environments, highlighting its potential for integration with ecosystems.

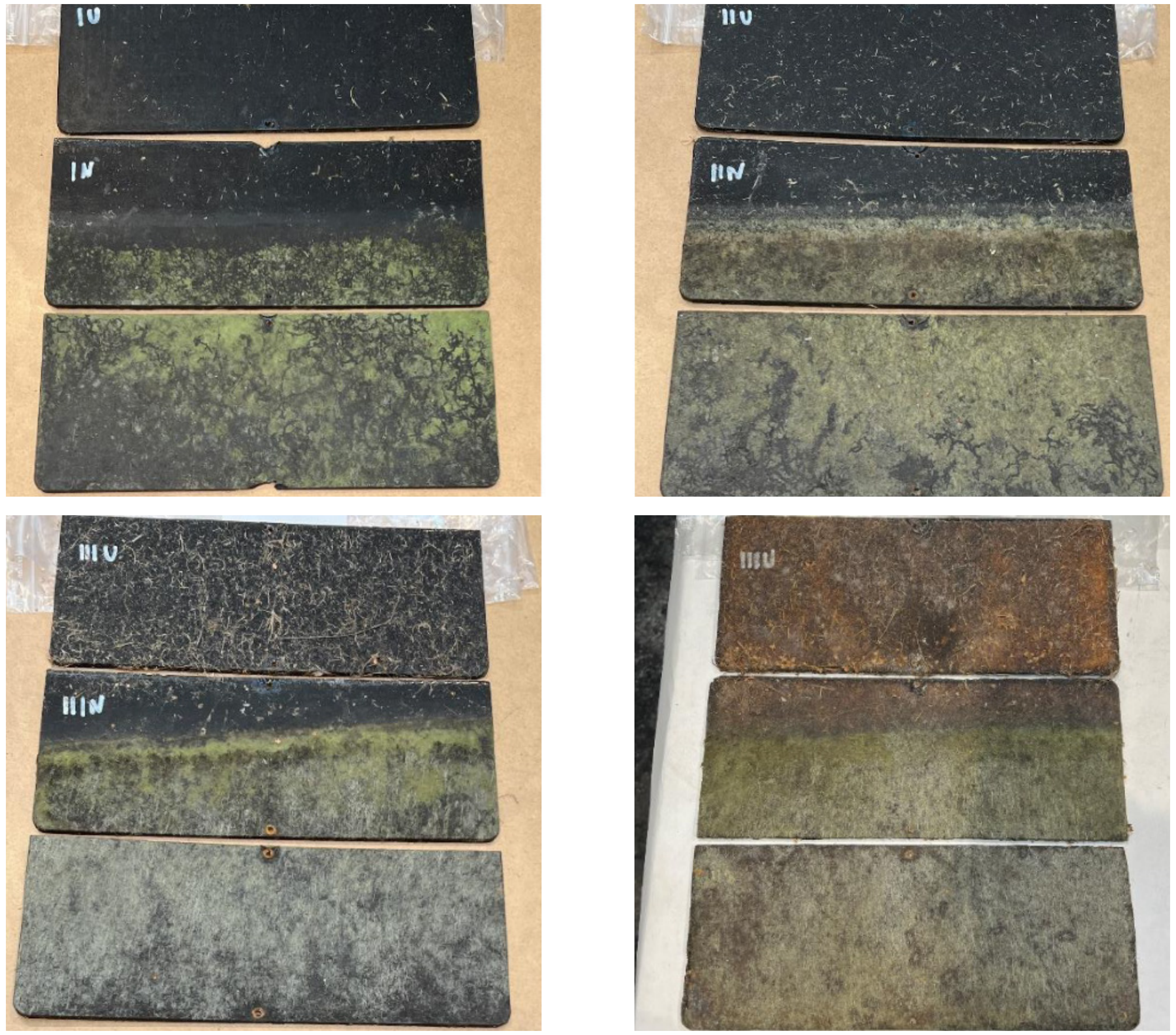

Figure 35. Monthly result of the panel in water (from left to right and top to bottom, month 1,2,3,4) (NPSP, 2024)

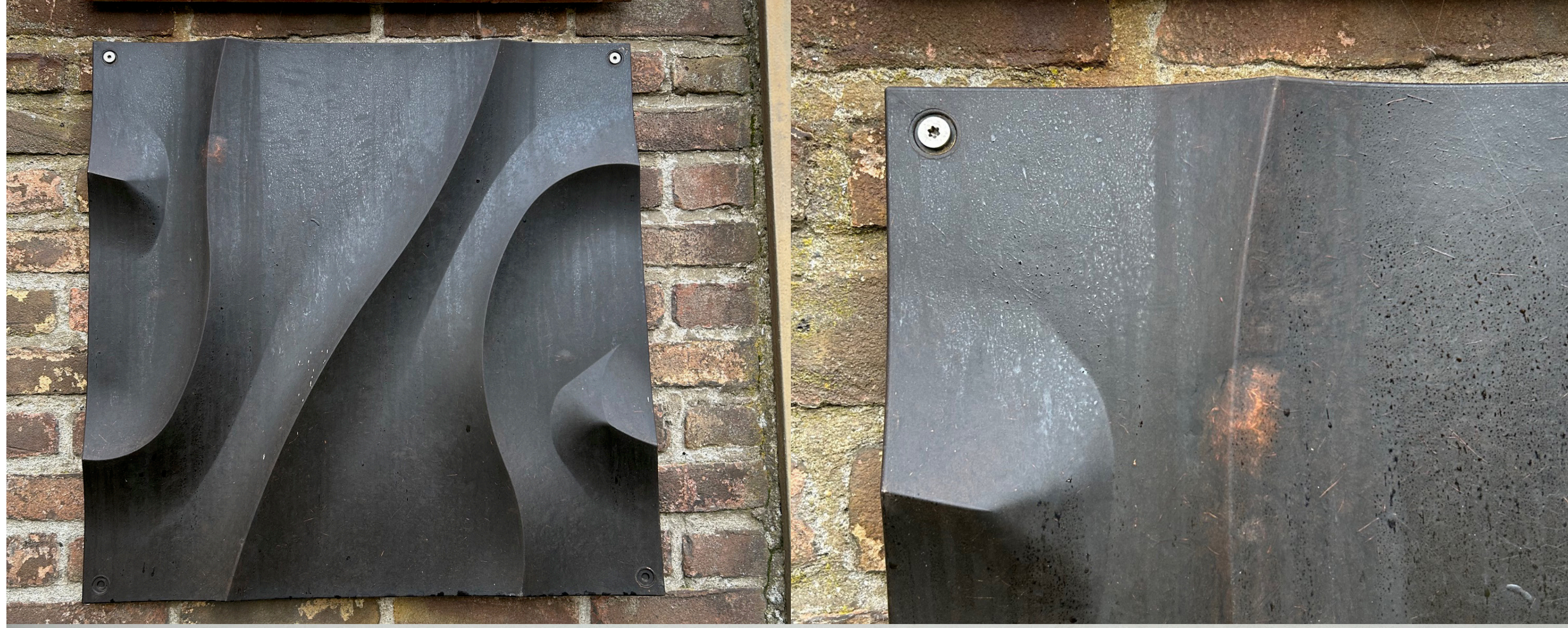

Figure 36. UV discoloration of the panels

Figure 37. N-8040 Sample from Water Test in Het IJ.

7.5 End of Life

The goal for the material is to last 50 years, but has not yet been proven. As the material is relatively new, there is limited information available regarding its end-of-life and life-cycle analysis. At the moment tests are being executed to determine these factors. However, what has been tested is that the material can be ground up and repurposed as new filler after its life cycle. The frequency with which it can be reused is still unknown.

Research is currently ongoing to assess the options for the material after it has reached its maximum recycling capacity. Since the material is not biodegradable, external researchers are investigating the use of fungi to either decompose the biocomposite or convert it into biochar through pyrolysis, which could subsequently be utilized as a soil conditioner. An overview of the End-of-Life Potential is presented in figure 38.

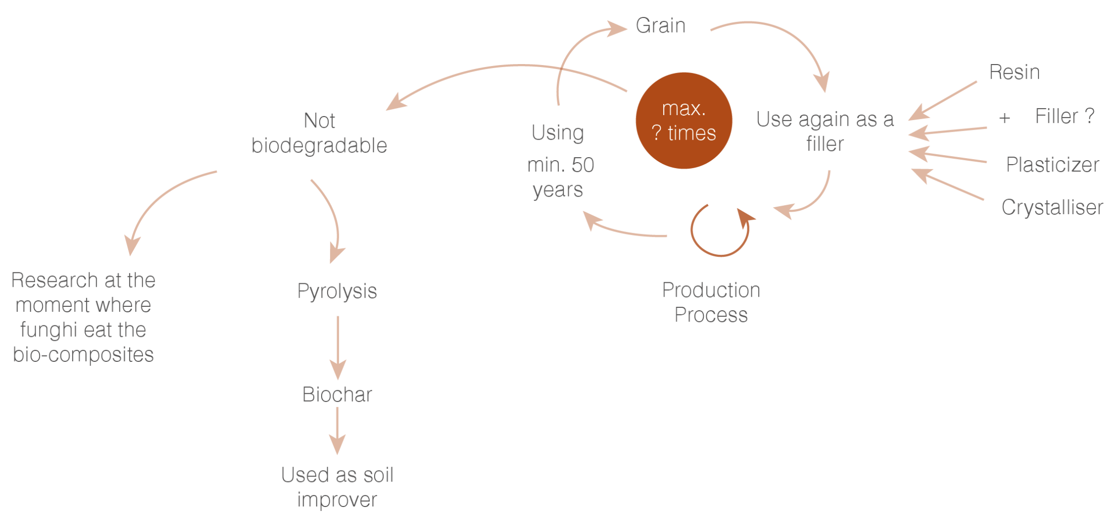

Figure 38. End of Life Potential of N-8040

7.6 Material Benchmark

The material benchmark is a tool in material driven research and design to assess and compare materials and its applications. It establishes a framework for evaluating materials against predetermined criteria. A material benchmark enables the mapping of a specific material within the context of alternatives, providing insights into its unique selling points (USPs) and limitations. In this project two material benchmarks are executed, one with N-8040 compared to other biocomposites and one where N-8040 is compared to alternative materials with the same application, facade cladding. The criteria used for comparing the materials are identical for both benchmarks. The material benchmarks tick technical, visual, durable and practical features. An explorative approach is used. The materials in the benchmark have been found in the material database of Material District (2024) and Biobasedmaterials.org (2024). The material benchmarks are found in Appendix C.

Benchmark - Biocomposites

The biocomposite benchmark indicates that while many alternatives are available, they frequently do not consist of 100% biobased or waste-derived materials. A material can be classified as biobased or waste-based even if it contains only a small proportion of natural or waste components.
Most companies that sell biobased or waste-derived biocomposites market them as biobased or waste-based materials, often without informing customers that this is only partially accurate. N-8040 being almost 100% bio- and waste-based, is an important USP to communicate to the users.
In terms of appearance, there are alternatives like *REY-Y-STONE* and *Paperstone* that offer biocomposites with a comparable appearance.

Benchmark - Application of Facade Cladding

In the evaluation of the benchmark of materials with comparable applications, it seems that N-8040's primary strength lies in its design flexibility due to the high form freedom. A value that *Riwood, Duplicor, Yitile* or *Yoroi* does not offer. Although N-8040 currently does not have a strong market position. Numerous recycled plastic panels, such as *Pretty Plastic*, provide similar functionality, often at a lower price.
Furthermore, various alternatives offer additional advantages: for example, *Respyre*, which includes a moss layer that enhances biodiversity, improves air quality, and provides thermal benefits, a rather simple concept with significant impacts. Another option is *Yitile*, which allows for customizable colors, and *Duplicor*, which offers insulation through a sandwich panel. In summary, for N-8040 to differentiate itself in the market, it will need to integrate an extra added value into its design.

7.7 Experiential Characterization

The experience of a material plays a crucial role in shaping product perception and fostering a connection between users and the product. Through its experiential characteristics, a product can differentiate itself from competitors and establish its uniqueness. Chapter 6.4 has discussed the research conducted by Thundathil et al. (2022) on the visual and tactile qualities of biocomposites. In this chapter, a similar study was conducted using N-8040. Six Master's students in Industrial Design Engineering from the TU Delft interacted with N-8040 and evaluated it across four experiential levels: **sensorial, interpretive, affective**, and **performative**. Finally, the students compared the N-8040 sample to seven other biocomposite samples from Nabasco, assessing them based on *beauty*, and *expected sustainability.*

The findings and results are used to create the design direction. The various correlations among the perceptual attributes of biocomposites identified by Thundathil et al (2023) are integrated with the findings from this user studies, with the goal to create a unique and highly valued experience of N-8040.

7.7.1 Method

To measure the experiential characteristics of N-8040, the *Experiential Characterization Toolkit* from the Material Driven Design approach is used for executing user tests. This toolkit was created by Camere and Karana in 2018. Some adjustments were made in the approach of the toolkit, in order to optimize the user test for this specific project. These adjustments were to include the tested attributes from the study by Thundathil et al (2022) in this test. As written in chapter 3.1, we experience materials in products on four levels; **sensorial, interpretive, affective** and **performative**. The Experiential Characterization Toolkit provides an approach to understand how people perceive a material on these four experiential levels.

Figure 40 gives an overview of the set up and method of the user tests. In total *six Master students from Industrial Design Engineering from the TU Delft* have completed the user test. They were recruited within own personal network.

Set up

The materials needed for the test are:

- Eight biocomposite samples derived by NPSP, among which the N-8040 sample. The samples are pictured in figure 39.
- User's booklet from the Experiential Characterization Toolkit. This booklet can be found in appendix D.
- Lists with the vocabulary of affective and interpretive attributes. These lists are also provided by the toolkit, but are adjusted with extra attributes commonly encountered in biocomposites.

Method

The steps during the test are:

- Let the students explore the samples themselves without revealing any information.
- The first step is to ask the student to rank all samples from most appreciated to least and from the sample expected as most sustainable to least.
- Then, point out the sample of N-8040 and mention that the questions from now on concern only this material.
- Introduce the user's booklet: The first step in the booklet is to explore the material with his/her senses, rating the material on a sensorial scale (max 8 min). These sensory qualities are qualities as, is the material *hard/soft, elastic/not elastic*.
- The second step is to select a maximum of three emotions that the material elicits from the vocabulary with affective attributes. The emotions are placed on the matrix from *unpleasant* to *pleasant* and level of *intensity* (max 8 min).
- The third step is to select three meanings from the vocabulary with interpretive attributes that describe their associations with the material and find a picture that associates for each meaning (max 8 min). Interpretive attributes are as *valuable/useless* or *masculine/feminine*.
- In the final step the student reflects on the most *pleasant, disturbing* and *unique* quality of the material and explains why (max 6 min).

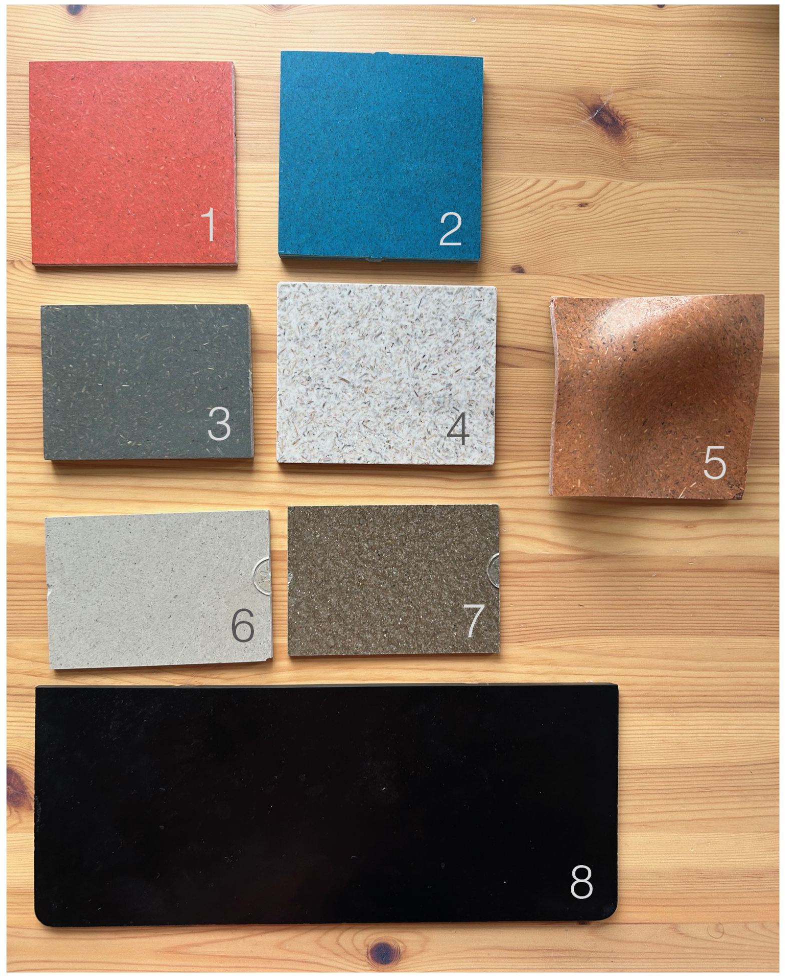

Figure 39. Biocomposite samples for the user tests

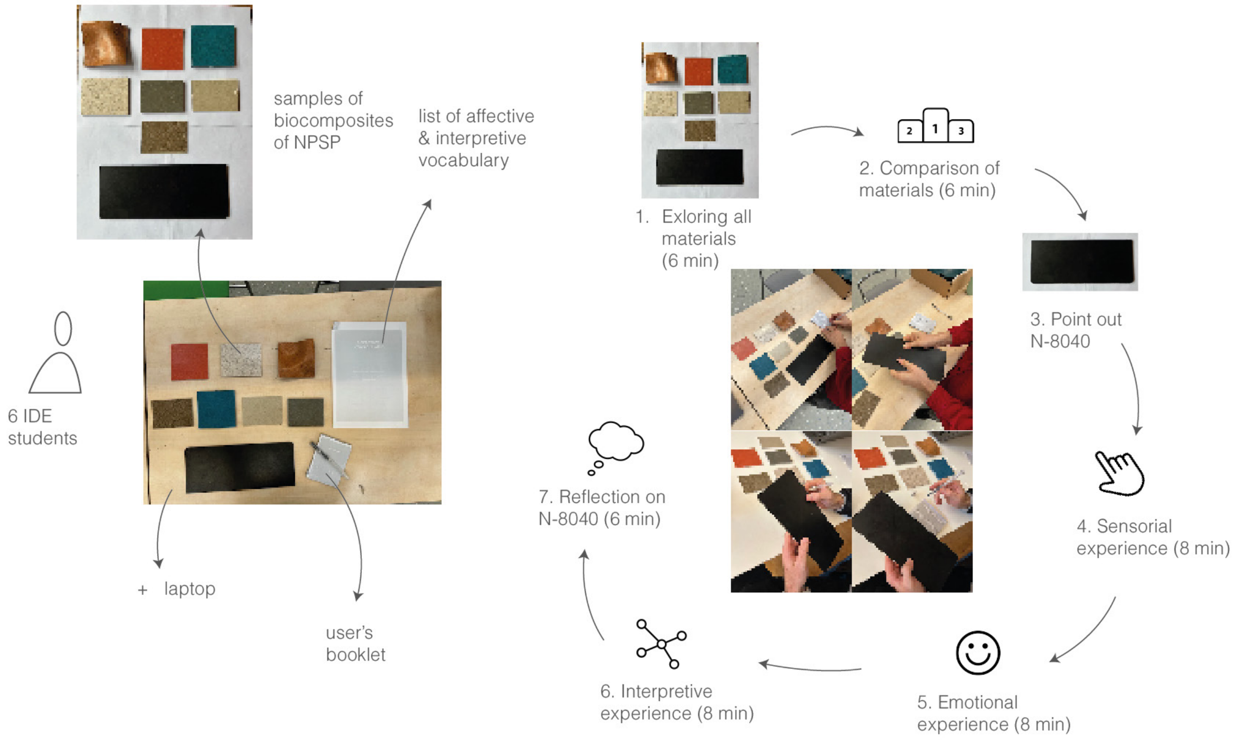

Figure 40. Set up and method of the user tests

7.7.2 Results

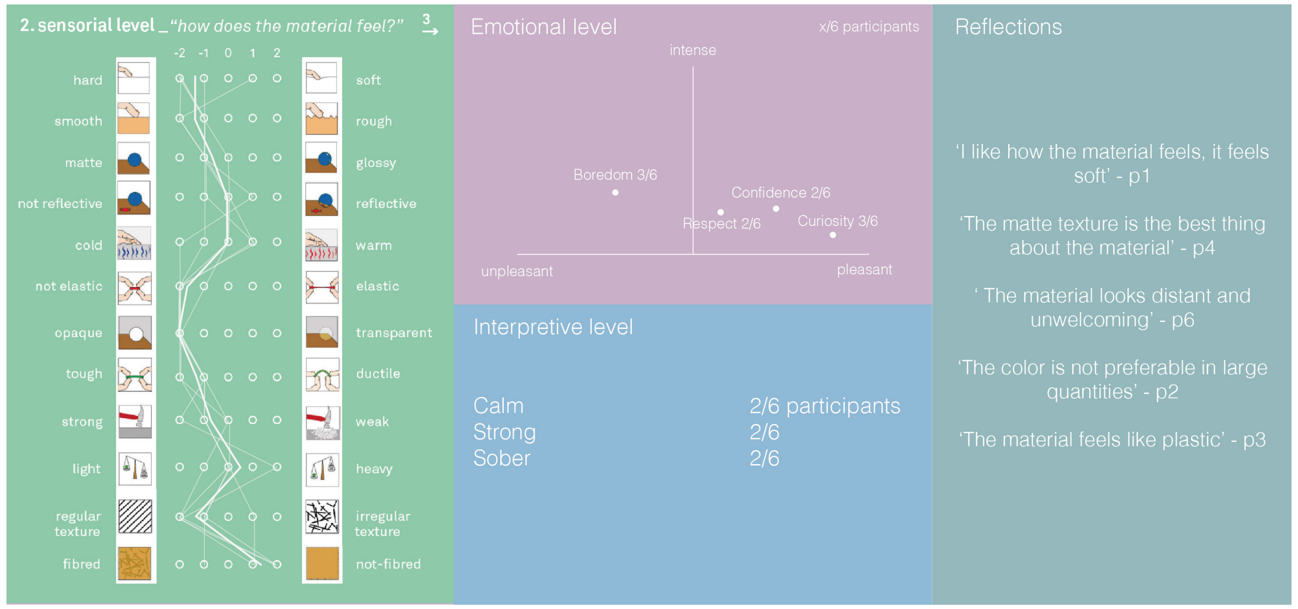

Figure 41. Results user tests on experiential characterization

See Appendix E for the individual results.

Performative

The performative level is not fully explored and researched. The focus for facade panels lies more on visual than tactile experience. From the observations that were made on a performative level, it can be concluded people were functional focused. Another common observation with most participants was that from all samples, they did not pick up the sample from N-8040 first, meaning that this sample does not catch their attention right away. One possible explanation is that the participants lack experience with the visual characteristics of the other samples, which sparks their curiosity. In contrast, N-8040 has a more familiar and recognizable appearance.

Sensory

The sensory results indicate that qualities such as *hardness, smoothness, toughness, regular texture,* and a *lack of fibres* are particularly prominent. A *regular texture, smoothness* and *lack of fibres* can be experienced as intertwining qualities, such as *hardness* and *toughness*. It's worth noting that other biocomposite samples typically exhibit visible fibers, which makes the absence of fibers in N-8040 all the more noticeable. This highlights the importance of context, as the frame of reference in which the material is presented significantly impacts how it is perceived.

Affective

On an emotional level, the most frequently mentioned feelings (3 of the 6 participants) were *boredom* and *curiosity*, followed by *confidence* and *respect* (2 of the 6 participants). During interactions with the material, participants observed small irregularities in the material resulting from various light reflections, and the 'think out loud' approach revealed that these observations primarily sparked *curiosity*.

"The little details on the material makes it look a little like natural stone." (curiosity) - Participant 1

"It looks like a standard material." (boredom) - Participant 2

Curiosity is perceived as the most pleasant of these four emotions, followed by *confidence* and then *respect*. *Boredom* is perceived as unpleasant. Interestingly, *boredom* scores highest in terms of intensity, followed by *confidence*, then *respect*, and *curiosity* the least intense. It is notable that *curiosity* is perceived as most pleasant, but with a low intensity. *Confidence* and *respect* are most likely related to the sensory qualities *toughness, hardness* and *colour*. Quoting participant 6:

"The material looks strong, it commands respect, if you want to break it, it looks like the material is going to win it from you." - Participant 6

Confidence was often named in relation to the black colour, from which the conclusion was drawn that they are related.

Interpretive

At the interpretation level, the attributes *calm, strong* and *sober* are the most common, each attribute is named twice among all six participants. The other attributes are all named once, meaning that there is quite some disunity on interpretive level.
Calm was noted for its deep, uniform color and smooth texture. One participant remarked that the material evokes the image of a starry sky, likely due to its dark hue and the subtle bumps visible upon closer inspection.
Strong is linked to the material's durability and toughness, which is again tied to its color.
Sober is mentioned by the participants because the material is relatively common, with people perceiving it primarily as practical and quite ordinary. This concept of sobriety is also connected to the material's dark color.

"I associate the material with a starry sky, it is calm, it has a dark colour and not so much texture." (calm) - Participant 4

"I think the material is strong, because it's hard and also because of the color somehow." (strong) - Participant 2

"It does not put any effort in being more than just a normal material" (sober) - Participant 3

Reflections

Among the six participants, four provided responses characterized as most pleasant that display some similarities. These responses included *matte, soft texture, basic, smooth* and *calm.* It seems that *matte, soft,* and *smooth textures* contribute to a *basic* and *calm* appearance, which is generally perceived as enjoyable.

"The matte and soft texture is the best thing about the material to me." - Participant 4

However, the feedback also pointed out some unsettling qualities; specifically, the material came across as *impersonal* and *cold.* Additionally, it was noted that the material appears and *feels cheap and unsustainable.*

"The material looks distant and unwelcoming." - Participant 6

"The color is not preferable in large quantities." - Participant 2

"The material feels like plastic." - Participant 3

It is evident that the most distinctive aspect of the material is not apparent from its exterior but lies within. The revelation that the material is both biobased and waste-based surprises all the test subjects, who describe this *unexpected sustainability* as its most unique feature. It appears that people have different expectations with biocomposites.

Biocomposites Benchmark

This again became evident from the comparisons between the samples where the subjects were asked to rank them from least to most sustainable material, without having provided any information about the materials. Figure 42 shows that N-8040 scores

"It's a very left-winged material (sustainable) packed in a right-winged appearance (strong, masculine and cold)." - Participant 6

significantly lowest on '*expected sustainability*'. The results indicate that visible fibers are associated with sustainability; the size of these fibers also impacts perceptions; larger fibers tend to create stronger associations with sustainability. Conversely, bright colors are linked to chemical dyes, leading to the perception that such materials are not sustainable, despite the presence of visible fibers.

Comparing the aesthetic appeal of the biocomposites reveals a preference for lighter colors, with the two cream-colored samples receiving high ratings. The blue sample stands out as rated beautiful, likely due to its striking and unique appearance. But it elicited mixed reactions; some participants fully loved it, while others were not fond of it at all.
The samples exhibited varying textures; some were more glossy, while others were more matte, and some felt rougher than others. Overall, the comparisons indicate that materials with a matte texture are perceived as pleasant and attractive. Both the N-8040 sample and the blue biocomposite have a matte finish and received high scores. In contrast, the grey samples were often described as dull and unappealing, which also reflected in their lower beauty ratings.

"I do not like the grey samples, because they look dull and boring." - Participant 2

Correlations

All results at **sensory, affective** and **interpretive** level combined resulted in a number of correlations, see figure 43. These correlations are based on own findings during the user tests, quotes and frequency of results.

- *Non-fibred x Boredom x Sober*
- *Irregular texture x Curiosity*
- *Tough x Strong x Opaque x Confidence x Cold*
- *Matte x Respect x Valuable*
- *Matte x Smooth x Sexy*
- *Black x Rejection x Aloof x Futuristic*
- *Smooth x Simple x Calm*

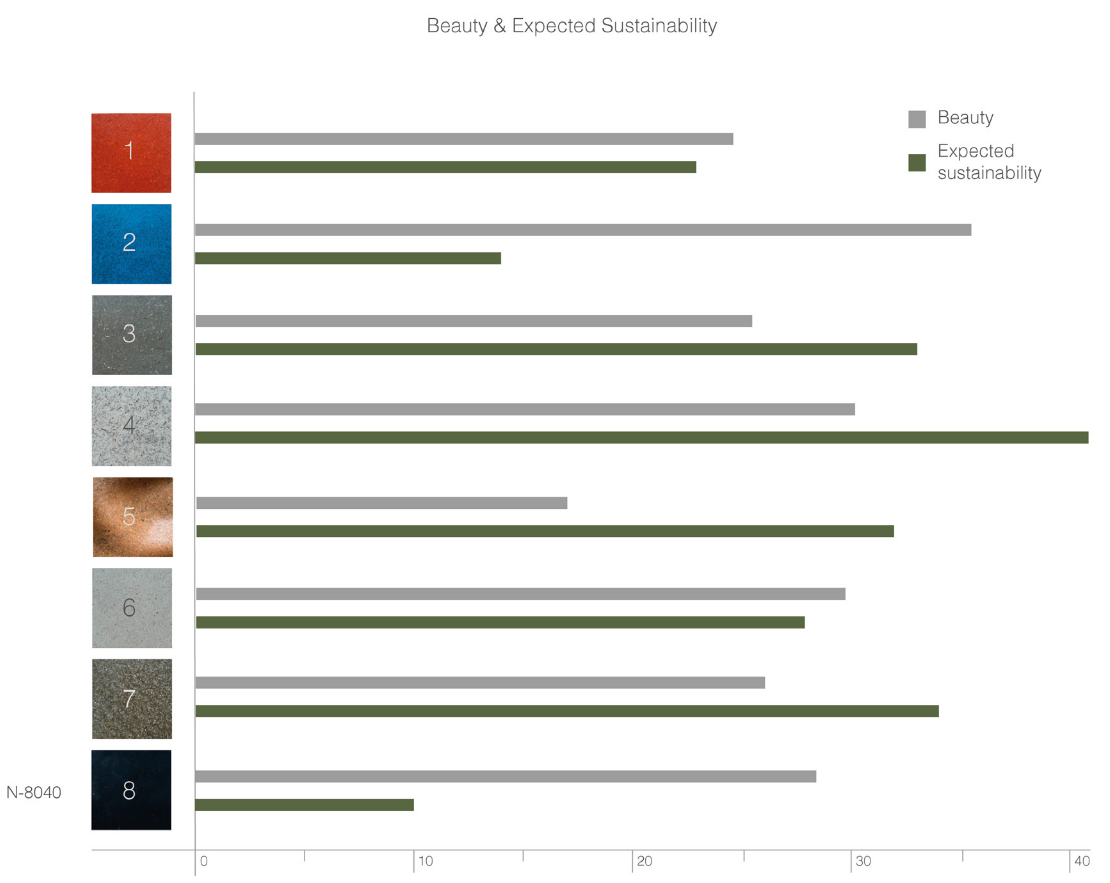

Figure 42. Results rating on Beauty and Expected Sustainability

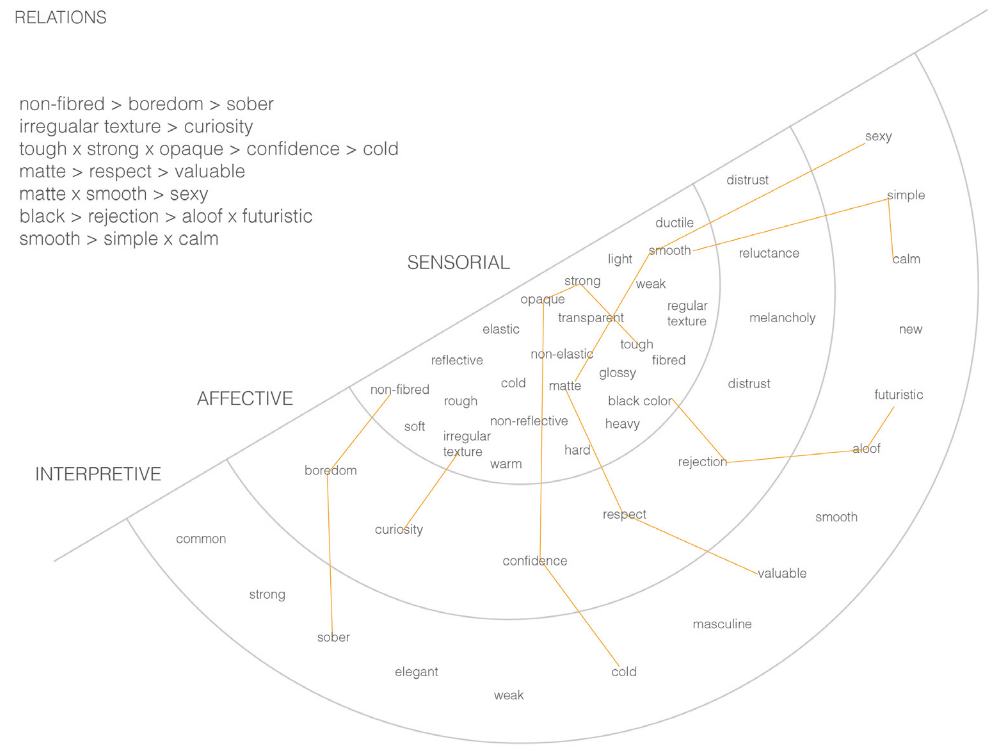

Figure 43. Relations on Sensorial, Affective and Interpretive level

Based on the correlations, the following themes have been developed, see figure 44. These themes reflect the participants' experiences and perceptions of N-8040, as well as their shortcomings and potential areas for enhancement. By establishing, selecting, and combining these themes, a vision can be formulated for improving the material and ultimately incorporating it into the design. These themes have been chosen for integration into the design based on the frequency of results from user testing and observations:

- Roughness in Details
- Raw vs Refined
- Authenticity leading to Recognition
- Genuine Presence

7.7.3 Discussion

The user test has several limitations, including the fact that not all samples share the same shape, thickness, and angles, which may influence how the materials are perceived. Ideally, all samples would have had uniform shape and thickness. Especially, the orange sample features a distinctly different shape, and its inclusion in the test may not have been beneficial.

Another limitation is that while it is known that all samples are biocomposites, the specific materials used in their composition are unknown. When the participants evaluated the various samples based on beauty and anticipated sustainability, no correlation can be established between the ingredients and their perceptions. For instance, a specific type of fiber or another unique material might lead users to perceive the material as highly sustainable due to its visual identity.

Finally, the performative aspect, 'what does the material make you do', was not considered. This seems less significant for a facade, as users do not hold the product in hand as they would with other consumer products. For a comprehensive evaluation, this level should also have been included in the test.

UNPREDICTED VISUAL DECEPTION When observing the material, its appearance and texture don't initially align with expectations. At first glance, it might seem more like plastic than a sustainable option. However, the true value of this material emerges in its ability to notice this surprise and captivate users, offering a sense of astonishment when its sustainable nature becomes evident.	SOPHISTICATION A quality that embodies elegance, refinement, and complexity. A material and facade combining innovation and timeless appeal, being well-crafted, intricate and cutting-edge. A charming whole.	ROUGHNESS IN DETAILS The intricate details and subtle complexities of the material captivate the eye, sparking curiosity and inviting a deeper investigation. Its unique texture and design are compelling enough to make passers-by pause, drawn in by its unexpected allure. What initially seems familiar transforms into something extraordinary upon closer inspection. This dynamic interplay between appearance and detail creates a magnetic quality, urging observers to step closer and engage.	SMOOTH SEXYNESS The material exudes an undeniable sense of sophistication and sensuality, defined by its matte, smooth, and deep black appearance. These qualities evoke an aura of understated elegance and allure, often associated with sexiness. The tactile smoothness of the material invites to touch. Its aesthetic amplifies its desirability, embodying a balance between mystery and boldness.	RAW VS REFINED Contrast captivates by sparking curiosity and creating dynamic visual interest. Think of the interplay between artificial and nature, an interesting combination. A material that embodies this duality, blending natural with artificial elements, invites exploration. Its fusion of raw and refined elements not only appeals aesthetically but also tells a story of balance.
SERENITY IN SIMPLICITY The material feels calm, simple, and smooth—something that evokes a sense of pleasure. Picture a bustling city, with people rushing by and vehicles zooming past. Then, imagine a facade that stands as a serene whole amidst the chaos. It's a sight to pause and admire, inviting you to take a moment, breathe deeply, and experience a sense of calm before continuing on your way.	BOLD CONFIDENCE A material that demonstrates its high-performance qualities, radiating confidence in both its design and construction. Like a solid rock amidst the hustle of city life, it exudes a sense of strength and reliability, earning respect.	AUTHENTICITY LEADING TO RECOGNITION A material, shape, texture, and form that is instantly recognizable to people as a facade from NPSP. It's a facade that instills a sense of pride and uniqueness, making residents feel special to have it in their city. Imagine people asking, "Do you live in the city with that NPSP facade?", a true landmark of recognition.	GENUINE PRESENCE A material that is transparent, showcasing exactly what it is without pretension, like an open book. The moment you see it, there's no ambiguity, everything you need to know is immediately clear, leaving no room for questions or uncertainty. It speaks for itself, embodying honesty and straightforwardness in every detail.	CALL FOR CONSCIOUSNESS Inspiring ecological awareness in people is the first step toward fostering a deeper connection with the environment and understanding its importance. How can a material and facade contribute to this? A well-designed facade has the power to engage a wide range of people, passers-by from all walks of life, sparking conversation and reflection on sustainability and our relationship with nature.

Figure 44. Themes

8. Brand Analysis of NPSP

8

8.1 SWOT Analysis

Since its founding in 1998, NPSP has acquired a rich knowledge and remains committed to exploring biocomposites and its products, positioning itself at the forefront of innovation in the biocomposites sector. A SWOT analysis (strengths, weaknesses, opportunities, and threats) for NPSP is discussed below, as illustrated in Figure 45.

Strenghts

NPSP is deeply committed to advancing biocomposites, exploiting an **in-house workshop** for material development through iterative research and tailored machine modifications. This approach enables quick configurations and a clear material vision. Using compression molding (discussed in Chapter FIXME), NPSP achieves highly customizable 3D shapes with a **high level of design flexibility** that can be labelled as one of their Unique Selling Points (USP). While the company does not maintain in-house product designers, it collaborates with design and architectural firms, leading to a strong professional network.

"The 3D production capability is one of our key USP's." - NPSP, 2024

Weaknesses

NPSP has a broad product range, from road signs to furniture, making **brand recognition less easy**. However, with a clear focus on facade panels, NPSP has the potential to strengthen its brand identity.

Another consideration is the cost of molds used in production, which limits cost-effectiveness and scalability. While personalized products can be created, they must be produced in batches. It is not as easy as 3D printing, which allows for greater flexibility. As a result, NPSP's production capacity is currently best suited for **small to medium-sized batches**.

Opportunities

NPSP has expressed a strong interest in advancing nature-inclusive facades, a concept developed in collaboration with Studio Marco Vermeulen. These panels, which include nesting boxes for urban wildlife, have gathered positive feedback and growing demand. The company is interested in **exploring further integration of fauna, flora, and rainwater** in its designs. Recognizing the growing emphasis on sustainable solutions, NPSP is aligning its strategies with the increasing demand for eco-friendly materials in the construction industry.

"We are interested in integrating flora, fauna or water storage into the panels." - NPSP, 2024

Threats

However, the growing demand for sustainable materials has led to **increased competition** (Kamalanon, P., Chen, J. S., et al., 2022). Traditional building materials remain easier to use due to their compliance with strict regulations, such as fire safety standards. This creates challenges for NPSP in ensuring to meet these requirements, necessitating time and research.
Additionally, **cost** remains a critical factor, as conventional materials are currently more affordable, leading project developers to overlook NPSP's products. However, there are opportunities for these panels if they can deliver long-term benefits, such as improved energy efficiency that reduces overall operating costs, making them a more appealing choice for developers over time.

	Positive	Negative
Internal	STRENGTHS - Customizable products - High form freedom - 3D products - Very environmenally friendly products (100% bio- and waste-based) - In-house lab: Good research & development (space for trial & error) - Multiple collaborations - strong network - Clear vision for materials	WEAKNESSES - Hard brand recognition for users - Less coherent vision for products - Mould in production process is expensive and a limiting factor - Can handle small to medium batches
External	OPPORTUNITIES - Nature-inclusive panels are well-received, NPSP is interested in more nature inclusive panels, integrating flora/fauna/water. - New shapes using 3D opportunities - Creating a unique experiental value - High demand for facadepanels compared to other products of NPSP - Growing policy for sustainable construction	THREATS - Growing competition on sustainable material development - NPSP panels are still more expensive than concentional construction materials - Strict laws and regulations on the safety of building materials.

Figure 45. SWOT Analysis NPSP

8.2 Finding the Sweet Spot

Finding the '*sweet spot*' is finding an optimal design direction for innovation based on feasibility, viability, integrity, and desirability. It searches for the intersection where innovation can thrive by aligning users' desires and needs with the opportunities NPSP can provide technical- and business-wise, while also creating a meaningful impact.
Using NPSP's SWOT analysis and input from NPSP, figure 46 was drawn up, providing a framework for finding this sweet spot.

In terms of human desirability, there is a demand for improving comfort and well-being inside and outside a building. As is a demand for sustainable materials

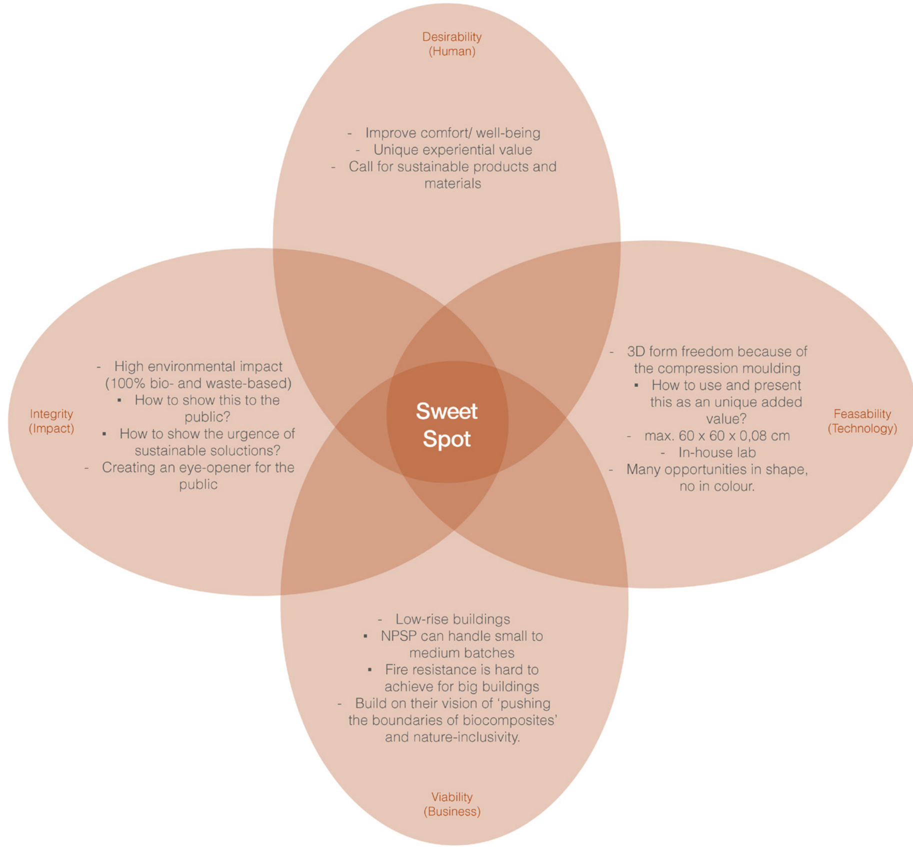

Figure 46. Finding the Sweet Spot for innovation for NPSP

and facades and a unique experiential value. A facade that goes further than aesthetics.

The material N-8040 is black because the resin is black. This means that there are many possibilities in shape and few to none in colour. NPSP can handle small to medium batches in terms of capacity. Plus, it is difficult to create fire resistant panels for high-rise buildings, as high-rise buildings require even stricter regulations. This results in a context to design until a *height of 20 meters.*

In terms of integrity, it is important to show the environmental impact of the material N-8040. The material is nearly 100% biobased and waste-based, but this is hard to notice from the material and so, people therefore do not know this. The material and product gain much more value with the public if they do know the sustainable character (Kamalanon, P., Chen, J. S., et al., 2022). N-8040 can be an eye-opener for the public, concerning material development and sustainability. As a result, it arouses much more interest among the audience.

All in all, NPSP's brand analysis leads to a specific design direction that can be concluded in the following:

- **Context**: The design focus is on low-rise urban buildings up to 20 meters.
- **Sustainability Awareness**: It is essential to effectively communicate the high level of sustainability of the material to the public.
- **Brand Recognition**: A clear and cohesive vision for nature-inclusive facade panels will enhance brand recognition and distinguish NPSP in the market.
- **Nature Integration**: NPSP's goal is to innovate by incorporating elements of flora, fauna, or water into facade designs, strengthening the connection between buildings and their ecosystems.
- **Added Value**: The panels should provide unique features and benefits that create sufficient value to encourage project developers to select NPSP materials over competing cheaper options.
- Human Comfort: The design increases people's comfort and well-being, encouraging an urban environment that enhances living and working conditions.
- **Eye-opener**: The design is an eye-opener for the public, showcasing the potential of sustainable materials and urgency for sustainable solutions.

Vision

Integrating the environment is the key to healthy and resilient cities.

9. Environmental Integrated Cities: Bio-Receptivity

9

Drawing from the research results and analysis, we can address the question "*What will the facade of the future look like?*" by introducing the concept of "*Environmental Integration" (EI).* While the 21st century has seen the emergence of Artificial Intelligence (AI), the next significant innovations are likely to arise from the convergence of nature and architecture. As Steve Jobs once predicted.

Addressing the Challenges of Dutch Cities: Integrating Vegetation and Rainwater

Dutch cities face significant challenges, as detailed in Chapter 4.2. Climate change increases the Urban Heat Island Effect, increases extreme rainfall, and elevates the risk of flooding. Concurrently, urban biodiversity is declining, with essential flora and fauna struggling to thrive. The solution lies in integrating vegetation and rainwater; plants naturally cool urban areas and manage rainwater. Furthermore, these two elements are the base for other living organisms. On a material level, the challenges due to unsustainable resource usage can be tackled by using carbon-negative materials like N-8040.

"The biggest innovations in the 21st century will be at the intersection of nature and technology." - Steve Jobs

By weaving vegetation and rainwater into facades, buildings can evolve into living entities, structures that purify the air, regulate temperatures, and manage rainwater while promoting biodiversity. These green innovations not only address pressing challenges such as the Urban Heat Island Effect, extreme rainfall, and biodiversity loss; they also enrich daily life by enhancing comfort, reducing stress, and deepening our connection to nature.

NPSP has already shown an interest in incorporating flora and rainwater into their facade panels. This initiative aligns with the understanding that blending greenery into architecture go beyond aesthetics; it fosters ecological awareness. Quoting Wouter (who monitored the nature-inclusive panels of NPSP):

"The first step is creating an ecological consciousness, making people curious." - Wouter, 2024

Unleashing the Potential of N-8040

Taking a closer look at the properties and possibilities that N-8040 offers, described in chapter FIXME, it shows that the material has the potential to support the growth of organisms in wet environments, which is the reason to integrate vegetation and rainwater in the facade panel.

A prominent result from the material benchmark, user tests on experiential characteristics and brand analysis of NPSP is the lack of visibility and communication on its sustainable characterization. While the material is carbon-negative, biobased, and composed of waste, these attributes are not readily apparent in its visual presentation. Adapting the material to clearly convey its sustainable identity will be essential for enhancing its appeal, which is a crucial part of the design direction.

Design Direction

Based on the potential of N-8040 and the challenges Dutch cities face in the 21st century, the following design direction is stated:

‘Design a façade panel for Dutch urban residential and business low-rise buildings (max. 20m) for NPSP from the biocomposite material N-8040, conveying its **sustainable identity**, that improves both the **state of the ecosystem**, by integrating vegetation and rainwater, **and the users**, by increasing well-being and ecological consciousness.’

Design

10. Ideation Process

10

The design direction represents a refinement and evolution of several preceding directions. In earlier iterations of the design direction, three key concepts were developed according to an ideation process. Following a C-Box evaluation, the concept that involves harvesting rainwater to support vegetation growth to foster a green environment was selected for further development. This concept of a bio-receptive panel concept was then subjected to additional research and refinement.

enhancing airflow within the structure, leading to a higher energy efficiency. This versatile functionality optimizes placement opportunities on all sides of the building. Ventilation panels can be installed solely on the south side, while other orientations might utilize a mix of rainwater harvesting panels and ventilation panels.
All in all, the AeroAqua Panel effectively addresses challenges associated with heat stress, extreme rainfall, and water scarcity.

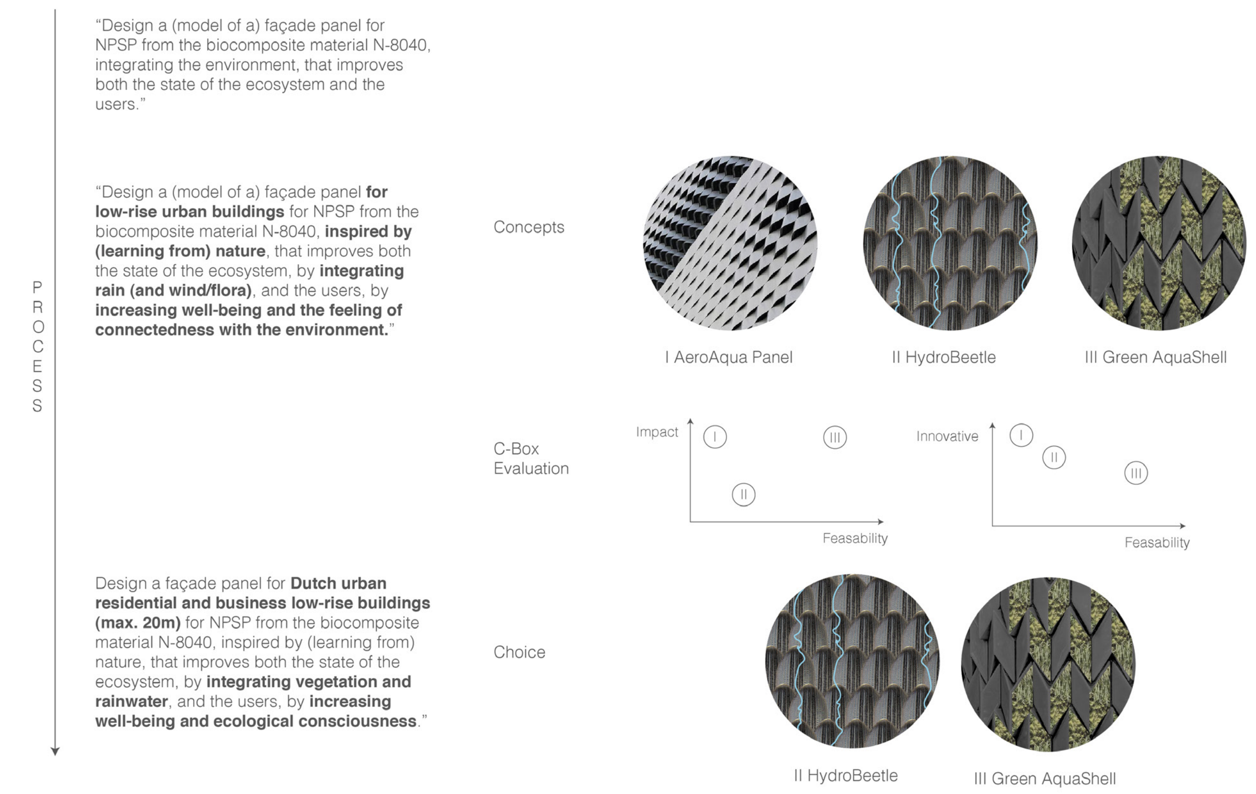

Figure 47. Process of the design directions and three concepts

10.1 Three Concepts

Concept 1: The AeroAqua Panel

The AeroAqua Panel features a rotating design that allows it to serve dual functions. With an opening positioned upwards, it collects rainwater, channeling it away from the back of the panels so that the building can capture and filter it. Conversely, when the panel is rotated to position the opening downwards, it facilitates natural ventilation,

Concept 2: The HydroBeetle

The HydroBeetle panel is inspired by the unique texture of the *Namib Desert Beetle*, which efficiently condenses moisture from the air using its hydrophobic and hydrophilic body parts. The hydrophilic bumps attract water droplets, which are then guided toward the beetle's mouth by the waxy hydrophobic surfaces. This interplay of texture and composition of hydrophilic and hydrophobic areas is what is both attracting and transporting water

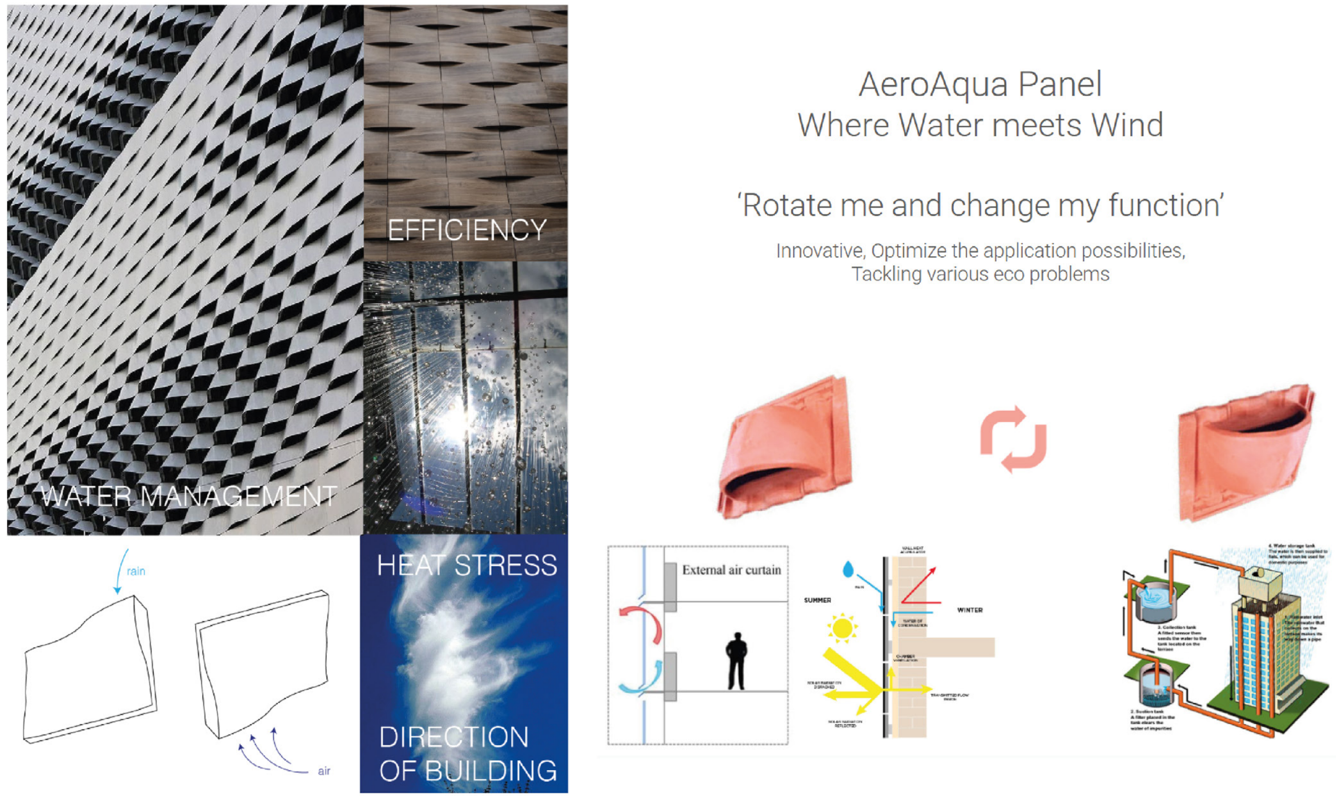

Figure 48. Concept 1: The AeroAqua Panel

droplets (Gurera, D., & Bhushan, B., 2020).
By mimicking the beetle's surface texture, the HydroBeetle panel can effectively control the flow of rainwater. This allows for rainwater to be redirected to a water recycling system at the base of the façade, or to nourish surrounding vegetation. In doing so, the HydroBeetle addresses issues of water scarcity while mitigating the risks associated with extreme rainfall.

Concept 3: The Green AquaShell

The Green AquaShell is a panel designed to harvest rainwater, serving as a foundation for growing vegetation and promoting a greener environment. Similar to shed roof tiles that become covered in moss over time, the AquaShell has the same effect. The AquaShell can either feature a coating that encourages mosses or other plant growth, or it can simply collect water to facilitate the natural arrival of spores and seeds by the wind. Rainwater harvesting offers the same benefits as those highlighted in the two previous concepts, while a green wall also contributes by filtering the air, cooling urban areas, and enhancing biodiversity by providing habitats for insects and various plant species. Another advantage of this concept is that the green vegetation slightly lifts up the dark colour of the panel, expecting it to make it perceived as more pleasant and less impersonal and harsh, see the results of the experimental characterisation from chapter 7.7.2.

Figure 49. Concept 2: The HydroBeetle

Figure 50. Concept 3: The Green AquaShell

10.2 C-Box Evaluation

The C-Box method provides a quick evaluation of ideas for desired features at an early stage, which is why it was selected to assess and determine the most promising concept. The axes of *feasibility, impact*, and *innovativeness* have been intuitively selected based on the design vision. The evaluation of the concepts is done individually, after gathering input on the concepts from fellow students (of Industrial Design Engineering).

Based on the C-Box evaluation, the *Green AquaShell* concept was ultimately chosen due to its feasibility and significant impact. This design incorporates not only rainwater harvesting but also vegetation that offers substantial benefits. Green panels, tiles, and facades are already in existence for a while, which makes this option less innovative than the others. So a decision was made to merge a design aspect from the *HydroBeetle* with the *Green AquaShell*: drawing inspiration from nature.

Briefly, why the *AeroAqua Panel* was not chosen. After a discussion with the NPSP, the following emerged:

> *''Nothing can get behind the panels because of fire safety.'' - NPSP, 2024*

The function of the *HydroBeetle* concept has a particularly low impact compared to the other concepts. That is why the *Green AquaShell* as a bio-receptive concept was chosen.

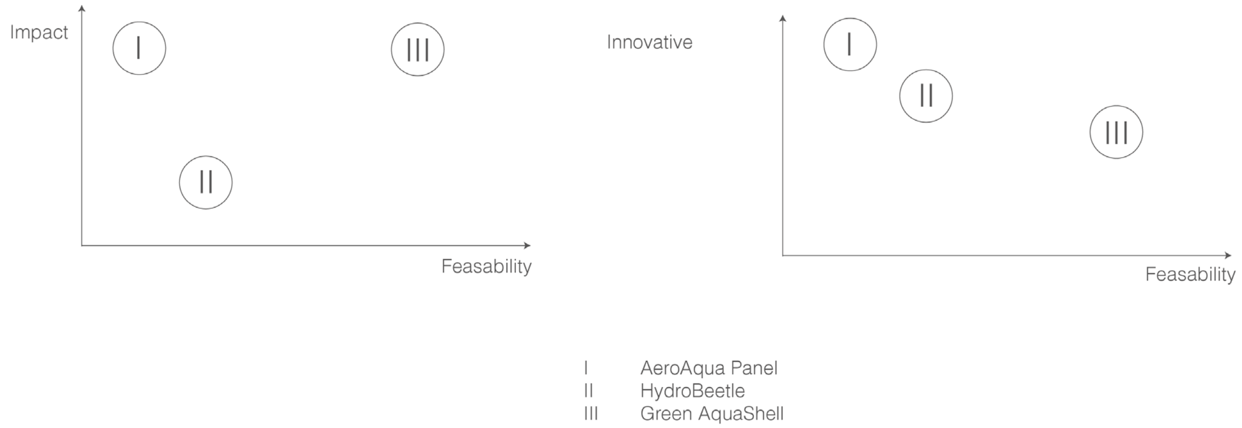

Figure 51. C-Box Evaluation

11. Bio-Receptive Facades

The challenge of designing a bio-receptive facade panel is approached from a top-down perspective, beginning with the overarching vision and then deconstructing it into smaller, manageable components. This process starts with establishing design guidelines informed by data gathered from literature reviews and field surveys. It is then followed by practical experimentation, ultimately concluding in an overall design.

11.1 Benefits of a Bio-Receptive Facade

Bio-receptive building materials offers multiple sustainable and economic advantages:

- Bio-receptive materials **facilitate the growth of microorganisms, macro-organisms, and plants** (Guillitte, O., 1995). The integration of vegetation on building facades can provide not only a habitat for plants, but also create a welcoming environment for various animal species. The results of the nature-inclusive panels have revealed that the nesting boxes have been underutilized, with a surprisingly low number of birds and insects making them their home. A possible cause for this lack of usage can be attributed to the absence of sufficient greenery on the panels. Creating bio-receptive panels for NPSP, will give them the opportunity to combine this knowledge and solution with their nature-inclusive panels. Expecting that the creation of a more fruitful environment will encourage birds and insects to take up residence in the nesting boxes, thereby enhancing the overall biodiversity of the area and promoting a healthier ecosystem.

“Birds and insects do not nest in the panels intended for this purpose, partly due to the lack of greenery.” - NPSP, 2024

- The green layer that develops on these surfaces provides **protection against harsh weather conditions** while simultaneously offering **thermal and acoustic insulation**, meaning that the green layer will effectively reduce the cooling load on buildings (Ottele, M., Koleva, D.A., van Breugel, K., et. al., 2010).
- Non-vascular plants, such as moss, play a critical role in **environmental sustainability**, globally sequestering up to 3.9 billion metric tons of carbon annually through the process of photosynthesis (Elbert, W., Weber, B., Burrows, S., et. al., 2012).
- The flow of water through these plants **cools the surrounding air** via evapotranspiration, decreasing the effect of the urban heat island effect (Glime, J. M., 2017).
- The unique structural characteristics of these plants enable them to capture dust and pollutants, thereby **enhancing air quality** (Haynes, A., Popek, R., Boles, M., et. al., 2019).
- In contrast to conventional green wall systems, bio-receptive facades are inherently integrated into the building materials, **functioning autonomously** without the need for external irrigation or significant maintenance.
- Finally, a bio-receptive or green facade is known for **enhancing people’s mental and physical well-being**. There has been multiple studies evidencing that greenery reduces stress and enhances comfort (Tzoulas, K., Korpela, K., Venn, S., et al, 2007).

11.2 Reshaping Public Perception

While bio-receptive facades provide a range of advantages, they are frequently viewed as problematic. Most people associate the disorganized and sudden growth of moss and lichens on surfaces as *dirty or deterioration* (Miller, A., Sanmartín, P., Pereira-Pardo, L., et. al., 2012), see figure 52.

To combat this perception, recent studies have explored the use of surface geometry as a design approach to encourage more organized and purposeful plant growth. This technique not only improves the function of bio-receptive materials but also enhances their aesthetic appeal, thus helping to reshape public perceptions and promote broader acceptance and appreciation. On a broad scale, bioreceptivity can be a tool for cultural change and a more holistic worldview (Karana, E., McQuillan, H., Rognoli, V., et al., 2023).

Next to reshaping people’s perception, incorporating visible living greenery into a building serves as a powerful metaphor for its relationship with the environment. It envisions the transformation of a building from being a mere structure into an active

Figure 52. Sudden growth of mosses in urban areas

participant in the urban ecosystem. By erasing the boundaries between nature and architecture, this approach emphasizes that buildings, much like living organisms, have the ability to grow, adapt, and thrive within their environments.

This perspective transforms our understanding of cities and promotes an ecological mindset that encourages individuals to raise ecological awareness and view urban environments as *interdependent systems* that prosper when human design aligns with natural processes.

Figure 53. The Urban Reef (UrbanReef, 2021)

11.3 Bio-Receptive Case Studies

Urban Reef - Pierre Oskam & Max Latour, 2021

The Urban Reef embodies a vision of the city as a lively and dynamic ecosystem, where urban spaces are intentionally crafted to promote vegetation growth and provide habitats for a variety of species. They have created porous, labyrinthine structures designed to capture rainwater and attract multi-species ecosystems.

The Urban Reefs are crafted using algorithms and are 3D printed with "living" porous materials, like ceramics and composites made from mycelium, river dredge, seashells and clay, mixed with seeds. These Reefs are designed to allow moisture in the air to circulate in the structures promoting a livable environment for fungi.

Each Reef structure is specifically designed for different urban applications and is categorized into distinct types, such as Rain Reef, Tidal Reef, and Zoo Reef. Each Reef is tailored to thrive in its unique urban setting. For instance, the Rain Reef is 3D printed from a porous material made from a mixture of seeds, coffee grounds, and mycelium, which is saturated with collected rainwater, making it accessible for the surrounding vegetation to grow (Urban Reef, n.d.).

Ossigeno Piastrella - Eduardo Brunelli, 2023

These facade panels are designed to turn building exteriors into green surfaces by its bio-receptive character. The smart geometry incorporates grooves that capture rainwater, creating conditions for algae and vegetation to grow. The grooves also provide shade and help regulate surface temperatures. In addition to supporting plant life, the thoughtful design enhances airflow.

Figure 55. Respyre (Respyre, 2021)

Respyre - Auke Bleij, 2021

Respyre is a design to transform concrete surfaces into eco-friendly ecosystems. Utilizing bio-receptive concrete, Respyre enables moss to grow on both vertical and horizontal concrete structures without the need for soil.

The process works as follows: a layer of specially formulated concrete is applied over a structure. This concrete is designed with enhanced porosity and a textured surface to promote optimal adhesion of the mosses. Thereafter, a bio-gel is sprayed onto the concrete layer. This coating enables the mosses to attach effectively while supplying essential nutrients and moisture.

After 12 weeks, the results become evident.
Once fully established, these mosses require no maintenance, resulting in a self-sustaining green

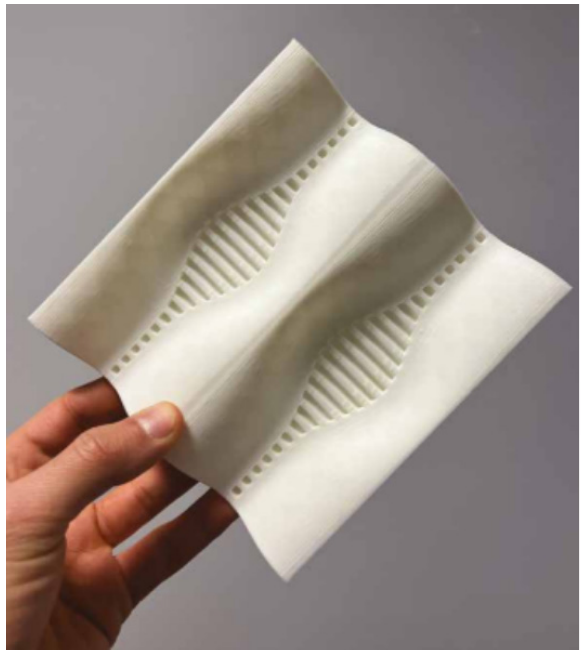

Figure 54. Ossigeno Piastrella (Eduardo Brunelli, 2023)

façade (Respyre, n.d.).
One drawback is that during the first 12 weeks, a temporary irrigation system is needed to provide the mosses with sufficient water.

11.4 Why Moss works for Building Facades

There is a reason why a lot of references use moss as a choice of vegetation to integrate in green facades, take a look at Respyre. Mosses have certain characteristics that make them highly suitable to integrate in facade applications.

Mosses are often characterized by their low-maintenance requirements and resilience. They can survive in tough environments, like dry, cold, and nutrient-poor areas, such as urban settings. As non-vascular plants, they lack a root system, allowing them to survive without soil (Brodribb, T.J., Carriquí, M., Delzon, S. et al., 2020). This unique trait enables mosses to absorb water and nutrients directly from the air, minimizing structural load, preserving the integrity of the underlying surfaces, and simplifying installation.

Although mosses lack roots, they still require water for fertilization and wind for spore dispersal. To thrive, mosses need a microclimate on and above their surface that ensures optimal moisture levels, shade or semi-shaded areas, and low wind speeds (Mustafa, K. F., Prieto, A., and Ottele, M., 2021). Mosses tend to flourish on darker shaded surfaces, as these colors effectively retain heat and moisture, creating ideal conditions for their growth (Kimmerer, R. W., 2021). Meaning that the natural dark hue of N-8040, in terms of color, supports the growth of mosses.

For the reasons above, mosses were selected as the type of flora to be included in the panel of N-8040.

When designing a bio-receptive panel aimed at cultivating mosses, it is essential to acknowledge that bio-receptivity is a natural process marked by unpredictable and spontaneous growth. This growth pattern evolves over an extended timeframe, often spanning several years.

11.5 Requirements

There are various methods to introduce or promote the growth of moss or vegetation on surfaces. Urban Reef incorporates the seeds directly into the material's composition, while Respyre applies a coating of moss spores on top of the material.

However, when examining the production process of N-8040 of NPSP, it becomes clear that it is not feasible to integrate a mix of seeds or moss spores into the N-8040 ingredients. This is due to the high pressure and temperatures of at least 140 degrees Celsius used during the pressing process, which would severely damage or destroy the viability of the organisms.

Therefore, it is essential to establish optimal conditions for moss to bond to the surface after the panel has been produced and installed. One effective approach, similar to Eduardo Brunelli's design, involves using geometry that channels water and features grooves to retain moisture. Below, a study conducted by Mustafa, K. F., Prieto, A., and Ottele, M. (2021) from the faculties of Architecture and Civil Engineering and Geosciences is discussed, which explores the impact of geometry on a self-sustaining bio-receptive concrete panel intended for façade applications.

Material Level

At the material level, there are ideal properties to encourage bio-receptivity of mosses, making mosses able to attach and grow:

- **High surface roughness** with **high porosity**. Porosity influences the amount of water a material can absorb and hold, which is vital for sustaining microorganisms and plants. Additionally, surface roughness helps establish a microclimate by retaining moisture, offering shade, and enhancing surface stability in harsh conditions (Tran, T.H., Hoang, N.D., 2017).
- **Neutral pH-level**, a *pH range of 7-8* has been found to produce the optimal chemical composition for enhancing the bio-receptiveness of the material (Guillitte, O., 1995).

Microclimate

When achieving an engineered growth of mosses in targeted areas, an established self-sustaining environment is needed: a microclimate. A microclimate refers to localized atmospheric conditions of a specific area that differ from the surrounding general climate. To achieve the most promising and optimal conditions for the mosses to grow in the targeted areas, Mustafa, K. F., Prieto, A., and Ottele, M., (2021) have researched what conditions are required for growing moss on a facade:

- **Presence of water**. Water is essential for facilitating bio-colonization (Bates, J. W., 1998). Water from various sources, such as dew and rain, needs to be catched, retained and slowly directed to the grow areas.
- **Shading**. Mosses thrive best in semi-shade or filtered light, as direct sunlight can dry them out. Naturally, forests, shady walls, or north-facing surfaces are ideal places for moss growth (Van der Hoeven, E. C., Korporaal, M., & Van Gestel, E., 1998).
- **Wind buffer**. Mosses can dry out in strong winds, making sheltered areas more conducive to their growth. Also, strong winds can lead to detachment of the mosses, a buffering zone will counteract this problem (Van der Hoeven, E. C., Korporaal, M., & Van Gestel, E., 1998).

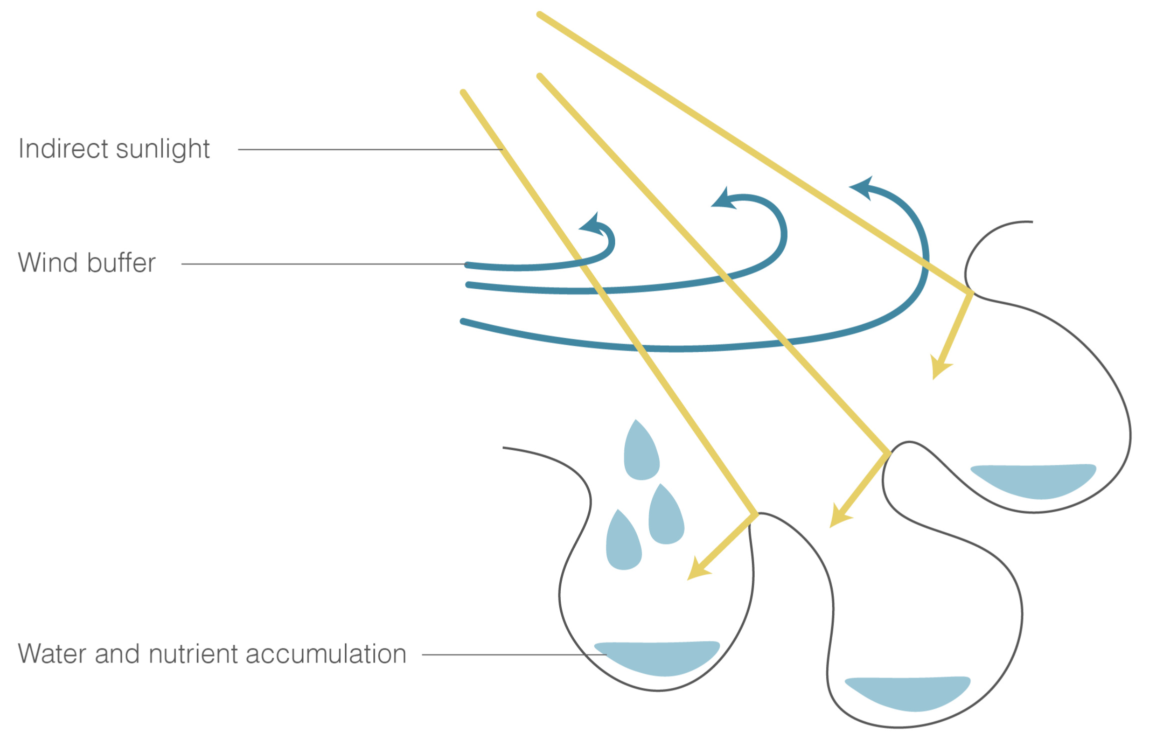

Figure 56. Encouraging a microclimate

- **Nutrient Accumulation**. Mosses need nutrients to thrive, supporting further growth and development.

These conditions can greatly be influenced through geometry. Mustafa, K. F., Prieto, A., and Ottele, M., (2021) have done research on the role of geometry for the bio-receptivity of mosses on six different designs of concrete panels. They and other studies, like the one of Rotondi, C., Gironi, C., Ciufo, D (2024) on bio-receptive ceramic surfaces, show that obtaining a microclimate for moss growth can be achieved through surface design at both the **micro** and **macro level**.

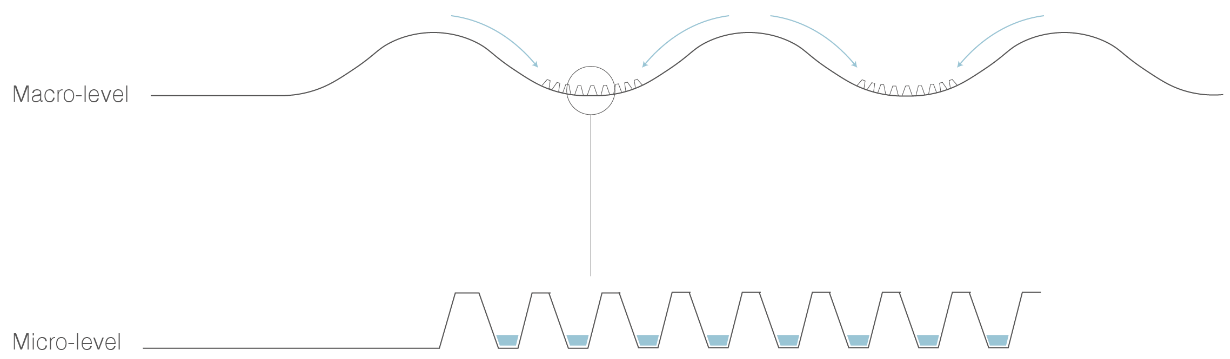

Figure 57. Macro- and micro-level surface

Macro- and micro-geometry

Macro-level geometry features determine the surface's overall contours, differentiating areas meant for growth and non-growth.
On micro-level, micro-grooves are a solution in facilitating moss establishment by gradually directing water towards accumulation areas and offering anchor points for moss growth. In synergy, these geometric levels work in harmony to influence the water distribution across the panels and to create a localized microclimate, to finally achieve growth in the desired areas (Mustafa, K. F., Prieto, A., and Ottele, M., 2021).

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As a result of their research Mustafa, K. F., Prieto, A., and Ottele, M., (2021) came up with a set of design guidelines for surface geometries that enhance the bio-receptive character:

- The panel should include a mix of **macro-depth geometry** and **micro-grooves** to optimize water collection.
- On macro-level the geometry contains continuous **'along the flow' obstacles**, meaning that the macro-surface differentiates in thicknesses in the vertical direction, in order to encourage the channeling of water to the specific growth areas.
- The **depth of the macro-surface** is a maximum of *20mm with a H/W ratio of 0.2-0.3*.
- The **depth of the micro-grooves** is ideally *5mm with adjusted W/H ratios*. This depth still encourages water circulation and is sufficiently small to catch water droplets and nutrients.

12. Texture: Growing Moss

12

At the material level, two key properties promote vegetation growth: a neutral pH level and high surface roughness and porosity. It is known that N-8040 has a pH of 7, which is advantageous for supporting vegetative growth. The other property can be evaluated through testing.

The porosity and surfacetexture of the material facilitate the attachment of water to the surface and provide a substrate for moss colonization. To investigate the effects of surface microtexture on moss growth, a 5-week experiment was conducted to address the following research questions:

1. **Is moss growth feasible on N-8040?**
2. **Are there significant differences in moss growth on various surface microtextures?**

The experiment involved applying an examined mixture of moss, sugar, water and buttermilk, to differently treated surfaces of N-8040, after which the samples are placed outside. Every week the progress of moss growth has been evaluated.

12.1 Research Set Up

Initially, the N-8040 material was subjected to three distinct surface treatment methods:

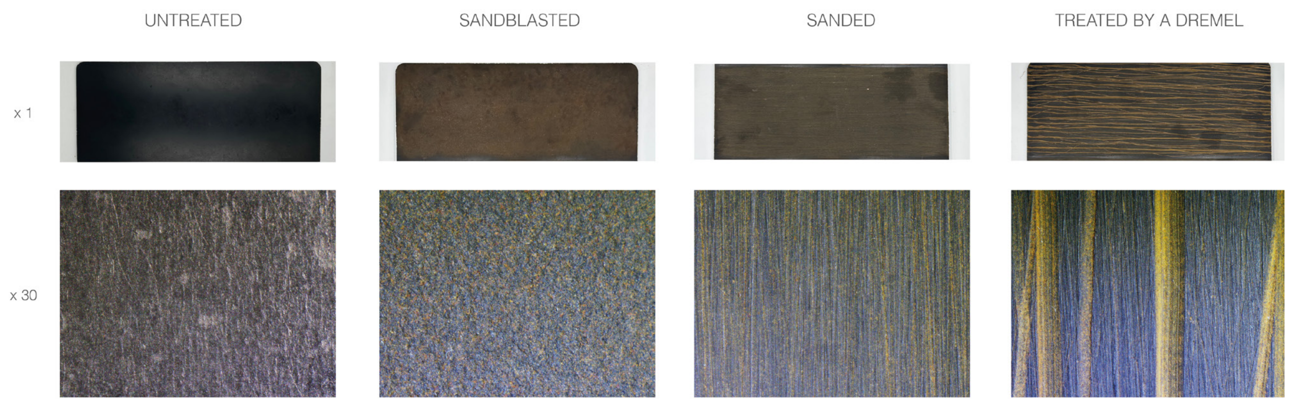
- *Sandblasting* to modify the surface texture.
- *Sanding* with coarse P60 sandpaper applied unidirectionally to create microgrooves.
- *Machining with a Dremel tool* to generate deeper grooves, also oriented unidirectionally.

Figure 58 provides a visual comparison of the treated surfaces, illustrating their appearance to the naked eye as well as under 30x magnification.

Numerous studies have investigated how to start growing moss yourself. It appears there are different methods where retrieved moss from outside is cut and mixed with either yoghurt or buttermilk. In this test, the 'recipe' is derived from the study by Perini et al. (2020). The specific quantities and ingredients are detailed in Figure 59. The test set up is inspired by the study of moss growth conducted by Mustafa et al. (2021).

The collected moss was extracted from between the bricks on the place where after the samples were installed with the moss 'slurry'. This approach ensures that the only variable being modified is the surface.
The moss was finely cut into small fragments using scissors. All the individual components were accurately weighed and stirred using a spoon.

The moss mixture was then applied manually to the samples until all exposed areas were fully covered. For experimental control, half of the surface treatments were intentionally left uncovered and an untreated sample of N-8040 is covered with the moss mixture. To maintain moisture while allowing the moss to breathe and receive sunlight, the samples were covered with a plastic film featuring ventilation holes. This methodology was inspired by Respyre, which employs a similar technique after spraying a moss gel onto concrete walls.



Figuur 58. Treated surfaces of N-8040

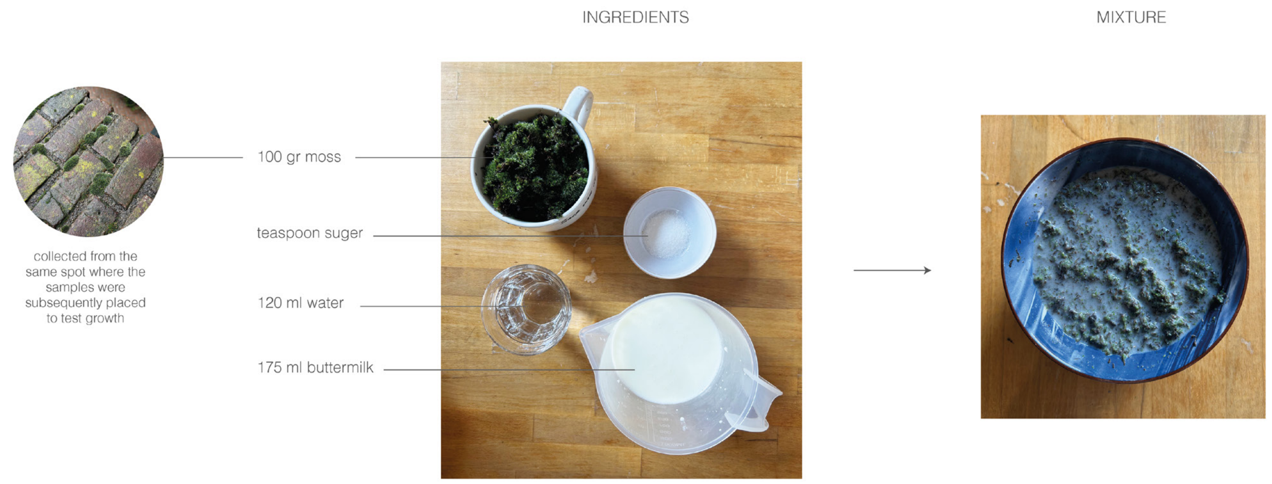


Figure 59. Ingredients of the moss 'slurry'

The samples were oriented horizontally and placed outdoors for a duration of *5 weeks*. This configuration was implemented to prolong moisture retention and to prevent the moss slurry from sliding off the surfaces. Besides, Mustafa et al. (2021) state in their research, *"The panels should be placed in a horizontal position until visible moss growth occurs."*

From *January 11 until February 15 in 2025*, the samples containing the moss mixture were placed outdoors, where they experienced an *average temperature of 2.6°C*, *approximately 2.6 hours of sunshine per day*, and an *average precipitation of 3.0 mm per day* (KNMI, 2025). Figure 60 illustrates the experimental setup.

12.2 Results

Test One

The method outlined above was derived from an initial test, in which the fungus completely dominated growth after two weeks (see figure 61). Following that, several modifications were on the method that could be potential contributing factors to this outcome:

- The **moss mixture** in the first test comprised a 2:1 ratio of yogurt to moss. Yogurt, having an average pH of 4.0, creates an acidic environment conducive to fungal growth (Michigan State University, 2024). To address

Figure 60. Test set up

this problem, the recipe has been changed to buttermilk (pH 4.5) mixed with sugar and water to achieve a more neutral pH.

- The **preparation** method for the moss mixture. Instead of using a blender in the first test, which may have excessively damaged the moss and its spores, the preparation was changed to cut the moss with scissors to minimize injury and enhance its potential for growth.
- The thick yogurt-based mixture was applied in a **dense layer**, potentially leading to inadequate gas exchange and sunlight penetration. In the test following up, a thinner layer has been applied.
- During the first test the samples were placed under a shelter due to heavy rainfall. This may have subjected the moss to **insufficient sunlight**, favoring fungal growth. Fungi are known to thrive in moist, dark environments (Talley et al., 2002), which may have contributed to their rapid dominance.

mark (Perini et al., 2020).

During some weeks, *week 1 and 3*, the moss exhibits a greener coloration; this is attributed to the moss being dry at the time the photograph was taken. Conversely, during the other weeks, the moss has absorbed moisture from rainfall, contributing to its wet appearance.

After 5 weeks, no obvious differences are evident among the moss mixtures on the various treated surfaces, and it appears that the mixtures remain fixed in their respective locations without removing or shifting across the samples.

In the photograph from *week 1 and 3*, white spots are identifiable, which represent fungal growth. This symbiotic relationship is commonly observed during the early stages of plant development, indicating the initial establishment of fungi and spores prior to the emergence of the moss (Michigan State University,

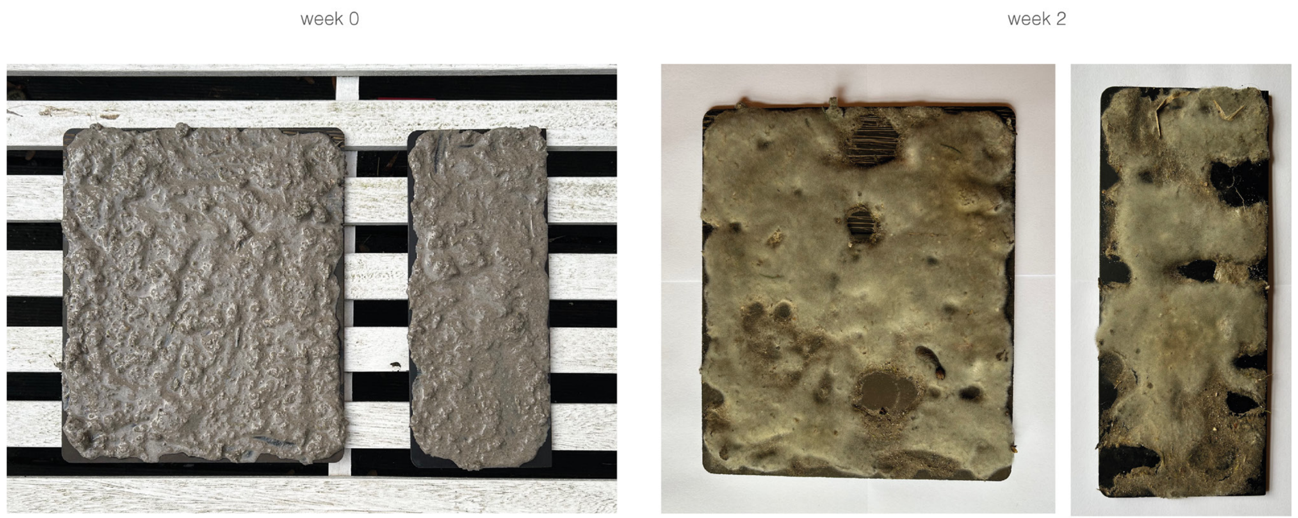


Figure 61. Test 1 of Growing Moss

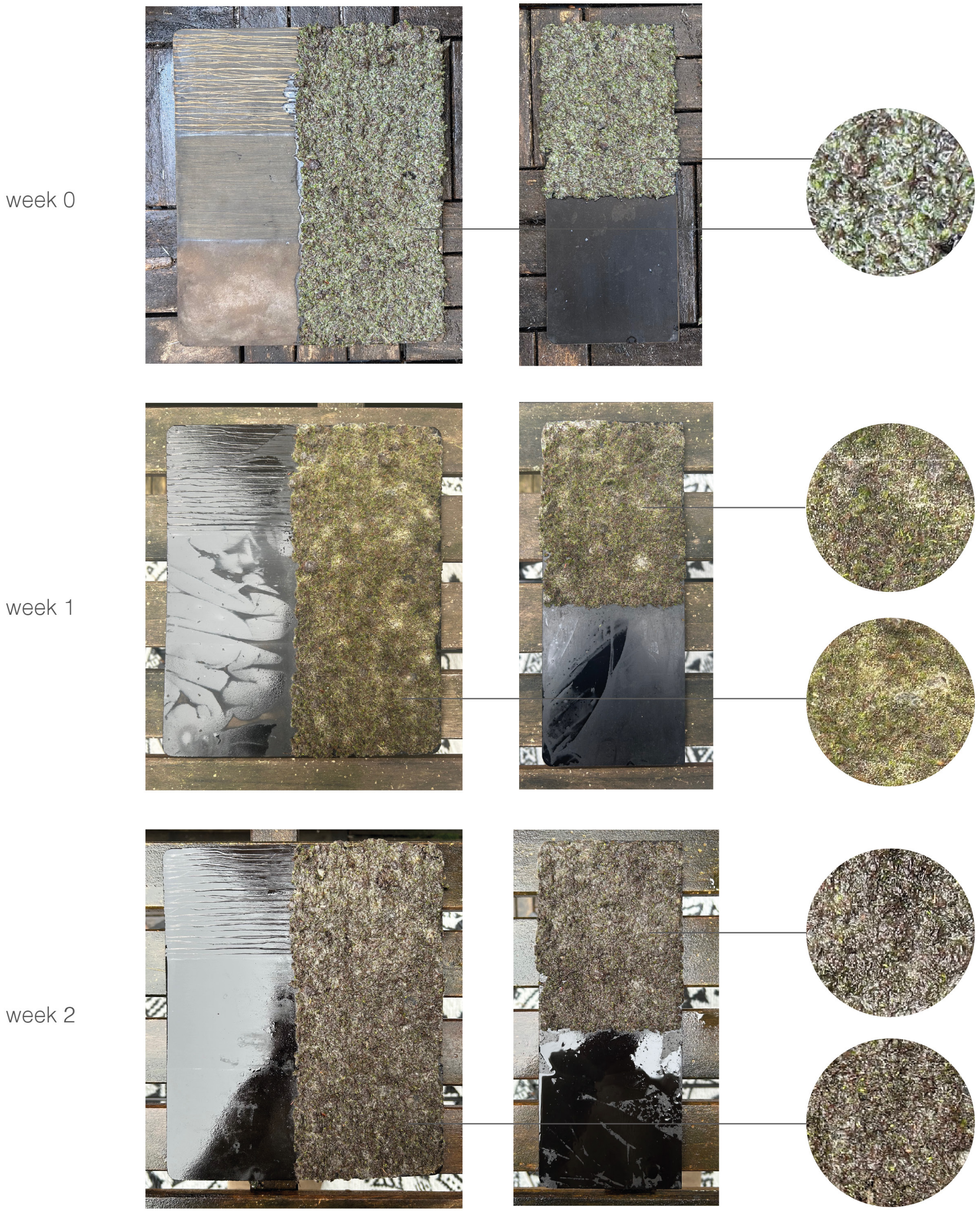
Refined Test

Figure 62 presents the visible results of the experiment. During the *five weeks* of observation, the moss remains viable, as indicated by the bright green appearance of the moss particles on the surface. However, no new moss growth has been observed, which is consistent with expectations, as new growth typically occurs around the eight-week

2024). It is remarkable that this fungal growth has also disappeared in the next week, meaning that this growth does not dominate the overall growth. The fungi appears during weeks when the panel is dry, so it is possible that a correlation exists between drought conditions and fungal growth. Another conclusion is that the fungi is more visible when the moss mixture is dry.

This research demonstrates the importance of ensuring that moss is not prevented from water for an extended period. As observed in *week 3*, the moss begins to dry out and starts to lose its adhesion to the material.

After five weeks, it can be concluded that the moss remains alive on both untreated and all treated surfaces, with no significant differences in growth between the various surfaces at this stage. To obtain more comprehensivev results, the study should be extended to at least eight weeks of observation.



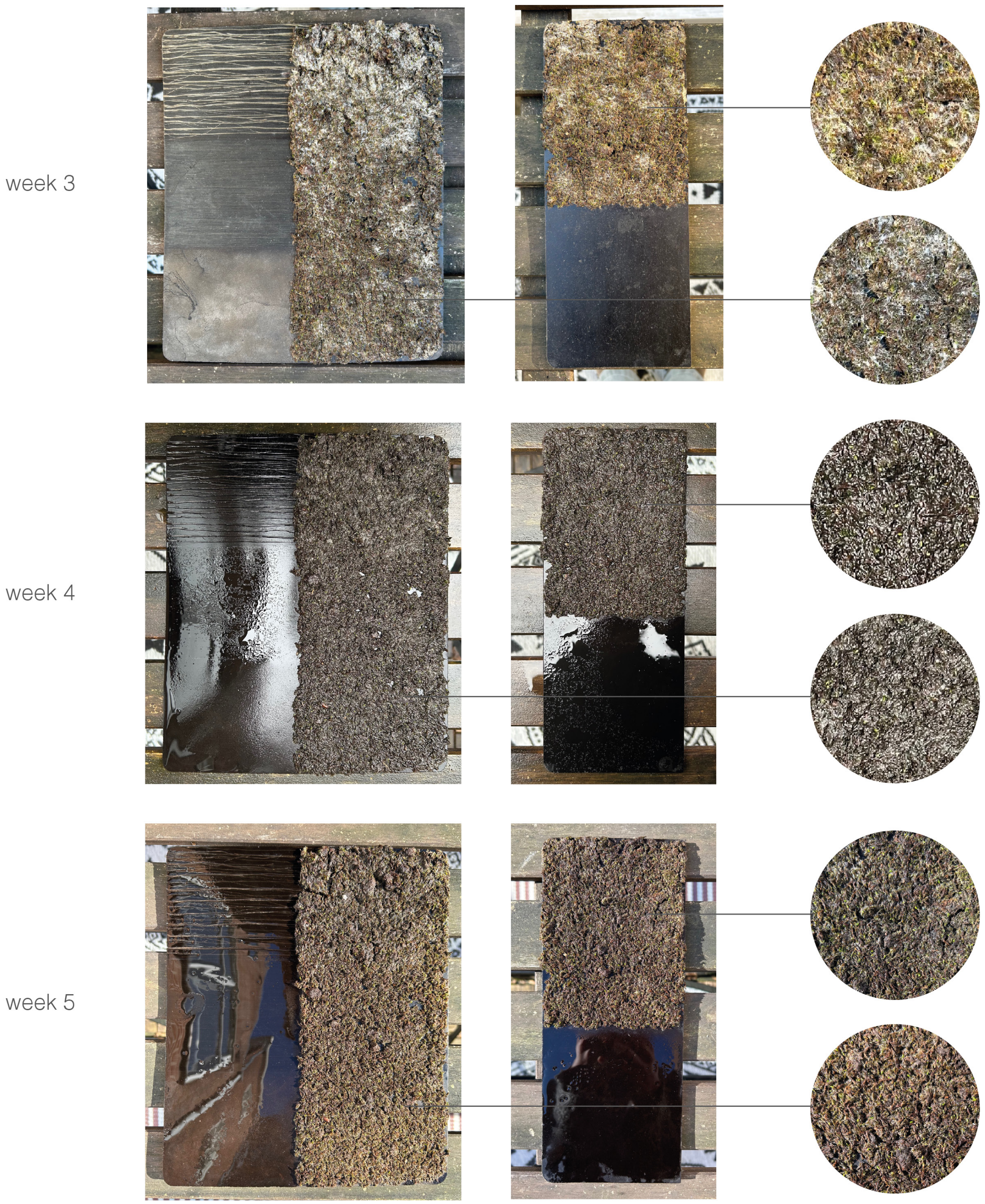


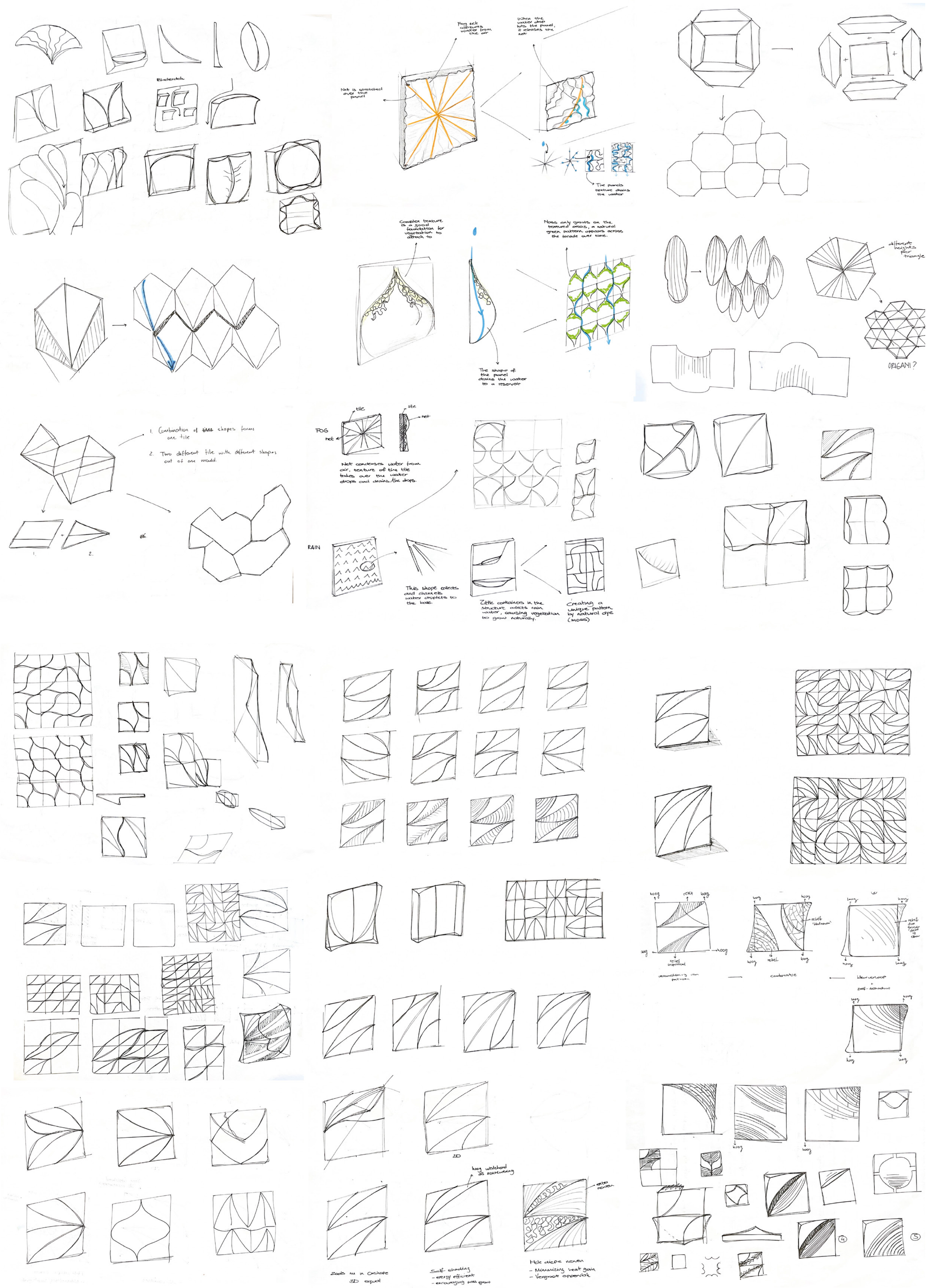
Figure 62. Weekly results moss growing test

12.3 Limitations

The testing conditions were suboptimal and substantially influenced the results. Mosses thrive at temperatures *between 15-25 °C* (Varela et al., 2021), and significant growth typically requires at least eight weeks (Perini et al., 2020); therefore, the five-week duration of the test is not enough to see results. Furthermore, the panels were evaluated in a horizontal orientation, further investigations are needed to assess growth in a vertical orientation.

13. Form

13



The design process, encompassing both a micro- and macro-geometry, was similarly separated into two distinct phases. Both design geometries were developed parallel to each other. The process combined structured and intuitive methodologies; starting with a systematic approach to the micro-groove design, followed by intuitive exploration of macro geometries. This was subsequently refined through iterations, with the final iteration tested in an experimental setup.

13.1 Micro-geometry

The micro-geometry, consisting of micro-grooves, is a critical component of the design. The grooves can be tailored to vary in size and pattern. Existing literature provides a framework for optimizing groove dimensions. Therefore, different patterns of the grooves have been considered in this design process.

The micro-groove patterns considered in this research are based on fundamental principles: straight, curved, crossed, and random lines, from which more complex configurations can be composed. Each pattern forms a rhythm that influences water flow dynamics and, consequently, the response of the moss. Before designing the macro-geometry, four micro-patterns are defined (figure 63, from left to right):

- No pattern
- Straight-line patterns
- Curved-line patterns
- Crossed straight-line patterns
- A random pattern

During the conceptualization of the macro-geometry, various groove patterns and alterations were applied depending on which configuration best complements the overall shape.

13.2 Macro-geometry

13.2.1 Ideation

Drawing inspiration from a variety of references, numerous sketches and designs were developed. The designs explored various aspects:

- **Geometry**: What is the shape of the panel, and how do they interconnect? Is the design organic or geometric? Are there multiple panels with varying shapes that fit together harmoniously, or is it a single panel?
- **Water Flow Movement**: How does the shape and depth of the panels affect the water flow movement? Is water collected solely in the grooves, or are there larger trays that serve as reservoirs?
- **Sun and Wind Interaction**: Is the panel

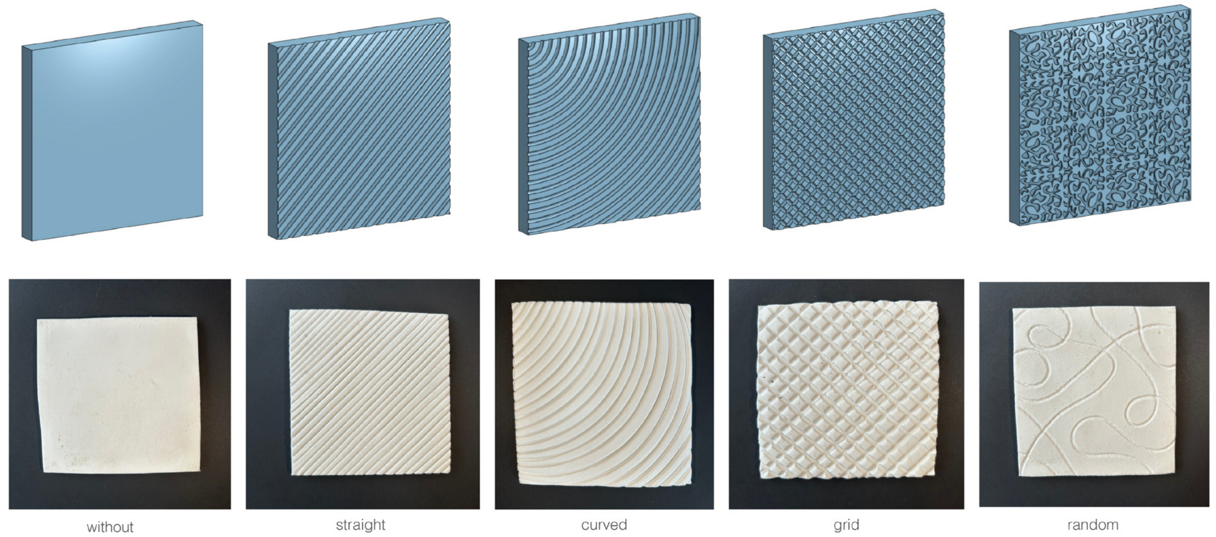


Figure 63. Weekly results moss growing test

symmetrical or asymmetrical, allowing it to function as a built-in solar and wind screen?

- **Bio-inspired Designs**: Where can inspiration be found from nature pursuing the same goal, how can these shapes and mechanisms be adopted in the panel?
- **Line Play and Patterning**: How to create a play of lines in individual panels and pattern formation across multiple panels, to achieve a sense of harmony and order that is aesthetically pleasing to the human eye? A primary requirement was ensuring that the panel could be positioned at any rotation and connect seamlessly to adjacent panels, allowing for maximum placement flexibility. This approach enables the creation of a unique arrangement each time or a structured pattern across the facade.

Various tools, including sketches, clay models, *Onshape* (a digital 3D modeling software), *Midjourney* (an AI image generator), and *Photoshop*, were utilized during the ideation phase.

After conducting explorations of various geometric forms, a square panel was selected as the design choice due to its widespread applicability and versatility, particularly in terms of mounting systems.

13.2.2 Bio-inspired Design

The design was motivated by the desire to draw inspiration from nature. Given the shared functionality between a leaf and the panel design, wherein both collect and drain rainwater, this similarity served as a key inspiration for the design.

The reverse curvature of the leaf controls the convergence process of the flow of the waterdrops, while the long-tailed apex allows for rapid water discharge with the centre of the droplet separation beyond the leaf tip (Liu, S., Zhang, C., Shen, T., et al., 2023). To optimize water flow and drainage, a double-curved surface is essential, featuring a central vein where droplets converge, and a tapered end for efficient drainage.The shape, curvature and length of the tail all affect the efficiency of water drainage of the leaf, see figure 64.
With the panel design, the requirements (curved surface, a vein in the base and a tapered end) for water drainage have been aimed to abstract and apply.

13.3 Iterations

Through a series of iterative refinement steps, the bio-inspired design was optimized to achieve its intended purpose and visual characteristics, see figure 65.
Appendix G shows different potential patterns per design with expected flow of water and/or location of moss growth of the iterations.

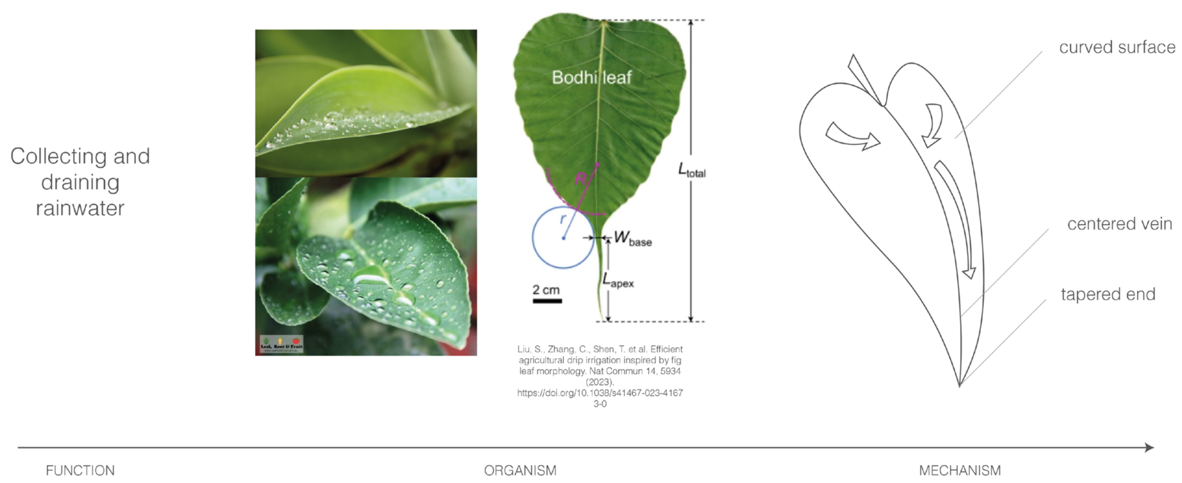


Figure 64. Biomimicry: leaf morphology on water drainage

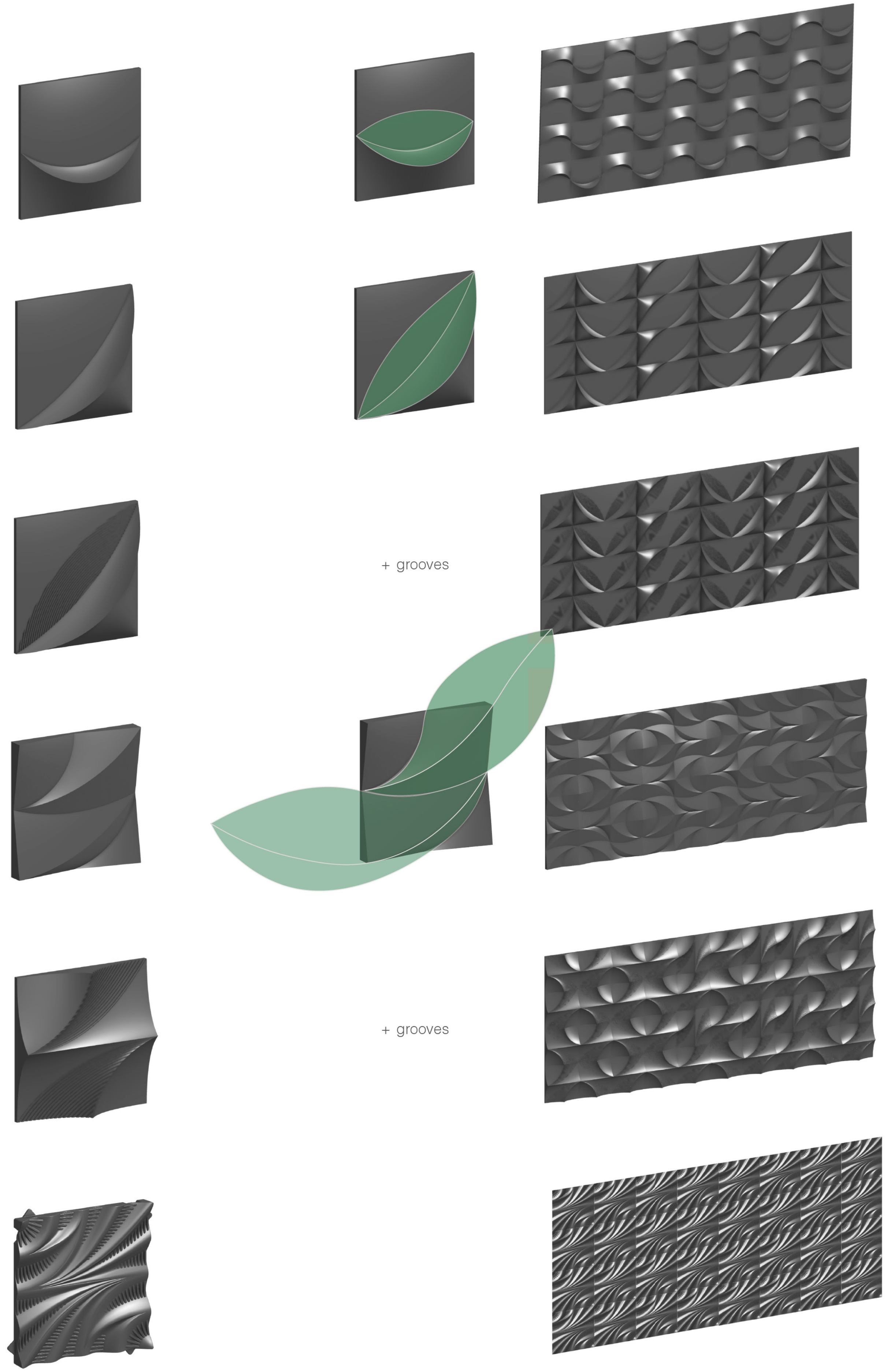


Figure 65. Iterations

The iterations were evaluated and refined based on four key criteria:

1. **Panel alignment:** Ensuring seamless alignment of the panels in all rotational configurations.
2. **Hydro performance**: Designing the geometry to facilitate the retention and channelling of rainwater movement (one of the factors in shaping a microclimate).
3. **Aesthetic harmony and variation**: Interesting line formations and potential for diverse pattern variations.
4. **Buffer zones**: Establishing sun and wind buffer zones (other essential conditions for shaping a microclimate).

13.4 Validating expectations: Water Retention Capacities

The test design draws inspiration from a similar study conducted by Mustafa, K. F., Prieto, A., and Ottele, M. (2021), which examined the water retention capacities of three panels. This research was performed in a laboratory setting. The two different designed panels were 3D-printed at a scale of 1:2, maintaining identical groove dimensions. The third panel tested is one design at a 1:1 scale, see figure 67.

Examining the water absorption of and its cooling effect on the panel was done by measuring the difference in weight and temperature after applying the same amount of water on all panels. Retaining more water and achieving a cooling effect will positively influence the growth of mosses. The supplies for the experiment are: a scale, a water sprayer, water, carrot juice and a thermal camera. The water used to spray on the panels was coloured with carrot juice to make the flow of the water visible.

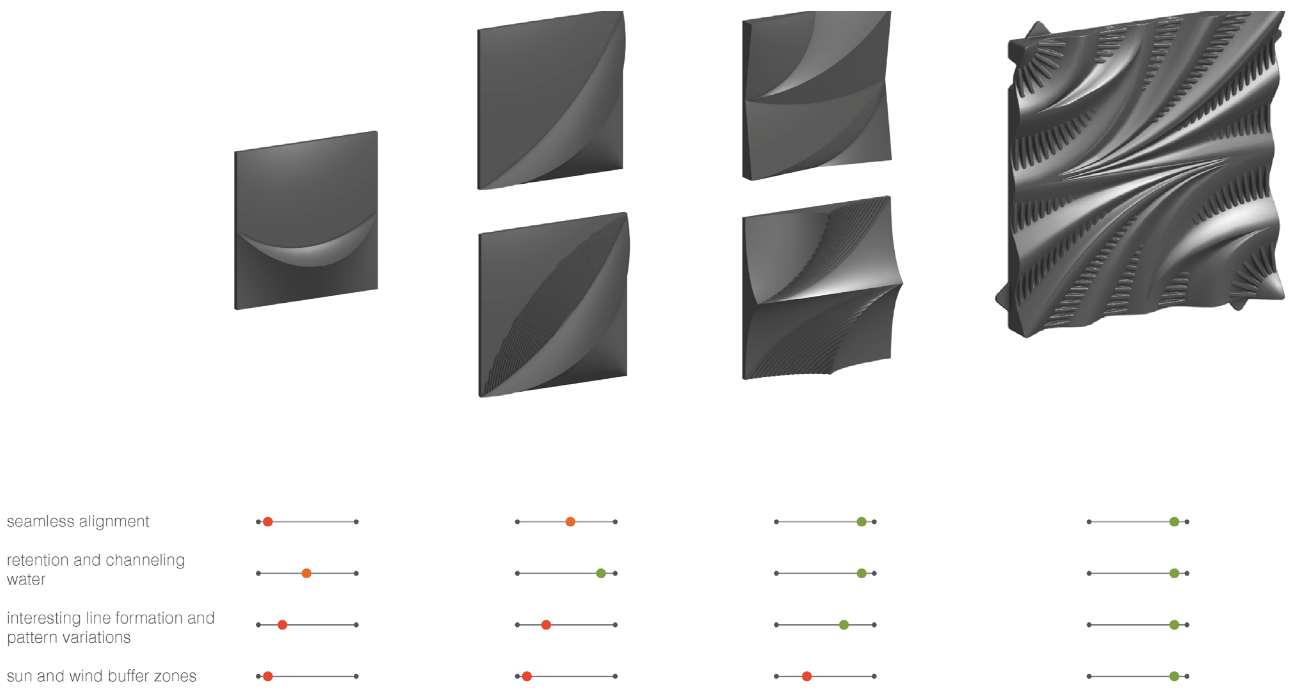


Figure 66. Assessment of the iterations

The assessment of the iterations is presented in figure 66.

To actually test the expectations about the potential of creating the best conditions for a microclimate based on geometry, a test was done between the last two iterations.

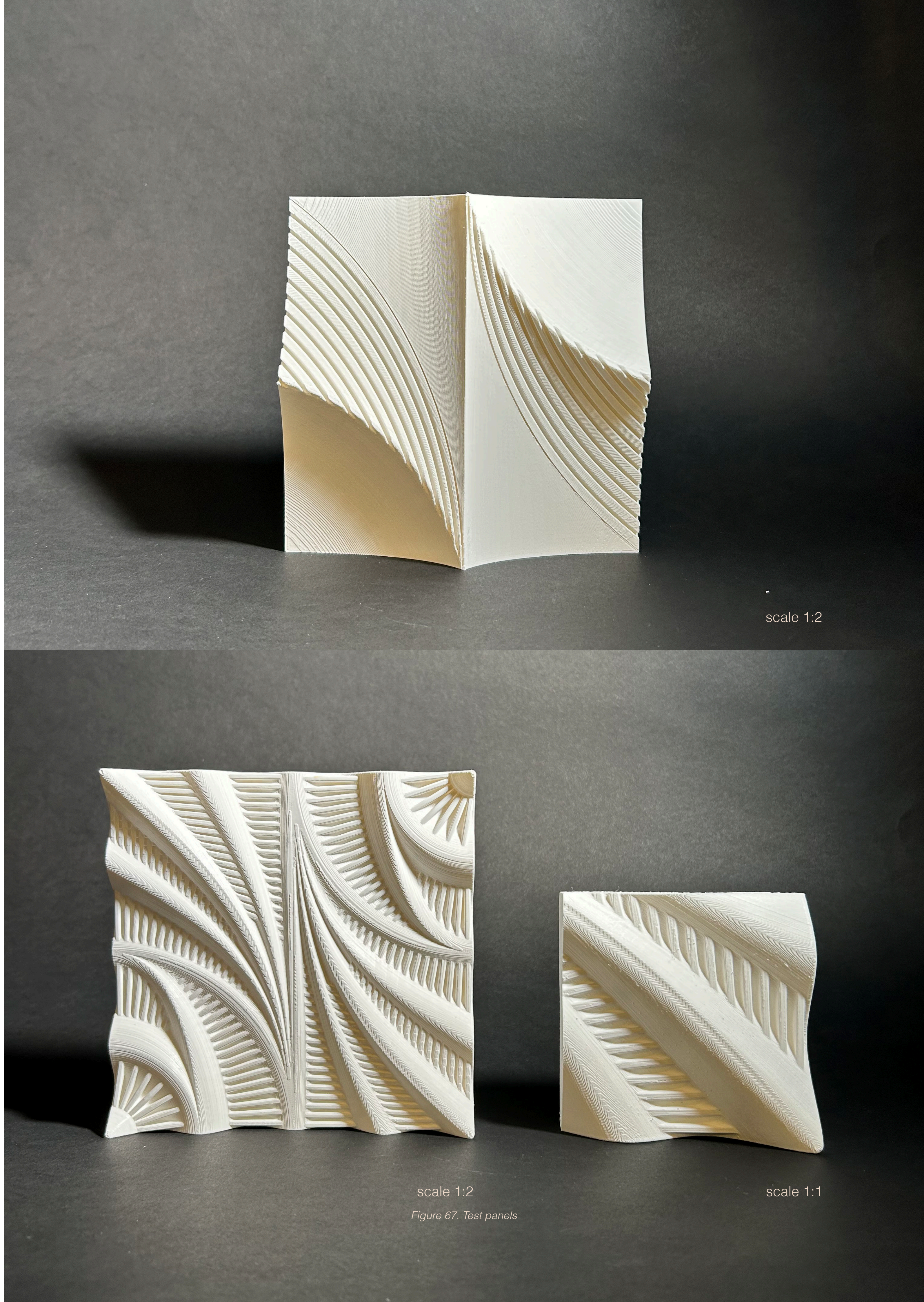


Figure 67. Test panels

For the experiment, the following steps were followed for all panels:

1. The weight of the panel was measured.
2. The panel was placed vertically.
3. *100 ml water* of *11 °C* with a water spray at a *distance of 40 cm* at an *angle of 45 degrees* was applied to the panel. See figure FIXME for the test set up.
4. After a period of *1 minute, 5 minutes* and *10 minutes*, the weight and temperature of the panel was measured.

Results

To clarify, the panels depicted in figure 69 are referred to as *panel 1, 2, and 3* from left to right. The water absorption results for these three panels, as shown in figure 69, indicate that *panel 2 and 3* absorb more water due to their geometry. While the weight difference is small, the percentage change highlights this effect more clearly, with *panel 2* showing a *2.3% increase in weight* compared to *panel 1's 0.9%*. Visual observation confirms this, as water readily adheres to the grooves of *panel 2*, while on *panel 3*, water tends to run off quickly, adhering primarily at the ends of the grooves.

Regarding the results of the cooling effect (figure 70), it appears that *panel 2* consistently remains

MATERIALS   TEST SET UP

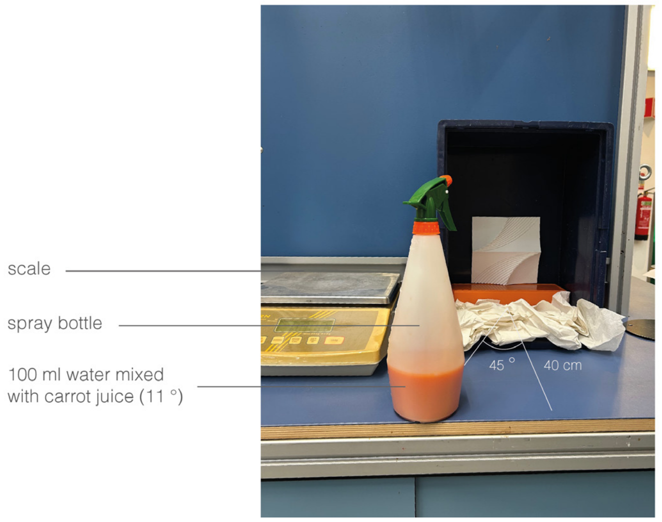


Figure 68. Test set up

cooler than *panel 1* across its entire surface after 10 minutes. *Panel 1* exhibits cooler areas corresponding to the groove locations *after 10 minutes*, with the flat surfaces appearing to cool down more rapidly. However, drawing definitive conclusions from these cooling results is challenging due to the varying initial temperatures of the panels prior to testing, which may have influenced the outcome.

Based on these findings, the design of panel 2 was selected.

after 10 min

before	0,110 kg	0,088 kg	0,064 kg
after spraying 1 min	0,111 kg	0,090 kg	0,066 kg
5 min	0,111 kg	0,090 kg	0,066 kg
10 min	0,111 kg	0,090 kg	0,066 kg
gain in %	**0,9%**	**2,3%**	**3,1%**

Figure 69. Results of water retention after 1, 5, 10 minutes

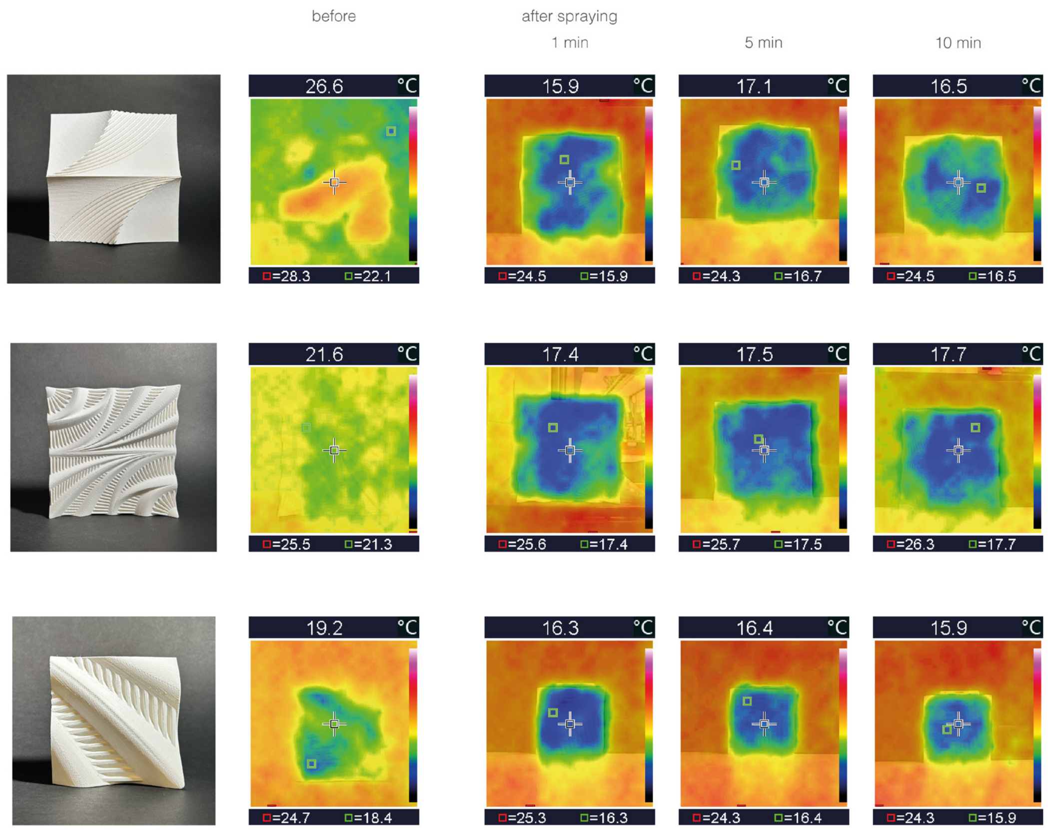
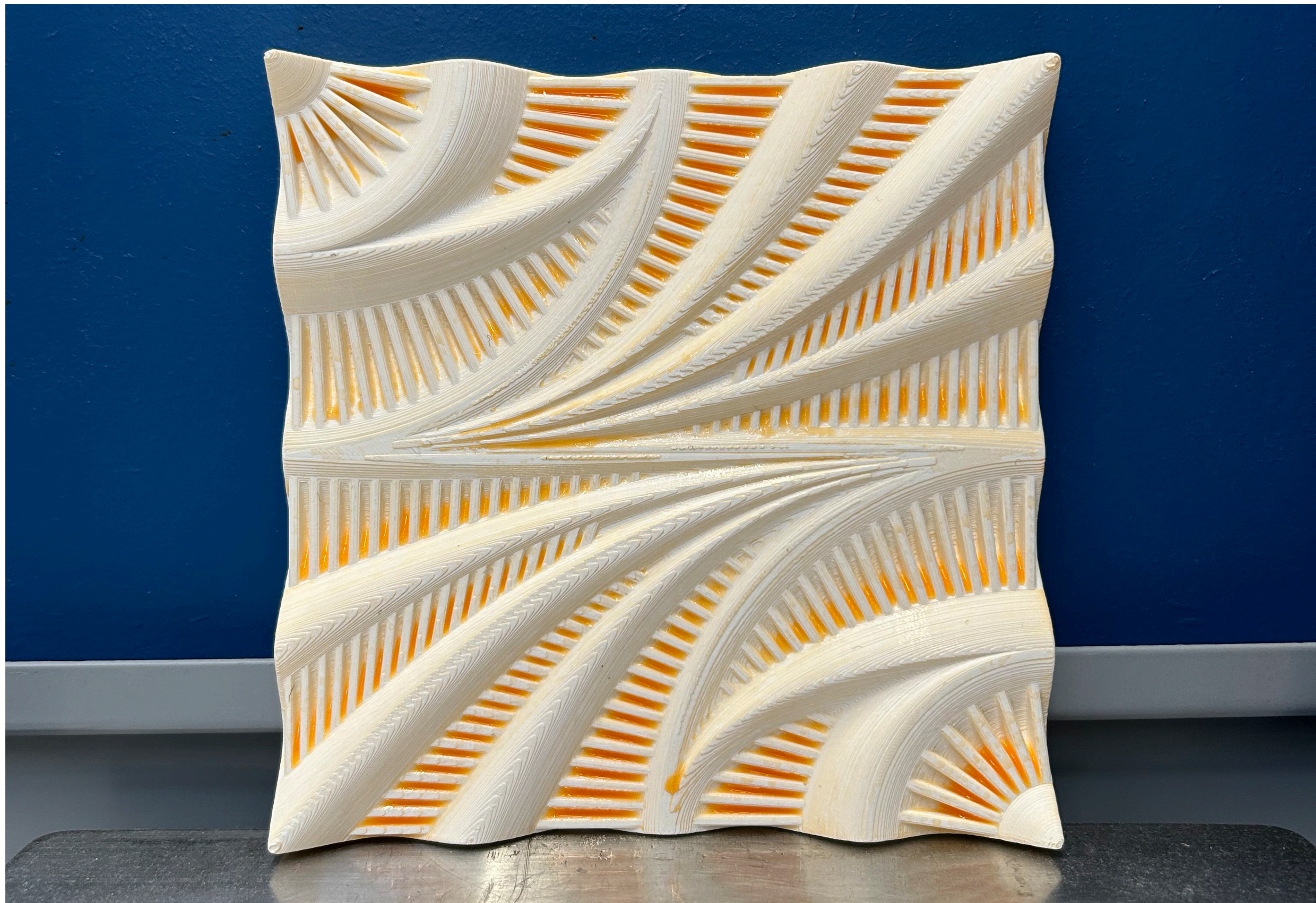
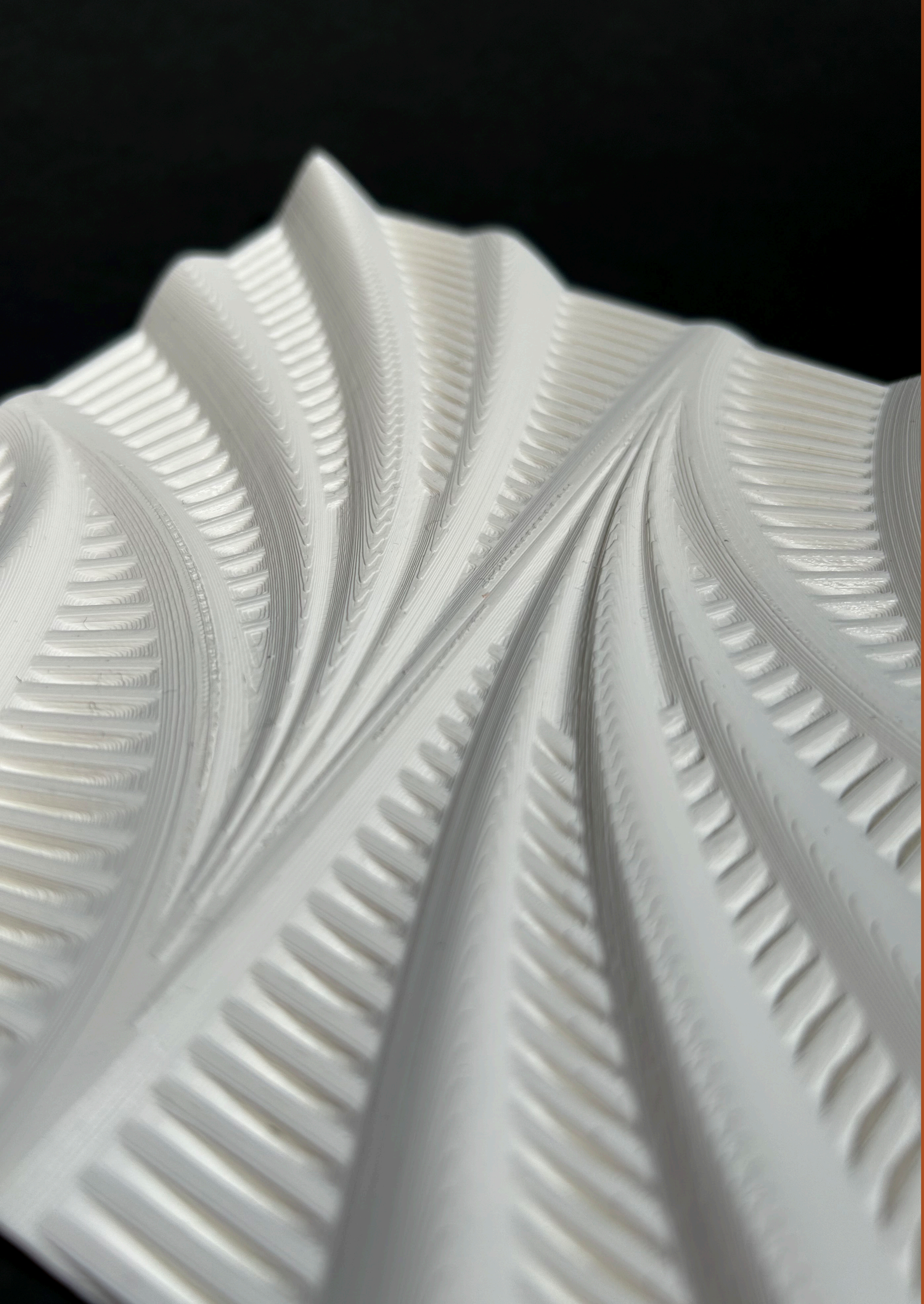


Figure 70. Results of temperature after 1, 5, 10 minutes





14. Material: Visualizing Fibres

14

The user tests described in Chapter 7.7 indicate that adapting the material to communicate its sustainable identity is of value for enhancing its appeal. The brand analysis of NPSP and the material benchmarking, demonstrates that this adaptation adds value to NPSP compared to how the material N-8040 currently performs relative to competing materials and products.

Consequently, it was decided to incorporate visible fibers into the material. The selection of these fibers is based on their availability to NPSP and several important properties.

14.1 Tweaking the Material

14.1.1 Adding Fibres

The visibility of the fibers is influenced by their hydrophobic characteristics. Hydrophobic fibers repel the dark resin, allowing them to maintain their color and remain visible in the final product. Maintaining the visibility of hydrophilic fibers within the material poses a greater challenge; however, this may be achievable if the fibers are sufficiently thick and firm to absorb only a minimal amount of resin (NPSP, 2024).

In collaboration with NPSP, the decision was made to incorporate the following fibers into the composition of N-8040:

- **Flax Fibers** (from Netherlands)
- **Coir** (Coconut Hair) (from India)
- **Banana Stem Fibers** (from Spain)

Figure 71. Preparing the mixture

Figure 72. The mixture of N-8040 with flax fibres

14.1.2 Results

Figure 73 illustrates the results of the addition of the different types of fibres to N-8040.

As anticipated, the flax fibers were fully absorbed into the material, making them invisible. In contrast, the coir and banana fibers remained visible to the same extent. In terms of visual properties, coir is slightly more orange in colour and these fibres are slightly longer than the banana fibres.
The difference in mechanical properties remains to be revealed in upcoming mechanical tests.

Based on their experience, NPSP can state the following about the expectations of the effect of fiber addition on the technical properties of N-8040:

"The addition of fibers to N-8040 results in a decrease in technical characteristics; however, these properties remain probably twice as high as our polyester panel." - NPSP, 2024

"The addition of fibers reduces the shrinkage of the panel, which is favourable." - NPSP, 2024

The failure in the corners on the smaller coir curved tile can be attributed to an insufficient amount of dough. It is expected that if this tile had been pressed with an adequate quantity of dough, such

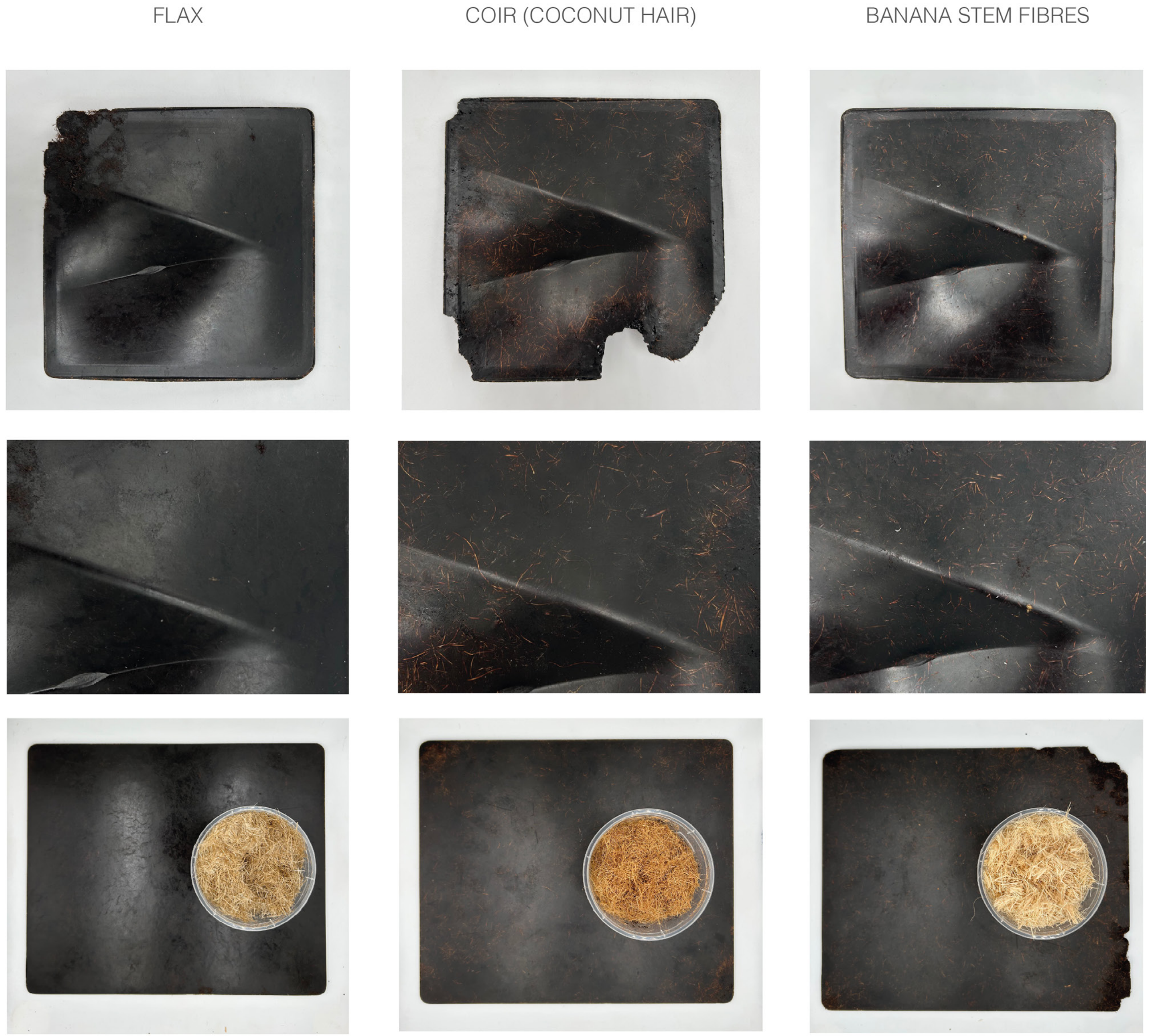


Figure 73. Results of the addition of flax, coir and banana stem fibres to N-8040

issues would not have arisen.
In the case of the flat panel containing banana fibers, the incomplete corners are likely due to either an excessive amount of dough being placed in the press or an over-addition of fibers to the mixture. This resulted in the dough becoming too dry, consequently hindering the material flow.

14.1.3 Conclusion

Following a discussion with NPSP, banana fibers were selected. This decision was driven by their lower Life Cycle Assessment (LCA) compared to coconut fibers, given that they come from closer sources.

While the impact of both fiber types on mechanical properties is expected to be comparable, the shorter length of banana fibers offers an advantage, particularly when molding complex and detailed shapes. Shorter fibers are less likely to cause issues during the pressing of the small grooves, unlike the longer coconut fibres.

Figure 74. N-8040 with banana fibres

14.2 Experiential Characterization of N-8040 with Banana Fibres

This test aims to compare the experience of the updated N-8040 material, with banana fibers, against the original N-8040 material (previously tested in chapter 7.7). The addition of banana fibers seeks to enhance the material's visual appeal and communicate its sustainable identity. The key objectives are to make the material appear more interesting and less impersonal and cold, as these were identified as primary negative experiences in the prior test.

14.2.1 Method

The method followed the procedure established in the previous test, detailed in section 7.7.1. This involved the Experiential Characterization Toolkit from the Material Driven Design Approach, developed by Camere and Karana (2018).
The difference between the prior and this test is that this test was conducted using only the fibre-enhanced N-8040 sample (see figure 75). The introduction of the other biocomposites was reserved for the final questions, which involved ranking the fiber-enhanced N-8040 in terms of beauty and perceived sustainability against the seven other biocomposite samples and the original N-8040 sample from NPSP (see figure 39). These biocomposite samples were identical to those used previously.

The test involved *six master's students in Industrial Design Engineering from TU Delft*. It is also crucial to note that participants were not provided with any information about the material or its applications before the test to ensure they approached the assessment without any prior knowledge or biases. For a comprehensive overview of the roadmap and methodology, please refer back to section 7.7.

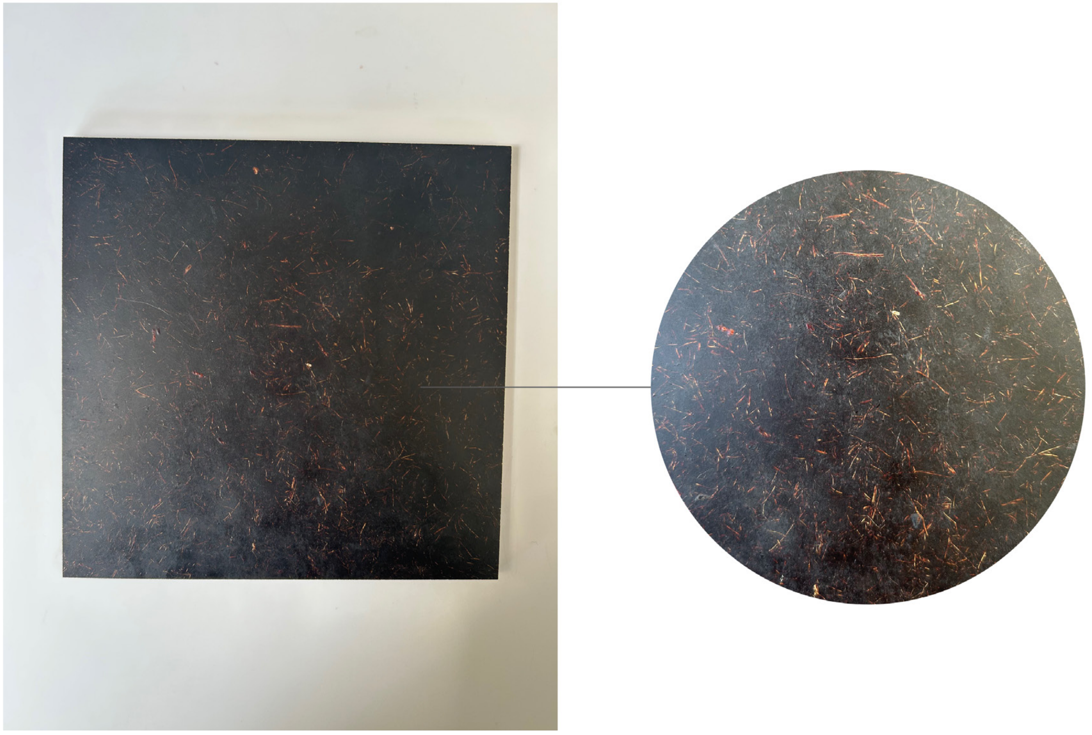


Figure 75. Test sample

14.2.2 Results

Before discussing the experiences at the performative, sensorial, affective and interpretive levels, *three of the six participants* made an explicit positive comment about the material as a first impression.

“Wow, it’s nice!” - Participant 6

Performative

The performative analysis revealed that the majority of participants *(four out of six)* chose to rub the material, indicating their curiosity about its texture, which they attributed to the visibility of the fibers. They were surprised by the material’s tactile properties:

“The material doesn’t seem smooth, but then when you touch it, it is, which is surprising.” - Participant 2

Another observation was that *five out of six* participants held the material up to the light, wondering how it reflects light and wanting to examine the woven fibers more closely.

“Hmm, when looking closer, the fibres make me think about what’s in the material and how it’s made.” - Participant 4

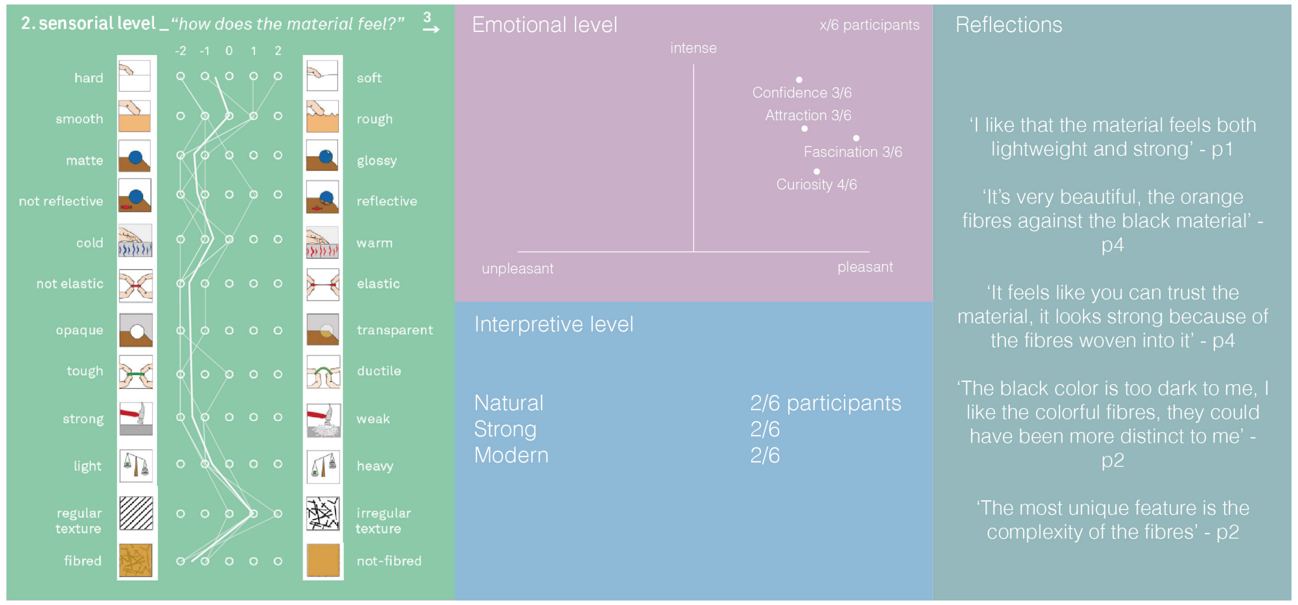


Figure 76. Results user test on experiential characterization N-8040 with fibres

Sensory

At the sensorial level, the most significant differences with the user experience test with the original N-8040 include the perception of an *irregular texture* and a *fibred surface*. It is interesting that the fibre-enhanced N-8040 is perceived as *stronger* and *tougher*. One possible explanation for this is:

“It feels like you can trust the material; it looks strong because of the fibers woven into it.” - Participant 4

Additionally, this material is perceived as *more lightweight* than the original N-8040. This could be attributed to the varying expectations or experiences people have with similar-looking materials that tend to weigh more.

Affective

First of all, it is evident that participants expressed more emotions with this material compared to the original N-8040. A total of *23 emotions* were noted by the six participants in this test, in contrast to *15 emotions* for the original material. This significant difference suggests that the tweaked N-8040 is more distinctive and imaginative.

Moreover, the set of emotional responses associated with the fibred material leaned much more towards the pleasant end of the spectrum. The average placement of the emotions of the original N-8040 lies in the middle on the unpleasant-to-pleasant axis. See Appendix FIXME for the individual test results.

In total two unpleasant emotions were recorded: *boredom* and *reluctance*. Comments on these feelings include:

“I find the material somewhat boring due to the black color. However, the colorful fibers prevent me from rating it as entirely unpleasant.” (boredom) - Participant 2

“I’m uncertain about the strength of the material, the fibers remind me of fabric, which isn’t very strong.” (reluctance) - Participant 6

The emotions most frequently reported by participants were *curiosity (4 out of 6), fascination (3 out of 6), confidence (3 out of 6),* and *attraction (3 out of 6). Curiosity, fascination*, and *attraction* seem to be interrelated and represent a sequential process: initially, participants express *curiosity* regarding the details of the fibers, wanting them to take a closer look. This *curiosity* evolves into *fascination* as they begin to wonder what is in the material and how it is made. Ultimately, this progression leads to the emotion of *attraction*, indicating that their interest has been sparked.

Confidence appears to be connected to the perceived strength of the material. This emotion was also perceived highly with the original N-8040.

Finally, two participants noted the emotion *pleasant*, even though it was not included in the predefined list of emotions.

“By seeing the fibres it is a confirmation that it is a sustainable material, I would be more likely to buy it for example.” - Participant 2

Interpretive

In terms of interpretive associations, the most frequently mentioned were *natural (2 out of 6), strong (2 out of 6)*, and *modern (2 out of 6).* The association with *natural* is caused by the visible fibers. Participants suspect that the material may be *natural*, although they are uncertain about its specific origin.

Notably, *modern* was also mentioned by *two participants*, both of whom envisioned the material being used in a contemporary, urban setting.

“It appears natural to me, the fibers make me think the material is recycled.” (natural) - Participant 4

“I see this material as part of a modern, urban building with geometric shapes.” (modern) - Participant 2

Reflections

Five out of six participants noted either the fibers or the color combination when describing the *most pleasant or unique* attributes of the material. Several characteristics related to the fibers were highlighted, including their complexity, which (according to the participant) adds depth to the material. The texture caused by the fibers was also perceived as unique or enjoyable. Additionally, participants described the color combination of the dark background with the fibers (referred to as golden, coppery, or orange) as distinctive and appealing. The contrast of a lightweight yet strong material was also regarded as unique and pleasant.

“The texture is nice; the detailed complexity of the fibers gives the material a deeper layer.” - Participant 2

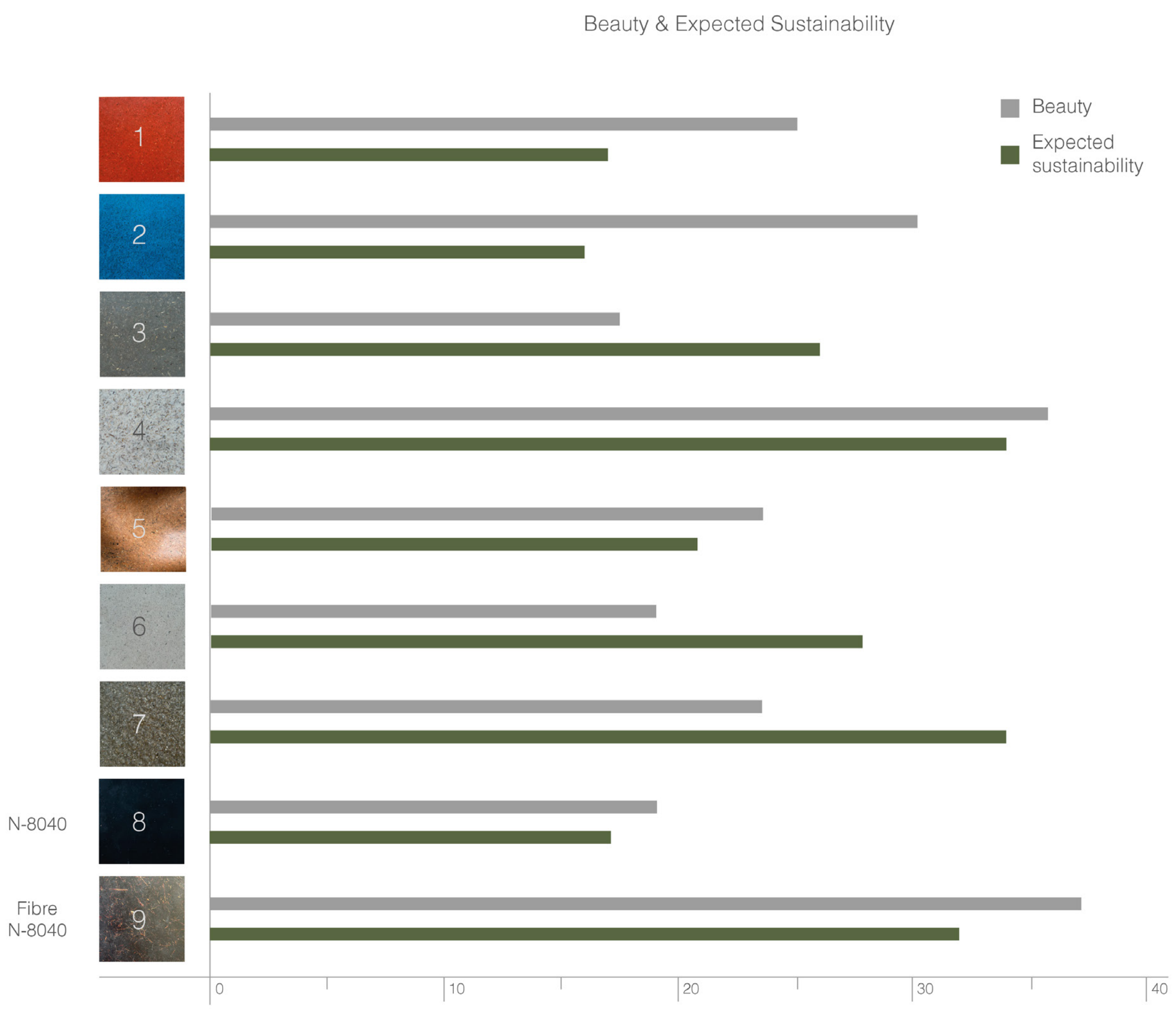


Figure 77. Results rating on Beauty and Expected Sustainability user test 2

Four of the six participants named a *most disturbing* feature, two participants did not. There was no clear correlation among the four disturbing features mentioned, these features can be referenced in appendix FIXME.

Biocomposites Benchmark

After presenting the other biocomposite samples alongside the original N-8040 material, participants rated the *beauty* and *expected sustainability* of the fibred N-8040 significantly higher than its original version. See figure 77 for the results.

In fact, similar to the previous test, three participants described the original N-8040 material as looking like plastic, uninteresting, and merely functional. In contrast, two participants specifically noted that the new N-8040 does not seem like plastic.
It can also be concluded that all the biocomposites with visible and recognizable fibers are perceived as more *aesthetically pleasing*.

"The black material looks like plastic, like the body of a traffic light." (original N-8040) - Participant 4

"It doesn't look cheap, like plastic, for example." (N-8040 with fibers) - Participant 1

Moreover, the modified N-8040 material is perceived as *more sustainable*, without any prior knowledge about it. Two participants even mentioned having experience with sustainable or recycled products, which enhances the perceived value of the material for them.

"I think it is a sustainable material, maybe it has wood in it?" - Participant 5

Conclusion

Texture: As no significant difference in growth was observed after testing moss on the various surfaces, the N-8040 surface will remain unaltered to enhance growth.

Form: Based on the outcomes of the water capacity tests, the design from the latest iteration has been selected.

Material: Among the three tested fibers, banana fiber has been found to be the most suitable option for achieving visible fibers in the material. This fiber will be incorporated into the original N-8040 formulation.

Experiential Characterization: The N-8040 sample containing fibers is perceived as more aesthetically pleasing and durable compared to the original N-8040. Consequently, the previous associations of being boring, impersonal, and cold have shifted to being viewed as natural, captivating, and modern.

15. Product: REVI

15

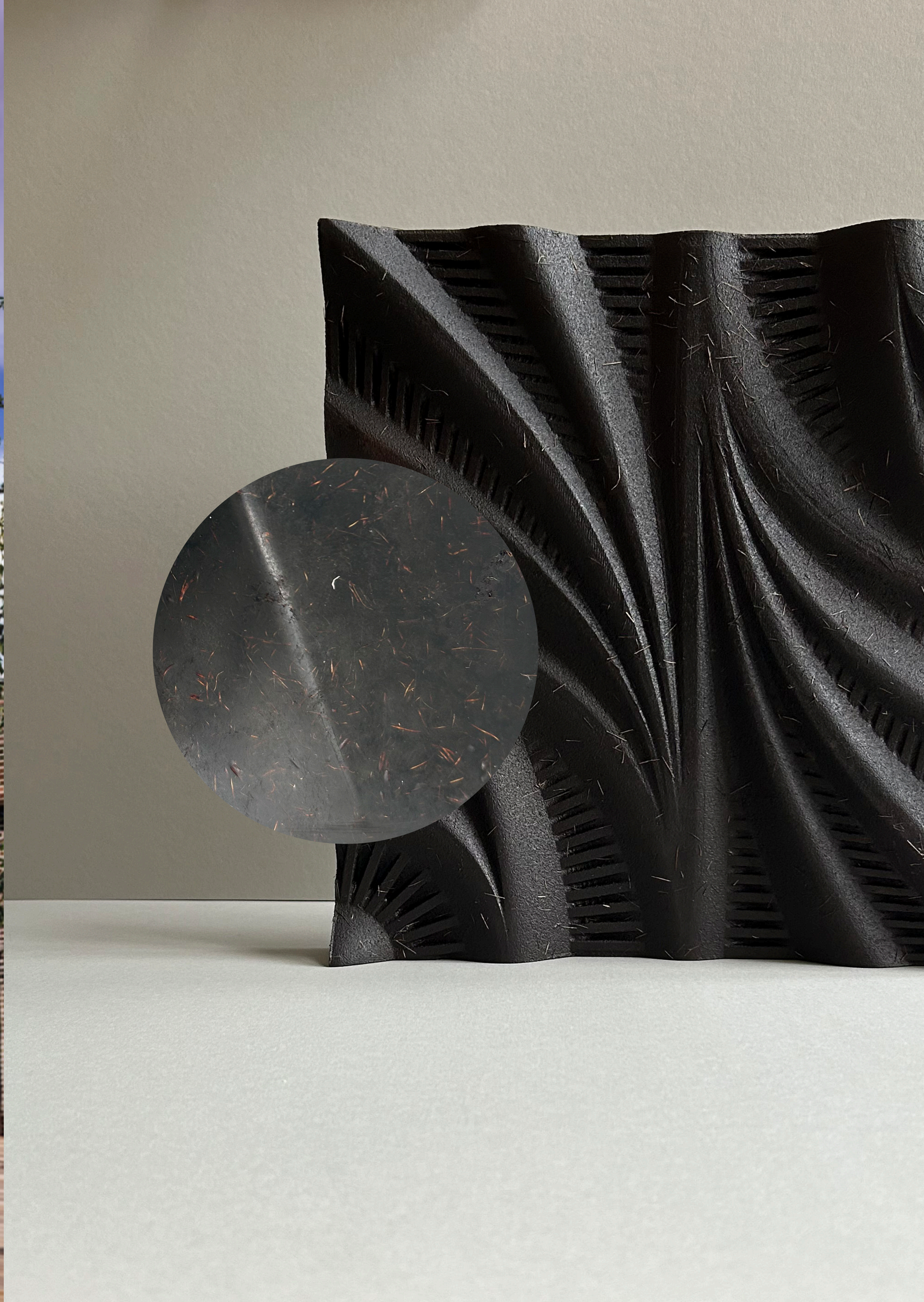

REVI

‘Regenerative Facade Solution for the Revival of Urban Areas’

Figure 78. Year 0 of application REVI

Figure 79. Year 1 after application REVI

Figure 80. Year 2 after application REVI



15.1 Shape

15.1.1 Patterning

Figure 81 shows how the panel is divided into *16 squares.* This segmentation facilitates the alignment of lines at corresponding positions on each side, resulting in a seamless alignment of all sides. This enables the freedom of selecting a different pattern for each installation, resulting in an unique appearance each time. Figure 82 displays several examples of uniform placement, with each panel arranged consistently. In the center, a structured pattern is implemented, while the image on the right features a random arrangement for an even more playful effect.

15.1.2 Aesthetics

The shape of the panel is derived from the '**Golden Ratio**', a mathematical ratio found in nature, art and design (figure 81). The Golden Ratio is derived from the Fibonacci sequence, where each number is the sum of the two preceding ones. The Golden Ratio is such a beloved tool in design due to its ability to create balanced, harmonious, and visually appealing compositions.

15.1.3 Rainwater Management

As described in chapter 13.2.2, the geometry of the panel is based on the geometry of a leaf. This leaf-inspired design incorporates several key features: a curved surface, a prominent basal vein, and a tapered end point, all to optimize water flow and drainage (Liu, S., Zhang, C., Shen, T., et al., 2023). The influence of the panel's geometry on the management of rainwater is illustrated in figure 83.

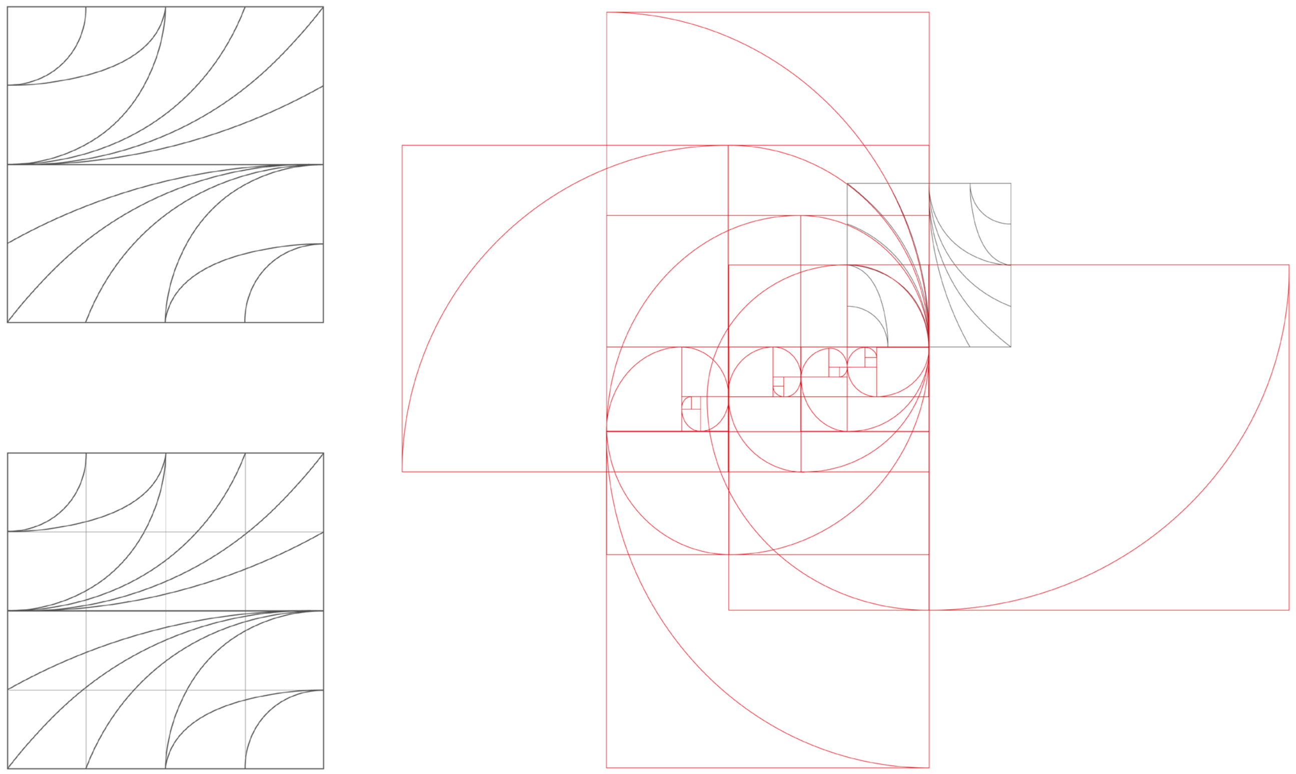


Figure 81. Construction of the shape

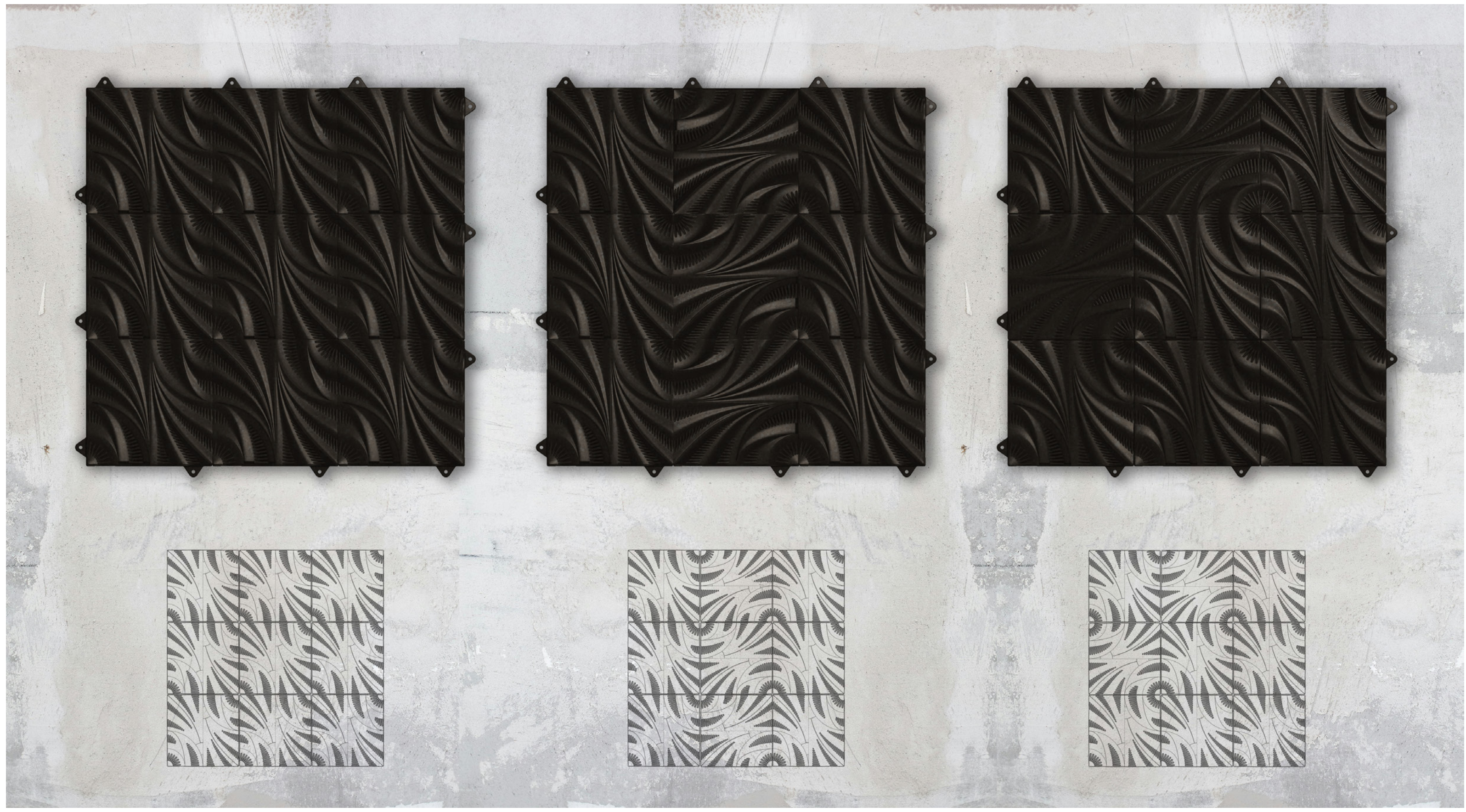


Figure 82. Patterning

Figure 83. Rainwater management

15.2 Measurements

The panel's dimensions and overall form were determined by the literature review and by considering the limitations and capabilities of both compression molding and CNC milling techniques. The key design choices were driven by the following considerations:

- **Size**: The panel's dimensions are based on an existing facade panel from NPSP, one that is 30x30 cm. While NPSP typically produces panels in a 60x60 cm format. The ultimate goal of this project was to actually produce a mould by CNC milling. To make this more feasible, the dimensions of NPSP's *30x30 cm* panel was chosen instead of 60x60 cm.

- **Micro-Groove Design**: As chapter FIXME describes, '*The depth of the micro-grooves is ideally 5mm with adjusted W/H ratios. This depth still encourages water circulation and is sufficiently small to catch water droplets and nutrients.'*
  In the panel's design, the depth of the grooves varies along the panel's surface, with a *maximum depth of 5 mm*. The grooves are *4 mm wide*, with a *4-5 mm spacing*. These dimensions were chosen to combine the desire for narrow grooves (to enhance water droplet retention) with the operational constraints of the CNC milling machine. The 4 mm wide grooves represent the smallest feasible milling width, while the 4-5 mm material spacing between grooves was dictated by the application of a release angle, as detailed in the subsequent section.

- **Release Angle**: To ensure easy removal from the mould, a *2-degree draft angle* was applied to all vertical surfaces to facilitate panel removal. All corners contain a *fillet of 1 mm* to enhance this release and prevent the panel from sticking.

- **Macro-Surface Design**: Another design requirement described in chapter FIXME is: *'The depth of the macro-surface is a maximum of 20mm with an H/W ratio of 0.2-0.3.'*
  The geometry of tha panel varies in such a way that the depth varies with *20 mm at the deepest point*. The H/W ratio varies as well.

- **Thickness**: The thickness of the panel is *6 mm* throughout. This was decided in consultation with NPSP. A consistent panel thickness is essential, resulting in uniform cooling and shrinkage. This way, no deformation occurs and the panel comes out of the press as designed.

With these measurements is the weight of the panel *0.97 kg*. This was calculated using the density of N-8040 without fibres. Given the weight and the properties of the N-8040 material, it can be concluded that each panel removes approximately *2.1 kg of CO2* from the air and stores it within the panel.

See Appendix G for the technical drawings.

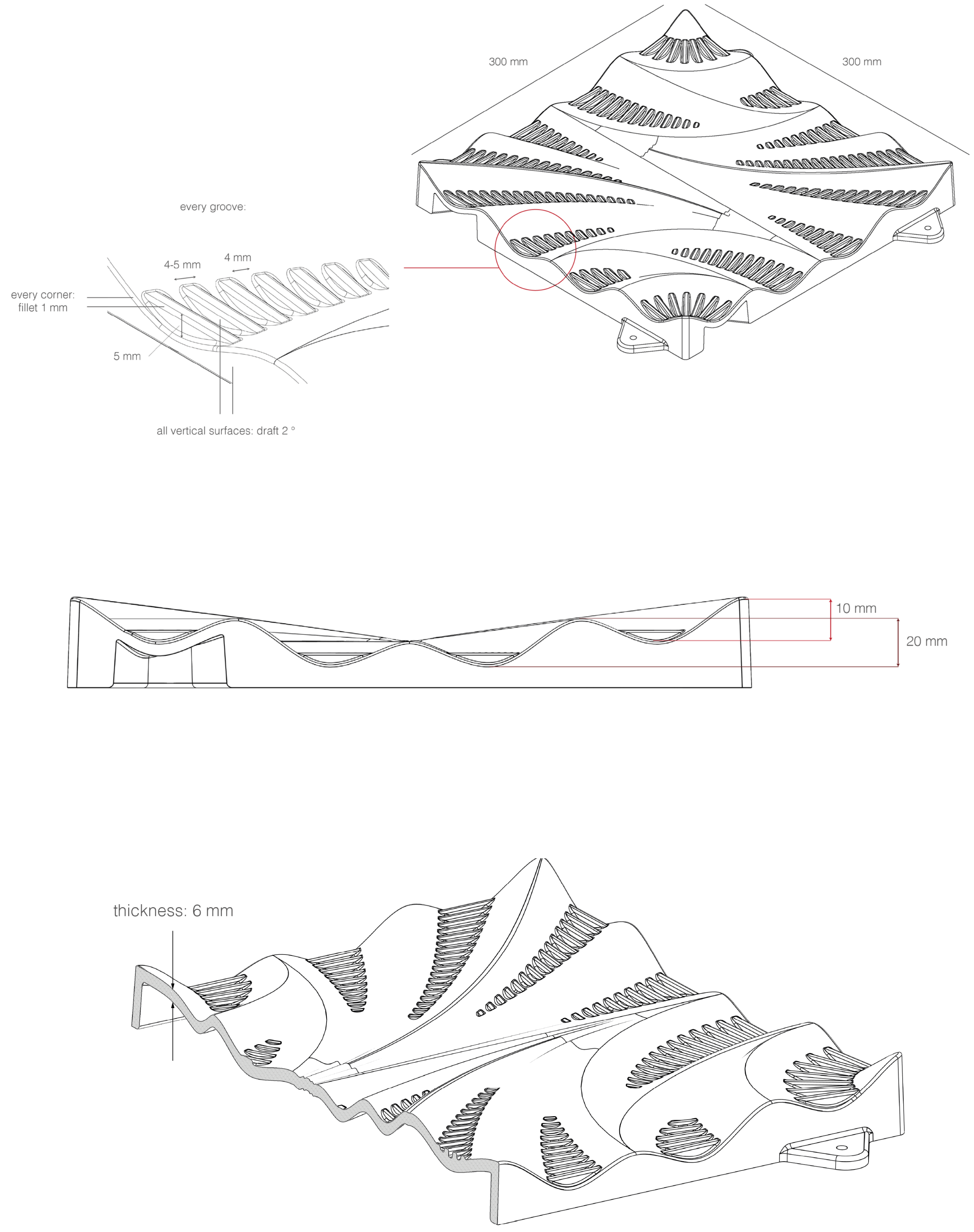


Figure 84. Measurements

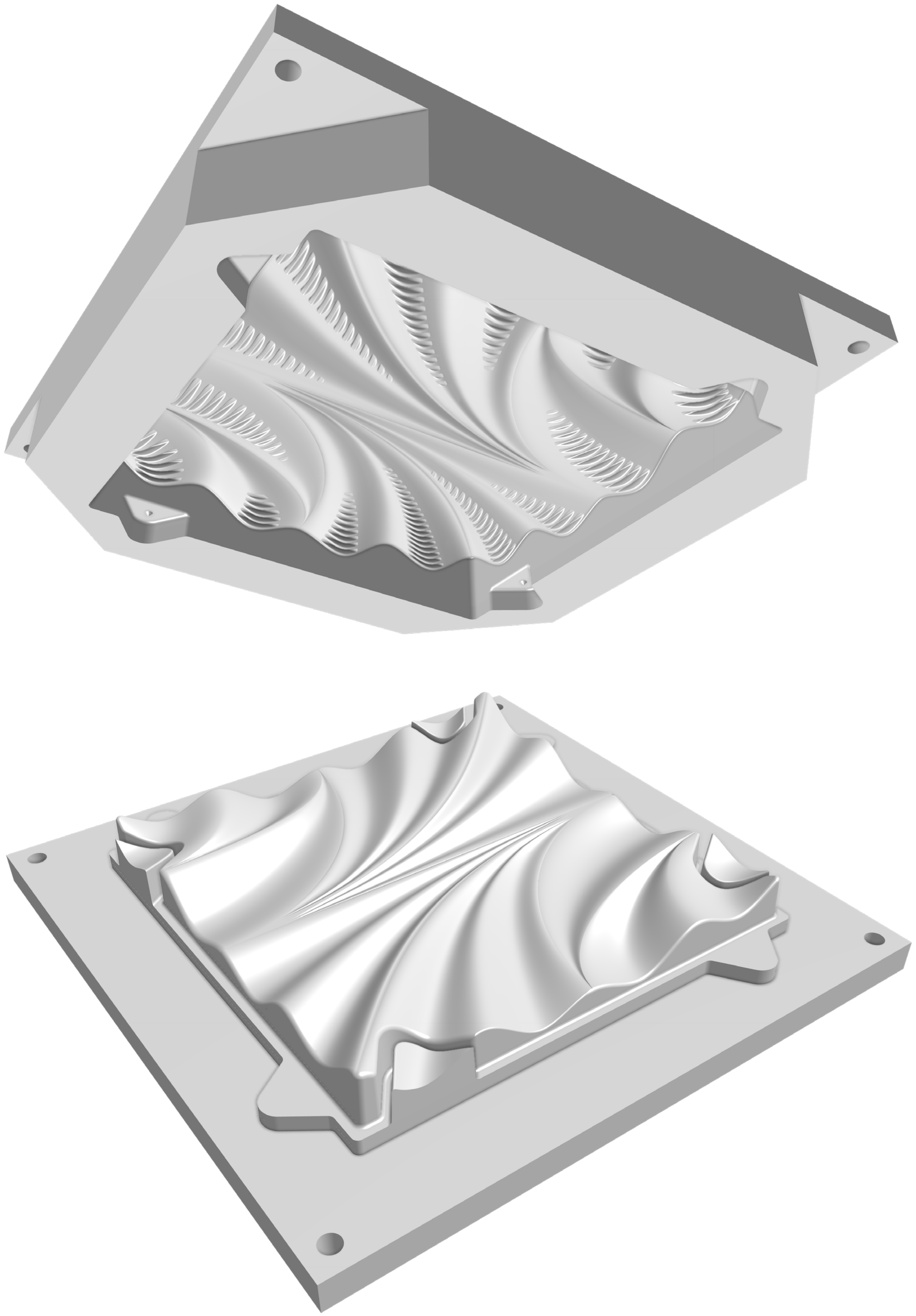


Figure 85. Upper and lower mould

15.3 Production

The production of the facade panel, detailed in section 7.2, is achieved by compression moulding. This process requires a mould constructed from steel or aluminum, manufactured via CNC milling. A representation of the mould is presented in figure 85. Technical drawings of the mould components are available in Appendix G. The CAD model of the mould was developed using Solidworks.
Should this panel be produced, *0.97 kg (the weight of the panel)* of prepared dough would be placed between the molds and then pressed for a few minutes. The exact pressing time will need to be finetuned. The production process will follow the procedure outlined in section 7.2.

The mold design was developed in collaboration with NPSP, incorporating their specific requirements and manufacturing practices. This finalized and approved mould design below is ready for CNC milling and subsequent compression molding operations after it is anodized. Anodization, a chemical process, creates an integrated protective layer on the surface. This treatment enhances the material's resistance to both wear and corrosion.

Key design considerations for the mold included:

1. The mould must allow for easy removal of the finished panel after the compression molding process, through integrated *release angles* and *rounded corners* in the panel design (detailed in section 15.2).
2. The mould design incorporates screw holes enabling its secure attachment to the top and bottom plates of the press (figure 86).

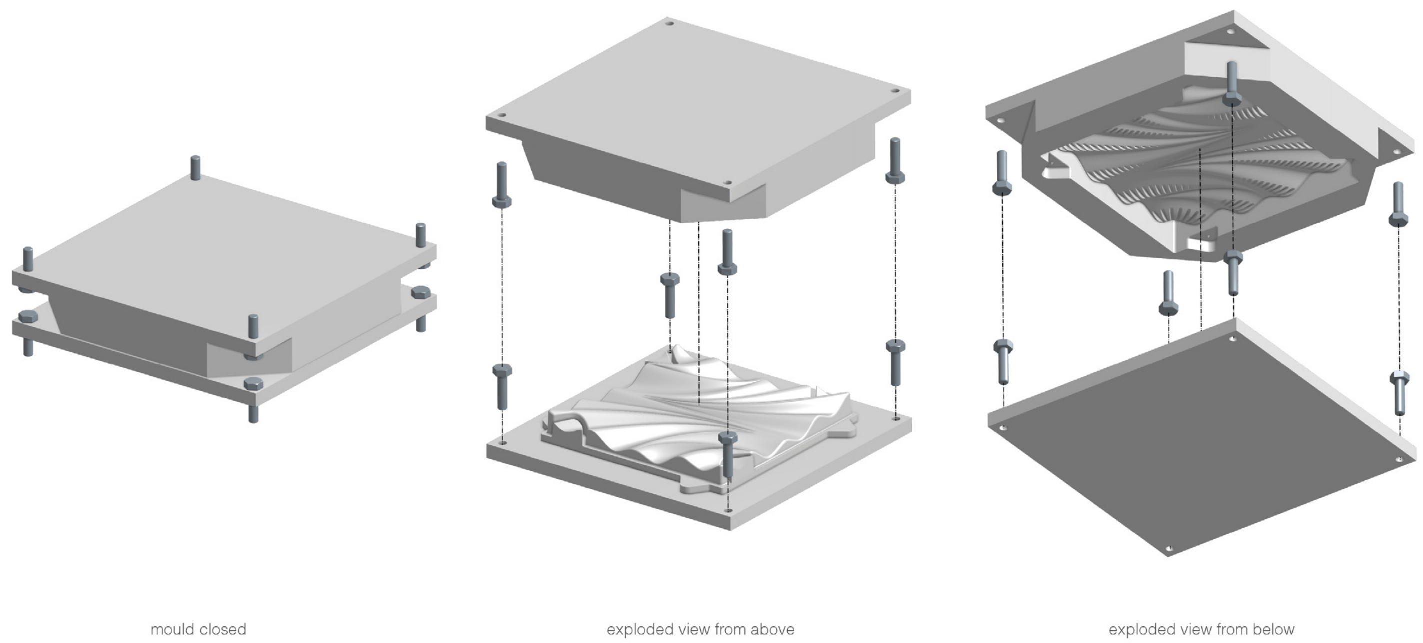


Figure 86. Exploded view mould

15.4 Mounting System

The panel is attached to the facade by a blind mounting system, based on the mounting system used by NPSP for their 30x30 cm panels. Figure 87 illustrates the system, which involves a wooden structure fixed on the building onto which the panels are screwed. These screw holes in the panels are drilled after pressing, at the designated drilling points.

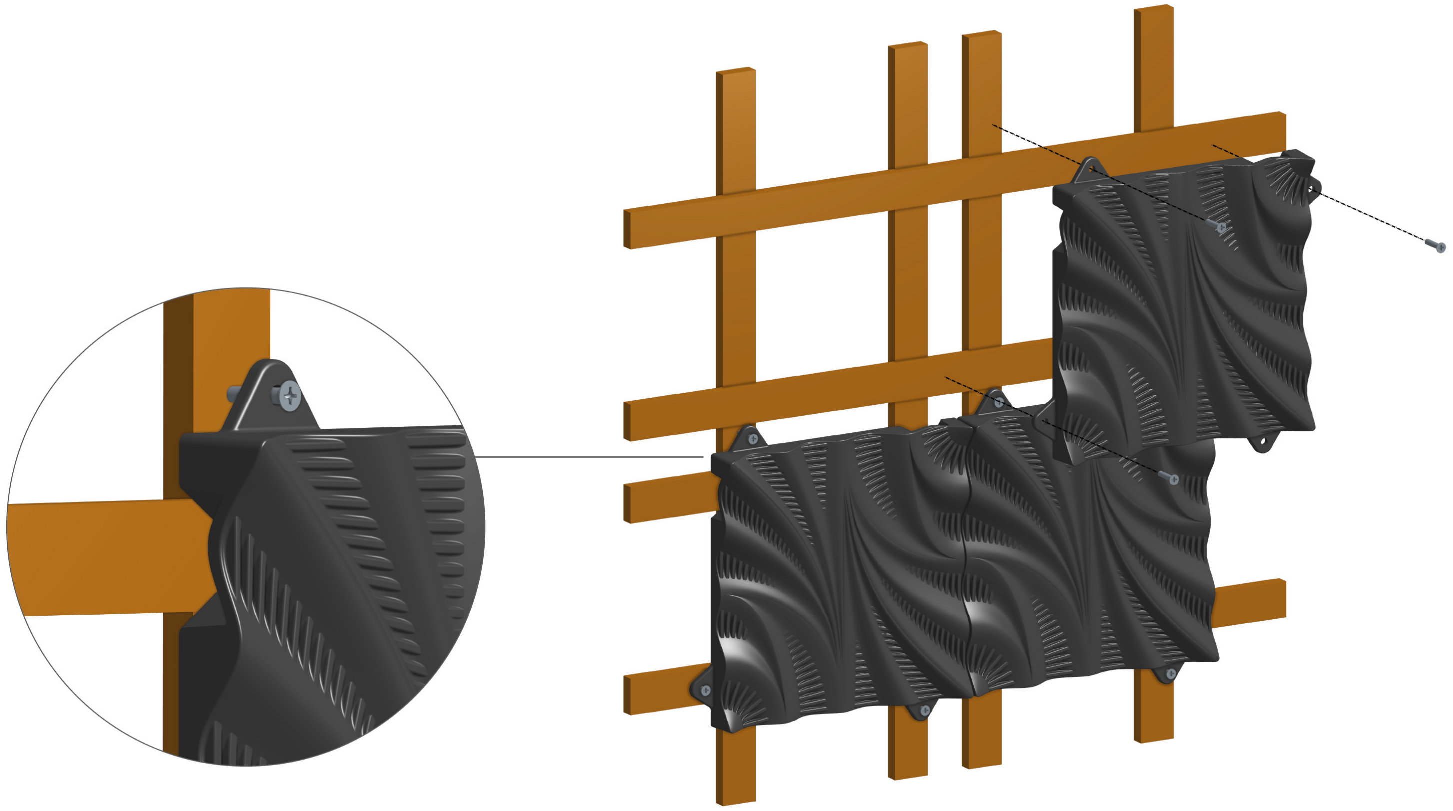


Figure 87. Mounting System

The detail view shows the overlapping panel arrangement. The notch on each panel interlocks with the fixing component of its neighbor, creating a blind connection.

A minor drawback is that, because of the overlapping characteristic of this system, some panels are not able to be attached with all four screws if adjacent panels are already secured. This is due to the limited space for screw insertion under the neighboring panel. However, NPSP has experience with this mounting design.

15.5 Moss Growth

Given the outcomes of the research on the potential of N-8040 to grow moss, it can be concluded that moss growth on N-8040 is possible, on both untreated and treated surfaces. The likelihood of moss growth on this panel after implementation remains uncertain. From the interview with *Auke Bleij of Respyre*, it appears that without forcing it, that chance is very small. The chances of moss spores landing exactly on this spot, especially on a vertical wall, are small. The solution is to force this with a *moss coating*. A requirement for this is to use a moss species that grows on a similar substrate to that of the facade panels.

According to Auke, a moss species that appears to be very easy to grow is; *Hypnum Cupressiforme* (figure 88). This moss species is found worldwide and grows on solid substrates such as bark, different types of tree trunks, rocks and walls (Luni, T. M., Oale, M. M., Mandi, M. R., et al., 2020).
Producing a moss coating with this moss species for the panels could be a subsequent research project, but the bottom line is the following:

1. Dry the Hypnum Cupressiforme.
2. Powder the dried moss.
3. Apply the moss powder in the form of a coating to the panel's designated growth areas.

While these steps increase the likelihood of growth, other factors play a significant role in determining its success. The façade's environment and surroundings, including local vegetation, its orientation and exposure to sunlight, and the accessibility of rainwater all have a profound impact on moss growth. However, the panel's design combined with the application of a moss coating increases the probability of successful moss establishment.

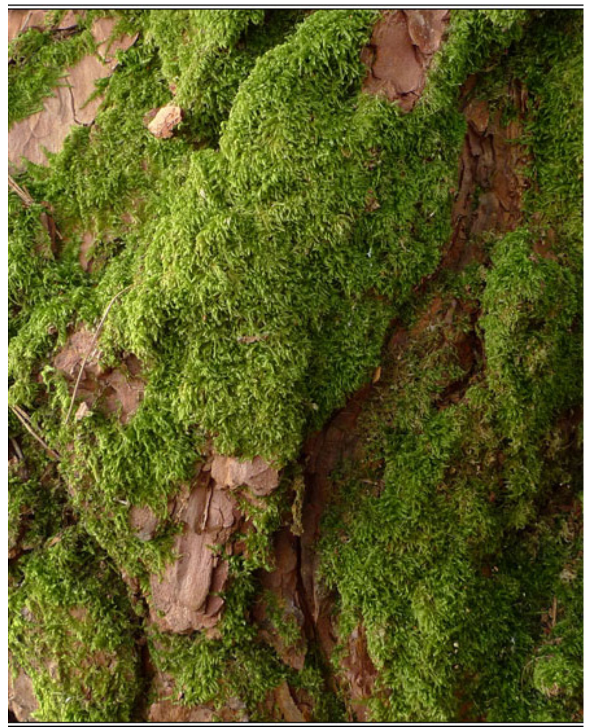


Figure 88. Hypnum Cupressiforme (irishwildflowers, n.d.)

15.6 Applications

The facade panel is intended for urban buildings, appropriate for both residential and commercial structures, with a height limit of approximately 20 meters to comply with fire safety regulations.

Discussions regarding the panel's potential and applications were held with *Peter Mooij of the AMS Institute (Amsterdam Institute for Advanced Metropolitan Solutions)*, a research institution focused on collaborative solutions for urban challenges. Quoting Peter:

"These kinds of innovative materials and applications are not yet widely used. People rather choose a well-known material (such as plastic), with decades of proof that this material guarantees and performs. It appears to be too scary to choose new materials where this guarantee has not yet been delivered." - Peter Mooij, AMS Institute.

So according to Peter's experience, project developers are often reluctant to embrace sustainable, innovative materials due to their increased cost and the unproven long-term performance and durability of the material.

Considering the reticence due to price, it is important to emphasise the added values and long-term benefit, such as thermal and acoustic benefits. Along with its positive effect on extreme rainfall and human well-being.

To kickstart the facade panel's adoption, increase awareness, and address doubts, the following application strategies are suggested:

- An ideal application would be a high-profile application to a well known, publicly accessible building. This application will maximize the impact, helping to showcase the panel's advantages, generating interest and confidence in the material. It would boost the visibility of the panel and allow others to follow this adoption. Examples of these high-profile institutions are for example, *Naturalis (Biodiversity Centre and Natural History Museum)* or *NEMO (Science Museum)*, both institutions with an affinity for science and sustainability. These buildings and their identity lend themselves very well for this facade panel.

- Another effective strategy targets schools and institutions focused on sustainability initiatives. These organizations can serve as pioneers, integrating the facade panels and demonstrating their benefits, encouraging wider adoption. To

keep it close, consider the facade of this Faculty of Industrial Design Engineering for example, representing the study's core principle: *"Design for Our Future."*

- Addressing the hesitations of property developers, publicly funded entities present a promising initial market. These companies often prioritize social good and dedicate more resources to sustainable projects. Examples include *Schiphol Airport* and water supply companies. NPSP has experience and proven successful sales to publicly funded organizations, like ProRail.

- Facade panels can also be effectively employed in renovation projects. This approach allows for the possibility of starting with a smaller section of the facade rather than requiring a complete facade. It provides an opportunity to showcase the material's performance and capabilities. Moreover, the contrast between the old building and the new panels can create a visually striking combination.

- Cities are growing and becoming more sustainable, which is why *2600 new electricity houses* are needed before *2050* in Amsterdam alone. This presents a prime opportunity for the application. Since these electricity houses are situated throughout the city and do not serve as residential or business spaces, people question the performance of the material less. Moreover, their low height *(max. 3 meters)* and the ground-level placement attract ground-dwelling insects to the moss, contributing to enhanced biodiversity.W

16. Conclusion

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16.1 Conclusion

This project focuses on the design objective: *"Design a façade panel for Dutch urban residential and business low-rise buildings (max. 20m) for NPSP from the biocomposite material N-8040, conveying its sustainable identity, that improves both the state of the ecosystem, by integrating vegetation and rainwater, and the users, by increasing well-being and ecological consciousness."*

This design objective comes from the challenges faced by urban areas today. The question why traditional facades are out of date can be answered with the challenges that cities are currently, and will probably be even more, facing in the future. These are challenges such as the Urban Heat Island Effect, extreme rainfall, loss of urban biodiversity and the use of unsustainable resources in construction. The solution to the latter problem lies in circular, renewable and co2-neutral or -negative building materials, for which biocomposite N-8040 offers a promising solution.

After a brief overview of façade designs from past decades, it can be concluded that a resilient and healthy city contributes positively to the ecosystem. With buildings being an important factor that functions not as isolated entities but in harmony with their environment.

Since the foundation of the project is the material, it employs the Material Driven Design Method developed by E. Karana and B. Barati (2015). This approach begins with an analysis of the material itself. Consequently, the biocomposite N-8040 was evaluated both technically and experientially, revealing its potential to support the growth of organisms in moist conditions. This potential, combined with urban challenges, suggests that integrating rainwater and vegetation can provide an effective solution. User tests assessing experiential characteristics led to modifications of the original biocomposite N-8040, incorporating banana fibers to enhance the material's experience. Initial perceptions of N-8040 suggested that the material is not sustainable. It also arouses negative emotions such as boredom. With the addition of the fibres, it was found that people perceived the durability of the material better, which increases the attractiveness of the material and that in turn adds value to NPSP. Also, with fibres, the material is considered more fascinating.

The design draws inspiration from several frameworks: the More-than-Human Design Approach, Regenerative Approaches, and Bio-inspiration. It employs surface geometry that facilitates controlled growth of vegetation, reshaping public perceptions of these organisms. What was once viewed as weeds or signs of decay is now appreciated.

Moss has been identified as an ideal vegetation choice due to its minimal maintenance needs and resilience. Additionally, green facades offer numerous benefits for the environment and occupants, including improved acoustics and insulation, as well as the air-purifying properties of vegetation.

The requirements for a bio-receptive surface span multiple levels. At the material level, a high degree of surface roughness and porosity, along with a neutral pH, are essential. Moreover, a microclimate must be established that effectively channels and collects water and creates a buffer zone for wind and sunlight. To achieve these criteria, several experiments were conducted to develop a façade panel that meets these specifications. A five-week experiment investigated moss growth on various treated surfaces of N-8040 but found no significant differences. As a result, the final design features untreated N-8040.

The façade panel draws inspiration from biomimicry by abstracting and applying leaf morphology and incorporating patterned surface grooves to create optimal conditions for moss growth. This geometry at both micro and macro levels ensures efficient rainwater collection and directs it to designated growth areas on the panel. To confirm these design principles, tests were conducted to measure water retention across two different panel designs, with the most effective design being selected.

Additionally, it was crucial for the panels to fit seamlessly together in multiple configurations, allowing for interesting linear formations and patterns. Given that the likelihood of moss naturally colonizing the panels is relatively low, an optimal strategy would be to apply a moss coating for initial introduction.

The final panel, named REVI, is intended for urban settings. While people are still reluctant to use new materials, it is designed for various applications, including renovations in schools and public organizations.

16.2 Discussion

Addressing Urban Challenges

This project aims to tackle several pressing urban issues: the urban heat island effect, extreme rainfall and flooding risks, loss of urban biodiversity, and the use of unsustainable materials. However, it remains uncertain whether the design will effectively mitigate the first three challenges, particularly in relation to extreme rainfall and enhancing biodiversity within the city. The likelihood that the panel can capture enough water to significantly lessen the impact of extreme rainfall events is probably minimal. Additionally, the project has not explored how many different organisms might find moss suitable as a habitat. The question persists whether fostering moss growth outside of its natural environment, and in isolation from other natural elements, can truly provide a viable habitat for organisms, and what real impact this may have on the city's overall biodiversity.

Effects on the Material

If the panels do retain sufficient water to support moss growth, it is unclear what implications this might have for the material itself. If the moisture significantly shortens the material's lifespan due to deterioration, questions arise about the sustainability of this option compared to materials that last significantly longer.

Moss Growth

In the test where a mixture of buttermilk and moss was applied to the material samples, the duration of five weeks makes it insufficient for drawing any definitive conclusions. A minimum of eight weeks is required for a thorough assessment. Furthermore, the test conditions did not include a vertical orientation, leaving it unclear what might happen when the panel is applied on an actual facade. Without a coating, the likelihood of any growth occurring in that position is quite low, indicating that some form of initial moss application may be necessary, a topic that has not yet been researched.

Production Considerations

Incorporating fibers into the material alters its properties and may cause different reactions to weather conditions. The benefits of this addition remain uncertain, and it may also affect the pressing conditions during production. There are concerns regarding whether the detailed grooves in the panel will be compatible with the fibrous material, specifically, whether the panel will be able to release successfully from the mold.

User Experience

The experiential qualities of the material have not been evaluated in relation to the panel's shape. People tend to have notably different reactions to flat samples compared to more complex shapes. Therefore, it is highly probable that the experience of the material in the design of the panel will differ significantly from the user tests conducted in this project. There is a possibility that observers prefer the original N-8040 material in the final shape of the panel.
Additionally, the design goal specifies that the façade panel should enhance user well-being and ecological awareness. Whether the panel, with or without moss growth, will genuinely impact the well-being and ecological awareness of passersby remains a challenging question that is difficult to quantify.

16.3 Recommendations

The next step is to mill the mold and press the panels in biocomposite. Ideally, a test facade would be lined with the panels where they would be assessed and reflected upon. NPSP is interested in this initiative, but whether this will go ahead and succeed remains to be seen. During this production process, it can also be investigated how the fibers influence the material and how it performs in outdoor conditions.

Another recommendation for in the future is developing a moss gel. It is a challenge due to the unpredictable nature of biological processes. *Respyre* has been exploring this area for some time and has expressed interest in collaborating on new materials. This partnership could be an excellent opportunity to combine their expertise with that of NPSP to achieve successful outcomes.

Considering NPSP's observation that *"birds and insects do not nest in the panels designed for this purpose, partly due to the lack of greenery,"* it would be worthwhile to integrate this design with the nature-inclusive facades from NPSP. Such a combination could enlarge the impact of the separate designs in enhancing biodiversity in urban environments. However, further research and testing are necessary, particularly to address issues such as preventing water accumulation in nesting boxes.

There already has been a discussion with *Peter* from *AMS Institute*. To actually implement these panels, a conversation with more people is needed to gain interest. It would be beneficial to alleviate any concerns about new materials and foster a greater acceptance and confidence in their use. Many people are unfamiliar with this type of material, which is primarily known within niche markets. To promote familiarity, the panels could be utilized as educational tools, when being installed in schools.
For example, *Studio RAP* successfully enhanced a traditional facade on P.C. Hooftstraat with their innovative cladding, creating a striking fusion of old and new. They have gained more recognition due to their association with the renowned location. A similar approach could be beneficial for these facade panels after they have been fully tested and fulfill all regulations.

16.4 Personal Reflection

During this project, I learned a lot about myself and my way of working.
In the beginning, I was meticulous about planning, crafting detailed timelines and checklists to guide my progress. However, as the project unfolded, I found myself letting go of that structure more and more, ultimately learning to trust myself and the process. About this process, this project has its ups and downs. Sometimes when I was stuck, I could be frustrated or stressed about it. It sounds cliche, but this project has proven me to "trust the process" and it will work out.

I really enjoy thinking about colors, materials, shapes and aesthetics. This project has shown me that this is a direction that appeals to me very much and I would like to develop further in this. I am so happy that I really enjoyed working on this subject. I noticed again that if you find something interesting you want to work on it yourself instead of feeling that you have to work on it. A feeling I haven't really had in my master's and I'm glad I have that again now.

I knew nothing beforehand about facades, moss, biocomposites and regenerative solutions. The project proved to me that it is fun to throw yourself into something that is new to you and that you know nothing about. It turns out that, as an Industrial Engineer, you indeed have the capabilities to immerse yourself in a project you know nothing about, to understand it and find your way around. Before I started this project, I was also unable to list the knowledge I could apply in a project. Once you start working on it, it turns out that you have these skills and come out naturally during the project.

What did frustrate me from time to time is that I have noticed that as an Industrial Engineer you know a little bit of everything and do not have a specialty. Sometimes this frustrated me a lot, that I got stuck somewhere and could not get any further, for example with making the CAD models in Onshape or Solidworks. I noticed that I had far too little knowledge and experience with that.

What I also learned during this project is not to be afraid to ask others for help or input, often people just like to think along.

When it comes to balancing study and life, I still find it pretty challenging to strike that balance. The graduation is always somewhere in the back of your mind. In the future, I aim to improve my ability to balance this. But maybe that's just part of being a designer, good ideas often pop up at the most random times!

In closing, I want to say that I'm proud of this project and to complete nearly eight years of study with this. I'm ready to step into the next phase with confidence and hope this project inspires growth in sustainable solutions and initiatives that will make a real impact!

17. References

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Abyzov, V. A., Pushkarova, K. K., Kochevykh, M. O., Honchar, O. A., & Bazeliuk, N. L. (2020, August). Innovative building materials in creation an architectural environment. In IOP Conference Series: Materials Science and Engineering (Vol. 907, No. 1, p. 012035). IOP Publishing.

Ahmed Ali K, Ahmad MI, Yusup Y. Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. Sustainability. 2020; 12(18):7427. https://doi.org/10.3390/su12187427

Afifa, Kashaf Arshad, Nazim Hussain, Muhammad Hamza Ashraf, Muhammad Zafar Saleem, Air pollution and climate change as grand challenges to sustainability, Science of The Total Environment, Volume 928, 2024, 172370, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.172370.

Abbass, K., Qasim, M.Z., Song, H. et al. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ Sci Pollut Res 29, 42539–42559 (2022). https://doi.org/10.1007/s11356-022-19718-6

Air. (n.d.). Environmental Health Atlas. https://www.atlasleefomgeving.nl/en/node/861

Akter M, Uddin MH, Tania IS. Biocomposites based on natural fibers and polymers: A review on properties and potential applications. Journal of Reinforced Plastics and Composites. 2022;41(17-18):705-742. doi:10.1177/07316844211070609

Bates, J.W. Is ‘Life-Form’ a Useful Concept in Bryophyte Ecology? Oikos 1998, 82, 223

Bilal, M.; Khan, K.I.A.; Thaheem, M.J.; Nasir, A.R. Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. J. Clean. Prod. 2020, 276, 123250.

Biobased materials. (2023, January 10). Biobased Materials. https://biobasedmaterials.org/

Biodiversity loss: what is causing it and why is it a concern? | Topics | European Parliament. (n.d.-b). Topics | European Parliament. https://www.europarl.europa.eu/topics/en/article/20200109STO69929/biodiversity-loss-what-is-causing-it-and-why-is-it-a-concern

The Biomimicry Institute. (2024, September 20). What is biomimicry - The Biomimicry Institute. https://biomimicry.org/inspiration/what-is-biomimicry/

Brodribb, T.J., Carriquí, M., Delzon, S. et al. Advanced vascular function discovered in a widespread moss. Nat. Plants 6, 273–279 (2020). https://doi.org/10.1038/s41477-020-0602-x

Camere, Serena & Karana, Elvin. (2018). Experiential Characterization of Materials: toward a toolkit. 10.21606/drs.2018.508.

Climate change: atmospheric carbon dioxide. (2024, April 9). NOAA Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Correa, J. P., Montalvo-Navarrete, J. M., & Hidalgo-Salazar, M. A. (2019). Carbon footprint Considerations for biocomposite materials for sustainable products: A review. Journal of Cleaner Production, 208, 785-794. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.099

De Brugh, M. A. (2024, September 11). In steden valt beduidend meer regen dan in de gebieden eromheen. NRC. https://www.nrc.nl/nieuws/2024/09/11/in-steden-valt-beduidend-meer-regen-dan-in-de-gebieden-eromheen-a4865332

Elbert, W.; Weber, B.; Burrows, S.; Steinkamp, J.; Büdel, B.; Andreae, M.O.; Pöschl, U. Contribution of cryptogamic covers to the global cycles of carbon and nitrogen. Nat. Geosci. 2012, 5, 459–462.

Giaccardi, E., Redström, J., & Nicenboim, I. (2024). The making(s) of more-than-human design: introduction to the special issue on more-than-human design and HCI. Human–Computer Interaction, 1–16. https://doi.org/10.1080/07370024.2024.2353357

Glime, J.M. Chapter 10: Temperature: Effects. In Bryophyte Ecology Volume 1: Physiological Ecology. 9. 2017. [Ebook sponsored by Michigan Technological University and the International Association of Bryologists]. Available online: http://digitalcommons.mtu.edu/bryophyte-ecology/

(accessed on 20 January 2025).

Global Alliance for Buildings and Construction, Global Status Reports 2017: https://globalabc.org/resources/publications/2017-global-status-report-buildings-and-construction

gorespyre. (n.d.). https://www.gorespyre.com/nl/

Guillitte, O. (1995). Bioreceptivity: a new concept for building ecology studies. Science of the total environment, 167(1-3), 215-220.

Gurera, D., & Bhushan, B. (2020). Passive water harvesting by desert plants and animals: lessons from nature. Philosophical Transactions of the Royal Society A, 378(2167), 20190444.

Haynes, A.; Popek, R.; Boles, M.; Paton-Walsh, C.; Robinson, S.A. Roadside Moss Turfs in South East Australia Capture More Particulate Matter Along an Urban Gradient than a Common Native Tree Species. Atmosphere 2019, 10, 224.

Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: implications for health in a changing environment. Current environmental health reports, 4, 296-305.

Huang, B., Gao, X., Xu, X., Song, J., Geng, Y., Sarkis, J., ... & Nakatani, J. (2020). A life cycle thinking framework to mitigate the environmental impact of building materials. One Earth, 3(5), 564-573.

IEA. World Energy Statistics and Balances (Database). 2019. Available online: www.iea.org/statistics (accessed on 12 August 2020).

Kamalanon, P., Chen, J. S., & Le, T. T. Y. (2022). “Why do we buy green products?” An extended theory of the planned behavior model for green product purchase behavior. Sustainability, 14(2), 689.

Karana, E., McQuillan, H., Rognoli, V., & Giaccardi, E. (2023). Living artefacts for regenerative ecologies. Research Directions: Biotechnology Design, 1, e16.

Karana, Elvin & Barati, Bahar & Rognoli, Valentina & Zeeuw van der Laan, Anouk. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design. in press.

Kimmerer, R. W. (2021). Gathering moss: A natural and cultural history of mosses. Penguin UK.

Leppänen S, Saikkonen L, Ollikainen M (2014) Impact of Climate Change on cereal grain production in Russia: Mimeo

Leon Wang, Leigh Wang, Yang Li, John Wang, A century-long analysis of global warming and earth temperature using a random walk with drift approach, Decision Analytics Journal, Volume 7, 2023, 100237, ISSN 2772-6622, https://doi.org/10.1016/j.dajour.2023.100237.

Liu, S., Zhang, C., Shen, T., Zhan, Z., Peng, J., Yu, C., ... & Dong, Z. (2023). Efficient agricultural drip irrigation inspired by fig leaf morphology. Nature communications, 14(1), 5934.

Luni, T. M., Oale, M. M., Mandi, M. R., Sabovljevi, A. D., Sabovljevi, M. S., Gaši, U. M., ... & Boi Nedeljkovi, B. D. (2020). Extracts Characterization and In Vitro Evaluation of Potential Immunomodulatory Activities of the Moss Hypnum cupressiforme Hedw. Molecules, 25(15), 3343.

Materials Archive - MaterialDistrict. (n.d.). MaterialDistrict. https://materialdistrict.com/material/

Manu, T., Nazmi, A., Shahri, B., Emerson, N., Huber, T., Biocomposites: A review of materials and perception, Materials Today Communications, Volume 31, 2022, 103308, ISSN 2352-4928, https://doi.org/10.1016/j.mtcomm.2022.103308.

Michigan State University. (2024, February 7). Friend or foe? Ancient partnership between moss and fungi. ScienceDaily. Retrieved January 24, 2025 from www.sciencedaily.com/releases/2024/02/240207195112.htm

Mikola, Teemu. “The role of biocomposites in the transition of plastics towards environmental sustainability and circular economy.” (2024).

Miller, A.; Sanmartín, P.; Pereira-Pardo, L.; Dionísio, A.; Saiz-Jimenez, C.; Macedo, M.; Prieto, B. Bioreceptivity of building stones: A review. Sci. Total Environ. 2012, 426, 1–12.

Murawski, A., Diaz, R., Inglesby, S., Delabar, K., & Quirino, R. L. (2019). Synthesis of Bio-based Polymer Composites: Fabrication, Fillers, Properties, and Challenges. In K. K. Sadasivuni, D. Ponnamma, M. Rajan, B. Ahmed, & M. A. S. A. Al-Maadeed (Eds.), Polymer Nanocomposites in Biomedical Engineering (pp. 29-55). Springer International Publishing. https://doi.org/10.1007/978-3-030-04741-2_2

Mustafa, K. F., Prieto, A., & Ottele, M. (2021). The Role of Geometry on a Self-Sustaining Bio-Receptive Concrete Panel for Facade Application. Sustainability, 13(13), 7453. https://doi.org/10.3390/su13137453

Mustafa, H. K., Anwer, S. S., & Zrary, T. J. (2023). Influence of pH, agitation speed, and temperature on growth of fungi isolated from Koya, Iraq. Kuwait Journal of Science, 50(4), 657-664.
Nabasco materialen |. (n.d.). https://www.npsp.nl/nl/nabasco-materialen

Neerslagextremen in Nederland, 1910-2022. (2023, August 15). Compendium Voor De Leefomgeving. https://www.clo.nl/indicatoren/nl059003-neerslagextremen-in-nederland-1910-2022#bronnen

Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., & Shepherd, M. (2017). Urbanization impacts on the summer heavy rainfall climatology over the eastern United States. Earth Interactions, 21(5), 1-17.

Ottele, M.; Koleva, D.A.; van Breugel, K.; Haas, E.M.; Fraay, A.L.A.; van Bohemen, H.D. Concrete as a multifunctional ecological building material: A new approach to green our environment. In The 19th International Symposium Ecology & Safety; Genov, I., Ed.; Journal of International Scientific Publications Ecology Safety; Info Invest: Burgas, Bulgaria, 2010; Volume 4, pp. 223–234.

Parisi, Stefano & Ayala Garcia, Camilo & Rognoli, Valentina. (2016). Designing Materials Experiences through Passing of Time. Material-Driven Design Method applied to Mycelium-based Composites.

Perini, K., Castellari, P., Giachetta, A., Turcato, C., & Roccotiello, E. (2020). Experiencing innovative biomaterials for buildings: Potentialities of mosses. Building and Environment, 172, 106708.

Planetary boundaries. (n.d.). Stockholm Resilience Centre. https://www.stockholmresilience.org/research/planetary-boundaries.html

Rodríguez, L. J., Orrego, C. E., Ribeiro, I., & Peças, P. (2018). Life-Cycle Assessment and Life-Cycle Cost study of Banana (Musa sapientum) fiber Biocomposite materials. Procedia CIRP

Rotondi, C., Gironi, C., Ciufo, D., Diana, M., & Lucibello, S. (2024). Bioreceptive Ceramic Surfaces: Material Experimentations for Responsible Research and Design Innovation in Circular Economy Transition and “Ecological Augmentation”. Sustainability, 16(8), 3208.

Sharma, N. K. (2020). Sustainable building material for green building construction, conservation and refurbishing. Int. J. Adv. Sci. Technol, 29(10S), 5343-5350.

Souza, E. “What Is the Environmental Impact of Each Building Material?” [Qual o impacto ambiental de cada material de construção?] 07 Jul 2022. ArchDaily. Accessed 7 Oct 2024. <https://www.archdaily.com/984663/what-is-the-environmental-impact-of-each-building-material> ISSN 0719-8884

Stedelijk hitte-eiland effect (UHI). (n.d.). Atlas Leefomgeving. https://www.atlasleefomgeving.nl/stedelijk-hitte-eiland-effect-uhi

Talley, S.M., Coley, P.D. & Kursar, T.A. The effects of weather on fungal abundance and richness among 25 communities in the Intermountain West. BMC Ecol 2, 7 (2002). https://doi.org/10.1186/1472-6785-2-7

Teixeira, L.F., de Vilhena Rodrigues, J., Cohen, L.A.F.P., Santos, N.S.S. (2021). A Material-Driven Design Approach Methodology in 3D Printing Waste Recycling. In: Sandhu, K., Singh, S., Prakash, C., Subburaj, K., Ramakrishna, S. (eds) Sustainability for 3D Printing . Springer Tracts in Additive Manufacturing. Springer, Cham. https://doi.org/10.1007/978-3-030-75235-4_6

The Global Institute of Regenerative Design, https://www.thinkplaceglobal.com/articles/3-frameworks-regenerative-design-in-practice/
Thundathil, M., Nazmi, A. R., Shahri, B., Emerson, N., Müssig, J., & Huber, T. (2023). Designing with biobased composites: understanding digital material perception through semiotic attributes. Design Science, 9, e6. doi:10.1017/dsj.2023.5

Thundathil, M.; Nazmi, A.R.; Shahri, B.; Emerson, N.; Müssig, J.; Huber, T. Visual–Tactile Perception of Biobased Composites. Materials 2023, 16, 1844. https://doi.org/10.3390/ma16051844

Tran, T.H.; Hoang, N.D. Estimation of algal colonization growth on mortar surface using a hybrid-ization of machine learning and metaheuristic optimization. Sdhan 2017, 42, 929–939

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kamierczak, A., Niemela, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landscape and urban planning, 81(3), 167-178.

Urban Reef. (n.d.). https://www.urbanreef.nl/

Van der Hoeven, E. C., Korporaal, M., & Van Gestel, E. (1998). Effects of simulated shade on growth, morphology and competitive interactions in two pleurocarpous mosses. Journal of Bryology, 20(2), 301–310. https://doi.org/10.1179/jbr.1998.20.2.301

Varela, Z., Real, C., Branquinho, C., do Paço, T. A., & Cruz de Carvalho, R. (2021). Optimising Artificial Moss Growth for Environmental Studies in the Mediterranean Area. Plants, 10(11), 2523. https://doi.org/10.3390/plants10112523

Vinod, A., Sanjay, M. R., Suchart, S., & Jyotishkumar, P. (2020). Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. Journal of Cleaner Production, 258, 120978.

WHO. Air quality and Health. In Fact Sheets on Sustainable Development Goals: Health Targets; World Health Organization Region Office for Europe: Copenhagen, Denmark, 2018.

Wieser, A.A.; Scherz, M.; Passer, A.; Kreiner, H. Challenges of a Healthy Built Environment: Air Pollution in Construction Industry. Sustainability 2021, 13, 10469. https://doi.org/10.3390/su131810469

Yadong, Y. and John A. Rogers Introduction: Smart Materials. Chemical Reviews 2022 122 (5), 4885-4886 DOI: 10.1021/acs.chemrev.2c00074

Yahia, A. K. M., Rahman, D. M. M., Shahjalal, M., & Morshed, A. S. M. (2024). Sustainable Materials Selection in Building Design And Construction. International Journal of Science and Engineering, 1(04), 106-119.

Yan, L., Chouw, N., Jayaraman, K., Flax fibre and its composites – A review,Composites Part B: Engineering,Volume 56, 2014, Pages 296-317, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2013.08.014.

Yaradoddi, J. S., Banapurmath, N. R., Ganachari, S. V., Soudagar, M. E. M., Sajjan, A. M., Kamat, S., ... & Ali, M. A. (2022). Bio-based material from fruit waste of orange peel for industrial applications. Journal of Materials Research and Technology, 17, 3186-3197.

Yim, S.; Ng, S.T.; Hossain, U.; Wong, J.M.W. Comprehensive Evaluation of Carbon Emissions for the Development of High-Rise Residential Building. Buildings 2018, 8, 147.

18. Appendices

18

Appendix A: Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Nina de Graaf **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Facade of the future: Designing a biocomposite façade panel

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The project starts with the material 'Nabasco 8040,' which is 100% biobased and 100% waste-based, developed by NPSP. NPSP develops and supplies biocomposite materials and products for public spaces, construction, design and mobility. Architect Marco Vermeulen, in collaboration with NPSP, designed a nature-inclusive biocomposite façade panel (from another partly biobased material, N-8012), with nesting boxes for birds and insects (see image below). This design inspired my graduation project, how a facade panel can be innovative and multi-funtional in general.

My challenge is to design a new façade panel for NPSP with their developed material (N-8040). Complying with the technical and experiential characteristics of the material. For instance, influences on the experience are its dark appearance (see the image below) and the use and exposure of fibres. The goal is to create the panel of the future: on that not only serves technical requirements of the building itself, but can improve the ecosystem and enhance the user experience.
A design that uses the opportunities that the level of form freedom offers, the panels are formed under high pressure and heat in a mould. The goal is to expand on the idea of designing with and for the environment (more-than-human design); contributing to the ecosystem and improving the overall user physical and experiential well-being, a win-win situation.

Why this material? Compared to other building materials, this is one of the most sustainable choices, it is a 'carbon sink' where CO2 is stored, it can be recycled multiple times and at the end of its life, the material can basically be reabsorbed into nature. If the panels contribute to fostering the surrounding ecosystem, they offer nothing but benefits for the environment. With high performance properties of the material and costs kept relatively low, this is the material of the future.

➔ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1 Nabasco 8040 material

image / figure 2 Facade panel with nesting boxes for birds and insects, by NPSP and Marco Vermeulen (2023)

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The construction and infrastructure sectors are major consumers of products with a high environmental impact and are one of the most polluting sectors. The CO2-emissions and harmful effects of the building sector have to be reduced, to be able to achieve the Sustainable Developed Goals.
This graduation project contributes by creating a façade panel using the biobased material Nabasco 8040. By using either the More-than-Human design approach (the human is not the center point of design), regenerative approaches, biomimicry and/or bio-integrate approaches. The panel will not only protect the construction, but is also an opportunity for expression how we envisioned design for future generations and a way of exciting users.

An environmental integrated design fuses the artificial and biological world, a win-win situation on environmental, social (proven to enhance the human well-being) and economic grounds (the material can be recycled multiple times with the costs kept low).

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a (model of a) façade panel for NPSP from the biocomposite material N-8040, integrating the environment, that improves both the state of the ecosystem and the users.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will be approached in different phases. The starting point of the project is the material, so the approach is based on the Material Driven Design Method:
- Problem framing and finding opportunities.
- Understanding the material, both technical and experiential elements. This includes a user test, encapsulating its characteristics, interviewing experts (NPSP, architects, other stakeholders), benchmarking the material, understanding its properties and process. What opportunities does this material offer?
- Creating an experience vision to help finding a design direction, to conclude with design criteria; who, what, where and why? Also created by searching for inspiration on environmental integrated design in literature and surrounding projects.
- Design product concepts with the More-than-human design approach/regenerative design approaches/biomimicry in mind.
- Lastly, protoype, test and reflect. I will conduct a final (user) test to examine the performance, experience and human-panel interaction. Concerning tests with the experience and interaction with flora and fauna, is more difficult and time consuming.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	1 okt 2024
Mid-term evaluation	28 nov 2024
Green light meeting	6 feb 2025
Graduation ceremony	5 mrt 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project perfectly blends Industrial Design Engineering and Architecture, which aligns with my passions and career aspirations. In the future, I aim to work in this field. It also brings together the interests I've had before or gained during my time at IDE, which are aesthetics, form-giving, materials, nature, and sustainability. Sustainability, in particular, is a key focus that I believe should be central to every project. I think, designing for our future is truly important and this project reflects the vision I have for the future, or at least reflects what the future needs.

What excites me the most in the design process is prototyping and building models, and this project offers the chance for that hands-on experience. On a personal level, I'm eager to take full ownership of this project—leading it, managing timelines, and maintaining structure. These are the areas I find most challenging, but I see this as a valuable learning opportunity for my professional career after university.

All in all, I'm excited to take on this final project at the TU Delft!

Appendix B: Interview Transcript

All experts:

- How do you envision the future of facades, and why?
- What developments do you currently see taking place in this area?
- What other trends do you observe that are shaping the future of facades?
- Where do you see opportunities for facades, and what advantages do these offer?
- Can you provide examples or describe any projects you have done that align with this vision?
- Which trends or materials do you believe will become standard in facade design over the next 10 years?
- How do you think climate change and sustainability will impact the function, design, and materials used in facades?
- What challenges could this future vision for facades present?
- What will be the environmental, social, and economic impacts of this vision for facades?
- How can collaboration between architects, ecologists, and biomimicry experts enhance facade development?
- Do you have any tips for me?

Questions to elaborate on per different field:

Architects:

- In your opinion, how can facades contribute more significantly to sustainable urban environments?
- Can you share your thoughts on the role of modern facades and its impact on occupant well-being?
- How do you balance aesthetics with functionality and sustainability when designing facades?
- What role do you think the production processes and building activities will look like in the future?

Ecologists:

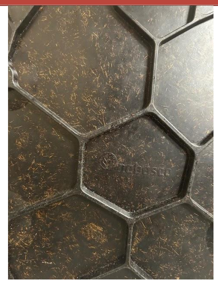
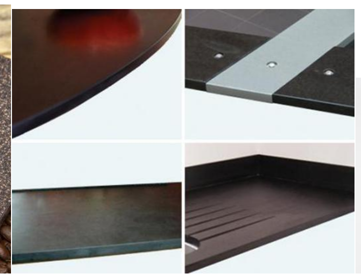
- Can you explain the potential impact of facade design on local ecosystems and wildlife, both positive and negative?
- How do you think facade design can contribute to enhancing the surrounding ecosystem?
- What are some key factors architects should consider from an ecological standpoint when designing facades?
- Which ecological problems would be best suited for façade design or need the most help through façades?
- Are there specific plant species or vegetation types that you recommend for use in living facades to maximize environmental benefits?
- What challenges do you foresee in balancing human architectural needs with serving the ecosystem in a facade?

Biomimicry experts:

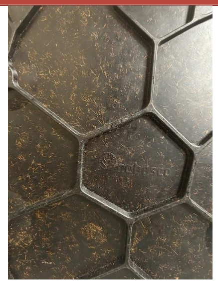
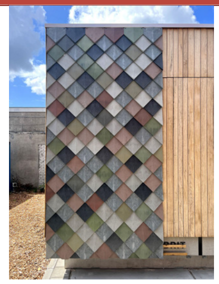
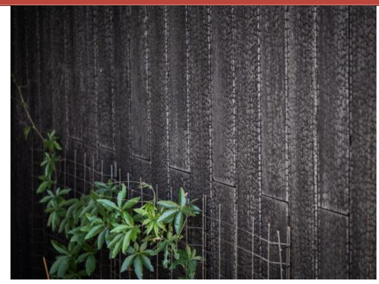
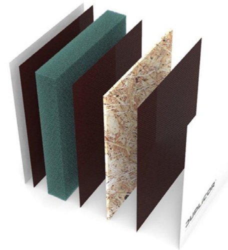
- How does using biomimicry as a design method work?
- How do you see biomimicry influencing the future of facade design, and what natural systems serve as the most promising inspirations?
- Can you share examples of current or past facade designs that effectively incorporate biomimicry principles?
- What are the main benefits of designing facades with biomimetic strategies in terms of energy efficiency and sustainability?
- What challenges do architects and engineers face when trying to implement biomimetic designs in building facades?
- Welke environmental problemen zouden zich het best lenen voor facade design geïnspireerd op de natuur?
- What potential do you see for facades that adapt and respond to their environment?
- Can you describe any research or technological developments in biomimicry that you believe will soon be applied to facade engineering?

Appendix C: Material Benchmark

Material Benchmark on Biocomposites

Material	N-8040	N-8040	Husk	REY-Y-STONE	That's Caffeine Tiles	Paperstone	Trashell	Biolaminate
								
Manufacturer	NPSP	NPSP	Sonite Innovative Surfaces Company Limited	Resopal-GmbH	Atticus Durnell	Paneltech International, LLC	Itke, Universität Stuttgart	Huis Veendam
Composition	Furan + Almond shells	Furan + Almond shells + Coconut hair	Rice husks	Recycled Paper + Bio-Resin (suger cane resin)	Coffee Grounds + Minerals + Plant-Based Resin	Recycled Papers + Non-Petroleum Based Resins	Coconut Shells/ Cereal Straw/ Black Coal Ash + Plant-Based Resin + Glowing Additives	Cattail + Organic Fillers + Jute + Glue based on Starch and Organic Fibres
Strength	High	Medium-high	Medium	High	Medium	High	Medium	Medium
Stiffness	High	High	Medium	Medium	Medium	High	Medium	Low
Weight	Medium	Medium	Medium	Medium	Light	Medium	Medium	Light
Hardness	Hard	Hard	Hard	Hard	Hard	Hard	Hard	Low
Biobased	100%	100%	50-70%	100%	70-90%	55%	80%	90-100%
Wastebased	100%	100%	22%	100%	30-80%	55%	80%	50-90%
Fire-resistant	Tested at the moment	Unknown	Poor	Unknown	Unknown	Unknown	Moderate	Unknown
UV-resistance	Tested at the moment	Unknown	Moderate	Moderate	Good	Good	Moderate	Unknown
Weather resistance	Tested at the moment	Unknown	Poor	Good	Good	Moderate	Moderate	Unknown
Acoustics	Good	Good	Moderate	Moderate	Poor	Poor	Moderate	Unknown
Odour	No	No	No	No	No	No	No	No
Texture	Smooth	Smooth/Rough	Rough	Medium	Smooth	Smooth	Medium	Medium
Glossiness	Medium	Medium	Matte	Satin	Glossy	Matte	Satin	Matte
Looking Natural/ Artificial	Artificial	Natural/Artificial	Natural	Artificial	Medium	Artificial	Natural/Artificial	Natural
Visible Fibres	No	Yes	Yes	No	Yes	No	Yes	Yes
Application	Facade Panels	Facade Panels	Interior Cladding	Cladding	Interior and Exterior Cladding	Furniture and Interior and Exterior Cladding	Interior and Exterior Cladding	Floors
Renewable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Form Freedom	High	High	Low	High	Medium	High	High	Low
Product Size	Medium	Medium	Medium	Medium	Small	Medium	Medium	Medium
Other Issues			Good insulation qualities	High elasticity modulus	Available in 5 different colors, obtained from natural dyes and colourants obtained from plants	Available in different colors	Glowing additives allows night lighting in an exterior facade	

Material Benchmark on Facade Applications

Material	N-8040	N-8040	Pretty Plastic Tile	Moss concrete	Yoroi	Yitile	Duplicor	Riwood
								
Manufacturer	NPSP	NPSP	Pretty Plastic	Respyre	Zwarthout - Shou Sugi Ban	Yi Design	Holland Composites	Fibreplast
Composition	Furan + Almond shells	Furan + Almond shells + Coconut hair	Recycled PVS (construction waste material)	Recycled Concrete Aggregates + Moss Seeds	Thermally Modified Bamboo	Ceramic Waste + Raw Ceramic	Natural Resin + Recycled PET Bottles	Rice husk + Calcite + Recycled PVC + Process Additives including UV Protectors & Colour Pigments
Strength	High	Medium-high	Medium	High	High	Medium	High	High
Stiffness	High	High	Medium	High	Medium	High	High	Medium
Weight	Medium	Medium	Medium	Heavy	Heavy	Medium	Light	Medium
Hardness	Hard	Hard	Hard	Hard	Hard	Hard	Hard	Hard
Biobased	100%	100%	0%	5-10% (moss)	100%	0%	5-10%	41%
Wastebased	100%	100%	100%	30-80%	0%	60%	70-90%	67%
Fire-resistant	Tested at the moment	Unknown	Good	Good	Good	Good	Good	Good
UV-resistance	Tested at the moment	Unknown	Good	Good	Good	Good	Good	Good
Weather resistance	Tested at the moment	Unknown	Good	Good	Good	Good	Good	Good
Acoustics	Good	Good	Moderate	Moderate	Good	Moderate	Good	Moderate
Odour	No	No	No	Moderate	Moderate	No	No	No
Texture	Smooth	Smooth/Rough	Medium	Coarse	Variable	Variable	Smooth	Medium
Glossiness	Medium	Medium	Variable	Variable	Matte	Glossy	Matte	Matte
Looking Natural/ Artificial	Artificial	Natural/Artificial	Artificial	Natural/Artificial	Natural	Natural/Artificial	Artificial	Artificial
Visibility Ingredients	No	Yes	Yes	Yes	Yes	Medium	No	No
Application	Facade Panels	Facade Panels	Facade Cladding	Facade Cladding	Facade cladding	Facade / Interior cladding	Broad variety of Building Applications	Broad variety of Building Applications
Renewable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Form Freedom	High	High	High	Low	Low	Low	High	Medium
Product Size	Medium	Medium	Medium	Medium - Large	Medium	Small	Medium - Large	Medium
Other issues			Available in four different colours and three different shades	Supports biodiversity, improves air quality, offers thermal benefits	Natural fire retardancy due to the charring	Colors can be customized		

Appendix D: Experiential Characterization Toolkit (Material Driven Design)

(Karana, E., Barati, B., Rognoli, V. et al, 2015)

AFFECTIVE LEVEL

(list of emotions)

frustration	love
boredom	amusement
disappointment	surprise
reluctance	confidence
confusion	enchantment
rejection	respect
disgust	attraction
melancholy	curiosity
distrust	fascination
doubt	comfort

(Karana, E., Barati, B., Rognoli, V. et al, 2015)

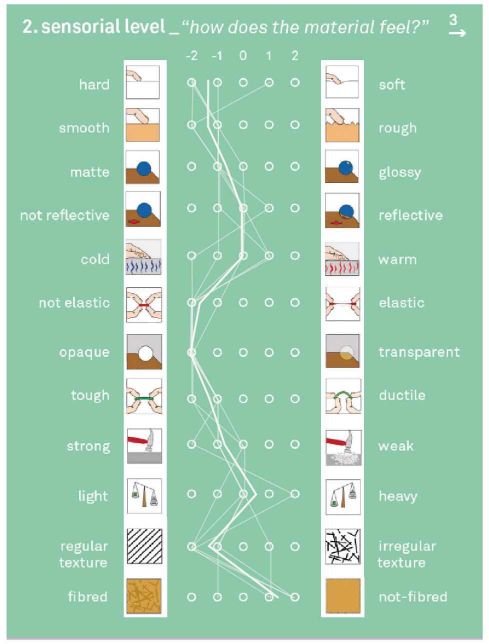
INTERPRETIVE LEVEL

(set of meanings)

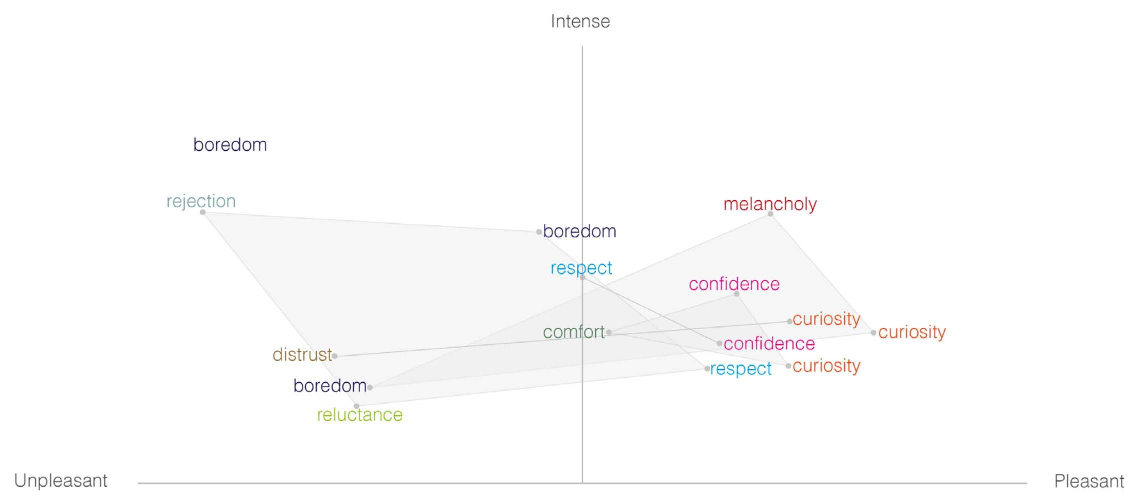
	OR	
aggressive		calm
cozy		aloof
elegant		vulgar
frivolous		sober
futuristic		nostalgic
masculine		feminine
ordinary		strange
sexy		not sexy
toy-like		professional
natural		artificial
hand-crafted		manufactured
beautiful		ugly
aged		new
valuable		useless
rough		smooth
strong		weak
simple		complex
interesting		boring
common		unusual
hot		cold

(Karana, E., Barati, B., Rognoli, V. et al, 2015)

Appendix E: Results Experiential Characterization - User Test 1 (original N-8040)



EMOTIONAL LEVEL



Boredom	3	Rejection	1
Curiosity	3	Distrust	1
Confidence	2	Melancholy	1
Respect	2	Reluctance	1
		Comfort	1

INTERPRETIVE LEVEL

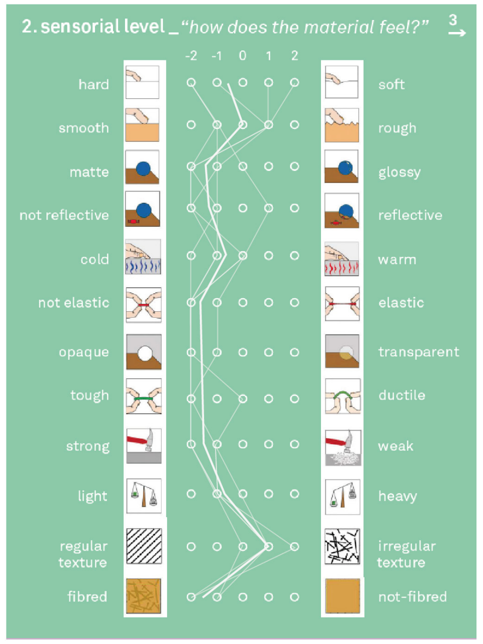
Calm Elegant Simple	Strong Smooth Calm
Masculine Aloof Sexy	Common Weak Sober
Sober Strong New	Valuable Futuristic Cold

Calm	2
Strong	2
Sober	2
Elegant	1
Simple	1
Smooth	1
Masculine	1
Aloof	1
Sexy	1
Common	1
Weak	1
New	1
Valuable	1
Futuristic	1
Cold	1

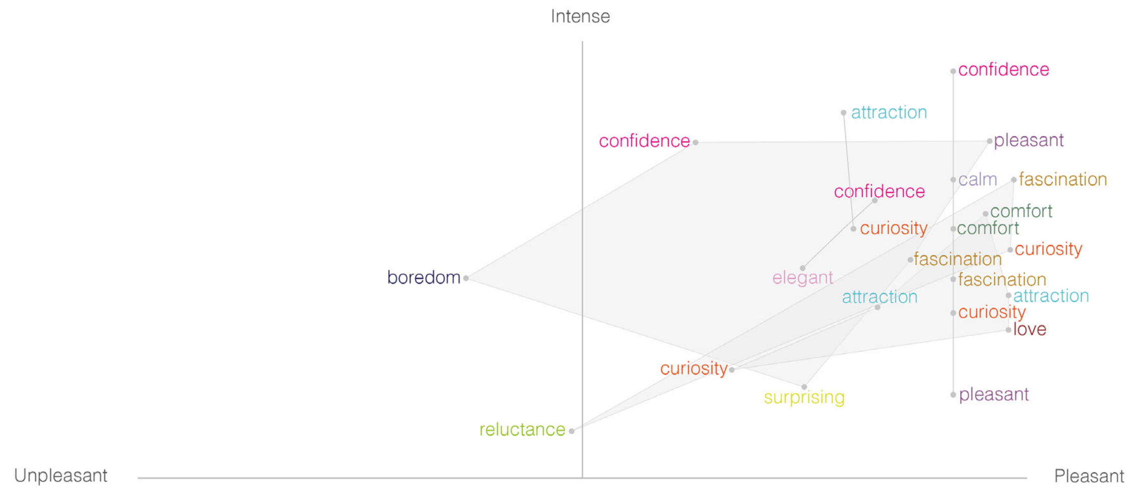
REFLECTIONS

PLEASANT	DISTURBING	UNIQUE
Matte	Look and feel does not match	Black color
Soft texture	-	Unexpected material
Sexy	Rejection	Unexpected material
Natural	Unpersonal	Texture
Smooth & calm	Black color	Unexpected material
Basic	Seems cheap and unsustainable	Sustainable

Appendix F: Results Experiential Characterization - User Test 2 (fibre-enhanced N-8040)



EMOTIONAL LEVEL



Curiosity	4	Calm	1
Fascination	3	Elegant	1
Confidence	3	Love	1
Attraction	3	Surprising	1
Comfort	2	Reluctance	1
Pleasant	2	Boredom	1

INTERPRETIVE LEVEL

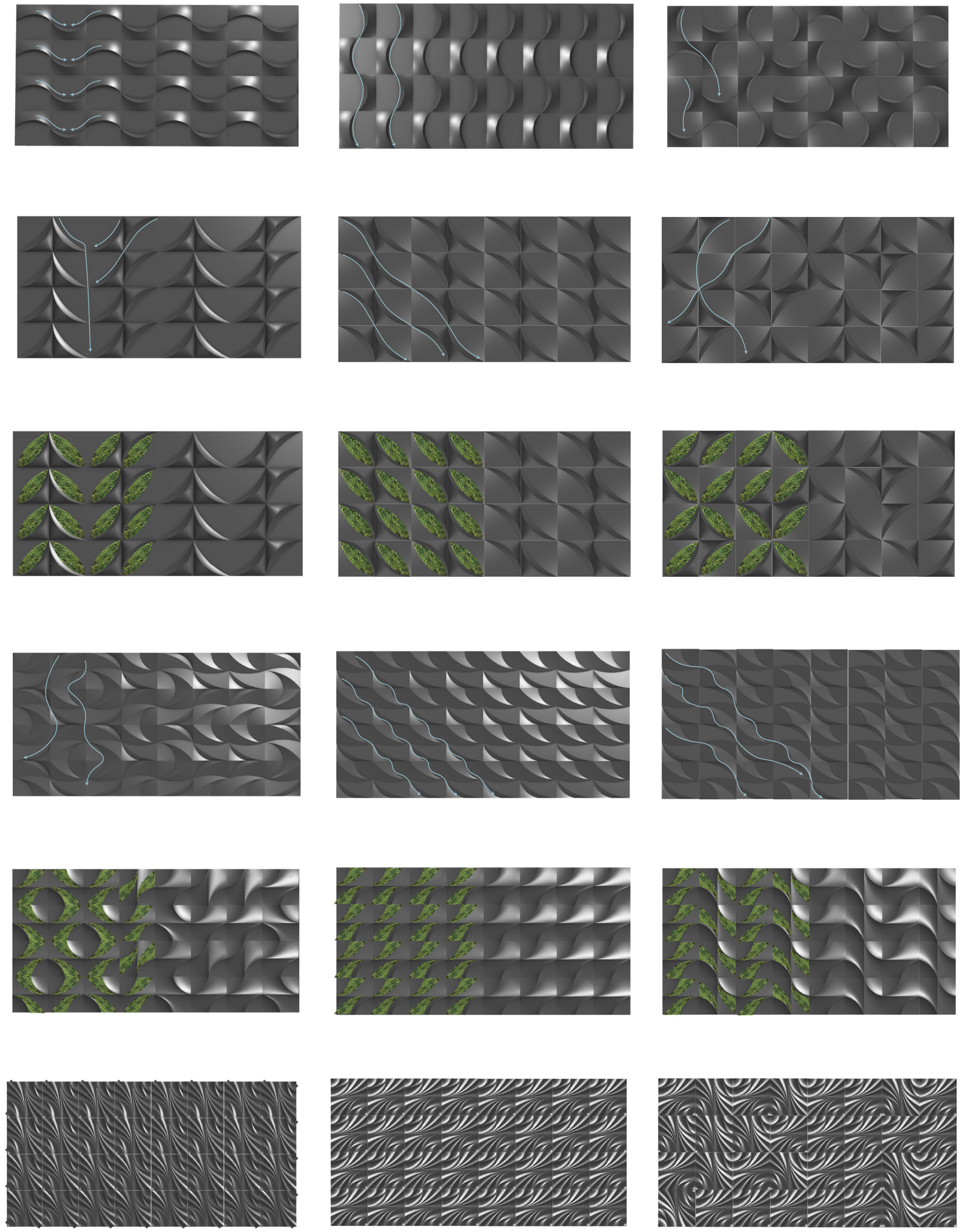
Professional Neutral Strong	Robust Modern Complex
Nostalgic Comfort Calm	Elegant Natural Strong
Modern Tough Interesting	Sexy Valuable Natural

Natural	2
Strong	2
Modern	2
Professional	1
Neutral	1
Robust	1
Complex	1
Nostalgic	1
Comfort	1
Calm	1
Elegant	1
Tough	1
Interesting	1
Sexy	1
Valuable	1

REFLECTIONS

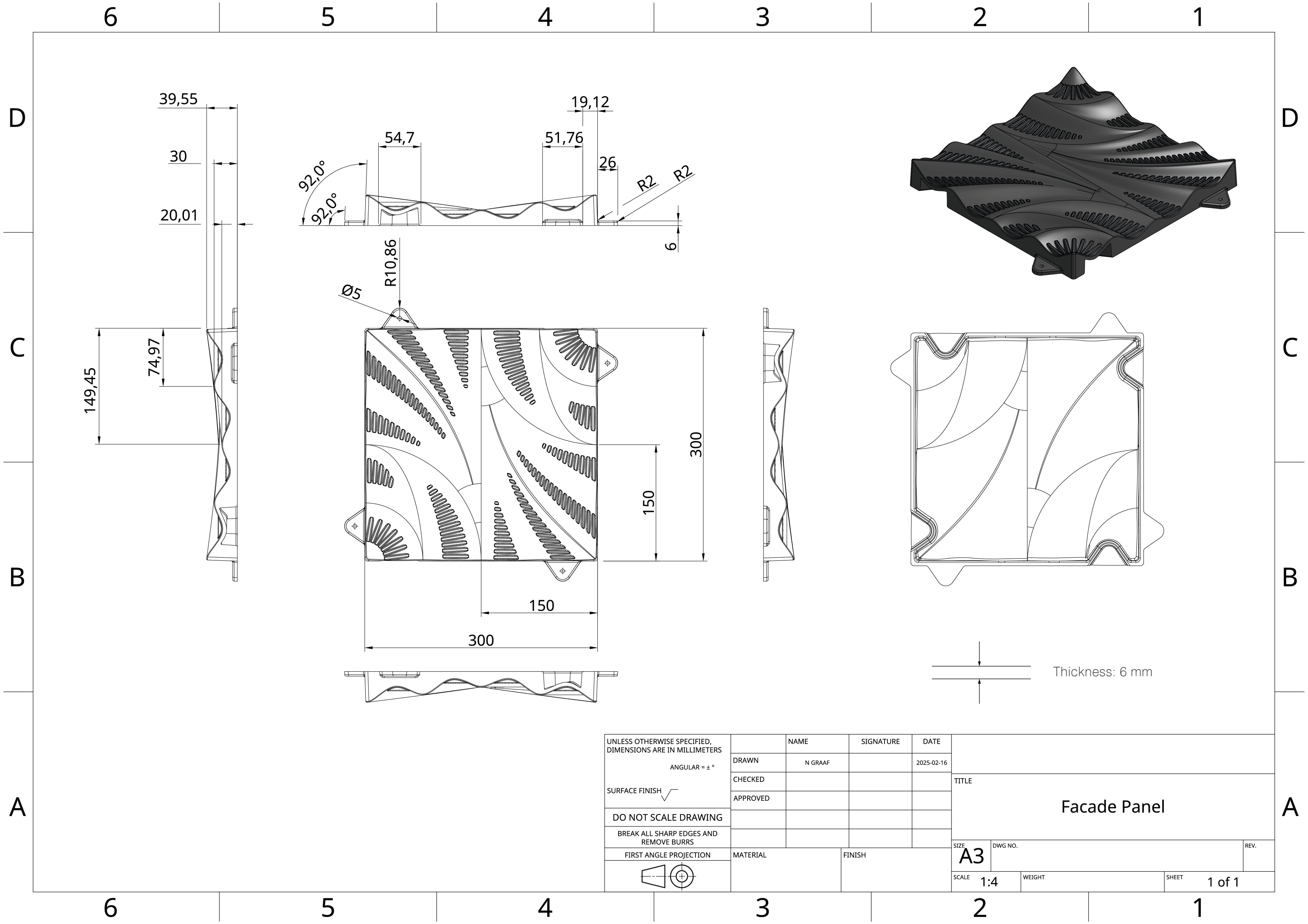
PLEASANT	DISTURBING	UNIQUE
Combination of lightweight and strong	Fibres that are too white	Combination of lightweight and strong
Combination of lightweight and strong	Black color	Complexity
Colors	-	Texture
Beauty, subtlety, trust	-	Natural
Colors	Feels slightly fragile	Colors and light reflection

Appendix G: Ideation - Patterning, Moss Growth and Water Management



Appendix G: Technical Drawings

Please see the next page



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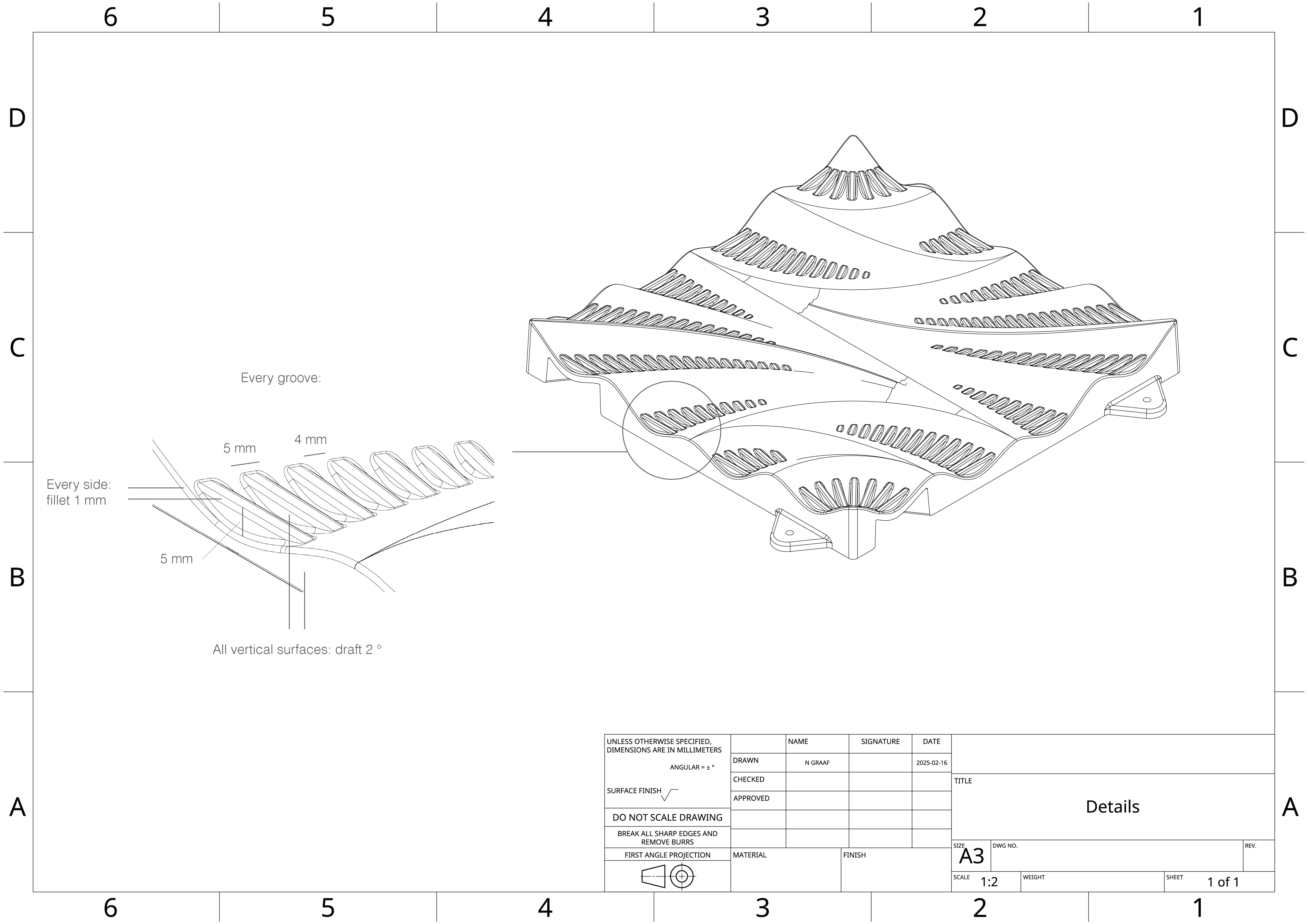
1 of 1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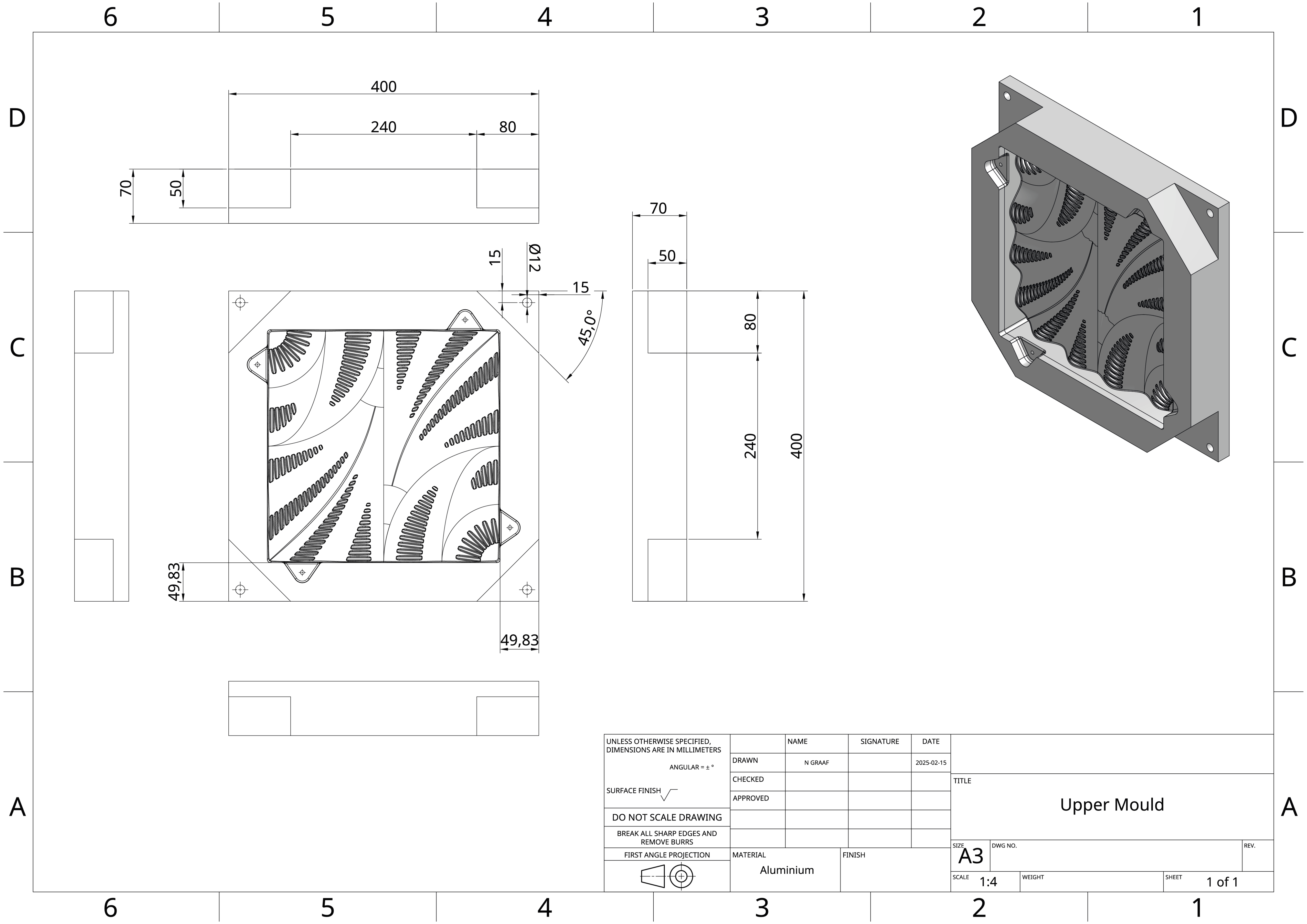
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Aluminium
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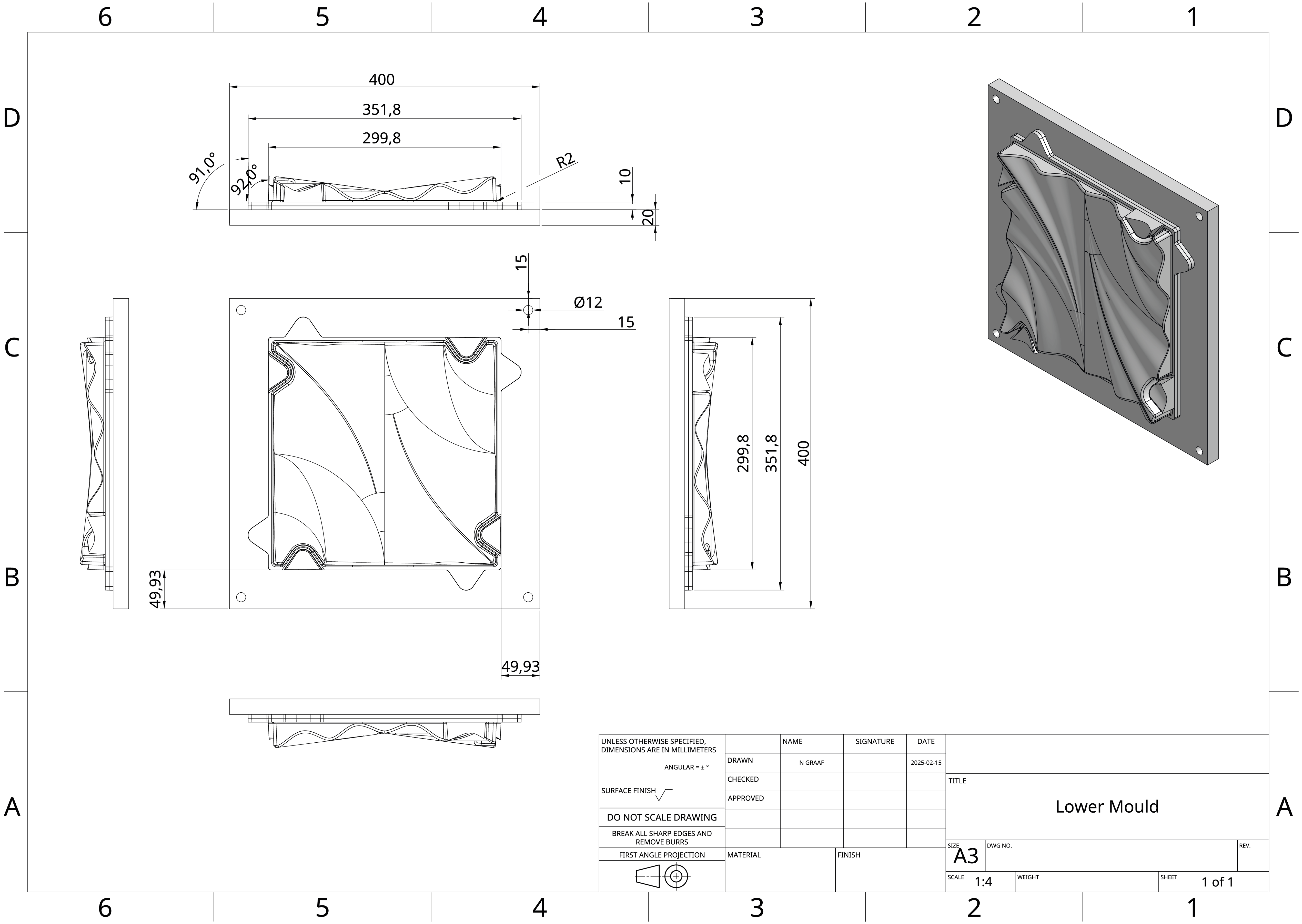
1 of 1



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1 of 1