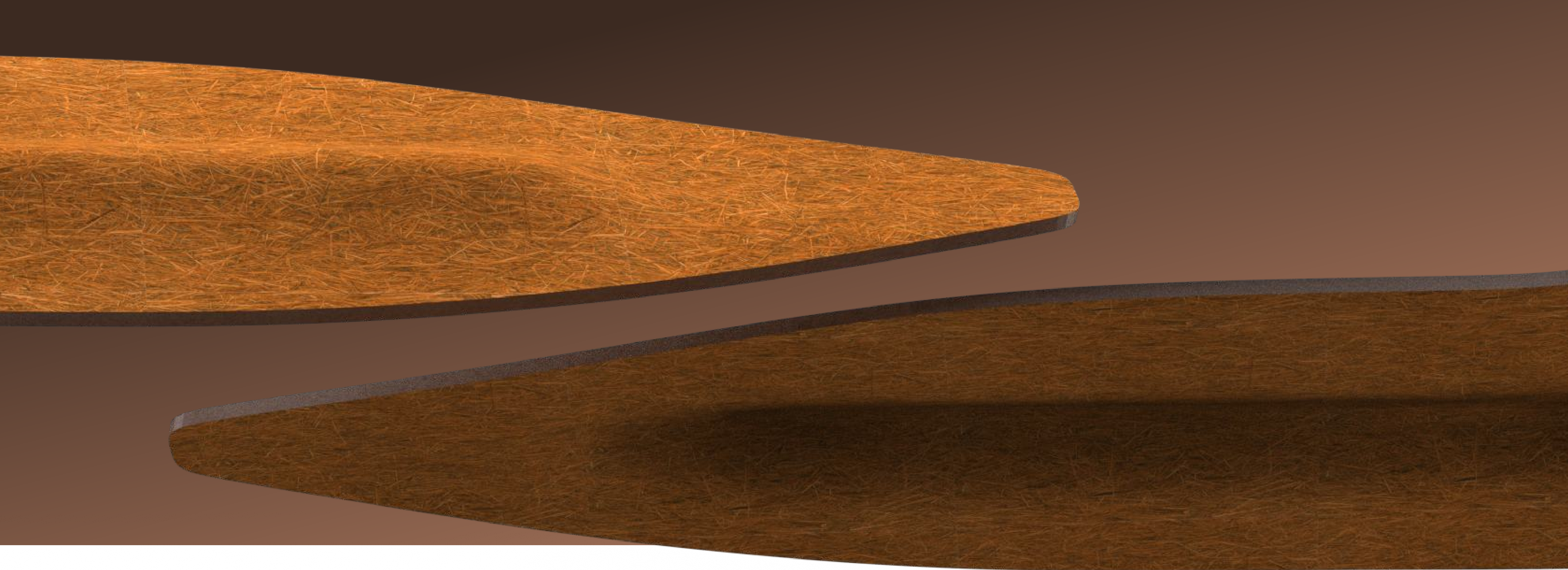




18th Sep 2024 Yanru Mo
Msc GRADUATION PROJECT

**Designing Applications of the New Carbon-negative
Material — A Bio-based Natural fiber Composite**

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MSc Integrated Product Design

18th Sep 2024

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**Designing Applications of the New Carbon-negative
Material — A Bio-based Natural fiber Composite**

This project explores the potential market opportunities and applications for a novel bamboo fiber-reinforced composite material using a bio-HDPE matrix. The research, conducted in collaboration with Eve Reverse, focuses on developing a thermoplastic composite with aligned short bamboo fibers to enhance mechanical properties in specific directions, allowing for programmable strength. The goal is to research the desirability of the new carbon-negative bio-based short fiber composites and designing its appropriate application.

The project adopts the Material Driven Design (MDD) method, combining experiential characterization studies, mechanical testing, together with prototyping to assess the composite's desirability, feasibility, and viability.

The testing of the bamboo fiber composite's mechanical properties, including its stiffness and strength, which showed comparable performance to traditional materials like plywood. Experiential characterization studies involved a series of observation-based experiments, questionnaires, and interviews to gather insights on potential consumers' perceptions and emotional responses to the material.

The results indicated that the bamboo fiber composite material offers a natural, warm aesthetic that elicited positive emotional feedback from users, including feelings of comfort and curiosity. These findings are crucial for establishing the desirability of this material in the marketplace, as they demonstrate consumer interest in products made from sustainable materials. Despite some concerns about the material's sustainability, it offers a compelling alternative for eco-conscious consumers.

The design vision can be concluded from mapping the findings of material characterization and market research. Following the vision, with the help of ideation groups, the idea of ceiling fan blade perfectly fit the vision and the requirement. Prototyping and functional testing further confirmed the feasibility of using bamboo composite materials. The study validated vacuum bag thermoforming as an effective manufacturing method for producing smooth, uniformly thick bamboo composite blades capable of complex curves. The project also explored the feasibility of remanufacturing a multi-layer plate by pile up bamboo composite which demonstrated the potential for producing larger composite structures.

Finally, from a viability perspective, the project aligns with the increasing demand for carbon-neutral products in the European Union, with legislation likely to support the development of sustainable materials. The result of quick LCA proved the sustainability impact is relatively low from cradle-to-gate calculation. The easy accessibility of raw materials, and relatively simple manufacturing process ensure it can be produced affordably while maintaining profitability. I believe that bamboo fiber composite has great potential to realize a low cost automatic production line, providing thermoplastic materials in the market as a sustainable alternative. This combination of environmental sustainability and economic efficiency positions bamboo fiber composites as a competitive alternative for future product development.

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Chapter 1

Introduction



1.1 Motivation

Global warming caused by CO2 emissions has been a problem for a long time, so all kinds of forces from policymakers and society are pushing for industry transformation to be carbon neutral and sustainable. Lots of actions have been taken to reduce and regulate carbon emissions; for example, from 2003 till the present, the EU Emissions Trading System (EU ETS) has been developed to reduce greenhouse gas emissions cost-effectively by setting a cap on emissions and allowing companies to buy and sell allowances, which incentivizes companies to innovate and invest in cleaner technologies.(EU ETS development 2015-2020, 2020) In 2015, 196 parties negotiated the Paris Agreement to put efforts in place to keep the rise in global surface temperature to 2°C, including reducing greenhouse gas emissions.(Wikipedia, 2024) The European Commission presented The European Green Deal in 2019, declaring that they are setting a goal to reach zero net emissions of greenhouse gases by 2050. The transformation needed to reach the goal started with industries that contribute more to carbon emissions, like transport, energy, agriculture, buildings, steel, cement, ICT, textiles, and chemicals. (EU Statement, 2019)

From the consumer side, they stand for their attitude by favoring purchasing sustainable products. In McKinsey's US consumer survey for 2020, more than 60% said they would pay more for sustainable packaging products.(Feber, 2020) Similarly, actively seek more environmentally friendly options when shopping.(Beeson, 2022) Another key finding in 2021 global report from The Economist Intelligence Unit, commissioned by WWF, shows a staggering 71% rise in online searches for sustainable goods globally over the

past five years.(World Wildlife Fund, 2021). Both policy statements and the consumers' willingness favor the sustainability goal. However, as the policy is getting more and more strict and complete to avoid greenwashing, green claims from product brands based solely on the so-called carbon offsetting schemes will be banned because they are not putting effort into reducing CO2 emissions.(European Parliament, 2024) This new policy means that besides the big industries, smaller companies must be more careful in selecting the supplier and have a more detailed analysis of the product's sustainability. This will be an excellent opportunity to promote sustainable materials like biobased, biodegradable, or circular materials for product manufacturing because they are typically considered costly compared with the common ones. So, my initial motivation is to develop products with sustainable materials, and I am happy to find Eve Reverse, a start-up composite innovation company with the same scope.

After discussing with Eve Reverse B.V., a company that aims to achieve carbon negativity throughout the life cycle of its composite-producing process, we set up the project assignment as follows.

1.2 Initial Assignment

Making products more sustainable means fewer CO2 emissions during manufacturing and requires good mechanical properties, making it competitive with common materials in the market, move the circular economy forward are essential. (Karimah et al., 2021b) Under this context, biobased fiber is getting increasingly popular in composite fields due to its high specific stiffness, low cost, renewability, sustainability, and eco-efficiency. (Rajak et al., 2019) This was when bamboo came into our sight for its massive CO2 intake when growing and good stiffness. Compared to other natural materials such as wood, flax and hemp, bamboo is known for its reproducibility, rapid maturity, and tolerance to water quality, making it stand out. (Emamverdian, 2020) According to research, bamboo fiber-reinforced laminates have mechanical properties relatively poorer than those of the flax fiber-reinforced laminates but have much better environmental performance, proving the feasibility of replacing the flax fiber composite for specific purposes. (Gu, 2018) Eve Reverse B.V. developed the first generation of HDPE-reinforced bamboo fiber composites based on that knowledge with the innovative idea of aligning the discrete fibers, trying to reach the properties of continuous fibers. By having the short fibers aligned, composites become programmable to carry forces in one particular direction by strengthening in one direction without equivalent requirements in other directions. This results in material savings, which means more sustainability and lightweight. Thus, the assignment statement of the project is : Researching the desirability of the new carbon-negative bio-based short fiber composites and designing its applications.

1.3 Project Context Introduction

In the composite industries, there is a great need for petroleum-based materials, notably polymers for matrix materials or reinforcement, which have exacerbated environmental issues since they are not only non-renewable but also extremely difficult to reuse and recycle economically. (Krauklis, 2021) So, the challenge is how to make a biobased composite that has competitive properties and is sustainable at the same time. So, to develop carbon-negative products and not rely on fossil fuels, Eve Reverse researched the feasibility of biobased matrix materials, collaborating with suppliers and university labs, which provided sufficient support on the technology and facilities for this research. The following part is a context introduction to the starting point of this project.

The technology of making composite laminates is basically producing mixed materials from two or more constituent materials. The constituent materials have two categories: matrix and reinforcement. In this project, the reinforcement will be short bamboo fibers with a length of around 1.5 centimeters. The matrix will be biobased SHA7260 high-density polyethylene (HDPE) in film. A special thing about this bamboo composite is that the fiber will be aligned due to the alignment will have better mechanical transmission with different damping effect for different orientation. (Rajak et al., 2019b) The composite-making process requires fiber feeding and aligning mechanisms, mold for heat pressing, and a thermoforming pressor. The process would be cutting the film according to the mold size, dispensing fibers between films, and then thermoforming the laminate using the thermoforming pressor.

Eve Reverse is a composite innovator aiming at something other than producing the composite but sharing the technology with other stakeholders to make products of it. The stakeholders that need to be considered in this project are raw material suppliers, .

material producers, and product manufacturers are the customers of Eve Reverse B.V. The material producer will cooperate with Eve Reverse B.V. using their technology and raw materials from suppliers to produce composites and sell them to product manufacturers, then finally making profits by selling products made by the composites. The end user is also a part of the stakeholders who recognize the product's value and make purchases.

Eve Reverse has already developed initial prototypes for aligned bamboo fiber composite production, including a short fiber aligning filter. However, there are a few opportunities for this project to explore, which are finding the proper fiber fraction, developing the laminate production process, mechanical property test, and user experiential tests to analyze the feasibility of production, reliability of the composite, potential user acceptance and assess its societal attributes and values. Also, there is much room to play with the final design for possible market applications; the design will use all the discoveries from previous research and experiments as guidance and boundaries. Ultimately, using the eco-audit tool can approximately quantify the material's carbon-negative capacity, referencing future adjustments.

This project has some limitations and risks that must be considered carefully; first of all, the current production prototype has a very low TRL level, which means it might have a high risk of breaking and couldn't promise a complete production. Mitigation actions on this could be actively checking the functionality and producing as many backup samples as possible. Secondly, the low TRL prototype might limit the composite material's surface, pattern, and texture changes

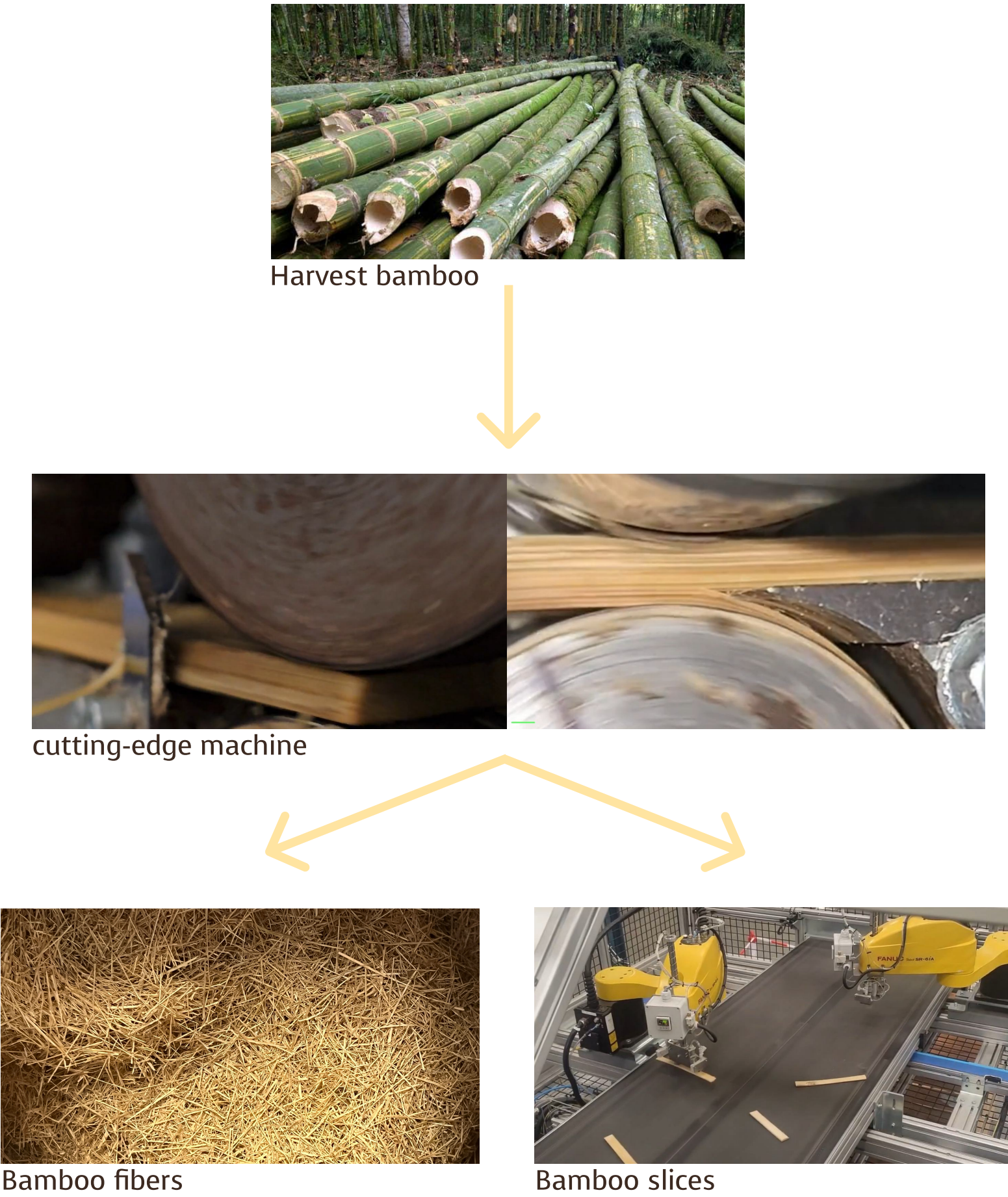


Figure 1 Bamboo manufacturing process
(Sourced from bambooiimport.com and www.bambooder.nl)

1.4 Defining the Research Framework

1.4.1 Problem Definition

Eve Reverse aims to achieve carbon negativity throughout the life cycle of its composite product-producing process. However, the company faces significant challenges. The specific methods and applications for implementing the composite are not yet determined, and the carbon dioxide emissions generated during the production process have not been quantified or addressed. These challenges collectively hinder the achievement of the company's goal of carbon negativity. To address these obstacles, it is crucial to discover and design the implementation for the composite, then evaluate and mitigate the CO2 emissions during production.

1.4.2 Scope and Research Questions

The scope of this research involves a comprehensive exploration of the sustainable application of natural fiber composites, explicitly focusing on utilizing aligned bamboo short fibers within a high-density polyethylene (HDPE) matrix. This project aims to achieve carbon negativity throughout the life cycle of composite production by addressing several key areas: defining the problem, evaluating the market potential, and developing design concepts. The research will encompass literature reviews, market research analysis, concept design, prototype development, and brief life cycle assessment (LCA) to ensure the feasibility and sustainability of the proposed composites.

According to the problem definition and scope, we can generate the research questions and queries according to the research plan tutorial from the TU Delft Library 2024. The questions selected for this project can be found in Table 1.

Table 1 Research questions

Question Types	Explanation	Research Questions
What?	Definitions of terms	What is the definition of bio-based short fiber composites?
		What are the types of short fiber composites?
		What kinds of materials are used for making bio-based composites?
		What are the technologies for making bio-based composites?
		What kind of matrix can bring less CO2 emissions?
		What experiential feeling can bamboo fiber composites bring?
How?	Relations between terms	How can the technical characteristics of composites affect its application?
		How can the texture of bio-based composites affect its experiential characterization?
		How to conduct experiential characterization tests on composite sheets?
Why?	Social relevance: benefits of the research	Why should we develop bio-based composites?
		Why bio-based?
		Why short-fiber?
Who?	Target group	Who benefits the most?
		What can the end user get?
Where?	Geographical demarcation	Which group of users will most likely purchase products made by bio-based material?

1.4.3 Approach and Methodology

To reach the goal of designing the implementation of this biobased bamboo composite, I must know the composite properties from different aspects. To thoroughly understand the user preferences of this composite and market opportunities, I employed a comprehensive research strategy that includes the Material-Driven Design method (MDD). This approach includes two aspects of material characteristics: the technical characteristics and the experiential characteristics. First, mechanical properties such as tensile strength and stiffness should be tested to determine their capacity to carry loads. Combined with interviews and questionnaires targeting customers and end users, will provide valuable insights of composite's experiential characteristics that guide effective product development. The way of embedding this design method in my project will be introduced in Chapter 2.2. After picturing the composite characters, the findings are compiled into a design vision for organizing brainstorming sessions. The concept design will be iterated and developed among the ideas. Then, I chose the best design for prototyping and used the spread sheet calculator by Jeremy Faludi for the quick Life Cycle Assessment (LCA), which can provide insights on further actions to reduce CO2 emissions.

1.4.4 Final Deliverables

The final deliverables for this project are comprehensive and designed to ensure a thorough evaluation and development of the carbon-negative bamboo fiber composites. These deliverables encompass various aspects of research, analysis, design, and testing, which collectively aim to address the project's goals and challenges. The detailed deliverables content are outlined in Table 2.

Table 2: Project Deliverables

Report	Literature research on natural fiber composites
	Field research on applications of natural fiber composites
	Mechanical characteristics analysis
	User experiential characteristics analysis
	Market potential opportunities and design vision
	Ideation iteration results and concept design
	Brief LCA of the concept
Prototype	A testable prototype in TRL 4 & Alpha prototype level

Chapter 2

Research and Design Methodology



2.1 Existing methodologies and frameworks

The problem definition and research goals highlight that this project adopts a unique design approach. Rather than starting from specific user scenarios, it focuses on exploring the properties of the composite materials to identify user needs that resonate with these properties. This approach aims to find the most suitable and effective entry points for introducing the materials to the market, thereby creating a bridge between the composite company and potential customers. The following methodologies are typically aimed at exploring material properties and implementing them.

2.1.1 Using Materials and Processes to Create Product Personality (Ashby & Cebon, 1993)

In this book, it is stated that a successful product not only provides function but also gives pleasure while using it. The pleasure comes from three aspects of the design: aesthetics, associations, and perceptions. By exploring the 5 attributes of aesthetics: sight, smell, hearing, taste, and touch, designers can build up certain aesthetic qualities. After that, Ashby pointed out that by combining fashion, custom, cultural background, and advertising association with the product, the product will no longer be systematic, but have unique personalities. Materials play an important role in providing different aesthetic qualities and personalities. So in Ashby's theory, while designing products, good material selection contributes to successfully shaping product personalities.

2.1.2 Integration of Sustainable Materials in Supply Chain Management (Okogwu et al., 2023)

In this paper, it gives a strategy on implementing the sustainable material into the supply chain.

The strategy includes assessing green procurement, doing LCA of all possible supplements, establishing circular economy principles, and carrying pilot programs & scaling. The purpose is to find a position in the current supply chain and replace the energy-consuming material with the sustainable material. This requires conversations with supply chain members, convincing them to make changes by showing the competitive material properties. In conclusion, this method focused on the functionality perspective of material implementation.

2.1.3 Material Driven Design Method(Karana et al., 2015)

Researchers at TU Delft developed the material-driven design (MDD) method, which provides a complete design strategy for designing concepts by researching the material's characteristics, creating a design vision based on its uniqueness, and developing a concept design (Karana et al., 2015). Both technical and experiential characteristics are considered in this method by using a mechanical properties test and experiential characterization interview toolkit(Camera & Karana, 2018). The steps of MDD method is shown below in Fig 2.

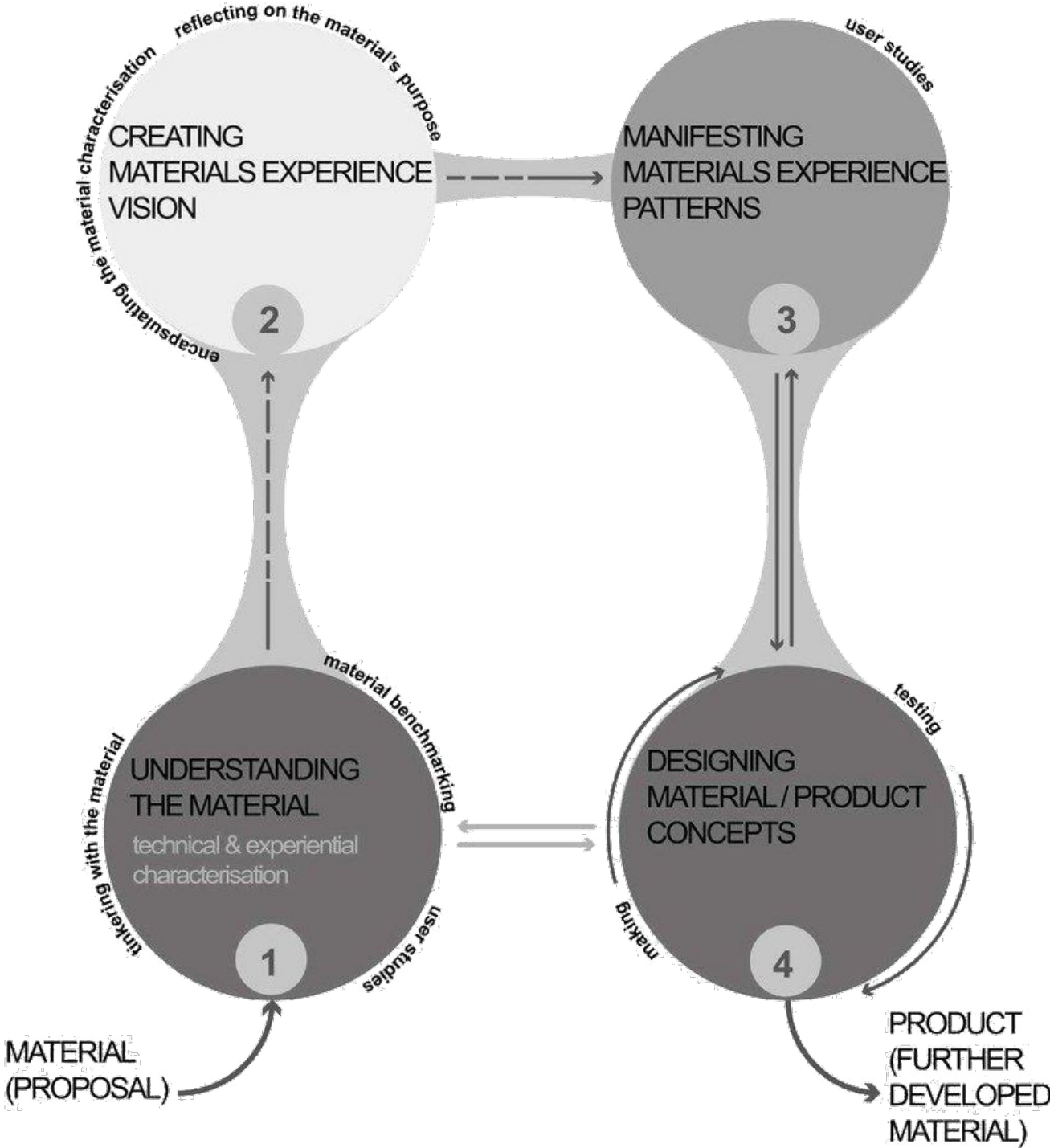


Figure 2 MDD Method's steps

2.2 Embedding Material-Driven Design in Research Methodology

Aligned short bamboo fiber composites are uniquely suited for the Material-Driven Design (MDD) method because this approach emphasizes exploring and integrating material properties into the design process. The inherent characteristics of bamboo fibers—such as their high specific stiffness, environmental benefits, and recognizable features—align perfectly with the MDD method's focus on leveraging technical and experiential materials' attributes. Also, the qualitative experiential interview toolkit can easily be adapted to my project, see Fig.\ref{fig:Experiential}. The following paragraphs show how I adapted the steps of the MDD method.

2.2.1 Understanding the material

The first step in the MDD method is to understand the material from all kinds of aspects. Technical characteristics give clear positioning among all kinds of materials so we can know which material it can compete with or replace and get inspired from their implementations. The experiential characteristics qualified the composite's personalities from the customer's eyes, guiding the designer to decide its relationship with people and the environment. From the market, we can learn the feedback and see the trends of other similar materials by benchmarking (see Fig \ref{fig:benchmarking}), from which we receive the signals of opportunities and risks. In this step, the designer dominates the interpretation of the qualitative research, which requires a keen sense of observation and great logic. So, the designer must look at the big picture while pursuing the details to find the potential connection between the two findings.

2.2.2 Creating materials experience vision

After understanding the composite's characteristics, its experience vision can be created by integrating previous findings on technical and experiential characteristics and the designer's tinkering, preparing for the product design ideations that come after. The vision describes how I would like to use the material's technical properties, which kind of products I want, and what kind of affective feeling I want it to bring to the customer under what context, with specific meanings. A metaphor is also highly recommended to help understand the image easily.

2.2.3 Manifesting materials experience patterns

This step is to continue discovering the customer's understanding between the created materials experience vision and the formal qualities of materials and products. From the original research paper, they classified the manifested attributes of the meaning by holding a workshop with a group of participants to discuss their pattern of evoking the aimed meaning from the vision and metaphor(Karana, 2020). In this project, I did not manifest the material experience patterns in this way. However, through the interview on material experiential characterization, I collected participants' reflections on their imagination of material implementation and other materials or products they associate with. I searched for clear evidence on supporting material meaning.

2.2.4 Designing concepts with material

With a clear statement of design vision and metaphor with specified meaning, I can start the ideation session by recruiting design students to do the ideation session together. Three groups of designers and students were recruited, with 12 people in total. The ideation session is widely used as a practice in TU Delft's teaching program, where, typically, the designers sit down together to brainstorm and sketch ideas on a given design topic. Then, the designers exchange sketches to inspire and iterate on the design. After several iterations, the designers set up a discussion group to evaluate and reflect on the iterated sketches and select a relatively satisfactory solution. Through this form of creative design, I can get many creative sketches quickly, which inspired the subsequent conceptual design from a relatively comprehensive perspective and multicultural background.

Chapter3

Science of bio-based fiber-reinforced thermoplastics



3.1 Factors in Material Development of Bio-based Fiber Composite

In designing a new composite material, it is essential to consider several key factors that influence the material's properties and performance. These factors include the types of fibers and matrix materials used, the orientation of the fibers, and the fiber fraction. Each factor is critical in determining the composite material's mechanical properties, usability, and effectiveness.

3.1.1 Fiber types and matrix materials

Various natural fibers can be utilized when developing bio-based fiber composites, each with unique characteristics. Natural fibers in composites include flax, hemp, jute, and bamboo. (Karimah et al., 2021) These fibers can be categorized based on long and short fibers. Long fibers typically provide higher tensile strength and stiffness. In contrast, short fibers are more accessible to process and can be used in more complex shapes.

Bamboo fibers, in particular, offer excellent properties for composite materials. As introduced in 1.2, bamboo cannot compete with flax but still has high tensile strength and stiffness. Also, it has better environmental performance compared with flax and hemp. In this project, we collect discrete bamboo fibers given by Bambooder, a bamboo product company with a production line of long fiber extraction, in which short pieces can be reused by us, making the composite more sustainable.

The matrix material is equally vital in composite design. Bio-based matrices include polylactic acid (PLA), polyhydroxyalkanoates (PHA), and bio-based polyethylene (HDPE). Each matrix material has distinct properties that affect the composite's performance. (Ramamoorthy et al., 2015)

PLA is biodegradable but brittle, and PHA is flexible and biocompatible, which makes it an ideal material for medical-related purposes. HDPE is chosen for this project due to its stiffness, durability, good processability as thermoplastics, and compatibility with bamboo fibers.

Additionally, the form of matrix materials also affects producibility. Matrices can be available in bulk, powder, or film form, influencing the composite preparation differently. A bulk matrix is more suitable for injection mold or forming solid products, and a powder matrix can be evenly distributed but requires extra operations and protection in the lab environment. Film matrices, for instance, can provide good fiber alignment and ease of layering, which is often preferred in composite manufacturing for achieving uniformity and reducing voids. In conclusion, bamboo fiber and biobased HDPE film have been chosen for development into composites, which balance strength and flexibility, making them suitable for this project. The density and strength can be found in Table 3.

Table 3 Material properties of bamboo and HDPE film

	Bamboo short fiber	HDPE SHA7260 film
Picture		
Density (g/cm³)	1.1	0.955
Tensile Strength (MPa)	-	26

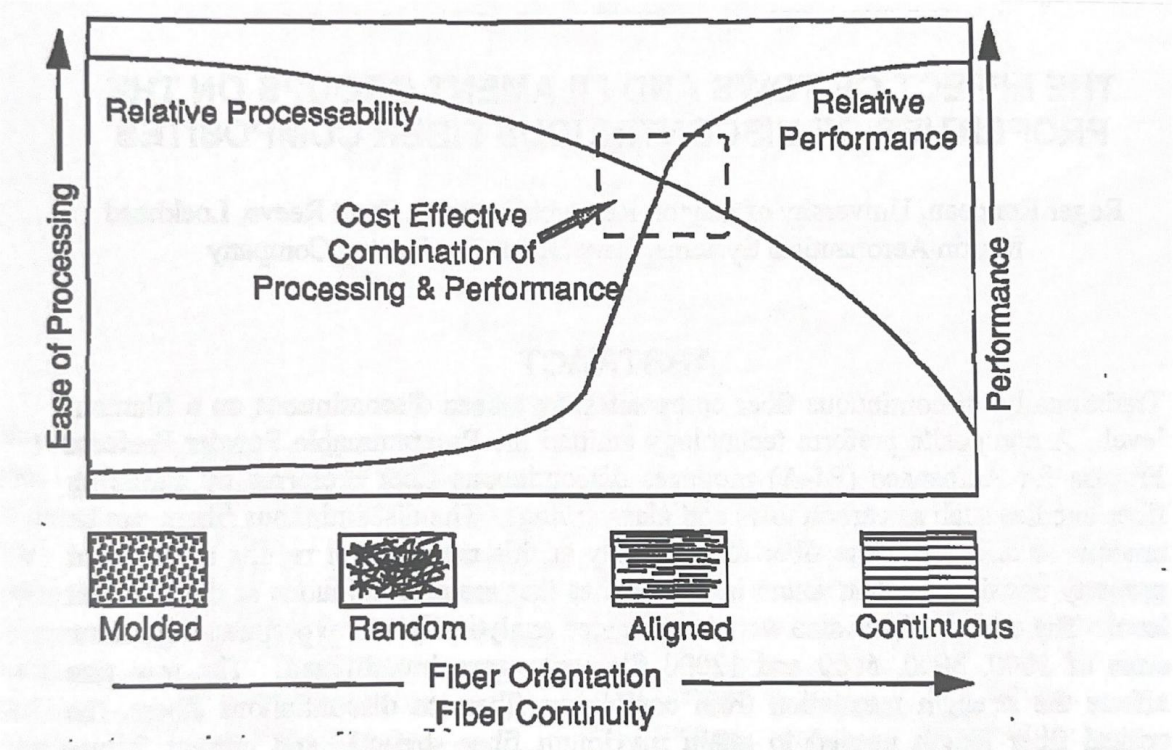


Figure 3 Oriented Discontinuous Fiber Composites Potentially Offer a Cost-Effective Combination of Processing and Performance

3.1.3 Fiber fraction

The fiber fraction, or the volume ratio of fibers within the composite, is another critical factor that impacts the composite's performance.

Higher fiber fractions typically improve mechanical properties such as increased tensile strength, stiffness, and impact resistance. However, a trade-off exists, as excessively high fiber content can make the composite more brittle, have a lousy surface look, and be challenging to process. The fiber fraction also affects the composite's quality. A significant porosity can be found on the surface of the composite if the fraction is too high (see Figure 4) and the melted matrix is squeezed to leak outside the mold if the fraction is too low.

To avoid matrix leaking and porosity, the recommended fiber fraction is between 40% to 50% volume fraction.

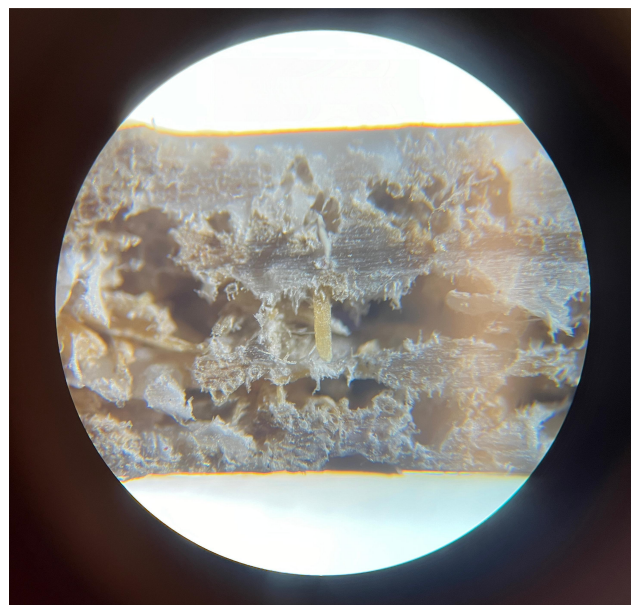


Figure 4 Surface fraction photograph

3.2 Composite Plate Producing Process

3.2.1 Standard process of thermoforming press

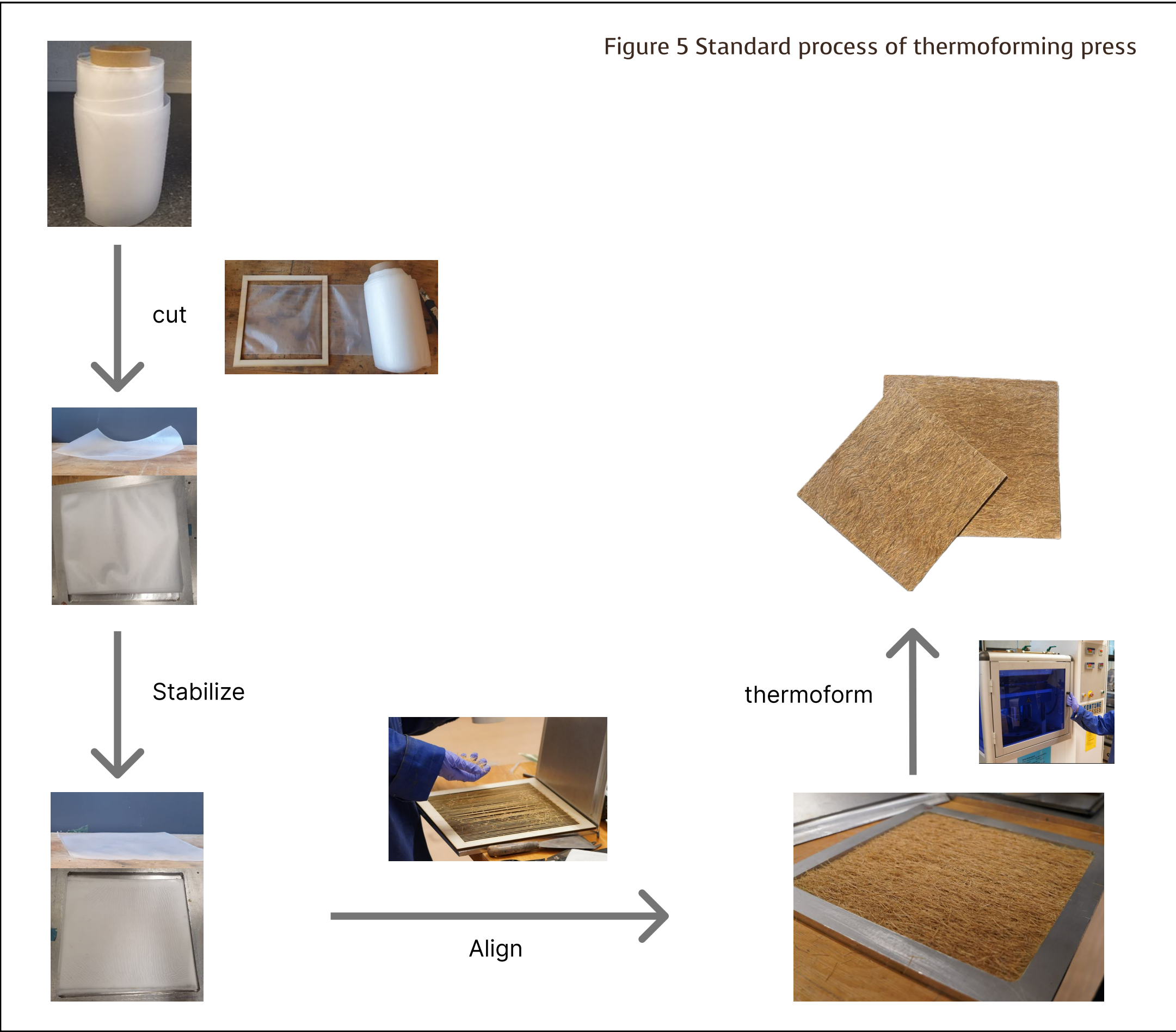
To make a successful press, several steps are needed:

- 1. Weigh the bamboo fibers according to the requirement of a certain weight/volume fraction;
- 2. Put the matrix in the mold with dispensed bamboo fibers between layers as a sandwich structure;
- 3. Close the upper mold and put the mold into the presser;
- 4. Set the oven as the required temperature and the required force, when the temperature reached, press the button to start pressing;
- 5. Set the timing for the pressing process, resetting the temperature to room temperature, and open the valve for cooling;
- 6. Release the presser's force and take out the mold, remove the upper mold and get the composite.

3.2.2 Stabilize the matrix

Several parameters need to be defined as controlled parameters for every press: Temperature during the press, Force during the press, and pressing time. Other factors that can influence the quality of the composite are the status of the matrix and the fiber fraction. The current bio-based HDPE matrix from the supplier is provided in rolls and looks wrinkled while trying to flatten it on a plain surface, which might lead to an uneven distribution of fiber. Therefore I preheated and pressed the matrix layers to help stabilize it.

There's a detailed introduction on parameter selection in plate production in section 9.3



Chapter 4

Understanding the Material: Technical Characterization



4.1 Methodology of Technical Characterization

Sustainable bamboo fiber reinforced polymeric composites have emerged as a viable material for different engineering applications, due to its superior mechanical, thermal, and environmental qualities. (Hasan et al., 2023) To the brief understanding of this bamboo composites' mechanical properties, the strength and stiffness of every sample can get from the tensile test. To prepare for the test, we prepared 4 different compositions, all of which have 44% volume fraction with HDPE matrix: bamboo long fibers, mechanically aligned short fiber, filter-aligned short fiber, and short fiber in random orientation. Here I used 10 KN load cells for the test.



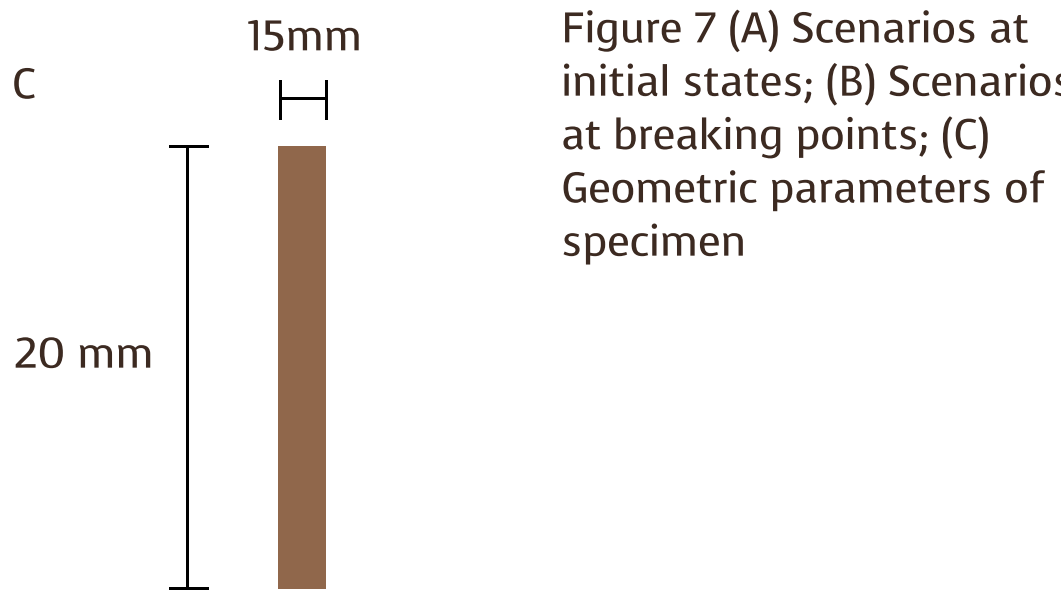
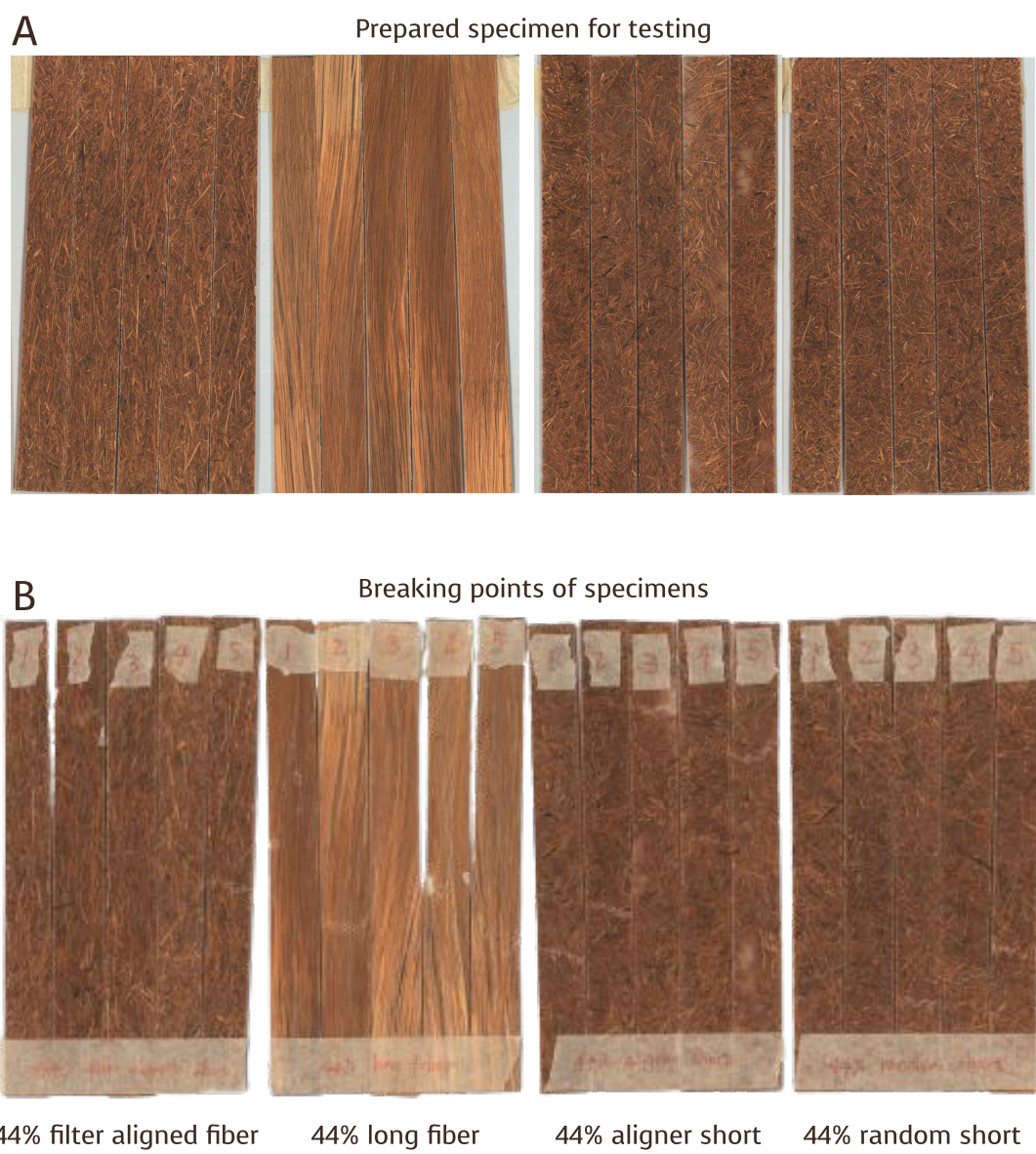
4.2 Sample preparation for testing

Based on the mechanical tensile testing guidelines specifically for unidirectional fiber-reinforced composites (NEN-EN-ISO 527-4 Test conditions for isotropic and orthotropic fibre-reinforced plastic composites), I developed a testing plan with the following objectives. First, to determine whether unidirectionally aligned fiber-reinforced composites exhibit higher strength along the alignment direction compared to randomly oriented fibers. Second, to investigate whether there is a significant strength difference between aligned fiber composites and long fiber composites. Third, to assess whether there are notable performance differences between bamboo composite plates produced with two different fiber alignment methods.

To address these questions, I prepared four different materials, all with a consistent fiber volume content of 44%, but differing in either their raw materials or processing methods. The materials are as follows:

- Aligned fibers using the filter aligner technique.
- Unidirectional continuous fibers.
- Aligned fibers adapted to the aligner device.
- Randomly oriented short fibers.

As explained in the testing guideline, the recommended specimen size should follow the dimensions for type 2 specimens. However, due to mold limitations, we were unable to achieve a length greater than 25mm. As a result, our final test specimens measure approximately 20cm in length, 16mm in width, and between 1.5 and 2mm in thickness.



4.3 Material Technical Characteristics

4.3.1 Results of tensile strength test

The results of the sample testing shown in Table 4 that the filter-aligned short fiber composite has 81% stiffness compared with the continuous bamboo fiber composite, which is still far from the 90% mentioned in the literature. However, it is very close, indicating that the short fiber reinforcement is practical and in line with expectations. Also, different ways of doing the alignment also affect the quality of the composite. There's significant growth in mechanical properties if you compare the filter-aligned sample with randomly oriented fiber, proving that by aligning the short fiber, we can get a competitive composite to replace long and continuous fiber composite.

Table 4: Tensile strength and Modulus of the tested samples

Material Name	Yong's Modulus(GPa)	Tensile Strength(MPa)
44% Long fiber	7.73	128.54
44% Filter short	6.26	57.23
44% Mechanical aligner short	3.07	21.56
44%Random orientation short	3.81	32.89

In this Stress-Stiffness graph Fig 8, the properties of 44% short fiber reinforced composites are generally similar to those of plywood. However, compared to glass fiber epoxy-reinforced materials (GFRP) and carbon fiber epoxy-reinforced materials (CFRP) which are widely used in high-performance applications such as automobiles and aircraft industries, there is still 1-2 orders of magnitude gap in both tensile strength and stiffness. (Ramamoorthy et al., 2015b) This gap is not only due to the strength difference caused by the fiber arrangement and fiber percentage but also because the epoxy matrix is far superior to HDPE in terms of performance. Hence, we can see the bamboo composite is competitive compared with other natural materials but is not stiff enough to be key structural components.

Nevertheless, we see that the elasticity of the composite material is slightly increased, and Young's modulus is significantly increased compared to the matrix material PE. Once again, the feasibility of bamboo fiber as a reinforcing material is demonstrated, and the organic combination of bamboo fiber material and HDPE is verified to be effective and reliable.

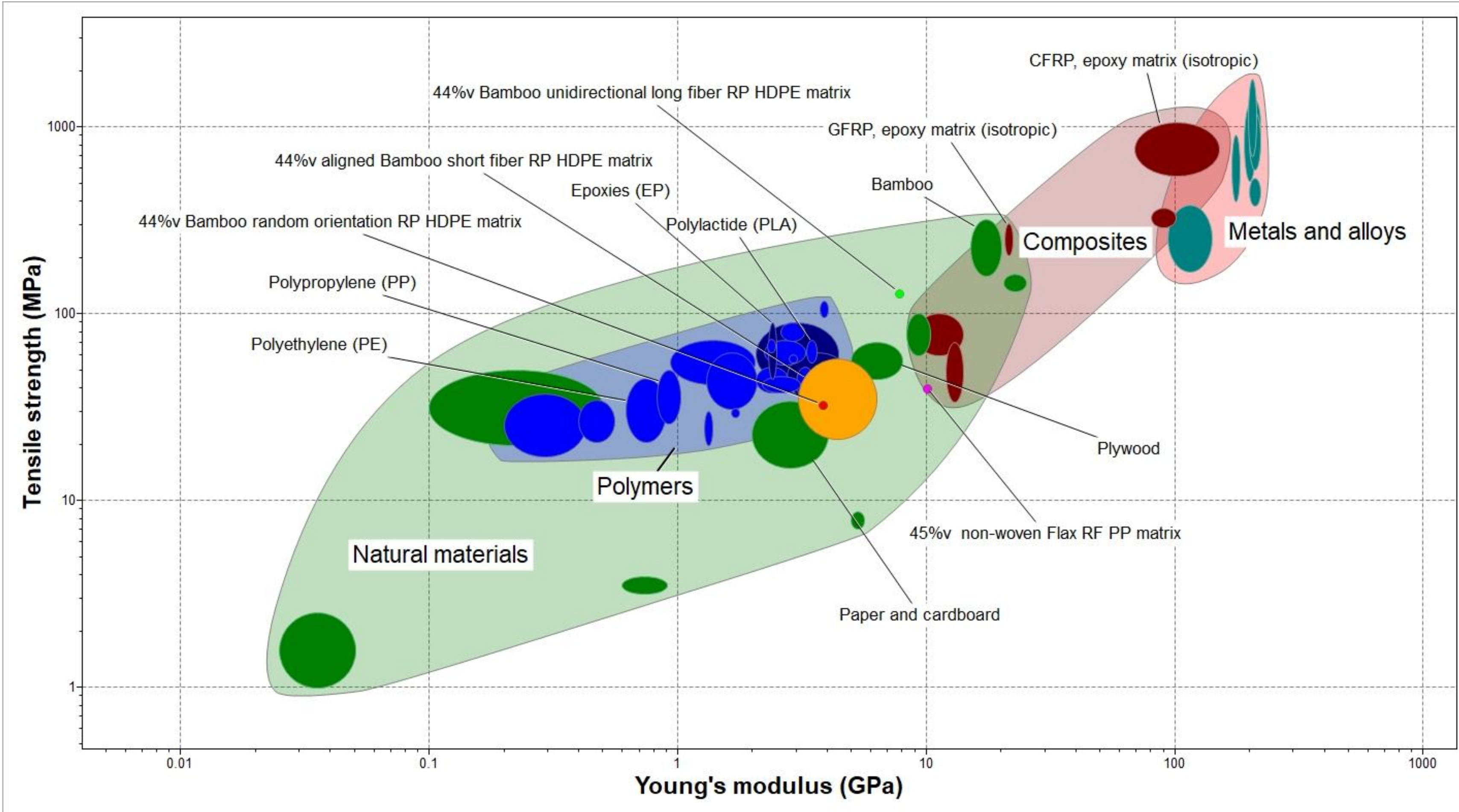


Figure 8 Stress-Stiffness illustrations from Granta Edupack

Chapter 5

Understanding the Material: Experiential Characterization



5.1 Methodology of Experiential Characterization

For material experiential characterization, inspired by the Experiential Characterization Toolkit (Camera & Karana, 2018) to gather user experience feedback from 4 aspects: performative, sensory, interpretive and emotional (see Fig 9).

From Ferraro's paper, which provided the reference design flow of NFC. A stakeholder model is used to get the image of influences of stakeholders on industrial design materials and manufacturing selection (Ferraro et al., 2023) To get a more generalized view of market potential, inspired by the paper, I decided to conduct interviews with 15 people representing different stakeholders: 5 material suppliers and manufacturers, 5 composite researchers at TU Delft, and 5 potential sustainable product users.

user's booklet

start

user ID // material //

age // nationality //

date //

1. performative level _"what does the material make you do?"

How do you touch the material?

pressing

caressing

rubbing

fiddling

grazing

pounding

compressing

pushing

poking

How do you move the material?

folding

flexing

lifting

picking

weighing

squeezing

bending

smelling

How do you hold the material?

holding

grasping

seizing

pinching

grabbing

2. sensorial level _"how does the material feel?"

hard

smooth

matte

not reflective

cold

not elastic

opaque

tough

strong

light

regular texture

fibred

soft

rough

glossy

reflective

warm

elastic

transparent

ductile

weak

heavy

irregular texture

not-fibred

notes / further comments

4. interpretive level _"what do you associate with the material? how do you describe it?"

meaning 1

meaning 2

meaning 3

5. final reflections _"why do you think the material is...? and how is this connected with the answer at other levels?"

what is the most pleasant quality of the material?

what is the most disturbing quality of the material?

what is the most unique quality of the material?

5.2 Adaption of the Experiential characterization toolkit

Different from the original application method of the toolkit, this project involves two samples with different surface treatments. I prepared these materials to utilize the tool for evaluating the same properties of different samples to understand participant preferences. The final design will use the material with the highest preference. Both samples are made from the same material and fiber orientation, except one is covered with a plastic film during thermoforming for a smoother and glittering finish (named sample 1, the other is named sample A). You can see the difference between them in Fig 10. Therefore, I modified the original toolkit to suit comparison needs and added additional questions or attributes based on my samples' characteristics. The following section will detail how I adapted this toolkit to better suit in my project.

Figure 10 Sample 1 and Sample A

Figure 9 Material Driven Design Toolkit

15

Starting from the Experiential Characterization Toolkit (Camera, 2018), I adapted it to fit my research questions better and named it Experiential Characterization Digital Form in this report. First of all, I changed the format from a host-lead interview toolkit to an online form for more efficient interview work, see in Figure 11. Some sensorial attributes from the original toolkit template were also removed because of their irrelevance to biobased fiber composites;(Parisi et al., 2016) at the same time, new questions relating to the composite topic were added. The form comprises 4 sections: First impression, Sensorial feelings, Interpretive and affective level feedback, and Demographic information. In the following paragraph, I will explain why the structure and content of the interview is designed.

For the first section on giving first impressions, the participant is asked to write a short sentence about their instant feedback after a quick glance at the material. The first impression is usually based on visual perception. Therefore, I isolated the visual aspect from other sensory inputs and placed it in the first subsection. In the latter part of this subsection, participants complete a series of multiple-choice questions using a sliding scale to evaluate the visual attributes of the samples from different visual perspectives.

In the third subsection, participants are invited to provide both perceptual and emotional feedback on the materials. For perceptual feedback, participants choose three different adjectives to describe each sample and explain why they selected these words, detailing how these adjectives reflect the material's characteristics. This helps us understand which sensory impressions are most significant.

For emotional feedback, participants use three different words to describe the emotions evoked while interacting with the materials. They also rank these emotions by intensity and indicate whether they are positive or negative. Analyzing this feedback helps us position the material for applications. Materials that evoke more positive emotions are typically better suited for products that have close interactions with users, thereby enhancing their appeal and likelihood of purchase.

After collecting demographic information, I conduct brief interviews with participants, tailoring questions based on their backgrounds.

For potential consumers, I ask about their views on the material's sustainability and their imagined application scenarios. This helps identify the most likely applications to be accepted by consumers.

For composite material researchers, I inquire about material performance, raw materials, processing methods, and their experiences in improving material sustainability.

For industry professionals, I ask about their experiences and advice on marketing new materials, and their perceptions of the material's potential based on their interaction and understanding of its properties.

Composite experience test

* Indicates required question.

Introduction

Welcome to Yarnu's material experiential test! This test includes **2 rounds of material experiential test** on **2 different composites** made by the **same material**, each round will take 15 minutes, with a 10 minutes questionnaire and 5 minutes discussion. So **in total** it take approximately **30 minutes**.

Now please start with the first one infront of you and remove the lid.

1. Which Sample are you evaluating with?

Mark only one oval.

- ☐ Sample 1
☐ Sample A

Chapter 1 - Your first impression

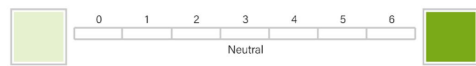
Take some time to **observe** the sample **only**, you can look at it distantly, closely and from different perspectives. Then answering the following questions based on your intuition without hesitating.

2. What's your first impression on it? *

1.1 First sense: Sight

What does it look like to you? Give a score on each value scale.
You can always look at the sample at any time you want to confirm the feeling.

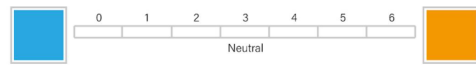
3. not very intense color/very intense color *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not ☐ ☐ ☐ ☐ ☐ ☐ ☐ very intense color

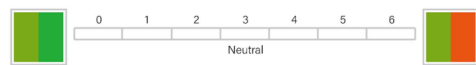
4. cold color/warm color *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ warm color

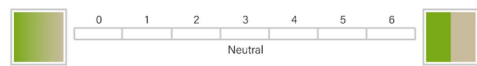
5. similar color to each other/contrasting colors with each other *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
simi ☐ ☐ ☐ ☐ ☐ ☐ ☐ contrasting colors with each other

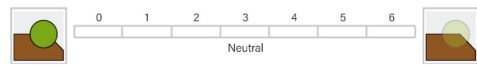
6. gradual color transition/sudden color transition *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
grad ☐ ☐ ☐ ☐ ☐ ☐ ☐ sudden color transition

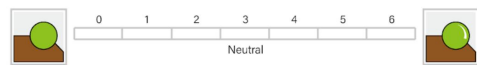
7. not transparent/transparent *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not t ☐ ☐ ☐ ☐ ☐ ☐ ☐ transparent

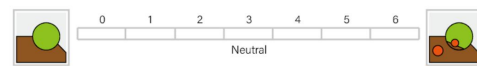
8. opaque/matte/shiny *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
opa ☐ ☐ ☐ ☐ ☐ ☐ ☐ shiny

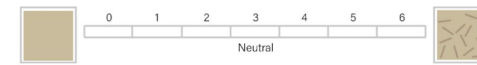
9. not reflective/reflective *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not r ☐ ☐ ☐ ☐ ☐ ☐ ☐ reflective

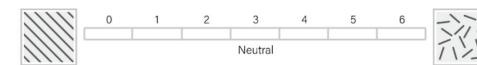
10. not fibrous/fibrous *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not f ☐ ☐ ☐ ☐ ☐ ☐ ☐ fibrous

11. homogenous texture/random texture *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
horr ☐ ☐ ☐ ☐ ☐ ☐ ☐ random texture

Chapter two - Other sensatol feelings: Touch, Smell and Hear

Intro:

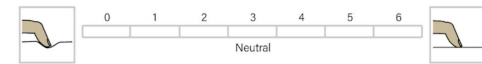
It is the time open the phone infront of you to record your interaction with the sample. Make sure the camera can catch your face and your hand movements. Your face will be blurred if presenting on report is needed.

- Now start filming take some time to **feel** the sample. Feel free to explore the material **with all of your senses** but better **not to break** it, thank you.
- Once you think you complete your exploration, you can stop filming and continue the questionnaire.

2.1 Second sense: Touch

What does the touch feel like to you? Give a score on each value scale.
You can always interact with the sample at any time you want to confirm the feeling.

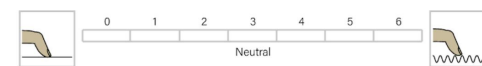
12. soft/hard *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
soft ☐ ☐ ☐ ☐ ☐ ☐ ☐ hard

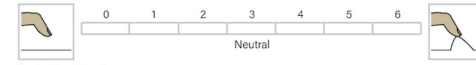
13. smooth/coarse *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
smc ☐ ☐ ☐ ☐ ☐ ☐ ☐ coarse

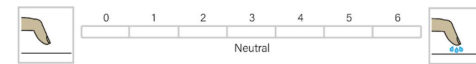
14. not sticky/sticky *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not s ☐ ☐ ☐ ☐ ☐ ☐ ☐ sticky

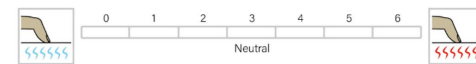
15. dry/humid *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
dry ☐ ☐ ☐ ☐ ☐ ☐ ☐ humid

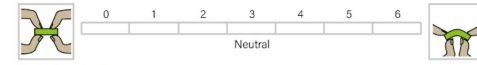
16. cold/hot *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ hot

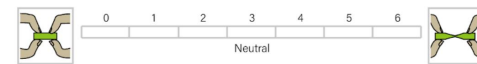
17. not flexible/flexible *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not f ☐ ☐ ☐ ☐ ☐ ☐ ☐ flexible

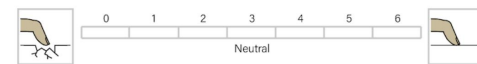
18. not elastic/elastic *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
not e ☐ ☐ ☐ ☐ ☐ ☐ ☐ elastic

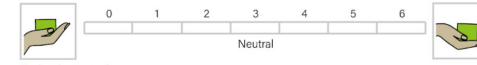
19. fragile/resistant *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
frag ☐ ☐ ☐ ☐ ☐ ☐ ☐ resistant

20. low density/high density *

 0 1 2 3 4 5 6
Neutral

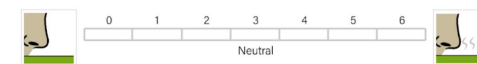
Mark only one oval.

0 1 2 3 4 5 6
low ☐ ☐ ☐ ☐ ☐ ☐ ☐ high density

2.2 Third Sense: Smell

What does it smell to you? Give your mark on each value scale.

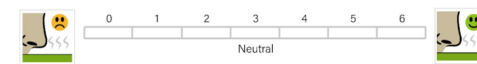
21. odorless/very odorous *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
odo ☐ ☐ ☐ ☐ ☐ ☐ ☐ very odorous

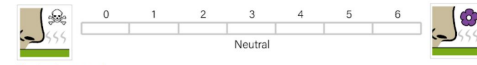
22. disgusting smell/pleasant smell *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
disg ☐ ☐ ☐ ☐ ☐ ☐ ☐ pleasant smell

23. chemical smell/natural smell *

 0 1 2 3 4 5 6
Neutral

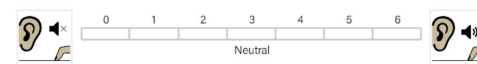
Mark only one oval.

0 1 2 3 4 5 6
cher ☐ ☐ ☐ ☐ ☐ ☐ ☐ natural smell

2.3 Fourth sense: Hearing

What does it sound to you? Give your mark on each value scale.

24. silent/very sonorous *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
sile ☐ ☐ ☐ ☐ ☐ ☐ ☐ very sonorous

25. serious sound/high-pitch sound *

 0 1 2 3 4 5 6
Neutral

Mark only one oval.

0 1 2 3 4 5 6
seri ☐ ☐ ☐ ☐ ☐ ☐ ☐ high-pitch sound

2.4 Technical properties

What do you think the properties of the material are? Give your mark on each value scale.

26. absorbent/waterproof *

Mark only one oval.

0 1 2 3 4 5 6
not a ☐ ☐ ☐ ☐ ☐ ☐ ☐ wear-resistant

27. not resistant on fire/resistant on fire *

Mark only one oval.

0 1 2 3 4 5 6
not r ☐ ☐ ☐ ☐ ☐ ☐ ☐ resistant on fire

28. not resistant to chemical agents/resistant to chemical agents *

Mark only one oval.

0 1 2 3 4 5 6
not c ☐ ☐ ☐ ☐ ☐ ☐ ☐ resistant to chemical agents

29. not resistant to atmospheric agents/resistant to atmospheric agents *

Mark only one oval.

0 1 2 3 4 5 6
not i ☐ ☐ ☐ ☐ ☐ ☐ ☐ resistant to atmospheric agents

30. not wear-resistant/wear-resistant *

Mark only one oval.

0 1 2 3 4 5 6
not i ☐ ☐ ☐ ☐ ☐ ☐ ☐ wear-resistant

31. not resistant to UV rays/resistant to UV rays *

Mark only one oval.

0 1 2 3 4 5 6
not i ☐ ☐ ☐ ☐ ☐ ☐ ☐ resistant to UV rays

32. insulating electric/conductor electric *

Mark only one oval.

0 1 2 3 4 5 6
insu ☐ ☐ ☐ ☐ ☐ ☐ ☐ conductor electric

Chapter 3 - Material experience in interpretive and affective level

3.1 Give interpretive feedback on the material

33. If you can only interpret the material with **3 words**, what will you choose and why? *

Give at **most 2 layers** of reflections on the reason behind each word.

For example:

- [meaning] - [1st level reflection] - [2nd level reflection]
- [modern] - [the color make it look **modern**] - [color **red** makes it **modern**]
- ...

You can take the word given below as references. And of course you can use any word in your mind.

Hardcore	Ecological	Detached	Nostalgic	Serious	Industrial
Female	Dirty	Dynamic	Ancient	Complex	Fast
Natural	Imperfect	Primitive	Motondless	Artificial	Digital
Real	Ordinary	Weak	Evilless	Clean	Business
Economic	Humble	New	Strict	Young	Unique
Decorative	Strong	Poor	Romantic	Attractive	Technological
Long-lasting	Simple	Slow	Strange	Precious	Hand-crafted
Aggressive	Artisanal	Healthy	Functional	Cozy	Not very
Formal	Poetic	Professional	Cosily	Rich	Sexy
Welcoming	Auspicious	Reverent	Outskily	Calm	Valuable
Elegant	Envious	Dangerous	Old	Alsof	Imnatural
Backlogged	Polluting	Suspicious	Toy-like	Feminine	Innovative
Harshline	Harmlens	Manufactured	Professional		

3.2 Give affective level feedback on the material

Here I invite you to give feedbacks on what your feelings towards material. Give at **most 2 layers** of reflections on the reason behind each word.

You can take the word given below as references. And of course you can use any word in your mind.

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

34. What's the **strongest** emotion the material brings to you? *

35. Is this emotion positive or negative to you? *

Mark only one oval.

- ☐ Positive
☐ Negative

36. What's the **2nd strongest** emotion the material brings to you? *

37. Is 2nd strongest emotion positive or negative to you? *

Mark only one oval.

- ☐ Positive
☐ Negative

38. What's the **3rd strongest** emotion the material brings to you? *

39. Is 3rd strongest emotion positive or negative to you? *

Mark only one oval.

- ☐ Positive
☐ Negative

Chapter 4 - Demographics question

40. Your email *

41. Your age *

42. Your gender *

Mark only one oval.

- ☐ Female
☐ Male
☐ Other: _____

43. Your role *

Tick all that apply.

- ☐ Consumer in general
☐ People working with composite manufacturing or supply chain
☐ People doing composite material related research or education
☐ Other: _____

Chapter 5 - Submission and Discussion

You can submit the form and Yarnu would like to have a short feedback discussion on your overall experience with the sample about 5 minutes.

Figure 11 Adapted questionnaire form

5.4 Material Experiential Characteristics Interview Demographics

In the end, there are, in total, 16 participants involved in my research. Five of them are women, and 11 of them are men. Some of the company's participants had limited time for material experiential tests, so only interviews were conducted, which provided great insights.

Table 5: Participants' Professional Background and Test Involvement

Num	Profession types	Material experiential test	interview
8	consumers	yes	yes
4	education and research related	yes	yes
1	composite related design&manufacturing	yes	yes
3	composite related design&manufacturing	no	yes

5.5 Sensorial quality feedback

5.5.1 First impression word cloud

In collecting the first impressions of the test subjects regarding the materials, no significant differences were noted between the two materials. Subjects frequently described the materials as having a natural quality, comparing them to wood and straw. The color and fibrous texture were also highlighted as prominent features. Additionally, some subjects noticed the plastic-like surface texture. Contrary to expectations, the uniform texture was mentioned frequently, emerging as a notable characteristic.



Figure 12 Word cloud results

5.5.2 Interactive insights

Participants' interactions with the materials did not show significant differences between the two samples, shown in Fig 13. It was observed that they were particularly interested in the surface gloss and texture, both visually and tactilely. Common interactions included stroking and bending the materials. Some participants also attempted to tap the material to produce sounds or brought it close to sense its smell. A few participants noted that the material exhibited different strengths depending on the direction of the interaction.

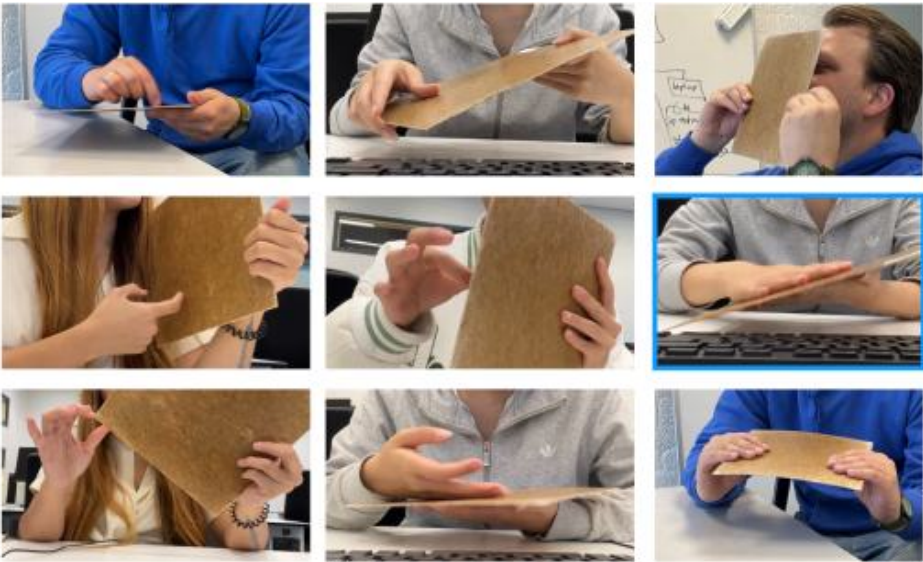


Figure 13 Participants' interactions

5.5.3 Statistics on Sensorial Quality Attributes

After calculations, the ratings for each material characteristic did not follow a normal distribution. Therefore, I used the Wilcoxon Signed-Rank test to analyze the ratings for each attribute. The results showed that most attributes did not have significant differences, except for three: soft and hard, not reflective and reflective, and opaque and shiny. Consequently, I averaged the remaining ratings to create a joint characteristic perception analysis (Fig.14) and a different significant perception analysis (Fig.15). The attribute names on both sides are neutral, representing opposite states. I painted the area of the graph in different color, classifying the result, Dark blue and dark green indicates a significant perception, green and blue indicate a moderate perception, light green and light blue indicate a slight perception, and grey represents neutrality.

Participants described the material as fibrous and not elastic for the most significant sensorial attribute. At the second level, they noted it was not sticky, warm, dry, and had a random texture. At the third level, participants highlighted a pleasant smell, natural smell, coldness, lack of flexibility, high sonority, and low density. These descriptors help identify the sensory impressions and attributes most strongly associated with the materials.

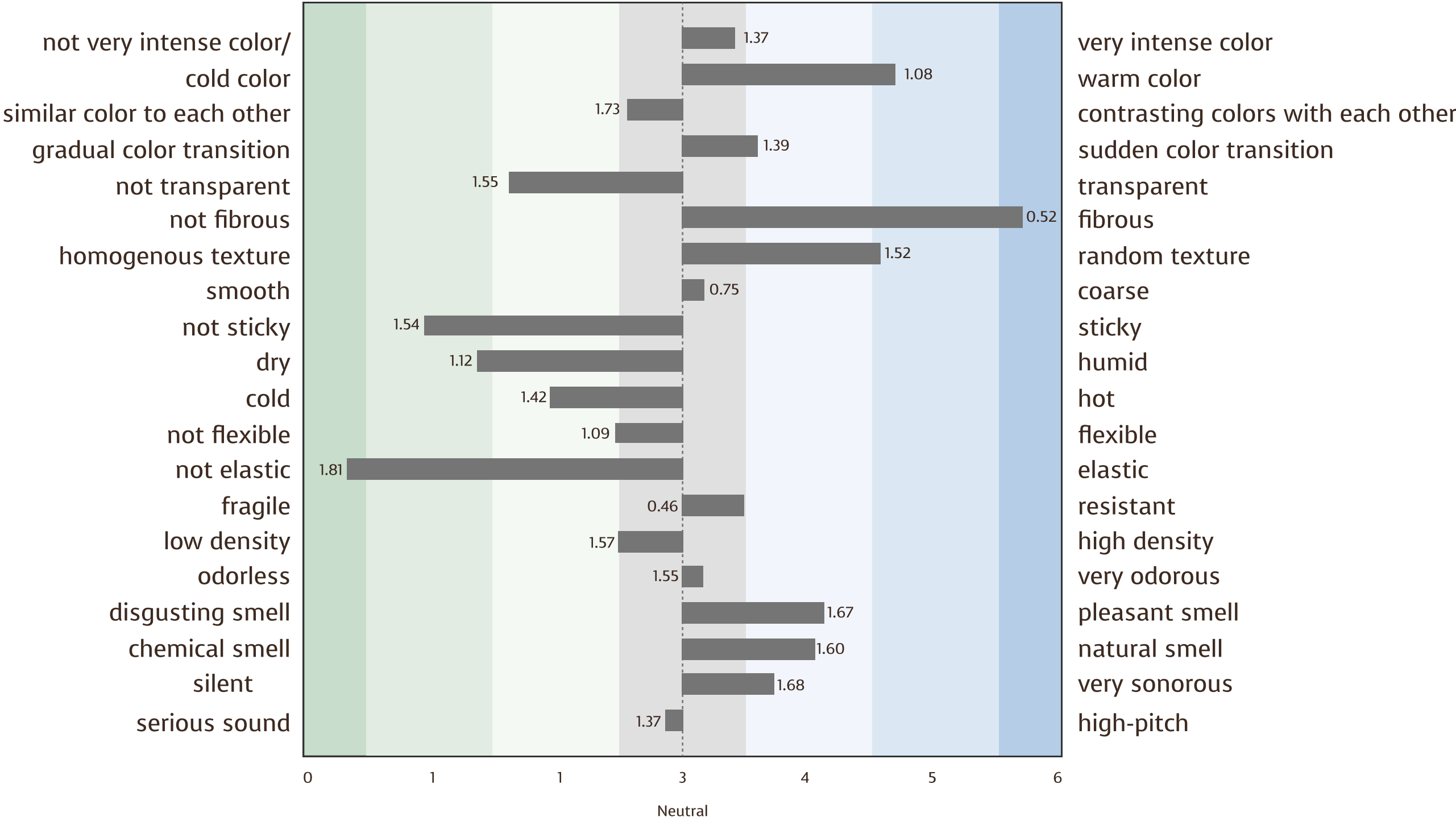


Figure 14 Sensorial feeling feedbacks

5.5.4 Statistics on Sensorial Quality Attributes

For the perception attribute that two different samples are very different from, Participants noted that Sample A was hard, not reflective, and matte, while Sample 1 was more tough and shiny.

5.5.5 Statistics on Mechanical Properties Attributes

Also, the joint technical properties inferred from the samples include being electrically insulating, waterproof, and resistant to atmospheric agents but not resistant to chemical agents and fire.

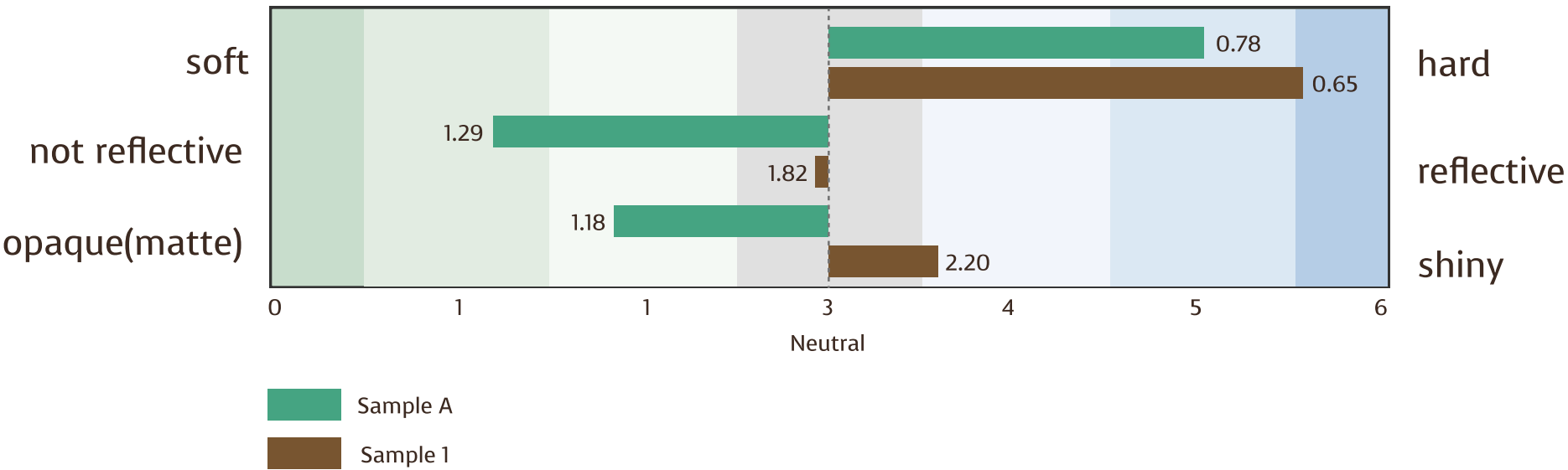


Figure 15 Sensorial feedback with significant differences

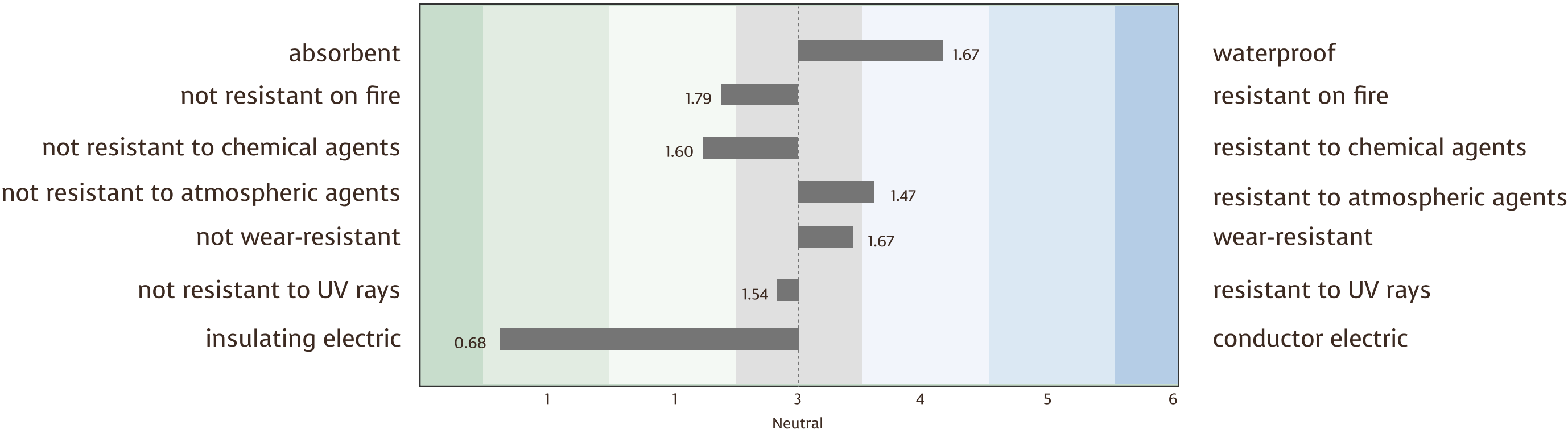


Figure 16 Mechanical properties conjectures

5.6 Material Interpretation

The complete descriptions from respondents for Sample A and Sample 1 can be found in Appendix. Here, I use word clouds to describe the differences and conclusions of their interpretations qualitatively. Overall, there is no significant difference in the diversity of words used to describe the two samples, with 29 different words for Sample A and 27 for Sample 1. The most frequently used word for both samples is "natural," indicating that the composite material's overall impression aligns with the initial perception of a natural feel.

Notably, "Ecological" is the second most frequently used word for Sample A, while "Artificial" appears more frequently for Sample 1. Respondents noted that Sample A's matte surface resembles natural materials, while the reflective surface of Sample 1 appears more artificial. Other descriptors, such as "Calm," "Decorative," "Harmless," and "Humble," are predominantly positive. However, a few negative terms like "Boring," "Imperfect," "Primitive," "Cheap," and "Simple" were also mentioned, attributed to the random distribution of fibers giving a rough, handmade appearance.

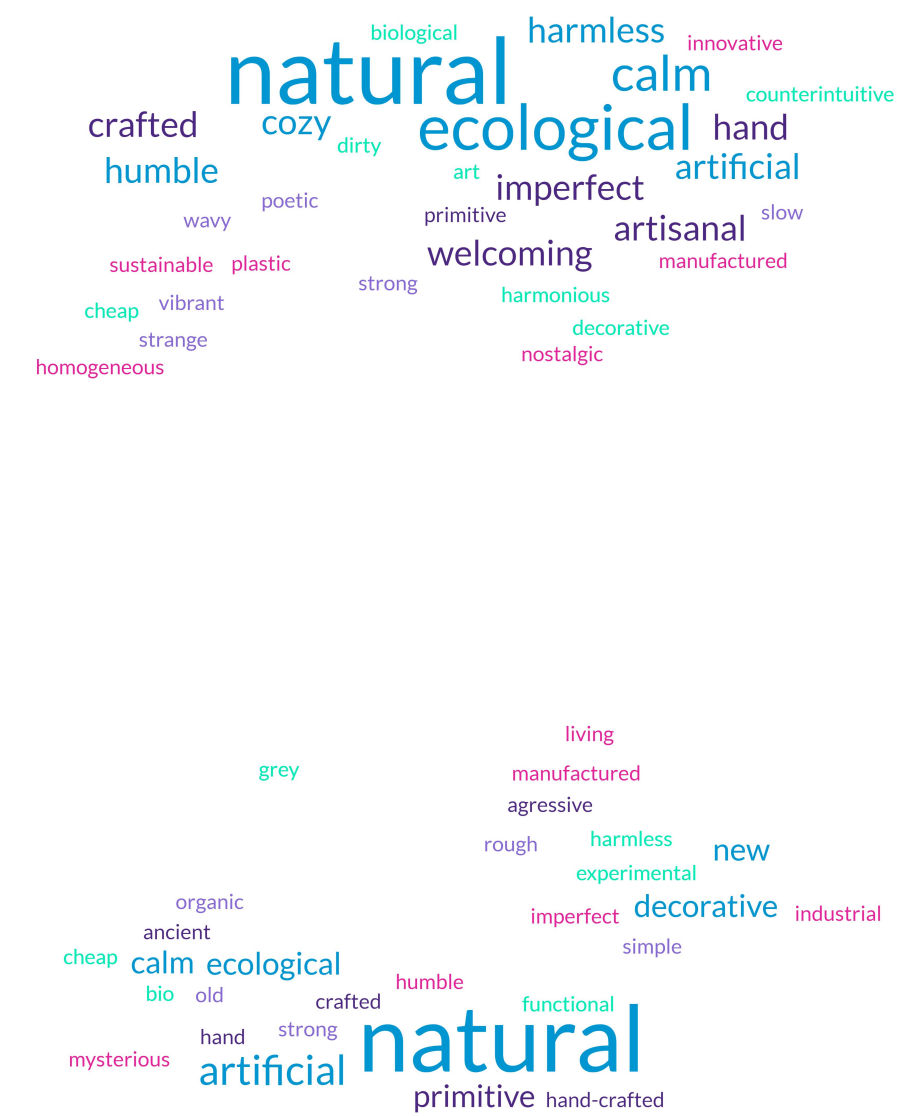


Figure 17 Word clouds for interpretation

5.7 Emotional Reactions to the Composite

Respondents' emotional feedback for the two samples showed more significant differences than their interpretations of feedback. Besides "Curiosity," which overwhelmingly emerged as the most potent emotional response for both samples, Sample A was also associated with "Comfort" as the second most prominent feeling. "Fascination," "Surprise," and "Doubt" tied for third place. In contrast, for Sample 1, while "Curiosity" remained dominant, the other emotions were less consistently mentioned. Favorable terms like "Comfort," "Attraction," and "Fascination" appeared alongside negative terms such as "Distrust," "Boredom," and "Doubt," each accounting for a significant portion of the feedback.

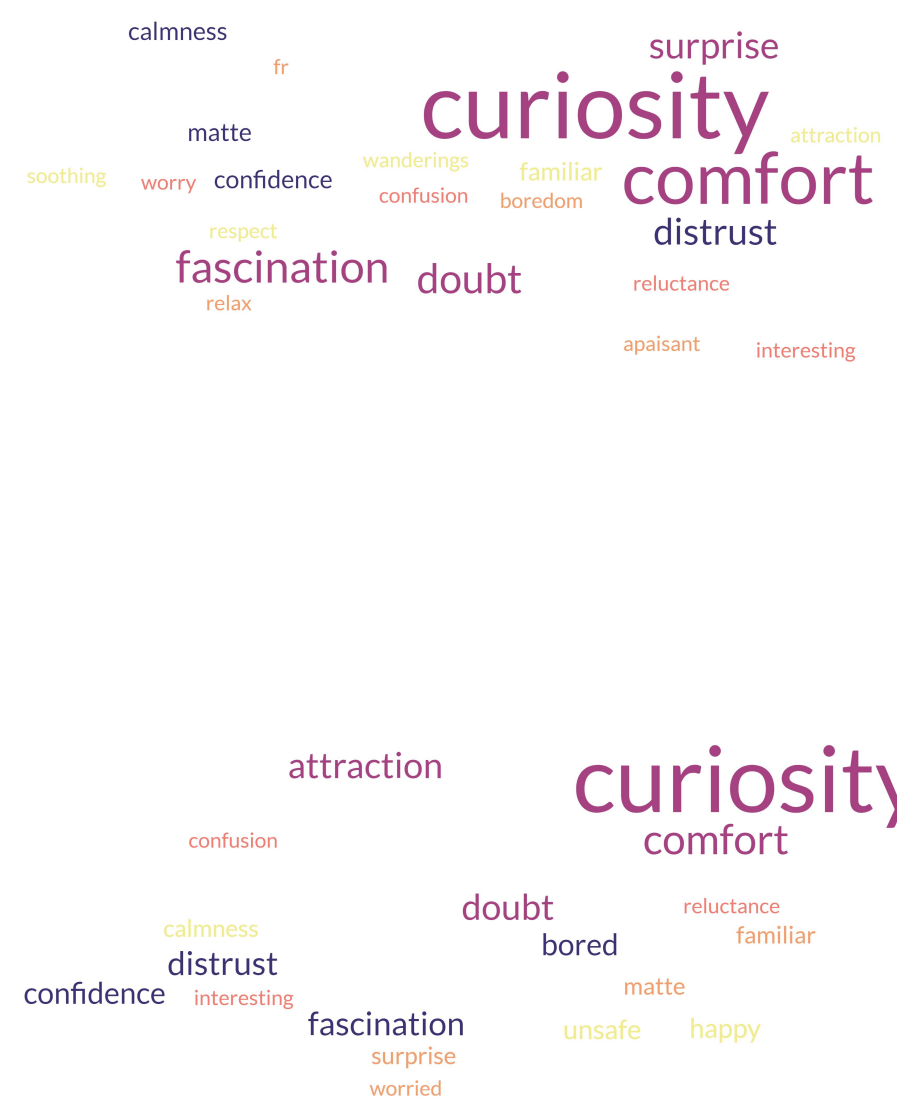


Figure 18 Word clouds for emotional reactions

In the interview, I invited respondents to rank each emotional feedback by intensity from first to third place and classify them as positive or negative, I gained insights into their attitudes toward the material. Sample A consistently received more positive ratings across all intensity levels than Sample 1. Notably, the most intense emotional feedback for Sample A included significantly fewer negative terms than Sample 1. From this, we infer that the sustainable nature of the material led potential consumers to favor characteristics like sustainability and naturalness. Sample A's appearance was closer to natural materials, whereas Sample 1's smooth and reflective surface, achieved through matrix treatment, was perceived as artificial. This discrepancy caused doubts about the material's sustainability, leading to a lower preference for Sample 1. Therefore, to align the material with the sustainability vision, we should opt for the processing method used in Sample A, which achieves a more natural appearance, for subsequent product design.

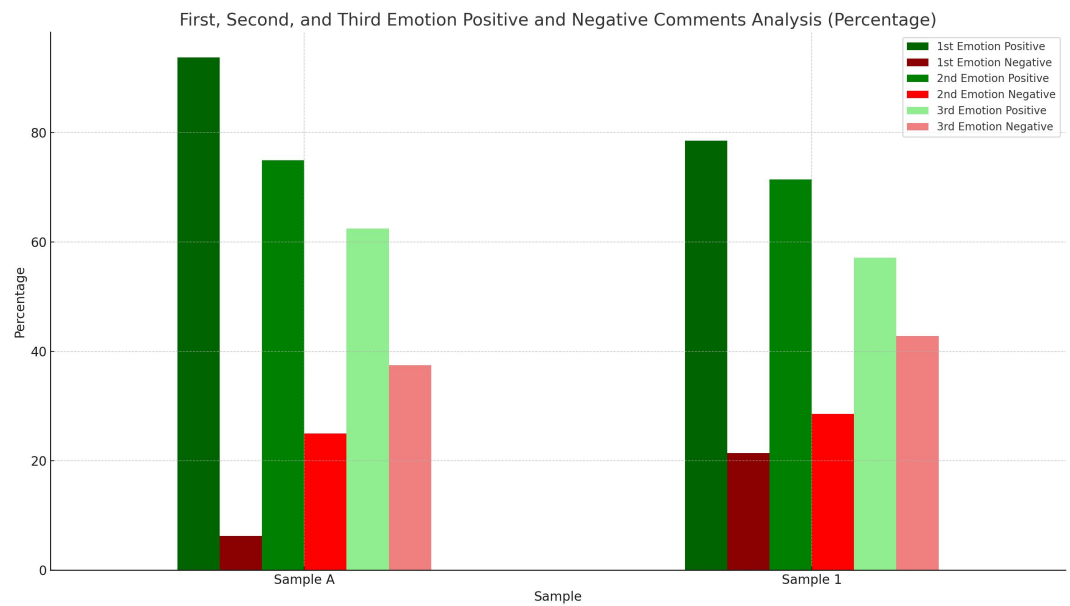
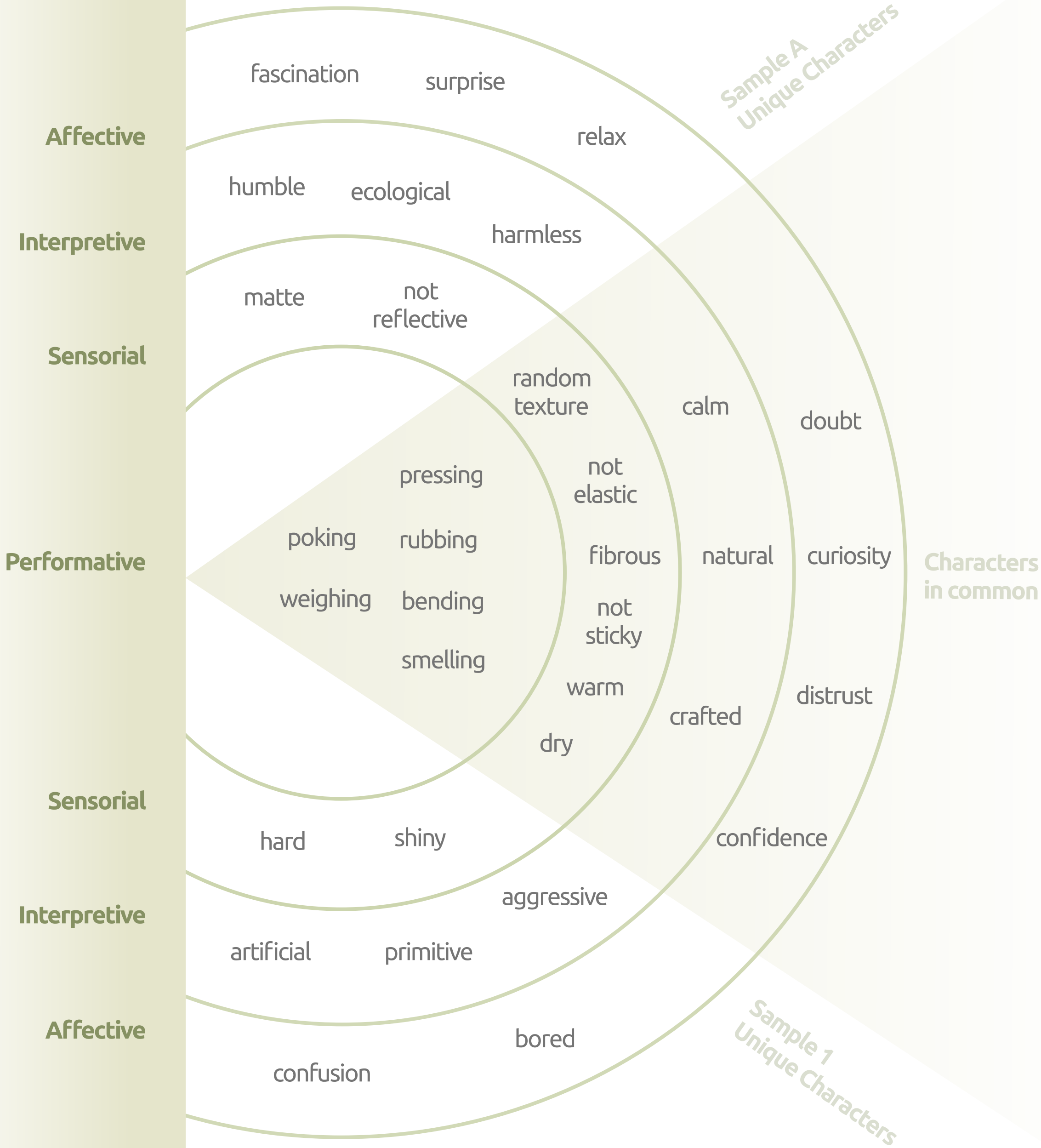


Figure 19 Results of interview

5.8 Experiential quality mapping

Hereby I summarized the experiential characteristics of two bamboo composite samples that contributed on what they attract people to do, what they let people perceive, and what they make people think.



Chapter 6

Understanding the Material:
Market Potential Research



(Sourced from <https://www.jec-world.events/exhibit-sponsor>)

6.1 JEC Market Potential Research

The material bench-marking method helps compare similar materials on how different attributes affect their application (Karana, 2015). During the JEC 2024, field research was done with the information from over 20 innovative bio-based materials collected. The Figure shown below was made to gain insights from those 5 typical implementations of bio-based fiber reinforcement composite.

It is clear that at current stage, flax still dominates the bio-based composite market, not only because of its good mechanical properties but also its unidirectional appearance. But only very few companies use bio-based material as the casing of products or for other decorative uses. This might caused by natural fibers' imperfections and roughness. The company is most likely to use natural fiber composites as the structural part, combined with our previous technical properties. This may be due to its competitive stiffness and lightweight.

Also it's interesting to find most of the implementations are in sports, automotive, or high-tech infrastructure fields. The possible reason for that may be the limitation on manufacturing makes NFC easier to form big-scale products. Another reason might be marketing considerations: a new kind of material can get better recognition with a good image if it's being implemented in high-end fields.

Table 6 Information collection from JEC Market

							
Material		hemp	Flax	Flax	Hemp Flax Bamboo	Flax	Hemp Flax Bamboo
Applications	Decorative						
	Structural						
	Sports						
	Automotive						
	Household products						
	Packaging						
Experiential qualities	Natrual color						
	Imperfections		/				
	Roughness						
	Scent intensity	/	/				
	Visible fibers						
	Naturalness						

☒ Yes ☐ No ☒ Strongly has ☐ Slightly has ☐ / Cannot tell due to incomplete demostration

6.2 Market opportunities

Overall, NFC is still in its early stages in the market, with the industry relatively concentrated. I believe there is tremendous potential for growth, especially in areas like household products, where NFC is currently less prevalent. While bamboo is already a common material in household items, the advantages of short bamboo fibers in terms of formability and sustainability remain largely unknown to the general public.

If bamboo fiber composites aim to enter the market without competing directly with flax fiber composites, this could be a promising opportunity. Bamboo fiber composites are well-suited for everyday applications that require minimal load-bearing, and the material is relatively inexpensive. Additionally, its natural appearance gives it a warm, approachable aesthetic. In the future, I believe bamboo fiber composites have the potential to capture a larger market share through a balance of quality, cost-effectiveness, and strategic marketing.

6.3 Limitations of market research

There are certain limitations to the field research presented here. Almost all of the data was collected personally by me during the 2024 JEC Composites Show through interviews and observations. The JEC Composites Show is widely recognized by industry professionals worldwide, and the annual event serves as a prime opportunity for key players in the composites industry to gather. In this context, the field research was an efficient way to quickly gain insights into the current state of the industry. However, the downside is that I may have missed valuable knowledge and perspectives from other global composites professionals who did not attend the event. Therefore, the conclusions drawn from this field research are based solely on the interviews and observations I conducted, which introduces a degree of limitation to the findings.

Chapter 7

Creating Material Experience Vision

Identifying Applications for Bamboo Plate



7.1 Design vision mapping

The Fig 20 illustrates the process of deriving a design vision for bamboo thermoplastic composites using the Material-Driven Design (MDD) method.

On the left, the analysis is divided into three aspects:

- 1. Tinkering: This involves hands-on experimentation to understand the material's practical properties. Designers noted that bamboo fibers provide a wood-like surface and maintain good stiffness, with natural aesthetics that look sustainable and appealing.
- 2. Technical Characteristics: The technical section details the mechanical properties, such as stiffness, density, and tensile strength, highlighting bamboo's strong environmental performance and potential for sustainable composite production. The matrix material's properties, like HDPE's processability and compatibility with bamboo, are also emphasized.
- 3. Experiential Feedback: This section captures sensory and emotional responses to the material. Users appreciated the natural look and feel of bamboo composites, noting its texture, smell, and warmth. These experiential characteristics can enhance product acceptance and appeal.

On the right, Benchmarking compares bamboo composites with high-end products and structural components, identifying gaps and opportunities for differentiation. Flax fibers are already seen as luxury materials; thus, bamboo needs unique branding to stand out.

Combining these insights, the bottom-right section outlines potential design directions, such as:

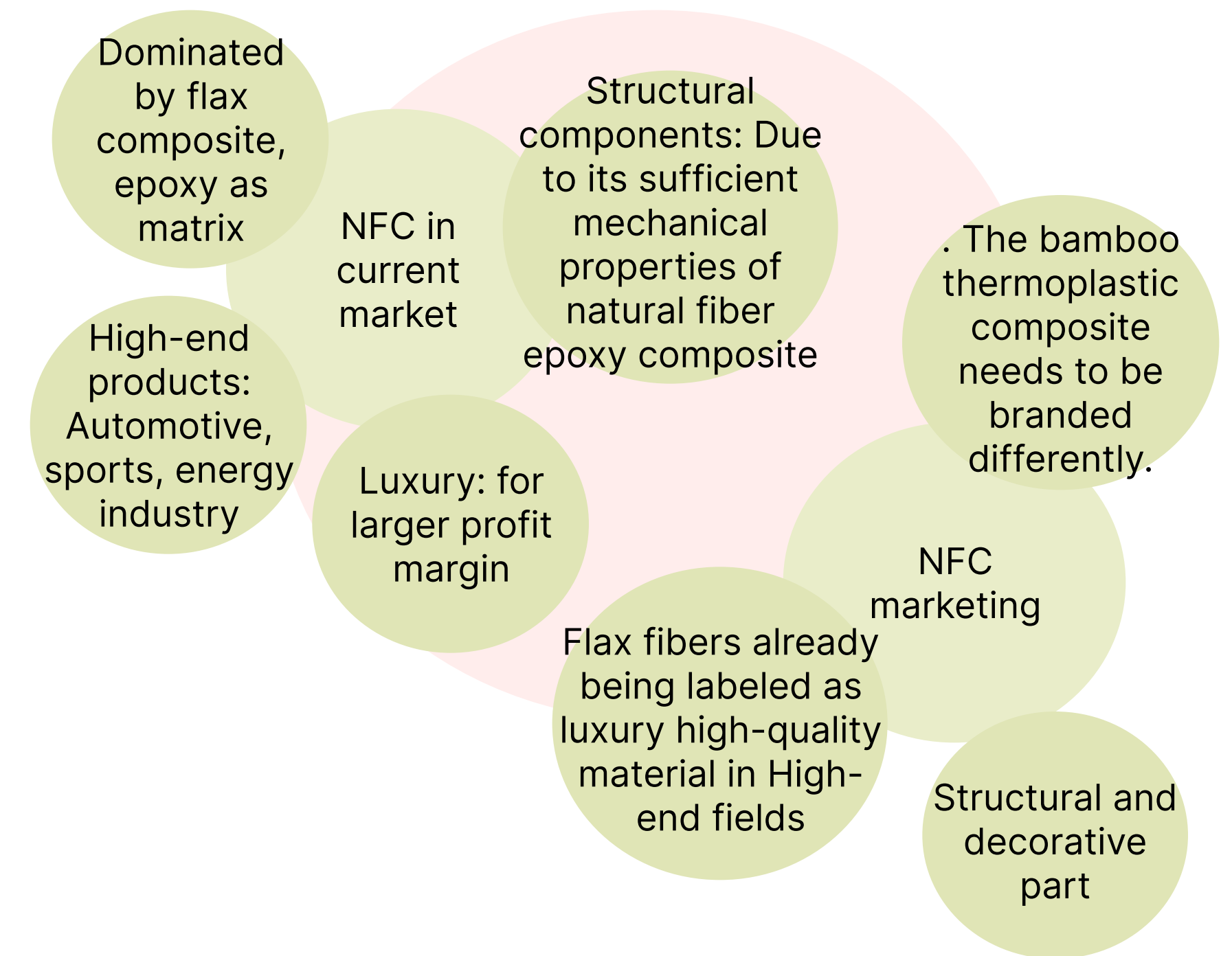
- Creating products that bring users closer to the material.
- Leveraging compress forming for complex shapes.
- Highlighting bamboo's natural wood-like qualities with a pleasant smell.
- Differentiating bamboo products from flax by emphasizing their unique sensory attributes.

This holistic approach ensures the design vision aligns with both technical feasibility and user preferences, leading to innovative, market-relevant solutions.



Dash

Benchmarking



WHAT IF?
 Articulate the opportunities based on the gaps between what you did and what others did.

Making products that stays around the user with closer distance

Design a product that make people feel comfort and intriguing while feeling it

Use compress forming as the main manufacturing method for curve shapes

Design a product that requires a certain direction of stiffness

The material can handle complex surface curvatures

Label bamboo products differently from flax products as natural wood-like things with a good smell

Figure 20 Design vision mapping

7.2 Vision

Bamboo composite plate is made of 100\% biobased material, biobased HDPE and aligned short bamboo fibers. The naturalness of the material together with the properties as thermoplastic makes it great potential to be sustainable alternative material choices. The alignment of the fiber makes it more efficient on specific direction of reinforcement. The texture of the fiber together with the matte look from the matrix, its pleasant smell and warm color forms a natural and wood-like look, makes it appealing to users to sense and stay close to the material.

Accordingly, design a household product with the function of holding a certain force, and requires close interactions which gives users pleasure, comfort and refreshed feelings by it's look, touch or smell.



Figure 21 Bamboo composite plate

7.3 Metaphor

Just like a plant in your home, this product originates from nature, bringing with it a sense of comfort and pleasant sensations through its appearance, touch, and fragrance. Its organic look delights your senses, and when you are close to it, you can almost smell the fresh straw and feel the texture of the wood. Its appearance at home reminds the user the feeling of eagerness of human nature to get close to nature with curiosity.



Figure 22 Metaphor
(Sourced from freepik.com)

Chapter 8

Ideation and Concept Design



8.1 Ideation

The vision and metaphor prepared in the previous chapter provided excellent references for brainstorming. After three rounds of idea sessions, we generated 18 ideation sketches, as shown in Fig 23. It is evident that large furniture items, such as tables, chairs, and cabinets, are pretty common. However, the frequency of occurrence does not necessarily mean these ideas are more likely to be adopted. We need to establish a list of requirements to filter these ideas. Next, I will discuss the criteria and process for selection. Finally, after one more round of filtering, I will choose the most suitable sketch as the starting point for the concept design and continue iterating.

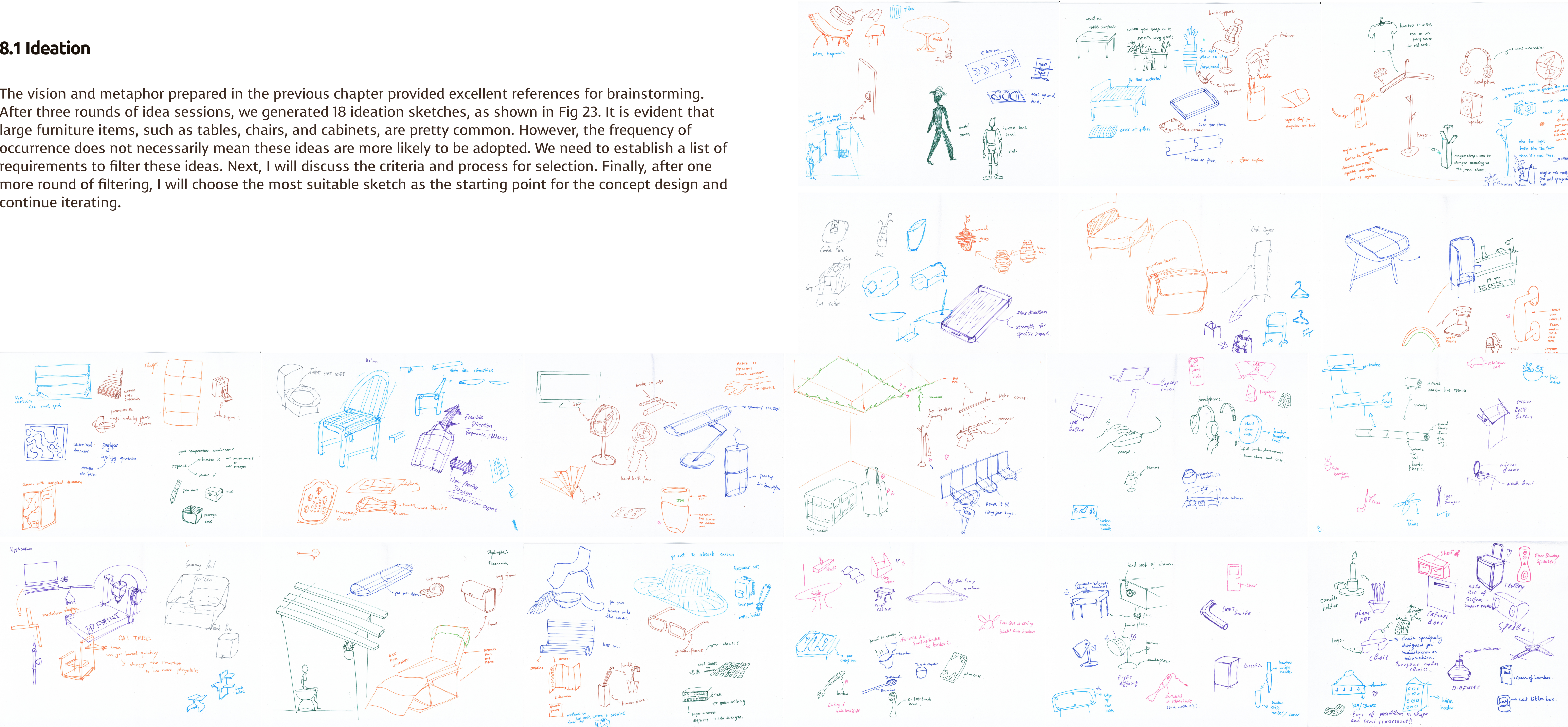


Figure 23 Ideation sketches

8.2 Idea validation

8.2.1 List of Requirements for Designed Products

The requirements list is how to select specific ideas from the ideation sketches. There is no ranking between those requirements, so they must be checked for every idea. Even if the idea is insufficient for only one requirement, it should be abandoned.

Table 7 Requirements list

	Requirements	Related chapters
1	Design a household products for daily use	7.1
2	Hold a certain load in a specific direction with the potential of cost-saving and sustainability	7.2
3	Cannot be critical structure parts of the product which failure could lead to injury or life threatening issue	4.3
4	Exposed to the user with close distance (proximity)	5.5
5	Have the experience of pattern to be innovative, natural and comforting	7.2
6	No hygiene or food safe related function (not related test on this material)	/

8.2.2 Analysis on ideas

After completing the selection process, only three creative ideas were retained: a coat hanger, a fan, and an electronics mouse or headphones. The Table 8 below explains why other ideas did not pass the selection criteria. This structured approach ensures that the most promising concepts are advanced for further development based on defined requirements and evaluation standards.

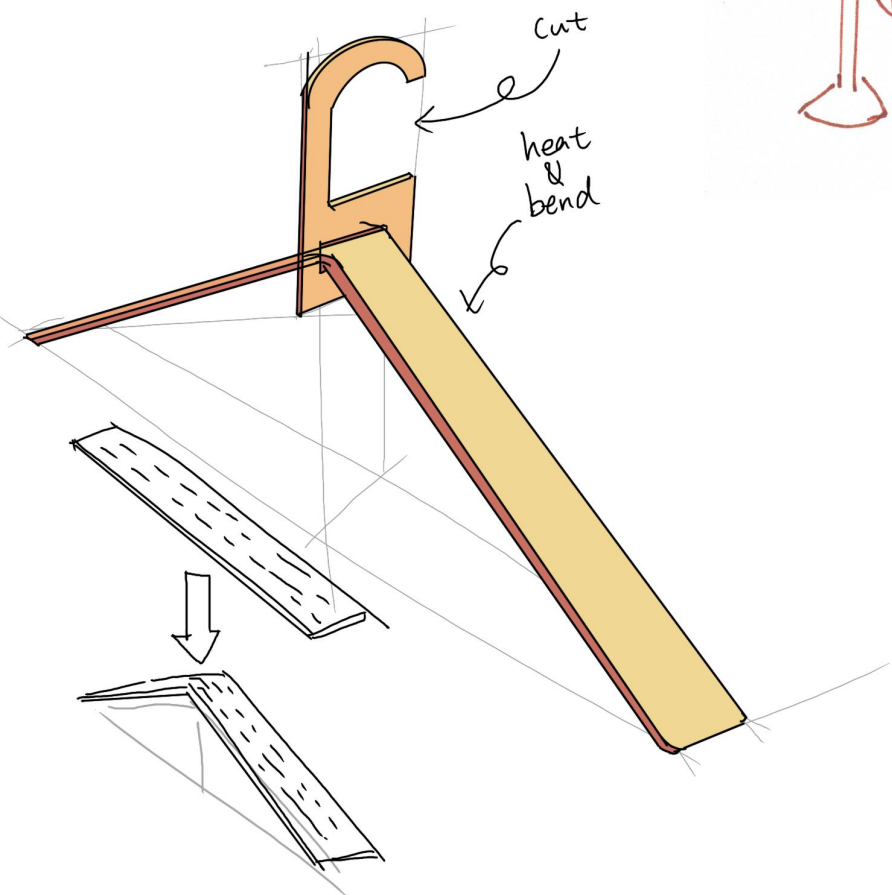
Table 8 Concept Selection Reasons

Item	Insufficient List Number	Reason
Table/bed frame	2	Not sustainable to make a table compared with wood or plywood
Chair	2	The chair leg or back will cause serious injury if failed
Shelf	2	No sign of cost-saving and sustainability
Phone case	2	No sign of cost-saving and sustainability
Screen	2	It has no function of carrying the load
Toilet lid	6	No hygiene-related function
Cutlery/knife handle	6	No hygiene-related function
Brick for building	1/4/5	Not household products. Cannot be sensed.
Glasses	2	No sign of cost-saving and sustainability
Ceiling	2	No sign of holding specific direction of load
Hat	5	It's uncomfortable to wear due to the weight and un-breathable matrix
Summer sleeping mat	2	No sign of cost-saving and sustainability
Door knob	3	In case of a fire it can cause serious injury
Study light/lamp	2	No sign of holding specific direction of load
Dust bin	5	Experience pattern is too simple
Luggage/backpack	2	No sign of cost-saving and sustainability
Speaker	2	It has no function of carrying the load
Vase	2	It has no function of carrying the load
Golf stick	1	Too specific group of people

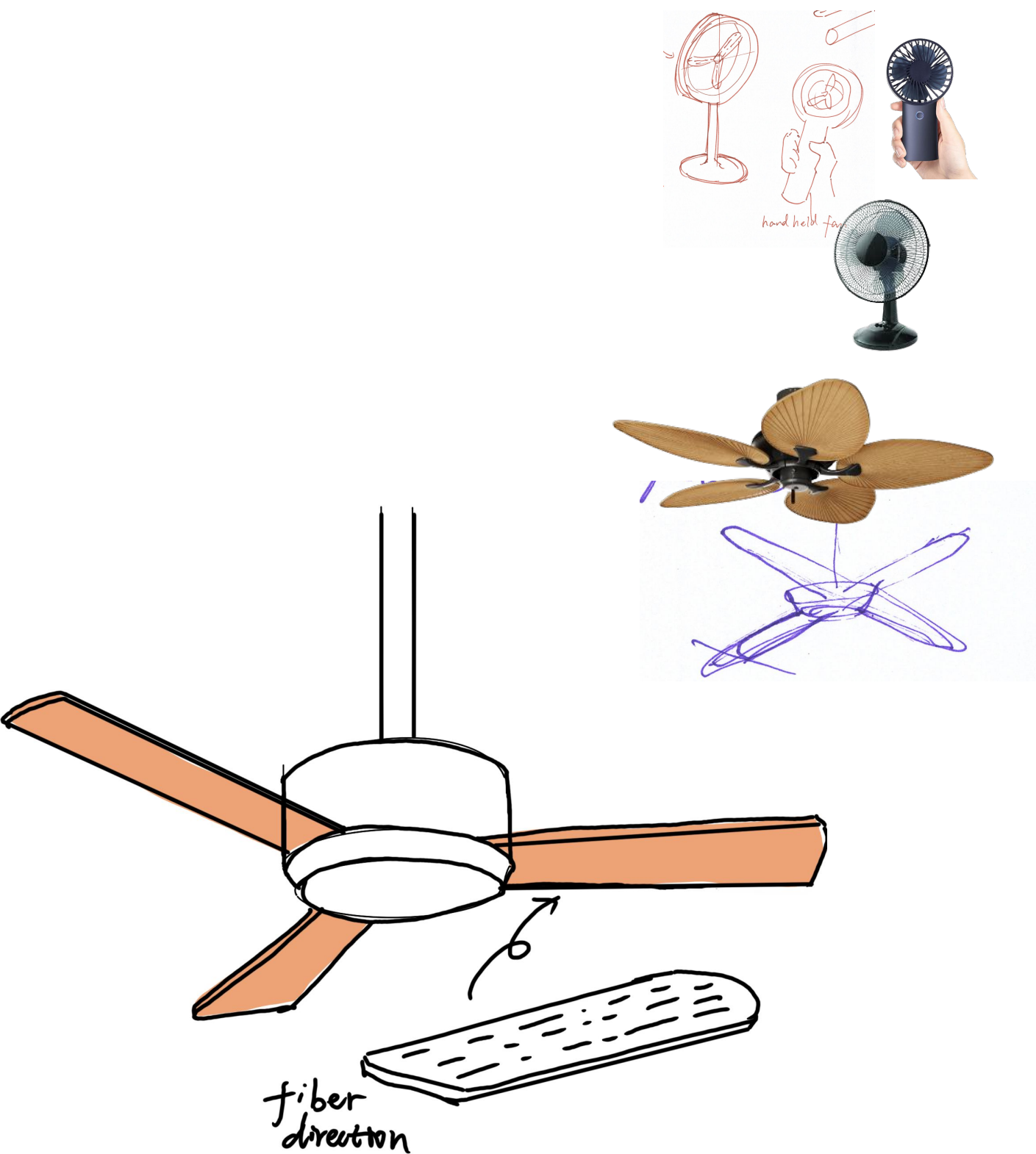
8.3 Preliminary Concept Design

These are the three most potential concept designs that meets all the requirements. They are coat hangers, ceiling fan blade and headphones.

(pictures sourced from Pinterest)



Concept 1: Coat hanger



Concept 2: Ceiling fan



Concept 3: Electronics

Figure 24 Three concept design

8.4 Concept Selection

8.4.1 Decision Criteria

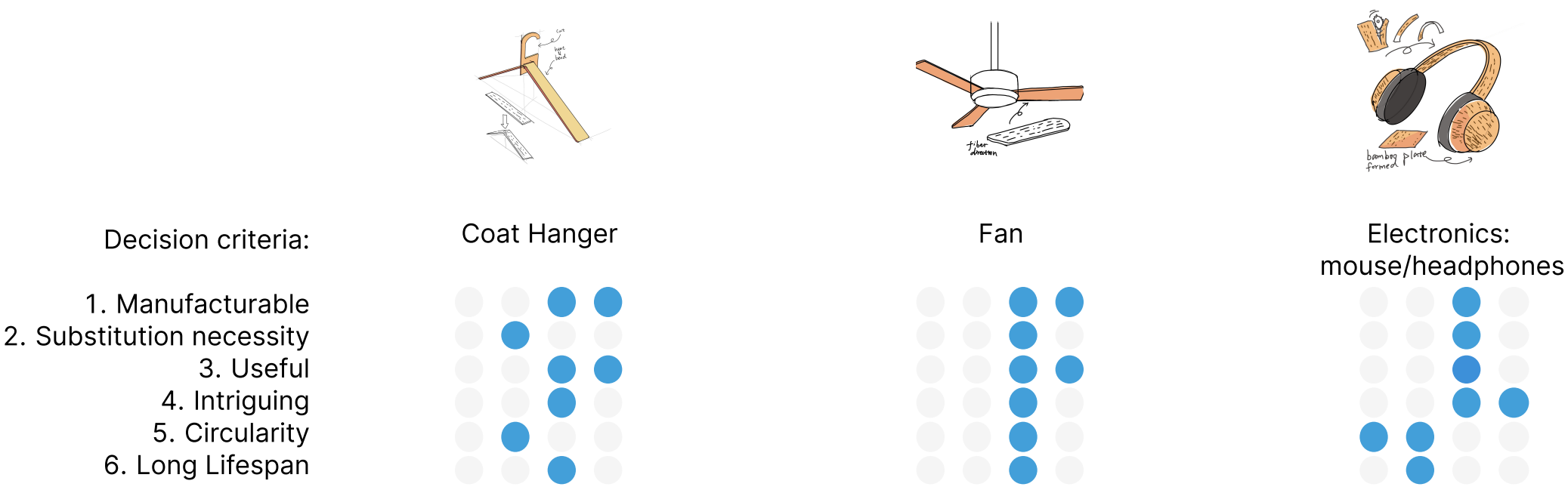
The design criteria are used to rank different concepts and identify the best one. They are listed from the most important to the least important. The first is manufacturability. Since I would like to reach a TRL level 4 for this project, the prototype needs to be validated in the lab. The second important thing is the necessity of substitution. For most household appliances, there are already various products with different appearances and materials to select from. If there is no sufficient proof that it has significant benefits, then the products are not worth making. The third criterion comes from the purpose of making use of the unique attribute of reinforcement in a specific direction. The fourth is Intriguing, which means the variety of sensorial feelings the product brings should be as many as possible, making it attractive to customers. The fifth and sixth are circularity and long life span; since our goal of developing biobased composite is to reduce carbon emissions, it would be nice if the product could be reused for other productions or be durable with a long life span before being dumped.

Table 9 Criteria fro idea evaluation

Rank	Criteria	Details
1	Manufacturable	Can be produced with lab facilities
2	Substitution necessity	The overall benefit of replacing to this new composite
3	Useful	Hold a certain load in a specific direction
4	Intriguing	Can activate multiple sensorial feelings
5	Circularity	Can be repaired, reused and reprocessed
6	Long Lifespan	The product is supposed to have a long life span (10+years)

8.4.2 Decision making process

We can use the Harrison Profile to evaluate each attribute of the creative ideas with weighted assessments. This qualitative ranking helps prioritize the preliminary concepts, with the highest scores indicating better alignment with the design vision.



Below, I will explain why each concept received its specific score.

I gave the coat hanger and fan a score of +2 for manufacturability because their shapes are relatively simple and lack complex curves. Electronics like headphones and mouse received a score of +1 due to their intricate curves and smaller parts, which increase manufacturing difficulty.

The coat hanger scored -1 for substitution necessity because it is a consumable item easily made from sustainable materials like wood or metal. Fans and electronics scored +1, as natural-looking thermoplastic composites can reduce costs and provide novel, sustainable alternatives.

Regarding usefulness, the coat hanger and fan scored +2 because they better utilize the strength of aligned fibers. In contrast, electronics scored +1 as polymers already provide sufficient strength, making fiber reinforcement somewhat redundant.

The coat hanger and fan scored +1 for intriguing qualities due to less frequent physical interaction with users. In contrast, electronics scored +2 because they are frequently handled, allowing users to fully experience the material's properties.

Regarding circularity, the coat hanger scored -1, and the electronics scored -2 due to their small size and complex shapes, making them difficult to reuse or recycle. The ceiling fan scored +1 as its larger blades can be more easily collected and reshaped in factories due to its thermoplastic nature.

Lastly, the coat hanger and fan scored +1 for a long lifespan as they typically have more extended usage periods. In contrast, electronics scored -1 due to frequent use and rapid market updates, resulting in a shorter lifespan.

In conclusion, the concept of fan, especially ceiling fan stand out to be the most potential concept.

8.5 Concept design sketch

lalala



Figure 25 Mood board of bamboo arts and products
(Sourced from Wikipedia, Freepik, lewisbamboo.com, africastyle.it, 1stdibs.com)

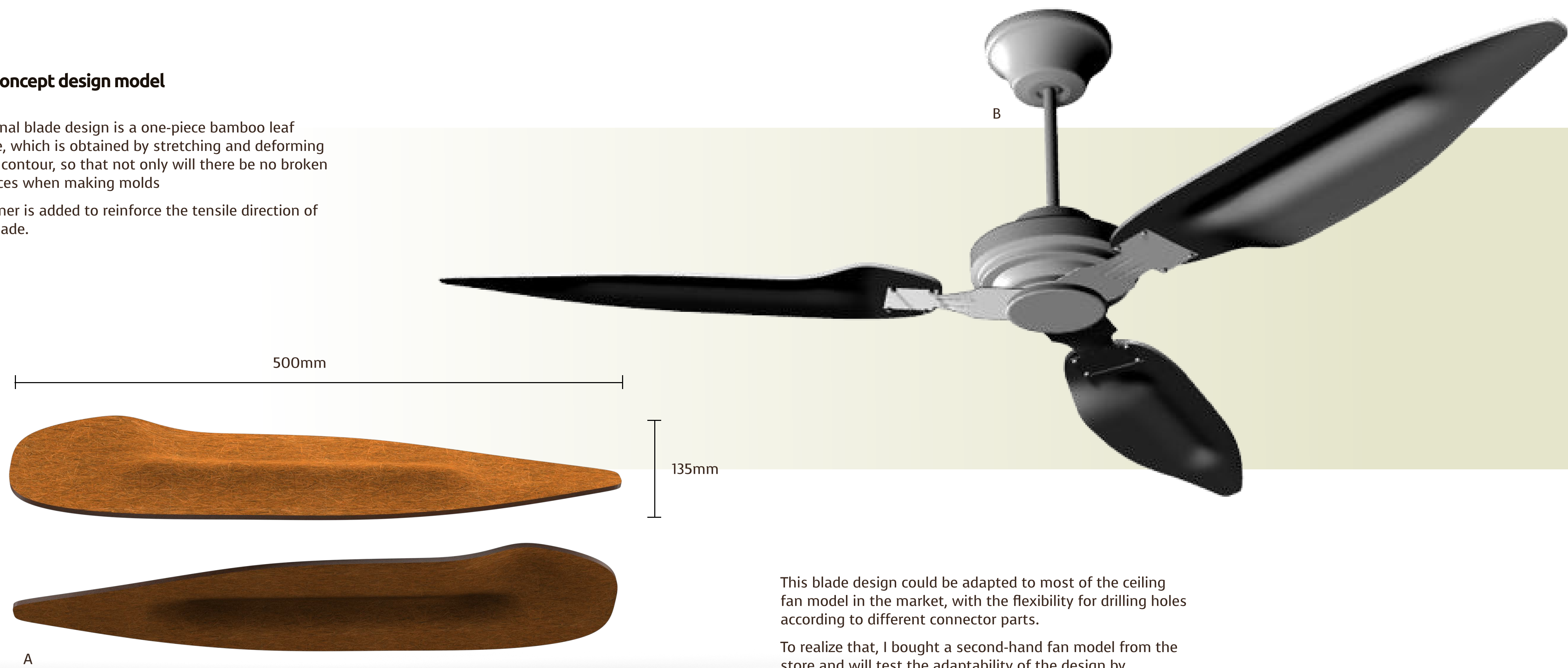


Figure 26 Schematic drawing
(Sourced from Pinterest)

8.6 Concept design model

The final blade design is a one-piece bamboo leaf shape, which is obtained by stretching and deforming a flat contour, so that not only will there be no broken surfaces when making molds

Stiffener is added to reinforce the tensile direction of the blade.



This blade design could be adapted to most of the ceiling fan model in the market, with the flexibility for drilling holes according to different connector parts.

To realize that, I bought a second-hand fan model from the store and will test the adaptability of the design by replacing the blade with the prototype.

C

Figure 27 Concept design 3d model (A, B) and physical model for blade replacement (C)

8.7 Concept design mechanical load and deflection analysis

In the design of rotating blades, several critical factors must be considered to ensure the optimal performance and safety of the structure. Understanding the forces acting on the blade and the material's ability to withstand these forces is essential to avoid mechanical failure. Additionally, selecting the appropriate blade thickness is crucial to balance strength and flexibility. Finally, identifying the material's resonance frequency ensures that the blade operates efficiently within a safe range of rotational speeds, preventing destructive vibrations.

Therefore, in this analysis, we aim to address the following key objectives:

- Find the relation between blade thickness and deflection rate caused by thrust generated by blade rotation in order to select appropriate blade thickness.
- Calculate the material's resonance frequency to find the proper range of rpm.

8.7.1 Stiffness analysis

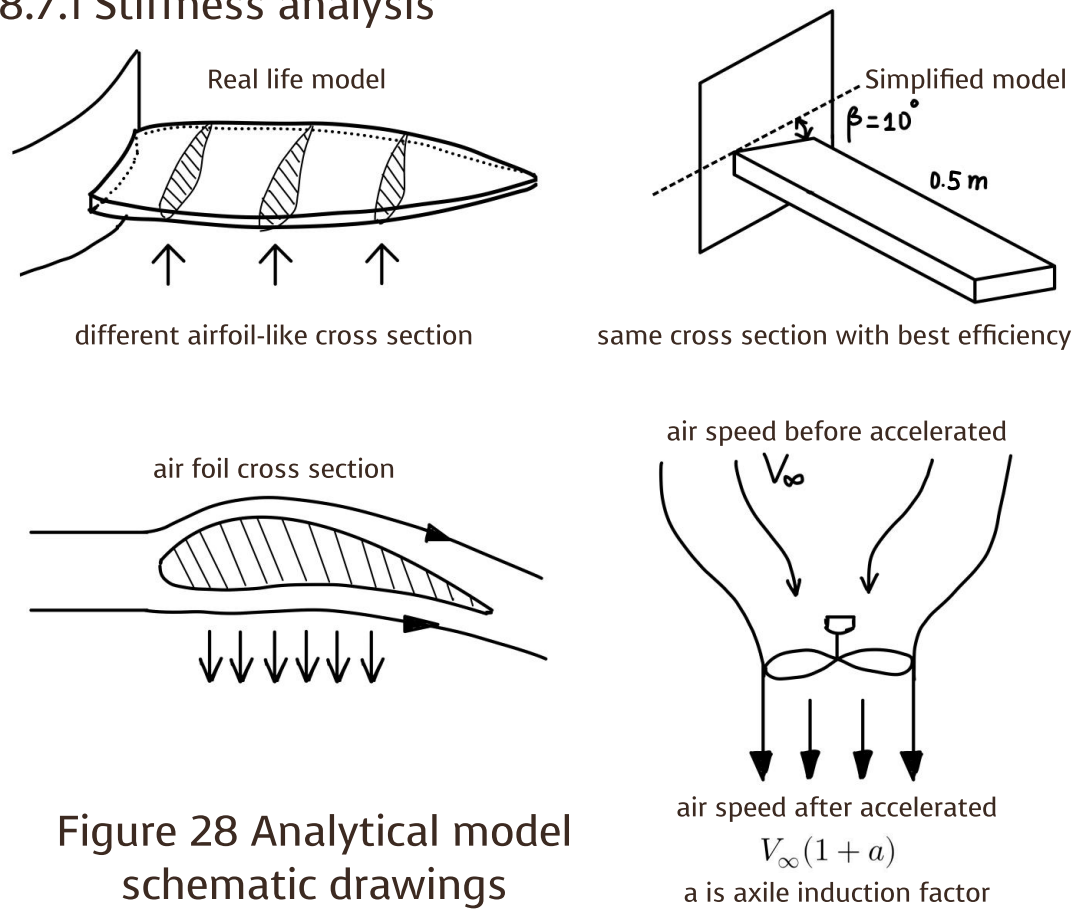


Figure 28 Analytical model schematic drawings

We can draw an air foil's sectional lift force diagram as follows:

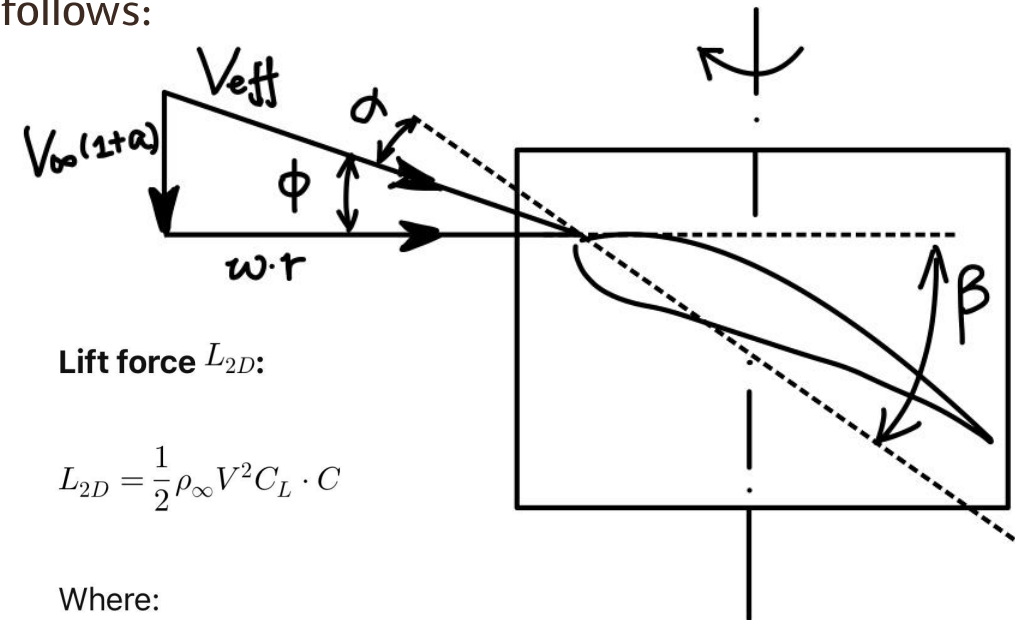


Figure 29 Velocity diagram of air flow

Lift force L_{2D} :

$$L_{2D} = \frac{1}{2} \rho_{\infty} V^2 C_L \cdot C$$

Where:

- ρ_{∞} is the air density
- V is the airspeed
- C_L is the lift coefficient
- C is the chord length

1. Where a is 0.3 when reach the best air speed acceleration efficiency $\rightarrow$ largest force according to Betz's law
2. C_L is lift coefficient, affected by:
 - a . airfoil
 - b . angle of attack
 - c . air properties (e.g., Reynolds number Re)

For any airfoil, we take $C_L = 2\pi\alpha$, so the maximum figure is $2\pi\alpha$.

From the velocity diagram, we can know:

$$\alpha = \beta - \phi = \beta - \arctan\left(\frac{V_{\infty}(1+a)}{\omega r}\right)$$

For residential ceiling fans, β has the range of 8° to 10° according to CBE Ceiling Fan Design Guide.

For RPM selection according to CBE Thermal comfort, the relative air speed ranges from 0.1 m/s to 0.8 m/s.

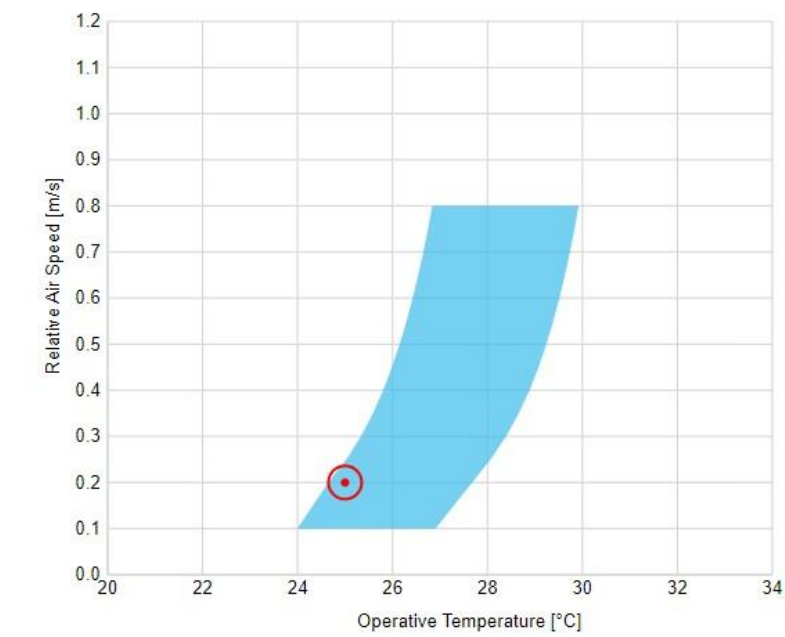


Figure 30 Illustrations of speed over temperature from CBE Thermal Comfort Tool

To simplify the function, we select airspeed at 0.2 m/s since most of the time in NL, the temperature is below 25°C .

So now we get everything we need, the graph on lift force - distance is shown:

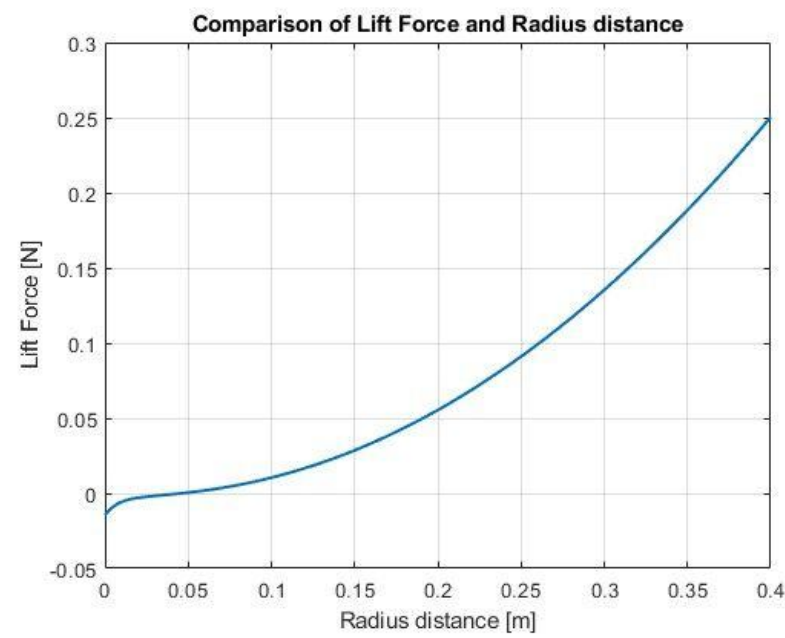


Figure 31 Illustrations of lift force over radius distance

According to Prandtl correction on wind turbine, the force near the edge should be close to 0 in reality, so we make two conservative simplifications:

1. Using analytical graph to calculate bending momentum.
2. Integrate the force and add it to the farthest point.

If our analytical conservative result doesn't fail, in reality it won't fail. We can have the blade load distribution like this as shown in Fig 32:

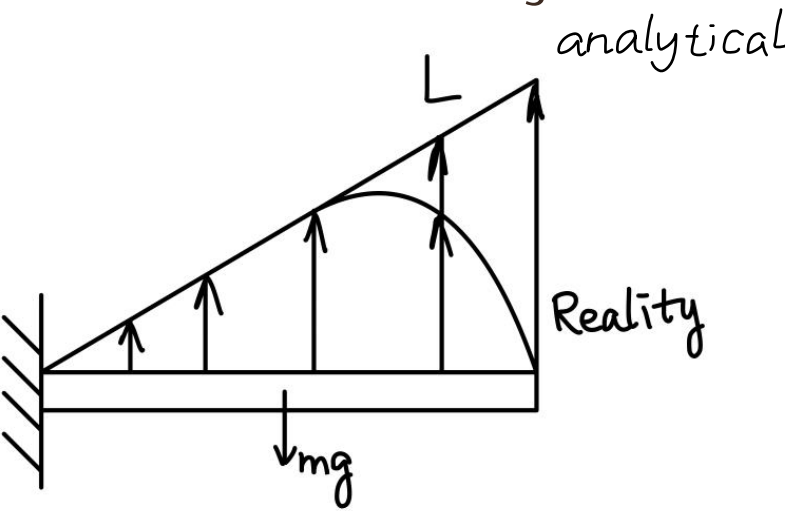


Figure 32 Analytical conservative load distribution

To calculate the load condition, two cases are considered, when blade is rotating (working), and resting; as shown in Flg 33.

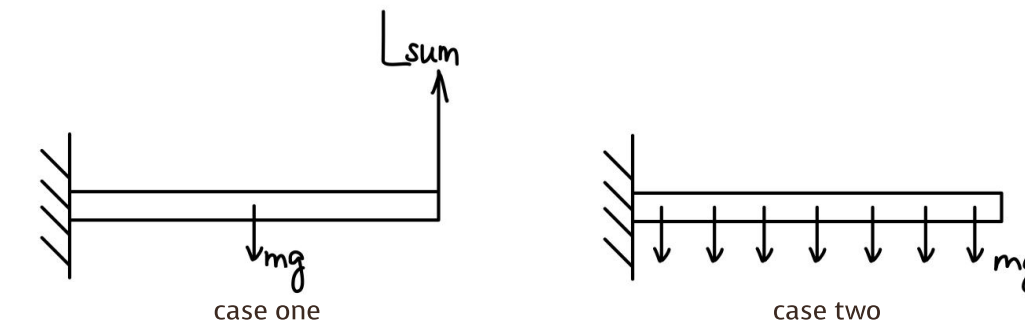


Figure 33 Case one: load distribution while working; Case two: load distribution while resting

Knowing the dimensions(with thickness as a variable) of the simplified blade model, we can get the inertia. By implementing two different beam deflection model formulas in two cases, we can get the graph of the relation ship of deflection and blade thickness, showed in Fig 34.

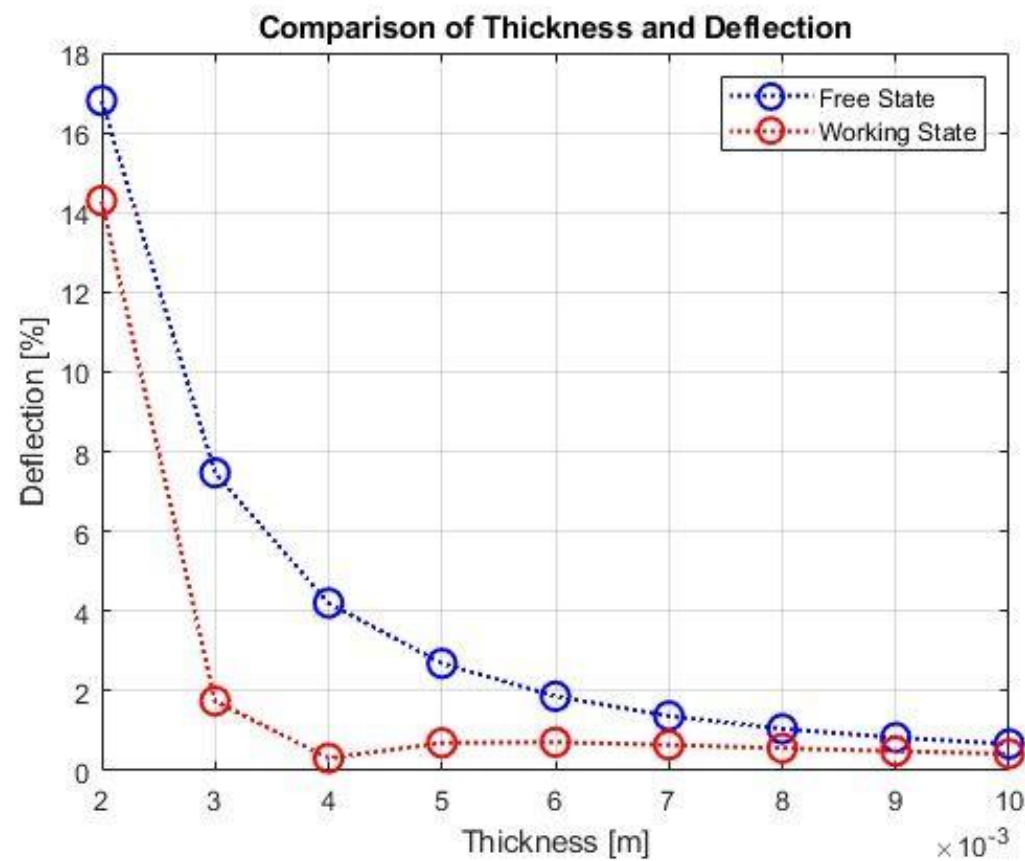


Figure 34

Different thickness is considered and plotted. The deflection decreased first rapidly, then slowly with growing thickness.

It is projected that 3 to 5 mm would be ideal thickness of the blade.

To check the tensile strength limits, I assume all the load is added along the tensile direction, the Fig 35 showed the relations between maximum stress and blade thickness. With the reference line of the composite tensile strength limit, it's clear that the blade will be safe if it's thicker than 2.6 mm.

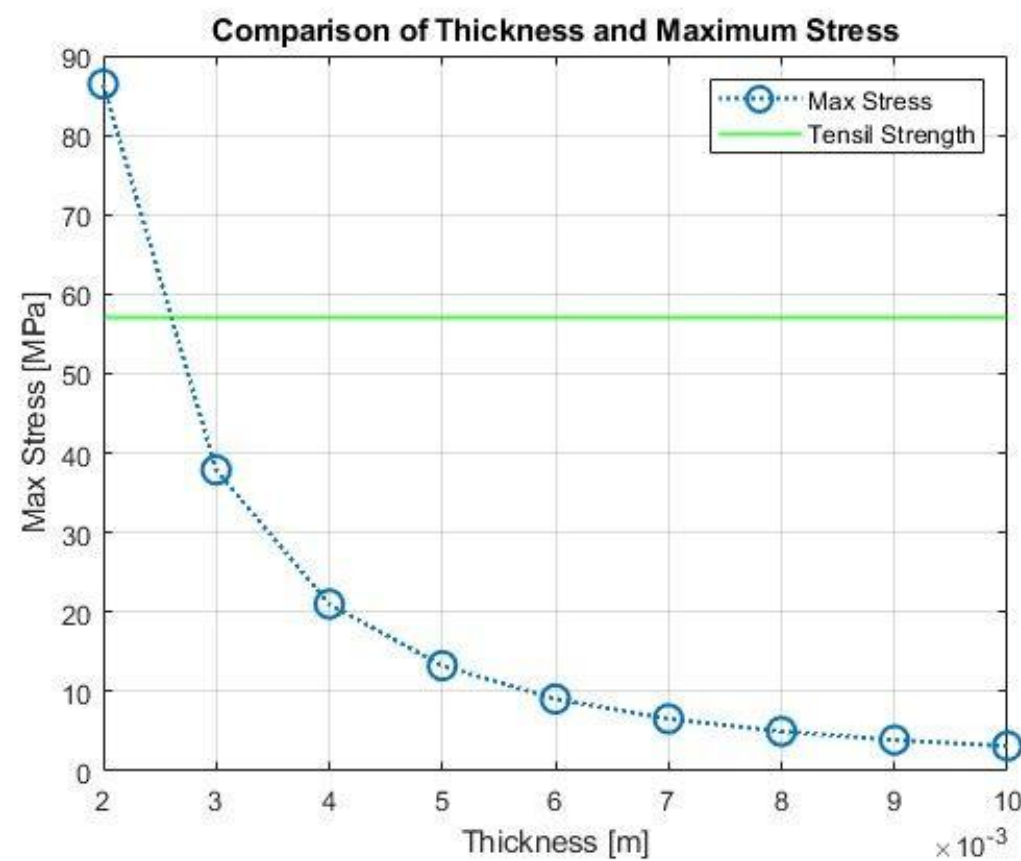


Figure 35

8.7.2 Resonance analysis

When considering resonance frequency, we have the function for one single blade:

$$f_n = \frac{\beta_n^2}{2\pi} \sqrt{\frac{EI}{PA}}$$

For β_n , when $n = 1$, $\beta_1 \approx 1.875$

$$E = 6.2 \text{ GPa}$$

$$I = \frac{bh^3}{12}$$

$$A = b \cdot h$$

$$\Rightarrow f_1 = 7.54 \text{ Hz}$$

When rpm = 250,

$$f_{\text{rotate}} = 4.17 \text{ Hz}$$

$\Rightarrow$ no resonance

Chapter 9

Embodiment Design



9.1 Prototyping method analysis

To develop a suitable and feasible manufacturing method, we begin by referencing the conceptual design model. The 3D model of the blade was created by deforming a flat surface into a curved one, specifically to accommodate the processing capabilities of thermoplastic composites. The initial decision to design the blade with uniform thickness was made to simplify the production of the material sheets and the subsequent forming process. My previous lab experiments influenced this decision, where I used bamboo composite plates with silicone and aluminum molds to thermoform a highly curved surface.

Therefore, in the early stages of prototyping method development, the most viable approach is leveraging this knowledge and designing aluminum molds for thermoforming. The process would involve creating a concave and a convex mold to match the blade's curvature. The multi-layered bamboo composite laminate would be placed between these molds and thermoformed to fit the desired shape. After forming, the blade would be trimmed and polished to achieve the final contours. A process flow diagram for this proposed prototyping method can be found in Fig 36.

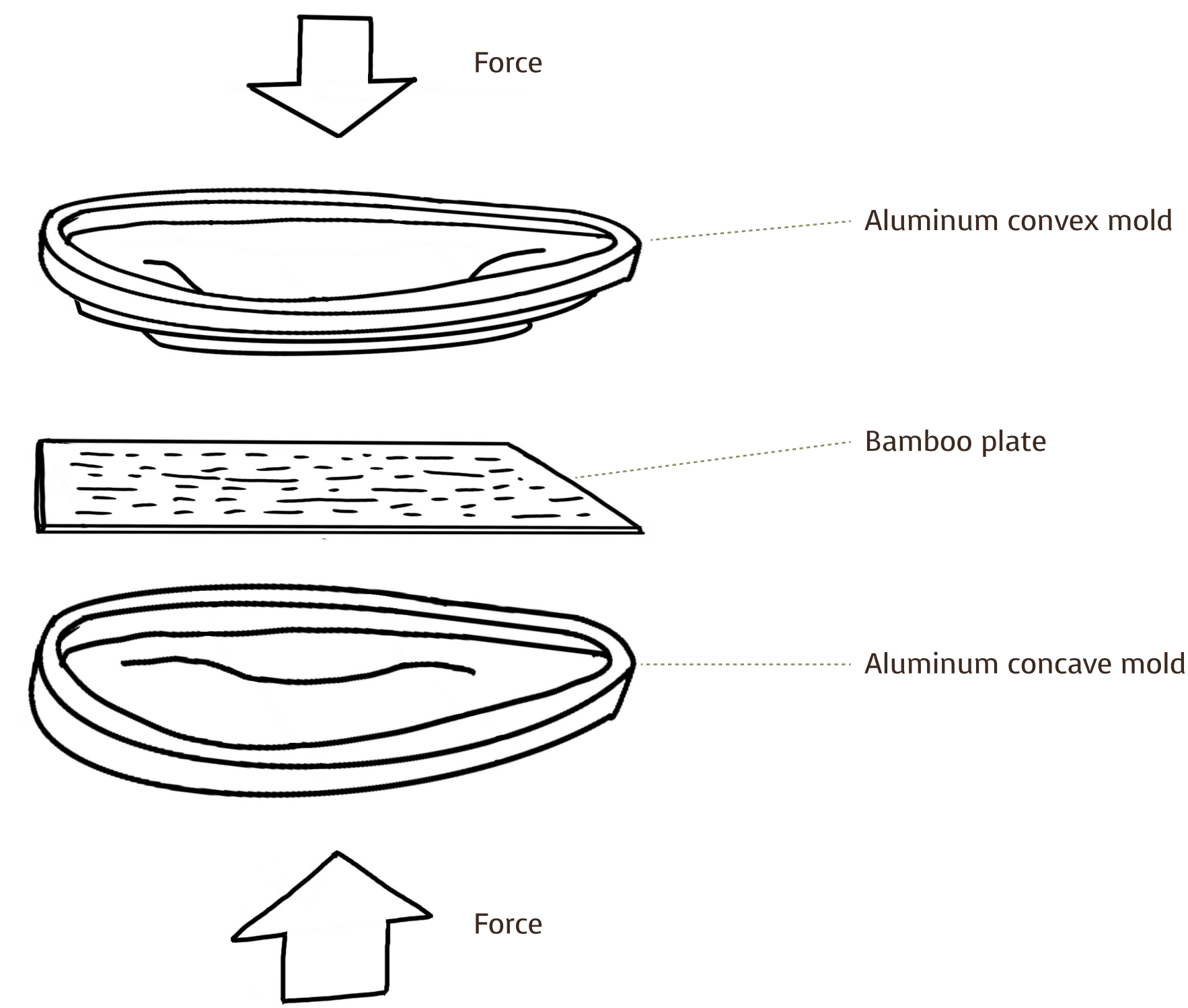


Figure 36 Process flow diagram

9.2 Prototyping programme diagram

During the actual mold design process and the search for equipment to machine the aluminum molds, we encountered unavoidable constraints that prevented us from finding staff capable of processing the molds within the required time frame. As a result, we changed our approach and opted for vacuum thermoforming instead. This method involves first 3D printing a concave PLA model, followed by the creation of a convex composite mold using high-temperature-resistant epoxy and glass fiber fabric.

With this setup, the integrated multi-layer laminate is placed on the mold, sealed in a vacuum bag, and then placed in an oven. Once the laminate's matrix reaches the melting and deformation temperature, a vacuum pump is used to press the laminate tightly against the mold, ensuring that it conforms to the desired shape as it softens. After cooling, the laminate retains the same curvature as specified in the design. This method eliminates the need for complex machinery and can be carried out in the lab using simple materials and equipment, making it highly suitable for the project's requirement to quickly manufacture thermoplastic composite prototypes. A detailed description of this process can be found in Fig 37.

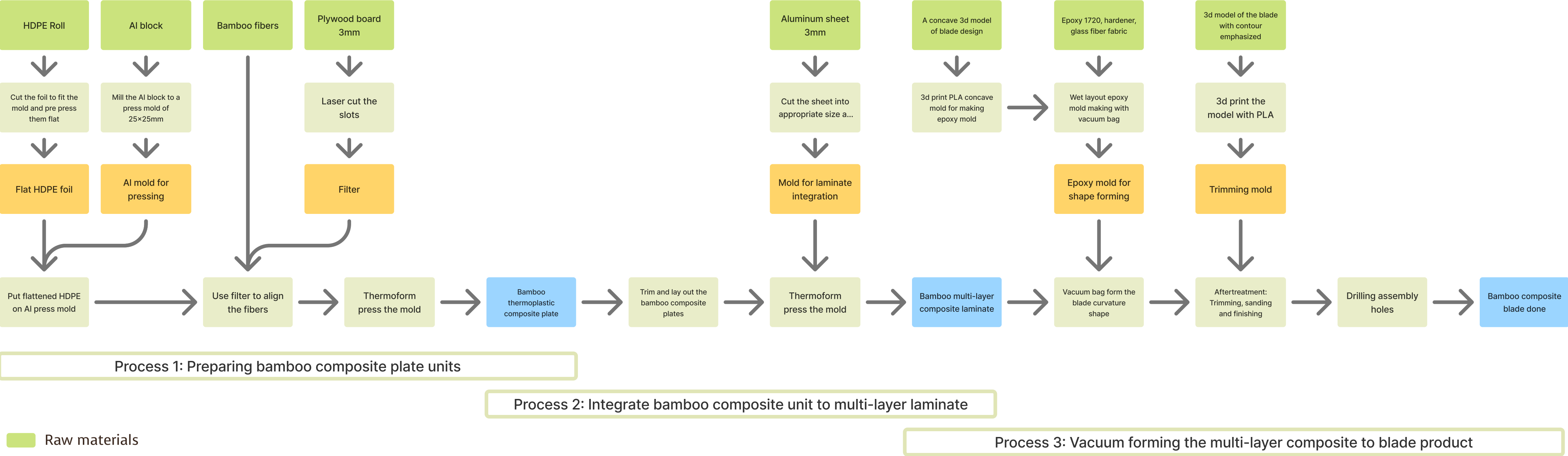


Figure 37 Detailed Process flow diagram

9.3 Process 1: Preparing bamboo composite plate units

A detailed overview of the bamboo composite manufacturing process can be found in section 3.3. Here, I would like to emphasize that the selection of temperature, duration, and pressure are critical parameters in controlling the state of the matrix. These factors play a pivotal role in ensuring the composite achieves the desired bonding and mechanical properties, making their careful adjustment essential to the success of the process. Fig 38 is the reference parameter when making bamboo composite plates.

According to the data-sheet of the matrix, the melting point is starting at 110°C till 130°C. After a few quality tests, I set the pressing temperature at 150°C and the pressing time for 10 minutes, which can make a perfect press under this condition.

However, when flattening HDPE foil, excessively high temperatures can cause the material to melt and stick together prematurely. After several rounds of experimentation, I found that the optimal conditions are applying a pressure of 30 kN at 90°C for ten minutes. This combination effectively prevents unwanted adhesion while ensuring the material flattens correctly.

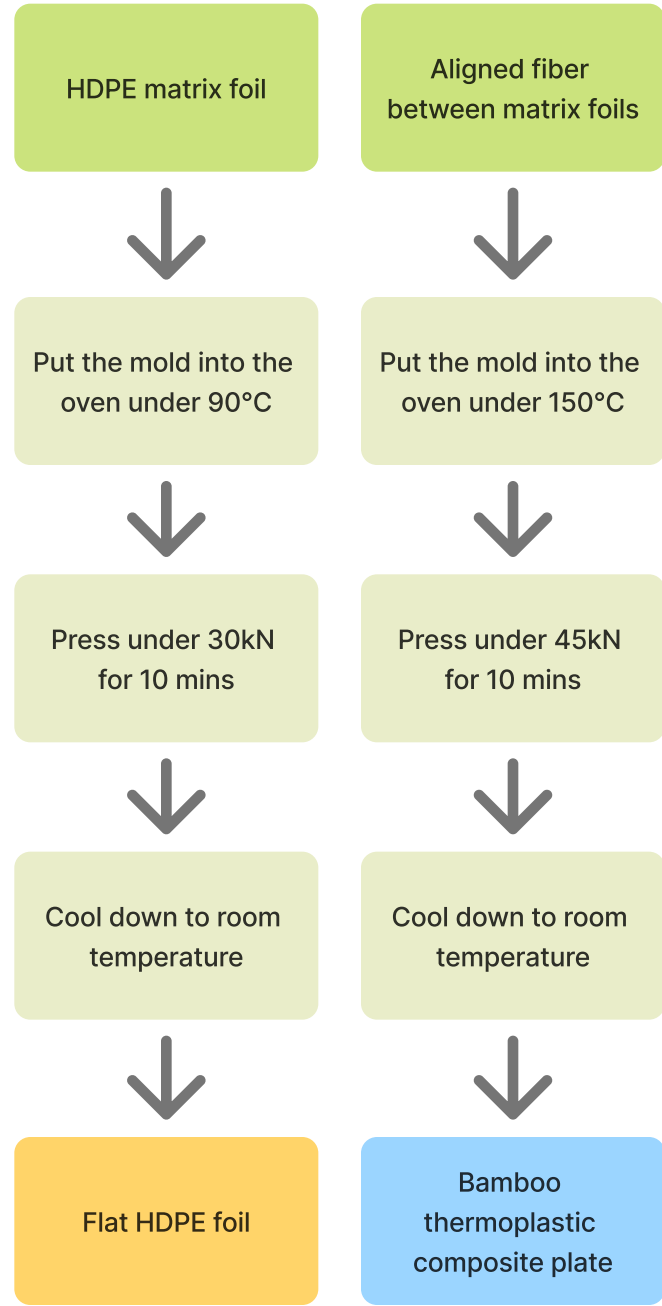


Figure 38 Process of making bamboo composite plates

9.4 Process 2: Integrate bamboo composite unit to multi-layer laminate

9.4.1 Multi-layer laminate integration mold

Due to the flowable nature of the matrix when melted, the thickness of the bamboo composite primarily depends on the fiber content. The simplest way to increase thickness is by stacking multiple bamboo plates together and re-thermoforming them to create new bonding. However, the available mold for producing bamboo composite plates is limited to a size of 25cm × 25cm, while our blade length is approximately 50cm. Therefore, it becomes necessary to bond multiple bamboo plates together.

We already know that the strength of individual bamboo short fibers and the HDPE matrix is lower than that of the composite material they form. This is because the strength of the composite comes from the friction between the fibers and the load transfer through the bonding between the fibers and the matrix. If we were to simply join two composite plates end-to-end, the joint would be extremely weak due to the lack of overlapping bamboo fibers to provide reinforcement.

To address this, we can stagger and overlap the bamboo plates, ensuring consistent thickness while also strengthening the joints, as illustrated in Fig. 39. This method maintains the structural integrity of the composite and enhances the strength at the connection points.

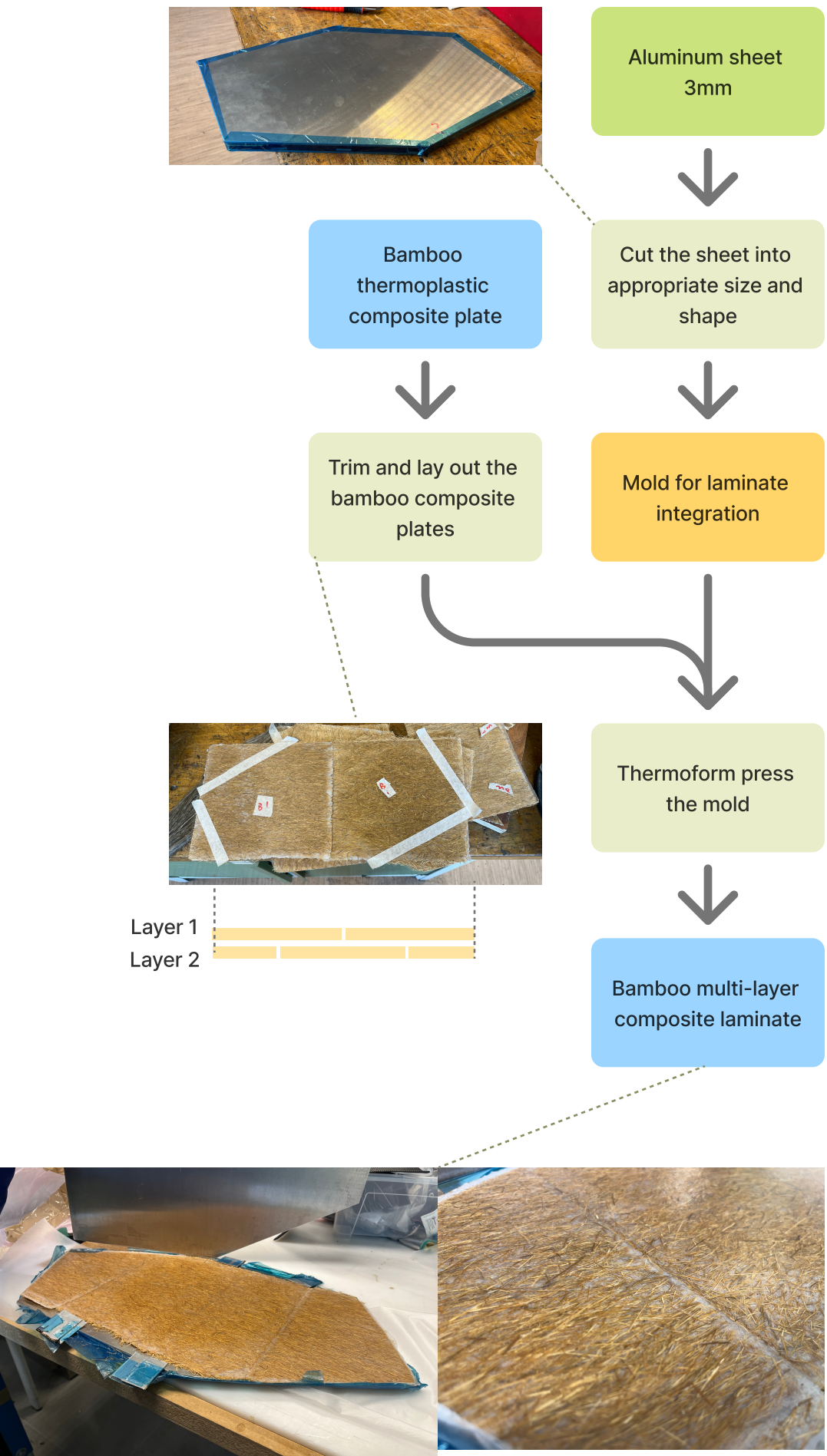


Figure 39 Integrating units method

9.5 Process 3: Vacuum forming the multi-layer composite to blade product

9.5.1 Vacuum forming epoxy mold making

When creating the vacuum thermoforming epoxy glass fiber mold, it is essential to consider the final appearance of the product. The fan blades are positioned higher up, within the upper field of view, so the side facing downward needs to closely match the design specifications and undergo finer surface finishing.

To ensure the underside of the blade aligns with the design, we need to create a convex epoxy mold whose surface corresponds to the 3D model and has a smooth finish that allows for easy demolding. To achieve this, we will need a concave mold to shape the epoxy mold, with its inner surface matching the original model. Since the wet layup method used to create the epoxy mold does not generate significant heat during curing, we can safely use 3D-printed PLA as the material for the concave mold.

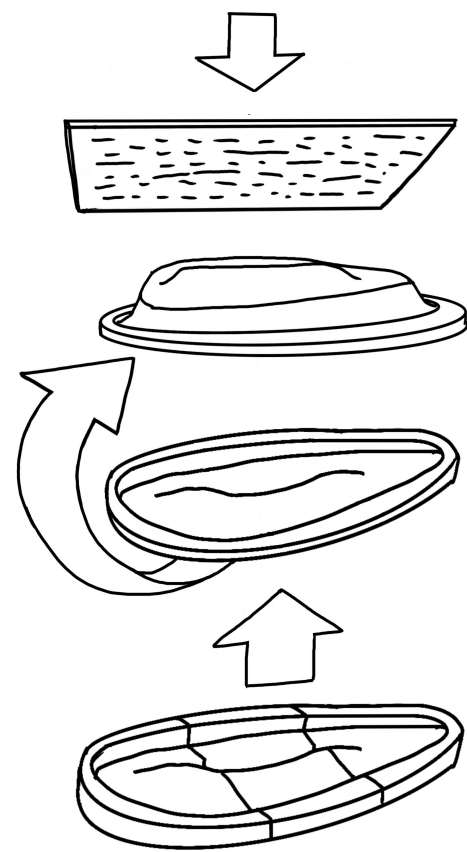


Figure 40 Epoxy creation

After the 3D-printed material is sanded, assembled, cleaned, and a release agent is applied, we can begin preparing the epoxy and glass fiber fabric mold. Considering that the deformation temperature of our bamboo composite is around 110°C to 130°C, and the set heating temperature is 150°C, we need to choose a high-temperature-resistant epoxy for the mold. The epoxy material we selected has the following characteristics:

Once the epoxy and hardener are mixed thoroughly in the correct ratio, a layer of epoxy liquid is applied to the surface of the 3D-printed concave mold. Next, pre-cut glass fiber fabric is laid onto the mold, ensuring it adheres tightly to the curved surface. Another layer of epoxy liquid is brushed on, followed by another layer of glass fiber fabric. This process is repeated 10 times to achieve a sufficient thickness capable of withstanding vacuum thermal forming.

At this stage, the epoxy has not yet fully cured, meaning the layers of glass fiber fabric may shift, leading to inaccuracies or surface defects. To prevent this, I used vacuum bag forming to ensure the epoxy and glass fiber fabric layers are tightly pressed against the 3D-printed mold. The mold is left to cure at room temperature. As shown in the process diagram, for the epoxy mold to achieve optimal heat resistance, it must be placed in a 50°C oven for 16 hours to cure fully.

Once fully hardened, the 3D-printed mold is separated from the epoxy mold. The epoxy mold is then sanded, cleaned, and a release agent is applied, resulting in a high-precision, easily demoldable surface. With the mold ready, we can proceed to vacuum bag thermoform the final bamboo composite blade.

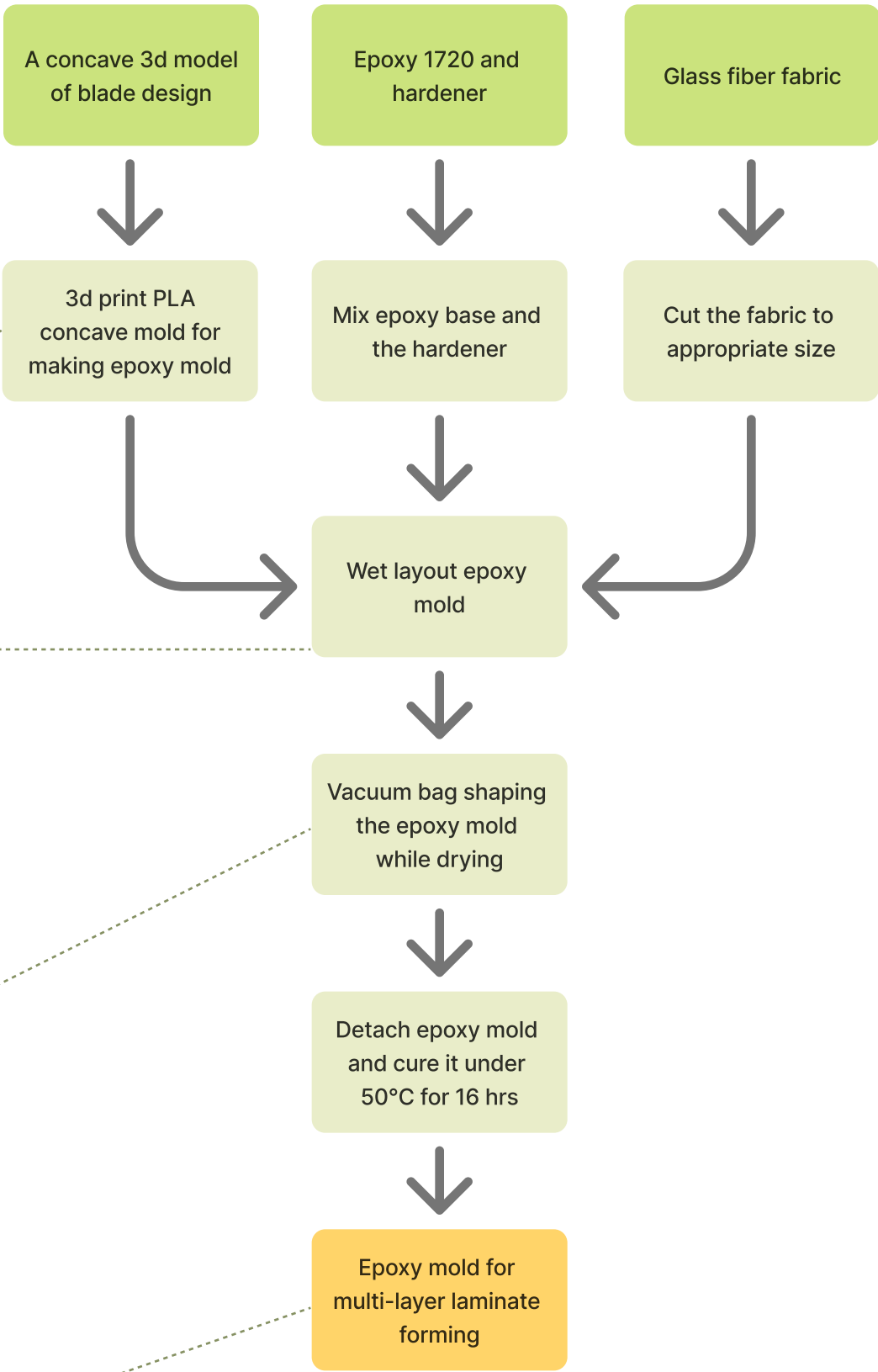


Figure 41 Process of manufacturing

9.5.2 Vacuum bag forming the blade

The principle behind vacuum forming is quite simple: it uses the pressure difference between the inside and outside of the vacuum bag to press the bag tightly against the mold, compressing the material and forming it into the desired shape. However, in practice, there are numerous details that require extra attention to avoid product defects or failures. Check Fig 42 to see the flow chart of vacuum bag forming process.

During the vacuum bag preparation, in addition to the mold and the bamboo laminate, several key elements need to be in place: a valve to control airflow, a breather to ensure even gas release, and given that the processing temperature is around 150°C, the standard perforated release foil cannot be used as it will melt. To address this, I cut a piece of vacuum bag foil to act as a barrier between the breather and the bamboo laminate, preventing them from sticking together.

Once the setup is ready and preheated, extreme care must be taken when opening the pump valve to gradually remove the air. A sudden creation of a vacuum can cause localized stress where the bamboo laminate contacts the curved mold, leading to cracks that compromise the product's aesthetic and structural integrity. After the vacuum is fully applied, the entire vacuum bag is placed in the oven for an additional 10 minutes to ensure the composite is thoroughly heated and any remaining air in the voids is expelled. The vacuum bag also helps the laminate maintain its conformity to the mold during cooling until it is fully solidified and ready for demolding.

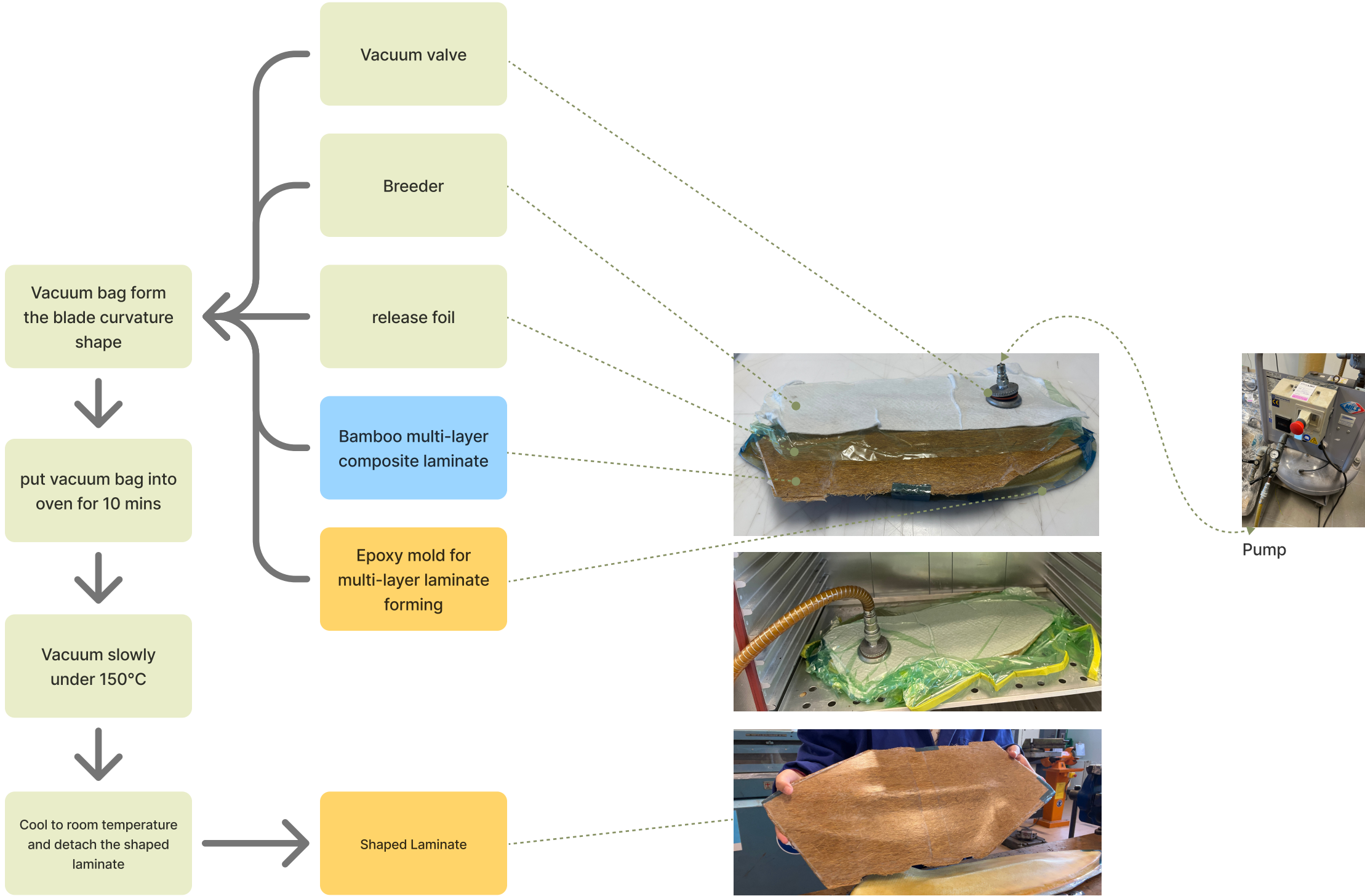


Figure 42 Vacuum forming

9.5.3 Trimming and aftertreatment

Once the pressed fan blade is formed, we need a trim mold to help identify the areas that need to be cut. To create this trim mold, I will 3D print another convex model. When printing this model, it's important to include structural reference points from multiple directions to aid in precise alignment and prevent displacement of the prototype during trimming. For this purpose, I chose to use the central stiffener as the reference point.

To save both material and time, I hollowed out the unnecessary parts of the mold. As shown in Fig. 43, the prototype blade and the trim mold fit closely together, with only minor gaps in areas with larger curvature. Overall, the fit is highly satisfactory, ensuring an efficient trimming process.

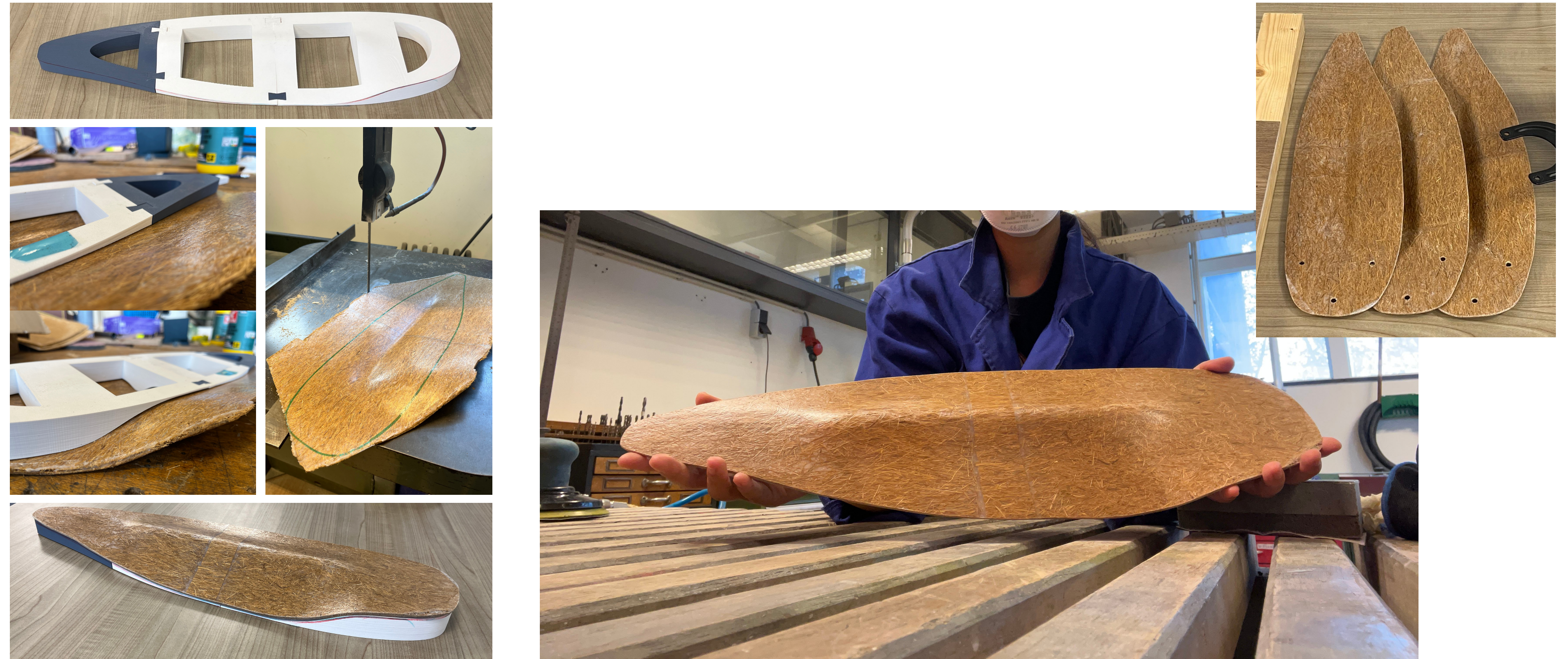


Figure 43 Following steps manufacturing

9.6 Prototype Assembly

The blade turned out to be stiff and functional at the thickness of 2mm. Compared with a wood fan blade with the weight over 500g+ More lightweight and stiff, more efficient the blade is while operating, and being transported. Due to the deformability of thermoplastics, the can be reformed and reshaped after a long time, contributing to a more sustainable living style.



80% light weighted than traditional wood blades

2mm Extremely thin natural-look blades



100% Bio based Can be reshaped and reused



Figure 44 Prototyping

Chapter 10

Quick LCA by Idemate calculator



(Sourced from Unsplash by CHUTTERSNAAP)

10.1 Context of Analysis

The motivation behind conducting a quick Life Cycle Assessment (LCA) for the bamboo fiber composite fan is to evaluate its environmental impact across various stages of its life cycle. (Eco Costs Value, 2023) As sustainability is a key focus of this project, understanding the carbon footprint, energy consumption, and potential environmental benefits compared to conventional materials is crucial. Bamboo fiber composites are often promoted for their eco-friendly properties, but a detailed analysis is necessary to quantify these claims.

In this project, I chose to conduct a quick Life Cycle Assessment (LCA) of raw materials through to the completion of processing, a process from cradle to gate. By focusing on key metrics like carbon footprint, the quick LCA enables informed decisions regarding the sustainability of the material and guides further design optimizations.

According to tutorials from TU Delft LCA online study platform, I followed the 4-step process of conducting analysis, which are:

- 1. Establish Goal of your analysis, Functional Unit, System and Boundary Limits
- 2. Quantify materials, use of energy, etc. in your system
- 3. Enter the data in an Excel calculation sheet
- 4. Interpret the results and draw your conclusions with regard to the goal of the study

10.2 Goal, functional unit, boundary, system

10.2.1 The goal of having fast track LCA

The household ceiling fan market is primarily dominated by three types of materials. The first is metal blades made from aluminum or zinc alloys, the second is handcrafted wooden blades, and the third is plastic blades. Since the appearance of my bamboo fiber composite fan blades closely resembles that of handcrafted wooden blades, while offering superior corrosion resistance and waterproofing I see wooden blades as the main competitor for bamboo fiber composite fans in the market. Therefore, I plan to compare the carbon footprints of all three blade materials in order to highlight the sustainability advantages of bamboo fiber products.

Regarding the functional unit, I have defined it as the carbon footprint of manufacturing one fan blade. For the boundary conditions, I have set the following limitations to narrow the scope of the discussion. First, due to the lack of data on the fatigue life and mechanical performance of the composite, as well as the absence of experience with bamboo composite remanufacturing, the analysis does not extend to the use or end-of-life phases. The calculation is limited to the stages from raw material acquisition to the completion of production, focusing solely on carbon emissions during this process. Second, the natural material's carbon uptake is not considered in the carbon footprint calculation.

A simplified process flow for the production of the three materials is shown on the right. In this system, all data sources, except for the carbon equivalent of bamboo composite, which is provided by the company, come from two databases: A and B. If a specific processing method is not available in the database, a similar method is used as a substitute. This may lead to increased uncertainty in the data.

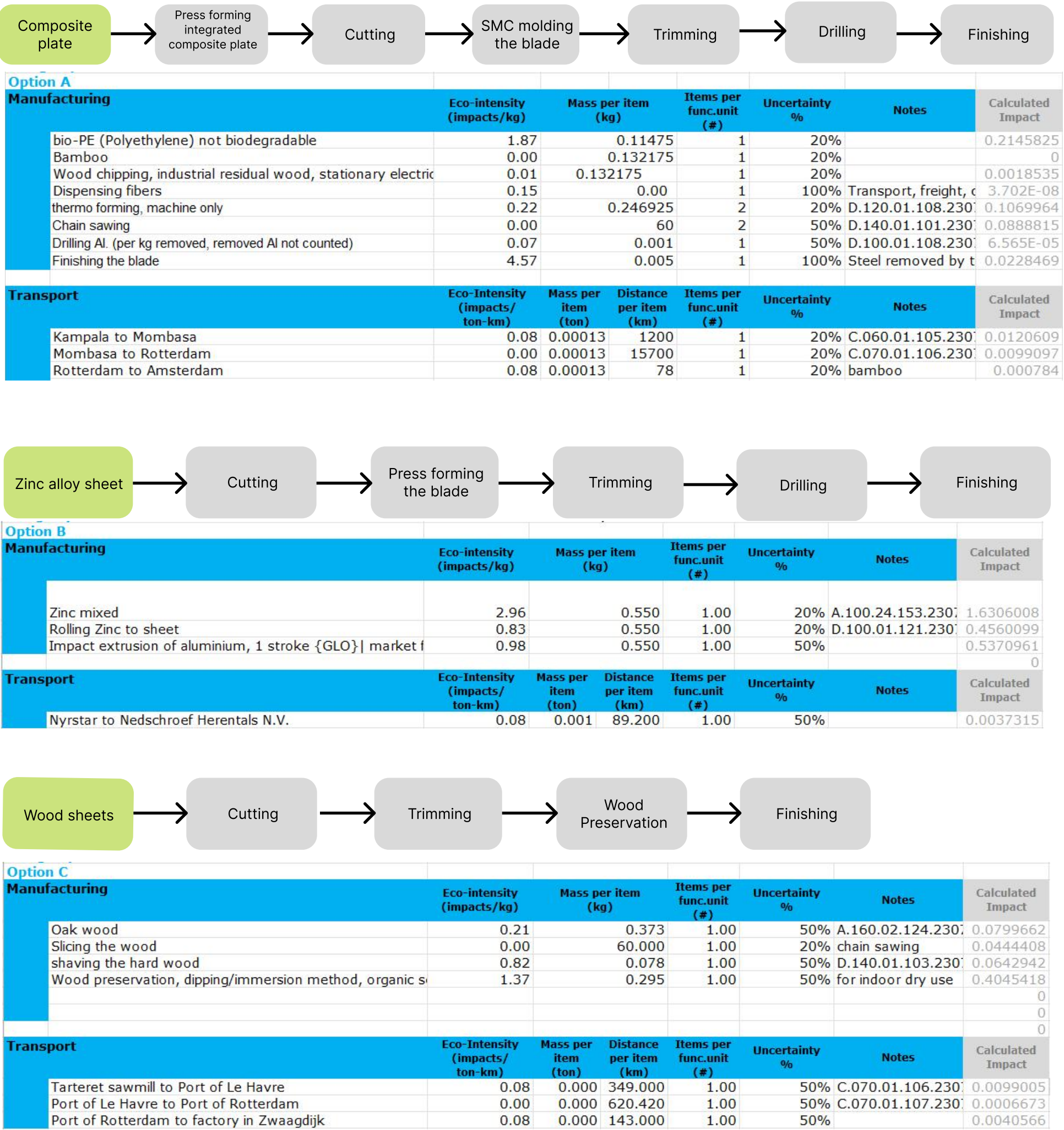


Figure 45 LCA results

10.3 Results and analysis of quick LCA

Analyzing the quick LCA results (See Fig 45) for three different materials used in fan blades—A (composite), B (zinc alloy), and C (wood)—we can derive the following insights:

1. Material and Manufacturing Impacts

- Composite (Option A): The primary environmental impacts are from the production of bio-PE (Polyethylene) and bamboo, with the highest impact coming from bio-PE. Other factors like wood chipping, thermoforming, and processing (e.g., drilling and sawing) also contribute, though to a lesser degree. Notably, the transportation impact is relatively low. The overall carbon footprint is low compared to the other options, indicating that the composite material is more eco-friendly in terms of emissions during production and processing. Notably, though I use vacuum bag forming to prototype, I still calculate quick LCA with the metal mold proposal, since it's more durable and produce less waste compared with the one time used vacuum bag.
- Zinc Alloy (Option B): This option has the highest environmental impact, largely driven by the rolling zinc to sheet process and zinc production itself. Additionally, the process of extruding aluminum and transport shows notable impacts. Zinc production is a highly energy-intensive process, which explains the large carbon footprint, particularly in the materials and manufacturing stage. This makes Option B the least sustainable choice in terms of CO2 emissions.
-

Wood (Option C): The wood fan blades have a moderate environmental impact. The most significant contributors are wood preservation methods and the processes of slicing and shaving the wood. Transport also adds some impact, though to a lesser degree than materials and manufacturing. While wood is a natural material and has the benefit of carbon sequestration, the preservation processes add environmental burdens, which elevate its carbon footprint compared to the composite but keep it lower than the zinc alloy.

2. Transport Impacts

In all three options, the transport impact is relatively minor compared to the materials and manufacturing stage. However, the composite has the least impact from transportation, likely because bamboo and bio-PE are sourced closer to the point of production or are less energy-intensive to transport.

3. Total Impacts (Summary Chart)

- Option A (Composite): Overall, this option has the lowest total environmental impact, making it the most sustainable choice among the three in terms of lifecycle carbon emissions.
- Option B (Zinc Alloy): The zinc alloy has the highest total impact, primarily due to the energy-intensive manufacturing processes of metalworking. This is clearly visible in the significant contributions from zinc production and aluminum extrusion.
- Option C (Wood): The wood fan blade ranks in the middle, with higher impacts than the composite but significantly lower than the zinc alloy. The carbon emissions are mostly driven by wood preservation processes.

Conclusion:

From a sustainability standpoint, bamboo composite (Option A) is the best option for producing fan blades, offering the lowest overall carbon footprint and the most eco-friendly balance between materials and manufacturing impacts. Wood (Option C) offers moderate sustainability but is burdened by preservation processes, while zinc alloy (Option B) is the least sustainable due to its high energy consumption and material processing requirements.

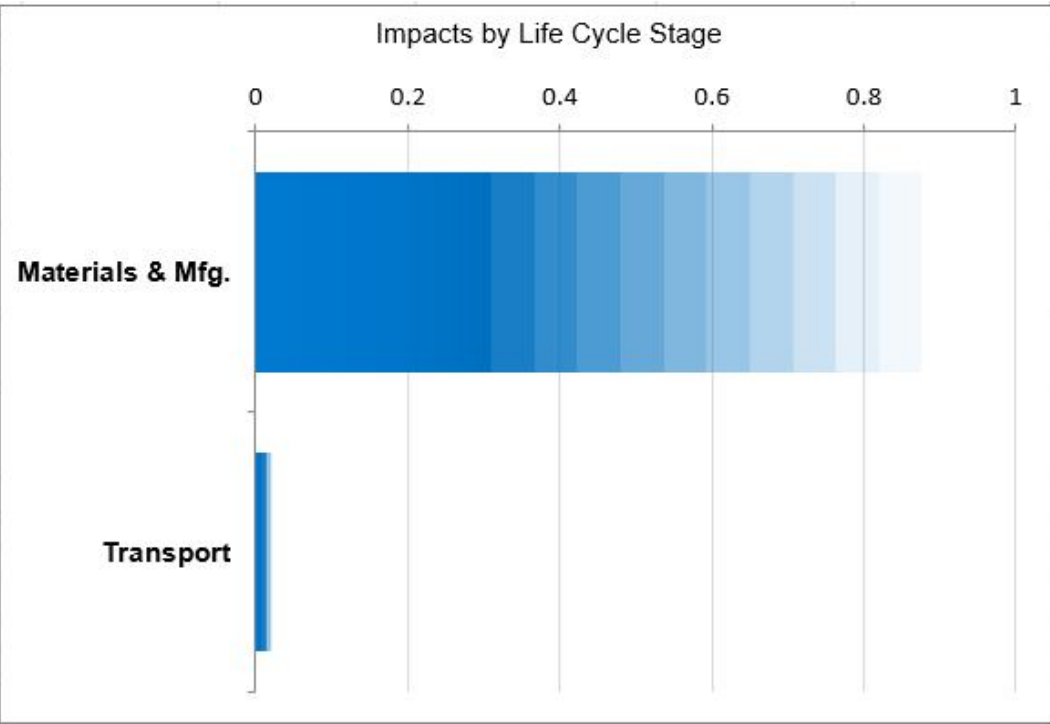
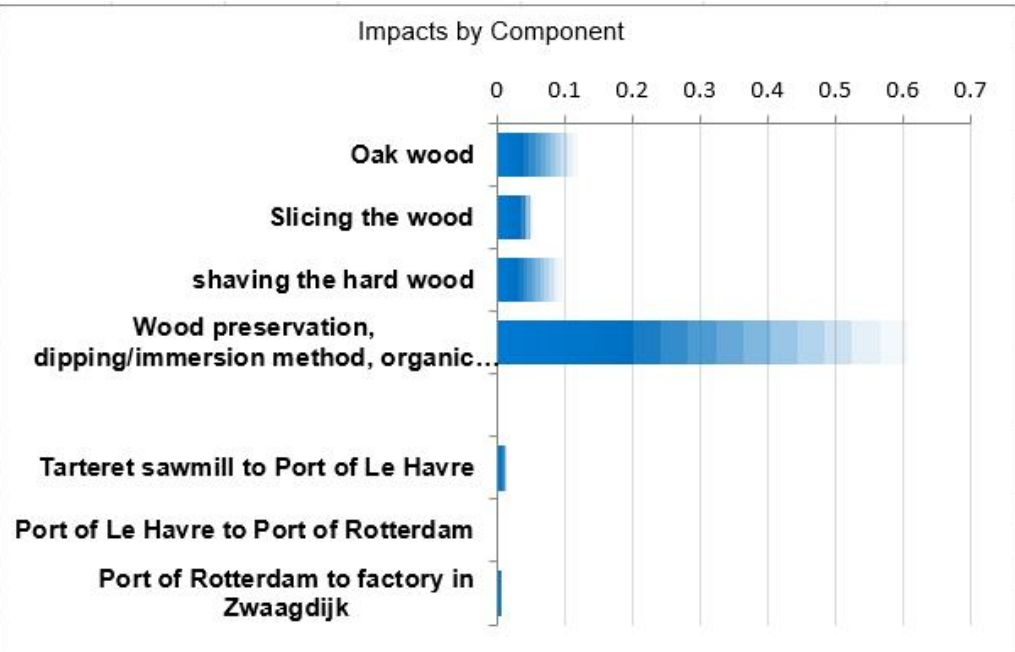
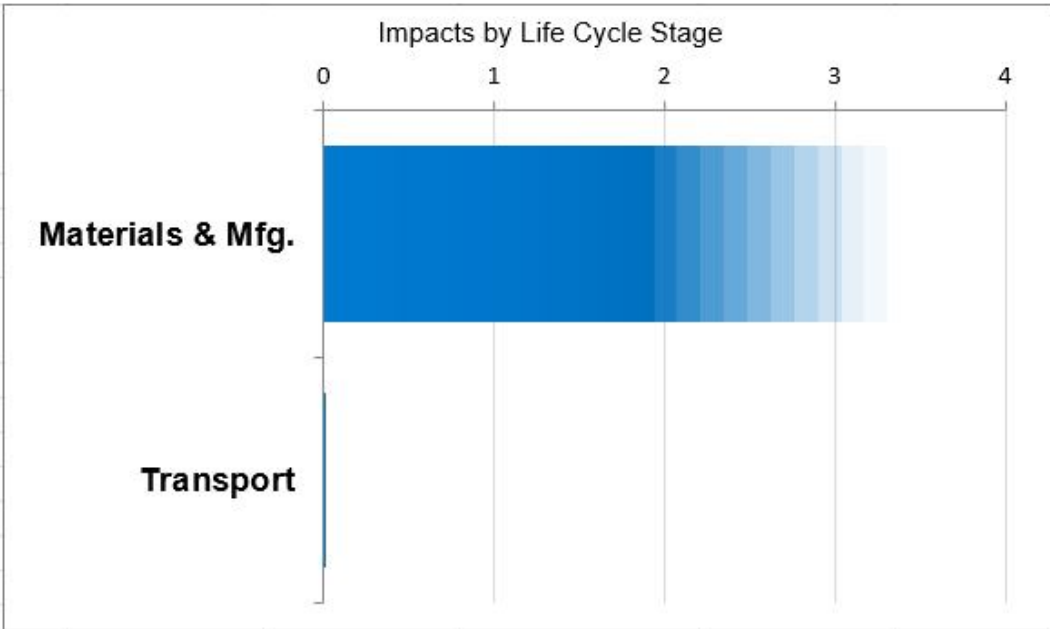
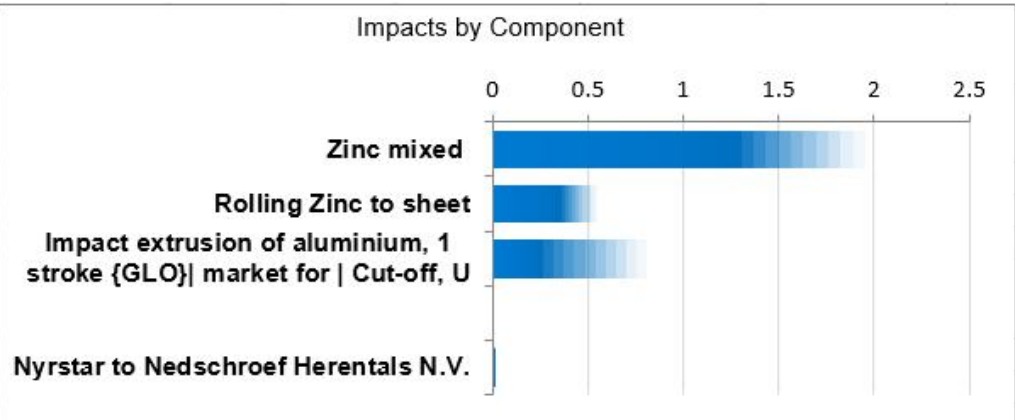
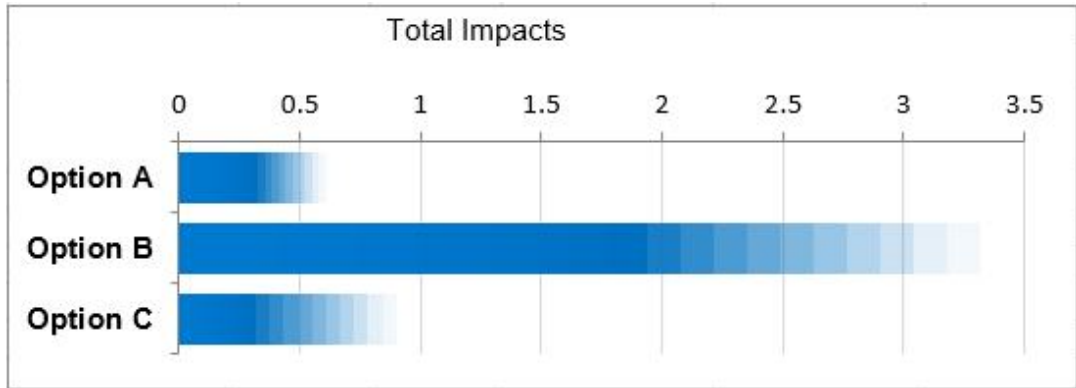
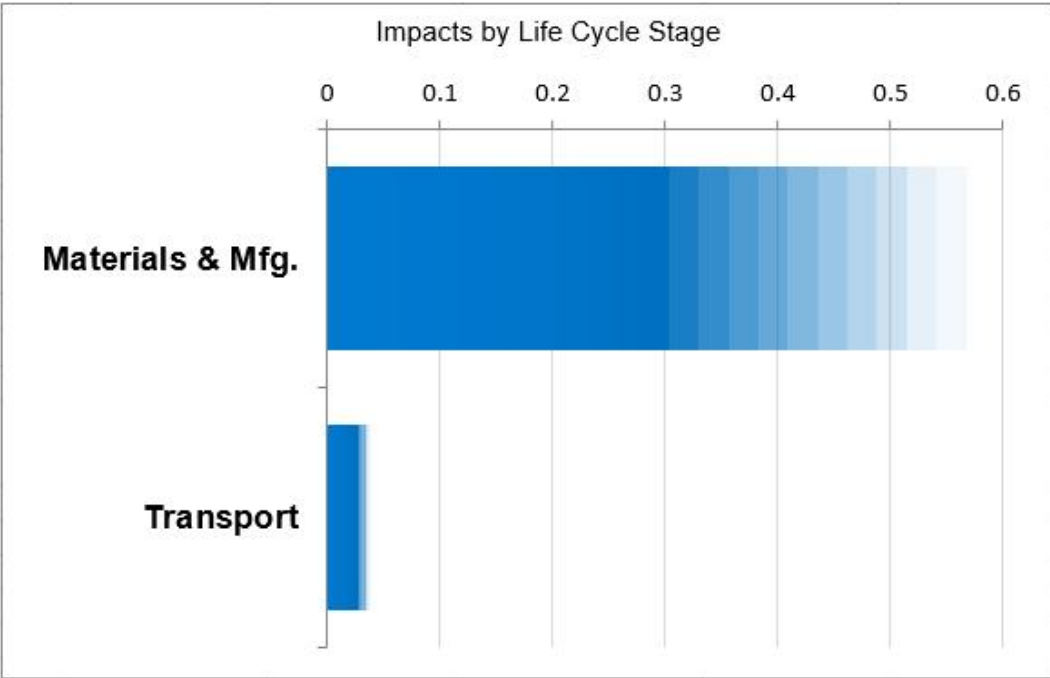
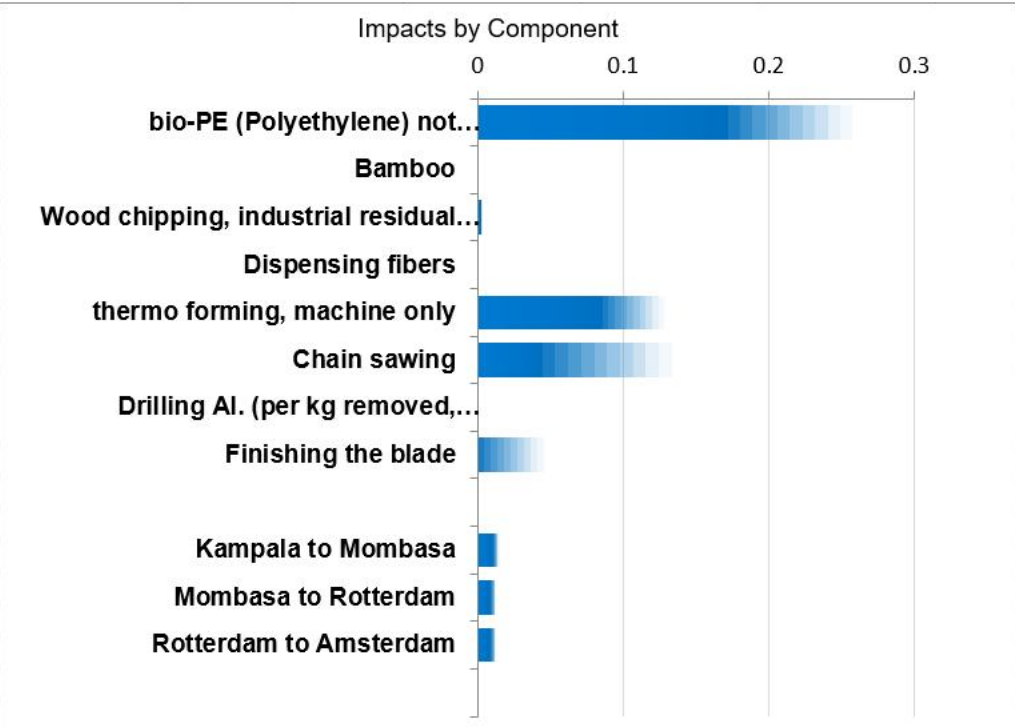


Figure 46 Diagrams of various impacts

Chapter 11

Conclusions



11.1 General Reflection

11.1.1 Research question and methodology

In my research question list, I have incorporated five types of questions that approach the topic from different angles. To address the definition-related questions about bio-based short fiber composites, I began by reviewing existing literature on these materials to understand their composition and how they are defined. This also helped me gain insights into the development of bio-based composites and their differences from non-bio-based materials. By comparing multiple sources, I was able to clearly identify the characteristics of bio-based composites and familiarized myself with common manufacturing methods. Additionally, I drew inspiration from other composite processing techniques. In terms of why I chose short bamboo fibers and bio-HDPE, my decision was influenced by the potential of fiber alignment to enhance material strength and the excellent stiffness and processability of bio-HDPE. Together, these factors made them an ideal starting point for my research.

To address the questions related to how experimental research can be used to explore material characteristics, contributing a good design, I investigated the methodologies and toolkits used in the Material Driven Design (MDD) method as a reference. I also reviewed case studies where other students applied this method in their research to identify similarities with my own project. By doing so, I was able better to adapt the research experiences and insights from those studies to support and enhance the experimental aspect of my project, ensuring that the methods chosen were relevant and effective for exploring the unique properties of my materials.

For broader questions exploring the significance of the experiments, I consulted relevant literature, laws, regulations, and policies to gain a foundational understanding of the current trends in natural materials and composites. This helped to highlight the societal and environmental implications of studying plant-based composites.

Regarding the questions focused on stakeholders, I conducted interviews with key personnel from the company, which provided insights into the existing market for bio-based composites, target customers, and collaborating manufacturers, giving me a solid understanding of the entire value chain. Additionally, during my field research at events like JEC, I gathered more relevant information. In the material characterization interviews, I specifically sought the opinions of industry professionals to further enrich my understanding.

11.1.2 Design and Prototyping

After exploring material characterization and establishing the design vision, I moved on to product design. This process was quite challenging, particularly due to the laboratory's relocation, which made prototyping progress difficult. Despite these obstacles, I successfully completed a scale prototype of a three-blade fan. However, this process consumed time that was originally allocated for user feedback testing. In reflecting on my design and its realization, I believe that using the vacuum bag for thermal forming effectively simulated the process of manufacturing with metal molds in a factory setting. The final product in the lab closely resembled the intended appearance, and being operated in the lab, so it successfully reached TRL level of 4. There were two defects on the vacuum-formed samples that need to be addressed. The first was due to the rapid compression of air, which caused uneven heating of the bamboo composite, leading to tears on the outer layer and leaving gaps on the surface. The second issue was due to larger curvatures on some surfaces, which caused the material to fold and wrinkle under pressure. These challenges are difficult to avoid in vacuum forming but could be resolved in future automated production lines in factories.

Regarding the overall design aesthetics, I am very satisfied. The one-piece design ensured smooth surfaces throughout the product. The inspiration drawn from bamboo leaves is evident in how the blade's silhouette changes from different angles, evoking the image of leaves swaying in the wind. This strengthens the connection between the material and the product. The overall appearance of the bamboo composite blade, like the material characterization samples, is natural with a matte, wood-like finish.

In larger household appliances like the ceiling fan, the smooth, comfortable colors and texture provide a relaxing visual effect, and the random arrangement of the fibers gives the product a vibrant and non-boring appearance. One point of concern is the visible gaps where the fiber alignment was interrupted, due to the limited precision of laboratory equipment, which slightly disrupts the overall consistency. However, I am confident that this issue can be resolved in future production by controlling the stacking order and precision in a factory setting.

11.2 Achievements

11.2.1. Created the Material Characteristics of Bio-based Bamboo Fiber Composites

This project has successfully built a comprehensive material profile for bio-based bamboo fiber composites. Through mechanical testing and user interaction studies, key insights into the material's strength, flexibility, and environmental performance were gathered. These findings provide a solid foundation for the future application of bamboo composites in product design, offering valuable data on how this sustainable material can be utilized in various industries.

11.2.2. Efficient Exploration of User Experiences Through Adapted Toolkit and Comparative Testing

In this project, we adapted an existing toolkit to efficiently collect comparative data between two materials, combining questionnaires and interviews. The user test effectively gathered insights into the experiential characteristics of bamboo composites versus another material. This methodology offers a robust and repeatable approach for future studies focused on understanding user preferences and the experiential attributes of similar materials, providing a blueprint for further comparative material research.

11.2.3. Optimization of Production Parameters for Bamboo Composite Manufacturing

This project explored and optimized key production parameters, such as temperature, pressure, and time, for bamboo fiber composite manufacturing. By refining these variables, the study offers critical insights for scaling up the production process. The results are invaluable for informing large-scale manufacturing efforts and ensuring that the bamboo composite can be produced consistently with high quality, which is essential for its industrial application.

11.2.4. Feasibility of Remanufacturing and Reusing Bamboo Composites for Larger Products

A significant outcome of this project is the validation of remanufacturing techniques for bamboo composites, including the possibility of reusing discarded composite material. By successfully demonstrating the feasibility of joining and remanufacturing smaller composite parts, this study supports the potential for producing larger-scale bamboo composite products, while also advancing sustainability by minimizing waste and encouraging material reuse.

11.2.5. Adaptability of Short Bamboo Fibers in Complex Molding via Vacuum Bag Thermoforming

The vacuum bag thermoforming experiments conducted during this project showed that short bamboo fibers can conform well to complex mold curves, producing smooth and aesthetically pleasing products. This confirms that bamboo fiber composites are suitable for intricate designs and complex shapes, providing valuable insights for future innovative applications of bamboo composites in a variety of fields, from consumer products to architectural elements.

11.2.6.Evaluating Success Possibility Through the IDEO DFV Framework

The success of a product can be evaluated using the IDEO DFV framework, which considers three critical factors: desirability, feasibility, and viability. In terms of desirability, the results from material characterization show that potential users have responded positively to the new bamboo fiber composite material, expressing curiosity and anticipation.

Although some users had doubts about its sustainability, I believe this material presents an excellent opportunity to offer consumers a sustainable alternative and ignite relevant conversations.

Regarding feasibility, the successful development and testing of prototypes in a laboratory environment confirm the practicality of this material for real-world application. Finally, in terms of viability, the ongoing push by EU legislation for carbon-neutral products suggests strong support for developing low-carbon materials, with subsidies potentially available for further innovation. Additionally, the low cost and easy availability of raw bamboo fiber materials, combined with the relatively simple manufacturing process, ensure that production costs can remain low, making the product attractive to consumers while also maintaining a healthy profit margin.

11.3 Discussions

11.3.1. Challenges in Future Bamboo Composite Production

Factors like fiber fraction, moisture, chemical treatment(Sawpan et al., 2012) are not included in this project, but are interesting to explore for establishing mathematical prediction on composites' properties. (Venkateshwaran et al., 2012) Also, the current manufacturing process for bamboo fiber-reinforced composites is labor-intensive and involves numerous steps that are difficult to scale for mass production. This significantly impacts the overall cost of the project, making it less viable for large-scale manufacturing. Moving forward, a major area for future research should focus on how to automate the production of bamboo composites. Automation could streamline the process, reduce labor costs, and improve consistency in material quality. Developing new techniques or machinery specifically tailored to the unique properties of bamboo fibers and bio-HDPE could unlock the potential for this material to compete on a commercial scale.

11.3.2. Variability in Experiential Characterization Data

During the experiential characteristic interviews, one limitation was the relatively small sample size, which contributed to a high variance in the collected data. The large variance makes it difficult to discern clear patterns or trends in how users perceive the material. In future research, increasing the number of participants and diversifying the sample group could provide more reliable insights. Additionally, more rigorous statistical methods may be necessary to analyze the data in a way that accounts for the broader spectrum of user preferences and interactions with the material.

11.3.3. Refining Comparative Testing Methods

Another challenge encountered during the experiential characterization interviews was adapting the toolkit for comparing two different materials. This process highlighted several inefficiencies, such as participants losing patience due to repeated questionnaires and the redundancy of certain questions. Additionally, I overestimated the participants' ability to distinguish subtle differences between the two materials, which led to redundant or incomplete data. Moving forward, the toolkit for comparative testing needs to be streamlined to avoid repetition, which could be achieved by merging overlapping questions or developing more intuitive methods for comparing multiple materials simultaneously. This would likely enhance data quality by keeping participants engaged and focused.

11.3.4. Industrial Viability of Manufacturing Techniques

While the prototype was successfully manufactured using an epoxy mold and vacuum bag thermoforming, this method is not ideal for large-scale industrial production. In this project, the vacuum bag method was used as a low-cost alternative to validate the molding process for small-scale production. For larger orders, however, metal molds are much more efficient, reliable, and cost-effective. Although vacuum bagging offers flexibility for small batches, future industrial applications would benefit from exploring metal mold alternatives, which can withstand higher production volumes and deliver consistent product quality.

11.3.5. Market Potential for Bamboo Composites

The market potential for bamboo fiber-reinforced composites is promising, given the overwhelmingly positive feedback during user testing. Participants expressed curiosity, surprise, and admiration for the material, which blends natural aesthetics with structural strength and versatility. The introduction of bio-based bamboo composites fills a gap in the market for materials that offer both a natural appearance and mechanical robustness. This combination of features sets bamboo composites apart from existing alternatives and suggests a strong future demand, particularly in sectors where sustainability and aesthetic appeal are highly valued.

11.3 Limitations

11.3.1. Limited Scope of Market Research

The market research conducted for this project was primarily centered around insights gathered from the JEC Composite Show, a leading event in the composites industry. While the event provided valuable information and access to industry professionals, the narrow scope of this field research limits the diversity of perspectives. Attendees at such events tend to represent a specific segment of the industry, and this may have excluded other potential stakeholders or market trends not present at the show. As a result, the findings may not fully represent the broader composite material market, limiting the overall market applicability of bamboo composite products.

11.3.2. Manual Fiber Alignment and Production Inefficiency

A significant limitation encountered during this project was the manual process of aligning bamboo fibers for composite production. This method not only lacks precision but also demands considerable time and effort. While the concept of aligned bamboo fiber composites shows promise, the current inefficiencies in production severely restrict creative experimentation and limit scalability.

11.3.3. Partial Life Cycle Analysis

The life cycle analysis (LCA) conducted as part of this project only considered a small portion of the material's overall life cycle, focusing primarily on the production phase. This limited scope fails to provide a holistic view of the environmental impact of bamboo composites versus traditional materials like metal. Although the bamboo composite showed lower emissions during the production stage, metals such as zinc have a very high recycling rate, making it difficult to definitively conclude which material is more sustainable in the long run. Without comprehensive data on the remanufacturing and end-of-life stages of bamboo composites, it remains challenging to assess the full environmental potential of the material.

11.3.4. Limited Product Applications with Thermoplastic Bamboo Composites

This project only researched bamboo fiber-reinforced composites in a thermoplastic format, which restricts the range of products that can be created. While thermoplastics offer certain advantages such as moldability and recyclability, they also limit the potential applications of bamboo composites in industries requiring high-temperature resistance or more durable, thermoset materials. The current limitations in material diversity restrict the bamboo composite's potential for broader applications, and future development efforts should focus on expanding the material's capabilities to encompass other composite types, thus broadening its application range.

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