VALIDATING THE END-OF-LIFE POTENTIAL OF BIOBASED COMPOSITES BY DESIGNING A DEMONSTRATOR PRODUCT

MASTER THESIS BY LICA BOOT

VALIDATING THE END-OF-LIFE POTENTIAL OF BIOBASED COMPOSITES BY DESIGNING A DEMONSTRATOR PRODUCT

MASTER THESIS BY LICA BOOT

Delft University of Technology
Industrial Design Engineering
February 2025

Master Thesis
MSc Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Author
Lica Boot
4832272

TU Delft Supervisory Team
Department: Sustainable Design Engineering
Chair: Ir. J. J. Joustra
Mentor: Ing. M. Slingerland

Company
Name: Eve Reverse
Mentor: Karel Brans

PREFACE

This thesis is the final project of my Master's degree in Integrated Product Design at the Faculty of Industrial Design Engineering at TU Delft. I dedicated my time to this project from September 2024 to February 2025. This report offers an overview of the work accomplished over the past six months. During this project, I learned to design from a materials perspective and gained a lot of hands-on experience producing composite materials. I could also apply and expand my knowledge, creativity and skills gained from my Bachelor's and Master's studies and extracurricular activities.

I want to express my gratitude to my supervisors. To my chair, Jelle Joustra, for his guidance and critical questions. His attention to my scope helped me to stay on track and maintain focus during this project. To my mentor, Mascha Slingerland, for her support throughout this project and introducing me to the applied labs. Her keen eye on my process and report writing contributed to the quality of my work.

I would also like to thank my colleagues at Eve Reverse for their encouragement, in-depth knowledge and valuable insights. Having access to so much equipment and materials was incredibly helpful. I appreciate the freedom they gave me to explore and shape my project.

Furthermore, I thank all the designers, researchers, students and experts who contributed to various activities during this project. Lastly, I want to thank my friends and family for their support.

I am proud to present my thesis 'Validating the End-of-Life potential of biobased composites by designing a demonstrator product'.

Enjoy reading!

ABSTRACT

Composite materials are valued for their high stiffness, strength, and low density, offering durability, which makes them a popular choice in sustainable design. However, the complexity of recycling composites at the End-of-Life presents a challenge due to the combination of different materials. While bio-based composites, with lower CO2 emissions, offer a more sustainable alternative to fossil-based materials, the recycling problem remains an issue.

This thesis explores possible EoL options for biobased composites during the early stage of industrialisation to prevent future waste. The Material Driven Design method is used to explore the first-cycle flax/furan composite material. A recycling method, separating layers through intentional delamination, was identified, preserving the value of the fibres for reuse.

Research and tests have shown that the recycled material can be used in new products, and the potential of the recycled material was evaluated through a demonstration design. The project confirms that the life cycle of Eve-tiles can be extended in this way and provides valuable insights into the challenges and opportunities of sustainable composite materials.

Keywords

Material Driven Deisgn, End-of-Life, Biobased composites, Intentional delamination, Industrial Design Engineering.

Abbreviations

LCA	Life Cycle Assessment
EoL	End-of-Life
NFRPC	Natural fibre-reinforced polymer composite
CO_2	Carbon dioxide
MDD	Material Driven Design
Fvf	Fibre volume fraction

READING GUIDE

This reading guide (Figure 1) provides an overview of the project timeline, with the seven chapter titles displayed along this timeline. It highlights which activities have been carried out in parallel and shows the three key decisions made throughout the project. After the concluding chapter, the references and Appendix will follow.

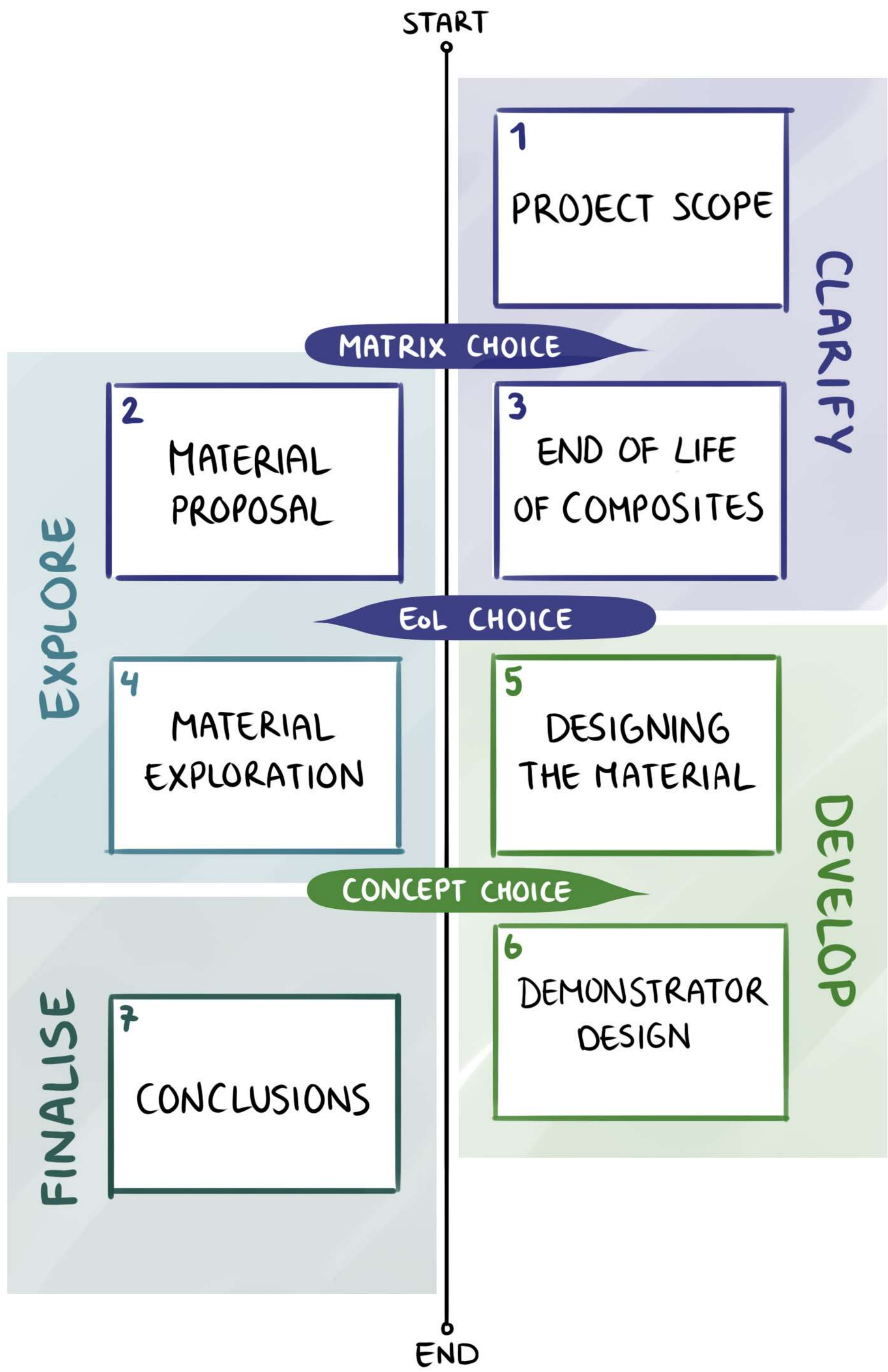


Figure 1: Reading guide

TABLE OF CONTENTS

PREFACE 3
ABSTRACT 4
READING GUIDE 5
TABLE OF CONTENTS 6

01 PROJECT SCOPE 8
1.1 INTRODUCTION 9
1.2 EVE REVERSE 10
1.3 PROJECT APPROACH 11

02 MATERIAL PROPOSAL 14
2.1 COMPOSITES 15
2.2 FLAX PROPERTIES 16
2.3 MATRIX OPTIONS 17
2.4 MATRIX CHOICE 19
2.5 TINKERING WITH MATERIAL 21
TAKE-A-WAYS 23

03 END-OF-LIFE OF COMPOSITES 24
3.1 WHAT IS END OF LIFE? 25
3.2 END OF LIFE OPTIONS 26
3.3 SELECTION CRITERIA EOL CHOICE 28
3.4 EOL CHOICE 29
TAKE-A-WAYS 31

04 MATERIAL EXPLORATION 32
4.1 MATERIAL ORIGIN 33
4.2 TINKERING WITH MATERIAL 35
4.3 TECHNICAL PROPERTIES 36
4.4 USER STUDIES 42
4.5 MATERIAL BENCHMARKING 46
TAKE-A-WAYS 47

05 DESIGNING THE MATERIAL 48
5.1 DESIGN VARIABLES 49
5.2 REQUIREMENTS 51
5.3 DESIGN VISION 52
5.4 IDEATION 53
5.5 PRODUCT CONCEPTS 55
5.6 CONCEPT CHOICE 59

06 DEMONSTRATOR DESIGN 60
6.1 PRODUCT PROPOSAL 61
6.2 DASHBOARD DESIGN 62
6.3 PRODUCTION OUTCOMES 64
6.4 VALIDATION 68
6.5 FEASIBILITY 70
6.6 DESIRABILITY 71
6.7 VIABILITY 72

07 CONCLUSIONS 74
7.1 CONCLUSION 75
7.2 LIMITATIONS & RECOMMENDATIONS 76
7.3 PERSONAL REFLECTION 77

08 REFERENCES 78

09 APPENDIX 82
APPENDIX 1: TINKERING WITH MATERIAL 83
APPENDIX 2: TINKERING FOR MATERIAL 88
APPENDIX 3: EOL TESTS 90
APPENDIX 4: OVERVIEW EOL OPTIONS 92
APPENDIX 5: TENSILE TEST 94
APPENDIX 6: THREE-POINT BENDING TEST 96
APPENDIX 7: PLOTS 98
APPENDIX 8: EXPERIENCE TESTS 100
APPENDIX 9: DESIGN VARIABLES 104
APPENDIX 10: IDEATION DIARY 106
APPENDIX 11: GROUP BRAINSTORM 108
APPENDIX 12: ELIMINATION IDEAS 110
APPENDIX 13: C-BOX 112
APPENDIX 14: FIRST-CYCLE MATERIAL 114
APPENDIX 15: INTERVIEW SUMMARY 116
APPENDIX 16: PROJECT BRIEF 118

01

PROJECT SCOPE

1.1 INTRODUCTION
1.2 EVE REVERSE
1.3 PROJECT APPROACH

1.1 INTRODUCTION

carbon negative
car·bon ne·ga·tive
adjective
1. If an organisation, activity, or thing is carbon negative, it takes more carbon dioxide out of the air than it produces.

What does it truly mean for a material to be "carbon negative"?

Flax fibres absorb CO_2 during their growth. With the help of sunlight and water, the CO_2 is converted into carbon hydrates and oxygen. These flax fibres can be used to make different type of materials from linen to biobased composites. This means that these materials store CO_2 in the form of CH_2O. If more CO_2 is stored than used during the lifecycle of the material, it can be said that this material is carbon negative (Figure 2).

With this in mind, we can understand that biobased materials are a sustainable choice when compared with fossil-based materials. However, it is important that the CO_2 that is captured in the material will be stored as long as possible. Therefore, it is important to look into the recycling opportunities for products made of biobased materials to ensure that this carbon storage can be extended.

This thesis project will adress this challenge, by exploring ways to extend the lifecycle of biobased composite materials.

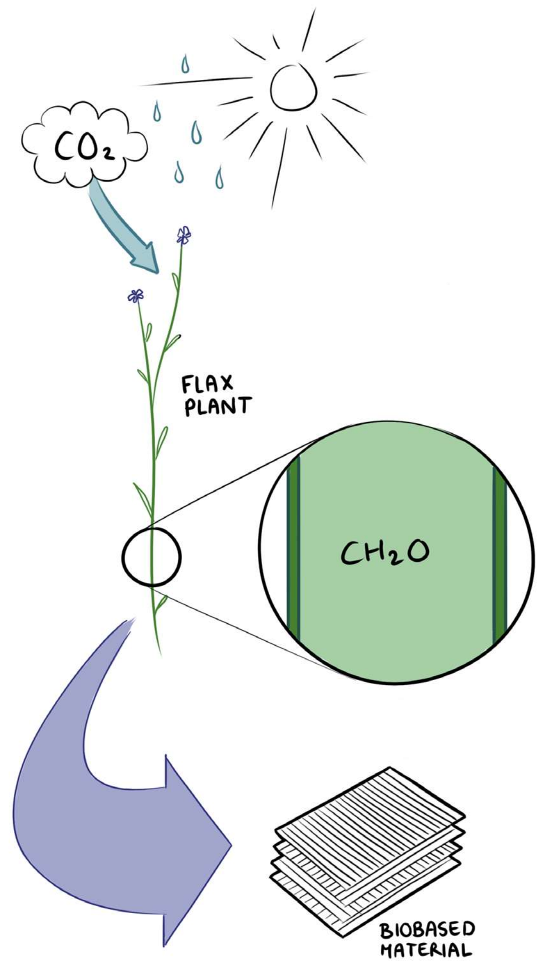


Figure 2: Process of storing CO_2

1.2 EVE REVERSE

Eve Reverse is a startup founded by experienced composite, materials, and industrialisation experts. They want to fight climate change by developing technologies to manufacture truly carbon-negative products. These are products that capture more CO2eq during manufacturing than they emit and have a long lifetime so that the product can store the captured CO2 for decades (Eve Reverse, n.d.).

Eve Reverse has developed the Eve-tile. The Eve-tile is a fibre preform consisting of scutched flax, processed in a unidirectional tile, including a natural stabilising agent to prevent fibres from splitting apart (Figure 3). The Eve-tile embraces the finite fibre length of natural fibres, reducing the energy required to make fibres continuous by eliminating processing steps like drawing, spinning, and weaving. Individual Eve-tiles are stacked in a mould with overlapping edges, after which a resin is added, and the mould is closed.

The first-cycle material made from the Eve-tile has qualities comparable to those of glass fibre composites with epoxy resin if compensated for the density (Table 1). The exact material qualities of a product made from the Eve-tile still need to be studied, as well as the EoL options. If performance tests show positive results and suitable applications are identified, the Eve tile could be an important step towards developing low-emission fibre preforms, paving the way for CO2-negative composites.

	Flax / furan	Glass fibre / epoxy
Density (kg/m^3)	1357- 1411	1600 - 1950
Tensile strength (MPa)	170,6 - 199,7	300 - 1100
Young's modulus (GPa)	17,0 - 31,2	35 - 45
Flexural strength (MPa)	175,0 - 407,0	300 - 900
Flexural modulus (GPa)	17,6 - 36,8	35 - 45
Price (€/kg)	6,43 - 8,27	22,3 - 31,6
Source	Eve Reverse Data base	Granta EduPack

Table 1: Values of flax/furan compared to glass fibre/epoxy

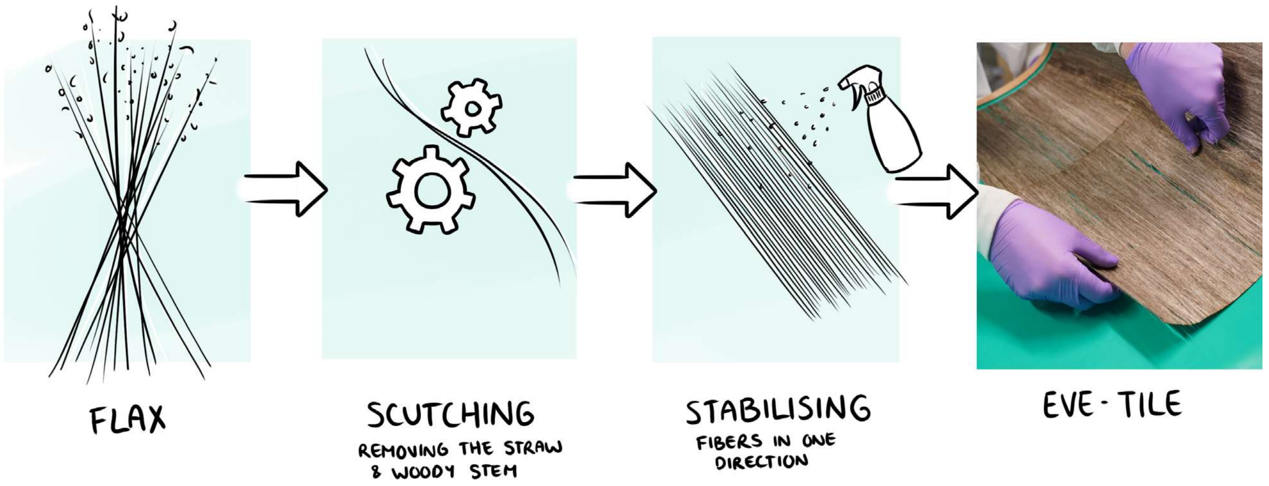


Figure 3: Production process of Eve-tile

1.3 PROJECT APPROACH

1.3.1 PROBLEM DEFINITION

A composite material is a synergy of two or more materials, resulting in a material with unique mechanical properties. The reinforcing fibres provide a unique combination of high stiffness and strength with low density. The matrix keeps these fibres together by giving rigidity and environmental resistance (Åström, 1997). These characteristics make composite materials very durable, which results in a long product lifetime. This extended lifetime is a reason why designers choose this material in terms of sustainability. On the other hand, combining different materials to get to these properties will complicate the recycling process at the EoL of products.

Since the emergence of composites in the 1950s, the composite industry has grown rapidly, with both demand and production steadily increasing. Composites are valued for their long service life, which results in minimal composite waste despite years of production. However, as the first generations of composite products began reaching their EoL, a new challenge emerged: the recycling of composite materials (Van Oudheusden, 2019).

While most composites are still manufactured with fossil-based materials, Eve Reverse focuses on bio-based composite materials with low CO2 emissions. Despite substituting fossil-based materials with bio-based materials, the recycling problem remains unsolved. Therefore, it is important to explore EoL options in the early stage of development to prevent future bio-composite waste.

1.3.2 PROJECT DEFINITION

This project aims to validate the sustainable potential of the Eve-tile in the circular economy by exploring EoL options and designing a suitable application for the EoL material.

To achieve this goal, this project will focus on the following objectives:

I. Selecting a promising matrix in combination with the Eve-tile.

II. Exploring EoL options of an Eve-tile composite.

III. Mapping out technical and experiential material characteristics of the EoL material.

IV. Demonstrating the EoL potential with a suitable application of the EoL material.

Based on the goal and objectives, the following main research questions are formulated:

1. **What is the most suitable EoL option for the Eve-tile composite within the scope of this project?**

2. **Given the most suitable EoL option, how can we demonstrate the EoL potential of the Eve-tile?**

1.3.3 METHODOLOGY

This section will explain the methods for answering the research questions formulated earlier. The first main research question will be answered at the end of the analysis phase of this project. The second main research question can only be answered if the analysis phase is over and will therefore be answered in the design phase of this project (Figure 4).

1. What is the most suitable EoL option for the Eve-tile composite within the scope of this project?

To make sure that the analysis phase will not cover the majority of the project time, sub-research questions are composed to structure this phase of the project:

Composites
1a. What is a (bio-based) composite?
1b. What are the technical properties of flax?
1c. What is a promising matrix in combination with the Eve-tile for this project?

EoL
1d. How are (bio-based) composites recycled currently?
1e. What are the EoL options of the Eve-tile in combination with the promising matrix?
1f. When is it viable to recycle a bio-based composite?
1g. What are the selection criteria for the best EoL option for this project?

Most of these questions can be answered by conducting literature research and talking to experts. To answer question 1e, a good understanding of the original material is needed (Eve-tile + promising matrix). Therefore, some elements of the MDD Method will be used to gain this understanding. This method will be explained later in this paragraph.

2. Given the most suitable EoL option, how can we demonstrate the EoL potential of the Eve-tile?

The second main research question can be split up into two sub-research questions, which will be answered during the design phase of this project:

2a. What are the unique properties (technical and experiential) of the EoL material of the Eve-tile composite?
2b. What is a suitable application to show the EoL potential of the Eve-tile composite?

These two sub-research questions will be answered using elements of the MDD Method. Unlike traditional design methods, we do not select the material based on the desired functions but start from the material. This method helps to push the boundaries of traditional material development and product design by exploring the 'unknown' (Karana et al., 2015). For this project, elements of the MDD method that are relevant to the scope of this project will be used.

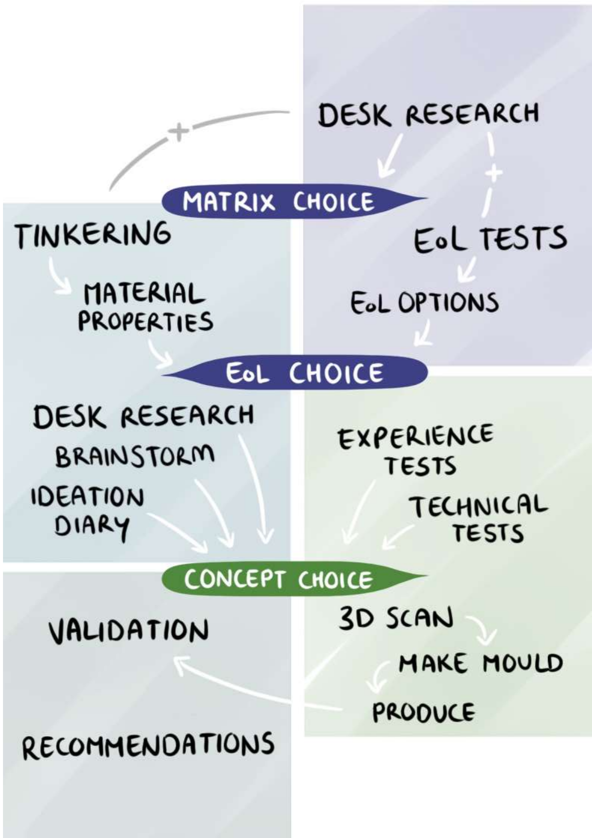


Figure 4: Methodology

The MDD method focuses on user experience and can steer the final design towards a use case. It is important to ensure that this does not distract from the goal of showing the sustainable potential of the material. the EoL material will be experienced differently than the original material. The MDD method consists of four steps (Figure 5):

1. The first step is 'understanding the material,' which includes material benchmarking, tinkering, technical tests, and user studies. These activities help to get a complete overview of the material's composition, how it reacts in different scenarios, and how people experience it.
2. In the second step, based on the findings of the first step, a material experience vision is created. The vision represents the design goal for this material and helps to express its role in relation to the product, its user, and the context.
3. The third step will reveal material experience patterns. For this, experiential qualities are extracted from the material experience vision. Then, other materials/products with the same experiential qualities are looked at to better understand this quality.
4. The fourth step involves designing material and product concepts. Using the knowledge and outcomes of the previous steps, concepts can be developed based on the material's unique technical and experiential qualities.

Based on the outcomes of steps 1 and 2, it will be decided whether step 3 will be executed or directly followed by step 4.

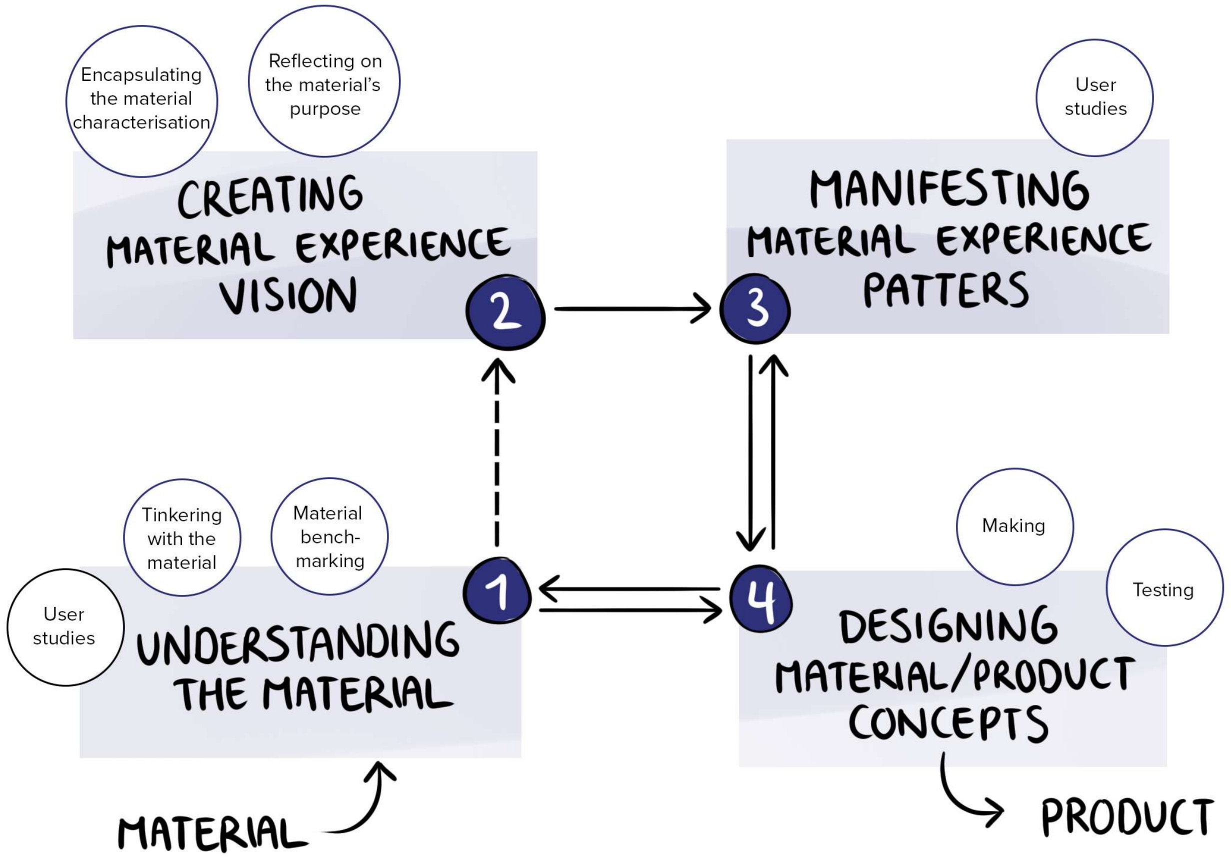


Figure 5: MDD Method

02

MATERIAL PROPOSAL

2.1 COMPOSITES
2.2 FLAX PROPERTIES
2.3 MATRIX OPTIONS
2.4 MATRIX CHOICE
2.5 TINKERING WITH MATERIAL

2.1 COMPOSITES

2.1.1 WHAT IS A COMPOSITE?

As mentioned before, a composite material is a synergy of two or more materials that result in a material with unique mechanical properties. A composite is comprised of a matrix and reinforcement. There are different types of composite materials, but in this thesis, composites are defined as fibre-reinforced polymers. This means that the reinforcement is a type of fibre, and the matrix is a polymer resin. The matrix binds the reinforcements together, protects the fibres from environmental effects, and gives the composite shape. The reinforcing fibres carry most of the load, thus providing strength and stiffness (Åström, 1997).

One layer of unidirectional fibres with matrix material is called a composite ply. A (laminated) composite is composed of multiple layers of composite plies. When these plies are stacked, the orientation of the fibres can alter the material's properties, allowing the creation of material with different properties in different orientations (Figure 6).

The properties of the composite material also depend on the material choice. Composites can be made from different types of fibres and matrices. Examples of reinforcing fibres are glass, carbon, and flax. The matrix material is either a thermoset or a thermoplastic polymer.

2.1.2 BIOCOMPOSITES

A biocomposite is a composite material reinforced with natural fibres, i.e., a natural fibre-reinforced polymer composite (NFRPC). The matrix of a biocomposite can be any type of polymer. Natural fibres are derived from biological origins, such as flax, cotton, jute, sisal, bamboo, and hemp.

Interest in natural fibres is growing due to benefits like low abrasion, low costs and excellent stiffness-to-weight ratio (Zhao et al., 2021). Natural fibres are also claimed to offer environmental advantages. Natural fibres have a reduced dependency on non-renewable resources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and biodegradability (Joshi et al., 2003). These environmental advantages will stimulate the use of natural fibres in composite materials. However, products made from biocomposites will not last forever. Therefore, it is important to explore EoL options of biocomposites and explore how these materials can still be used at the EoL. Developing recycling and disposal strategies will be essential to ensure that the environmental advantages of biocomposites are preserved throughout their entire lifecycle.

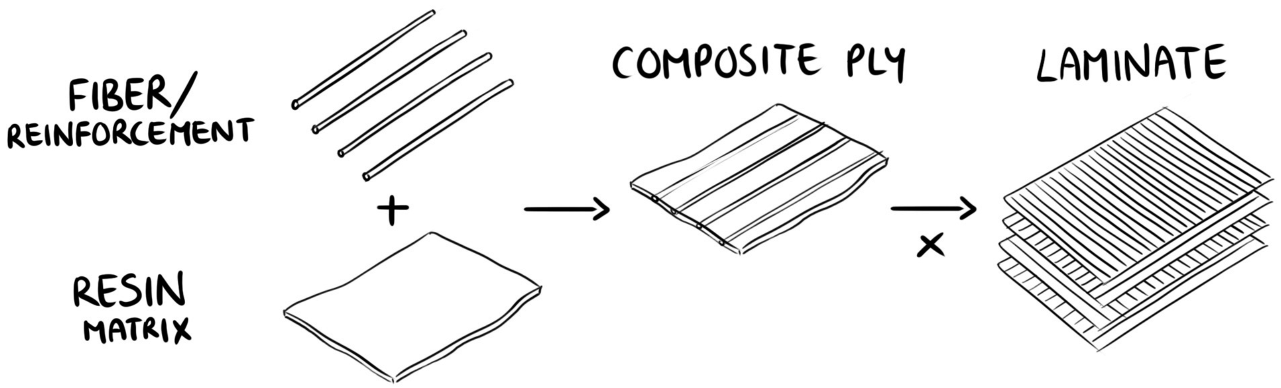


Figure 6: Construction of a composite material

2.2 FLAX PROPERTIES

For this thesis, the type of fibre is flax, as determined by Eve Reverse, as these are the fibres of which the Eve-tile is made. Flax is a bast fibre found in the stem of the Linum Usitatissimum. Over 80% of all flax is planted and harvested in France, Belgium and The Netherlands (Van In, 2019). Cultivated flax plants grow to 1,2 meters tall, with green, slender leaves and small flowers with five petals, which can have different colours depending on the species (Figure 7). The main constituent of flax fibres is cellulose, but it also includes hemicellulose, pectin, lignin, and waxes (Singleton et al., 2003).

Flax fibres are used in various industries due to their strength, durability, and eco-friendly properties. Short flax fibres are used to produce high-quality paper and insulation material, both for thermal and acoustic purposes and for padding pillows or mattresses. Thousands of years ago, long fibres were used to make linen fabric. Using flax to make fabric has the beneficial properties of being comfortable to wear, breathable, and elegant (Nigam & Yadav, 2019). Because of their high tensile strength, long fibres are also used to make ropes and twines. Both short and long fibres are used to make fibre-reinforced composites because of their high strength-to-weight ratio. The Eve-tile is made of long flax fibres, which will be the focus of this project.

When comparing flax fibre with glass fibre properties, it can be seen that flax fibres have a tensile strength that could compete with those of Glass fibres (Table 2). When considering the density of flax fibres, the specific modulus of flax fibres is higher than that of glass fibres.

	Flax fibres	Glass fibres
Density (kg/m³)	1400 - 1500	2500 - 2600
Tensile strength (MPa)	343 - 2000	2000 - 3500
Specific modulus (GPa)	45	29
Elastic modulus (GPa)	27,6 - 103	70 - 76
Price (€/kg)	0,29 - 1,48	1,52 - 3,09

Table 2: Flax fibres vs. Glass fibres (Yan et al., 2013)

Next to strength and stiffness, flax is also an attractive choice when looking at costs. Another important property of flax fibres is that they are highly hydrophilic. This means that they are highly prone to moisture absorption, which can reduce their mechanical properties (Moudood et al., 2018).

Figure 7: Flax fibres

2.3 MATRIX OPTIONS

This thesis will focus on the Eve-tile in combination with one specific matrix. To determine which matrix material will be chosen, an overview of realistic options was made together with employees of Eve Reverse (Table 3). To narrow down this list, a choice must be made between using a thermoplastic or a thermoset matrix.

Thermoset polymers are getting more attention by researchers because they outperform thermoplastic polymers in certain areas. One of the reasons for this is that thermoset matrices tend to have better adhesion with natural fibres, which also results in better mechanical properties. Additionally, thermoset polymers have good chemical resistance, which helps to protect the fibres from environmental effects. Another advantage is that thermoset polymers can be processed and cured at room temperature or within the safe temperature range for natural fibres. Their cross-linked networks also make them thermally stable and highly durable (Yan et al., 2013). However, a downside of using a thermoset is that there are few to no recycling options. Most proven techniques for recycling thermoset composites are based on shredding or grounding the composite and using the product as a reinforcing filler (Åström, 1997).

Thermoplastic polymers have the advantage of being thermally processed, which means they can be melted and reshaped for a new application. When looking at mechanical properties, thermoplastic polymers are more flexible and impact-resistant than thermosets, which are more brittle when cured. Lastly, thermoplastic polymers have shorter curing times (depending on the type of process) and can be processed using different manufacturing techniques, which gives more design freedom (Yan et al., 2013).

Thermosets are more suitable in combination with flax fibres if high mechanical performance is required. Thermoplastic matrices are a better choice if recyclability and flexibility are prioritised.

Matrix material	Polymer type	Notes
Bio UPE	Thermoset	70% biobased
Furan	Thermoset	100% biobased
Cleavable Epoxy	Thermoset	Not biobased, thermoplastic possibilities in the second lifecycle.
Plantics	Thermoset	Developed by Plantics, 100% biobased
Oribond (Orineo)	Thermoset	Developed by Orineo, 100% biobased
Elium PMMA	Thermoplast	Not biobased, has thermosetting possibilities
Bio HDPE	Thermoplast	Properties not ideal for long fibres
PA11	Thermoplast	Produced by Rilsan, 100% renewable origin
PHA	Thermoplast	100% compostable in nature
POND	Thermoplast	Polyester, similar to PLA
PLA	Thermoplast	Biodegradable

Table 3: Overview of possible matrix matrials

Together with the employees of Eve Reverse opportunities and challenges of these types of matrices were considered (Table 4). Because thermoset matrices are often used in the industry (because of the advantages mentioned above), Eve Reverse gets questions from external parties about the possibilities at the EoL of biocomposites with a thermoset matrix. This, together with the lack of knowledge about the recycling possibilities of thermoset matrices, makes it more interesting to look at this combination. The challenge will be determining what is still possible at the EoL for a composite made from a thermoset matrix in combination with flax fibres despite the limited recycling options for thermosets.

Thermoset		Thermoplast	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Historically used more often in combination with natural fibres.	Brittle when cured.	More recycling possibilities due to thermal processing possibilities	Lower heat resistance
Better adhesion with natural fibres.	Few to no recycling options.	Flexible and impact-resistant.	Less chemical resistance
Good mechanical strength and chemical resistance.		Shorter curing times.	Less stiff
Cross-linked networks make them strong and stable.		More options for manufacturing techniques.	
Suitable for high mechanical performance applications.		Suitable when recyclability and flexibility are prioritised.	

Table 4: Overview of advantages and disadvantages of thermoset and thermoplast matrix

2.4 MATRIX CHOICE

To be able to select one of the thermosetting matrices, selection criteria are established and prioritised to make a considered choice.

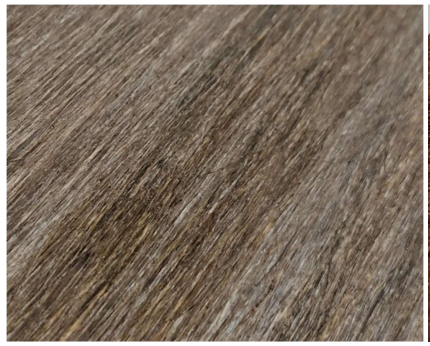
1. For this project, it is most important that the matrix material is available within the project scope so that it can be tested, prototyped, and designed.
2. For Eve Reverse, it is important that the matrix material is used in existing applications. External parties are interested in learning more about EoL possibilities for these matrices.
3. Technical opportunities and weaknesses and the number of possible EoL options that could help or limit this design process.

Based on these selection criteria, a new overview of possible thermoset matrices is made (Table 5).

Based on this overview, it was decided that the options Bio-UPE and Furan should be investigated further. The most important reason is that the material is available and has been successfully tested before in combination with flax fibres at Eve Reverse. Both materials are known in the industry, which is why Eve Reverse gets asked about the EoL of the material. The fact that the materials are already used in the industry also means that the outcome of this thesis could be applied in a shorter timeline. Cleavable epoxy will not be considered because it is not biobased, which does not align with Eve Reverse's mission. Plantics and Oribond are both startups working on the development of their material themselves. When choosing Plantics or Oribond, a collaboration has to be set up, which is difficult because they are keeping details about the material for themselves at this moment.

Polymer	Availability samples	Tested with Eve-tile	Known in industry	Strong points	Weak spots	End of Life options
Bio UPE	+/-	+	+	• Cure at room temperature • Mold at atmospheric pressure • Polyester is well known in industry	• Larger curing volumetric shrinkage • Poor heat resistance	• Mechanical recycling • Thermal recycling • Chemical recycling
Furan	+	+	+	• Excellent heat-resistant • Crosslinking and curing without curing agent	• Oxidation resistance is poor	• Mechanical recycling • Thermal recycling • Chemical recycling
Cleavable Epoxy	+/-	+	-	• Can be used as thermoplast in second cycle • Low shrinkage (does not produce by-products in curing process) • Excellent mechanical properties • Strong chemical stability	• Not biobased	• Reshaping • Mechanical recycling • Thermal recycling • Chemical recycling
Plantics	-	-	-	• Produced out of waste material from plants • CO2 negative	• Not open source	• Unknown
Oribond (orineo)	-	-	-	• Water resistant • Versatile curing range • 100% derived from annual plants	• Not open source	• Biodegradable • Compostable

Table 5: Comparison of thermoset matrices



	Bio-UPE	Furan
Availability material	+/-*	+
Biobased content (%)	70	100
Curing temperature	Room temperature	115 °C
	Energy is inside of polyester to cure	Curing in the oven
Heat resistance	Poor	Excellent
Density (kg/m3)	1210	1200-1350
Viscosity (cP)	530	<250

Table 6: Bio-UPE vs. Furan
**There are two types of Bio-UPE available. 3830 is the older version with which only a hand lay-up is possible, the problem is that this has never succeeded before at Eve Revere. 3831 is the newer version with which an infusion is possible as well, but this type is not available at the moment and has a long shipping time.*

Table 6 shows a comparison between Bio-UPE and furan. When deciding between Bio-UPE and furan, it is still important that the material is available and 'easy' to process. This way, making samples for testing within the project scope will be possible. Eve Reverse's mission is to develop a carbon-negative composite. Eve Reverse only delivers the reinforcement as a product. However, to showcase the potential of the Eve-tile, it is most interesting for them if the reinforcement, in combination with the matrix, has the potential to be carbon-negative.

One disadvantage of using furan is that the material needs to be cured in the oven; this means that energy is needed to cure the material, and brings design limits in size. Another poor quality of flax fibres and furan resin is that they degrade under prolonged UV exposure (Granta EduPack, 2024).

However, furan has other advantages, such as good fire resistance, which means it can protect flax fibres against heat until a certain point. The strength of flax fibres starts to decrease from 150°C and degrade at temperatures higher than 230°C. Furan also has good chemical resistance. This means that furan can protect flax fibres against chemicals/moisture. However, flax fibres are highly hydrophilic, so a surface treatment should be considered.

It has been decided that furan will be used as the matrix for this project due to the reasons mentioned above, as well as its greater availability compared to Bio-UPE and its 100% biobased content.

2.5 TINKERING WITH MATERIAL

To get to know the selected flax/furan material, one of the first activities of the MDD method will be executed. The MDD method encourages to tinker with the material to gain a better understanding of the material. Tinkering with the material means trying out all kinds of things without having any assumptions. This activity aims to learn more about the qualities of the material, recognise the constraints, and identify its potential. The tinkering activities are diverse, from cutting and shredding to boiling a sample. The tinkering activities will be performed with both first-cycle and recycled material. Interesting outcomes of this activity are material drafts (Figure 8), which will be described in this paragraph. A complete overview of the tinkering activities, including more pictures, can be found in Appendix 1. The most important take-a-ways are summarised on this page.

Lasercutting

Purpose: Is it possible to laser cut? Will it burn?
Process: The lasercutter made very neat cuts, both along and perpendicular to the fibres. The laser made the furan smell burned.
Take-a-ways: Laser cutting is a very good way of cutting the sample.

Bending

Purpose: What happens if a sample is bended?
Process: The different layers seperate from each other.
Take-a-ways: It might be possible to use separation of layers as a recycling option.

Sheet forming

Purpose: What happens if the sample is put through a sheet forming machine?
Process: The layers start to separate from each other.
Take-a-ways: It might be possible to use separation of layers as a recycling option.

Blending

Purpose: Is it possible to blend a sample?
Process: It is possible to blend a sample. The result is a powder with some fibrous particals.
Take-a-ways: It might be possible to use the powder to make a new material from it.

Granulator

Purpose: Is it possible to shred a sample?
Process: The granulator produces particals of around 1 x 4 mm.
Take-a-ways: Blending and granulating the samples gives a fibrous result.

Boil in water

Purpose: What happens to the sample if it is boiled in water for 2 hours?
Process: The sample feels softer and it is possible to peel the layers from each other.
Take-a-ways: Boiling the sample might make it easier to separate the layers.

1. Future samples will be cut with the laser cutter. This method gives the cleanest result. Cured furan has good heat resistance. However, proper ventilation of the laser cutter is essential since harmful substances can be released when furan is burned.

2. Bending the material makes the different layers split up. Running the sample through a sheet-forming machine confirmed this again. This could be an interesting finding to test for the fibres' recyclability.

3. Blending and granulating the samples gives a fibrous result. The pieces resulting from the granulator are a bit bigger; this retains more of the fibre value.

4. Boiling the sample makes the material softer and more flexible, allowing the different layers to be separated.

Figure 8: Overview of material drafts

TAKE-A-WAYS

Now that the matrix choice is made, the first sub-research questions can be answered:

What is a (bio-based) composite?
A composite material is a synergy of two or more materials that result in a material with unique mechanical properties. In this thesis, composites are defined as fibre-reinforced polymers. If the reinforcement of a composite material are natural fibres, this material is called a biocomposite.

What are the technical properties of flax?
- High strength and stiffness-to-weight ratio
- Low density
- Highly hydrophilic (high tendency to absorb moisture)
- Cost-effective
- Good insulation
- Low environmental impact

What is a suitable matrix in combination with the Eve-tile for this project?
Furan is chosen as the matrix for this project because it is 100% biobased, available within the project timeline, and relatively easy to handle.

The tinkering activities with the first-cycle material revealed some interesting findings. These findings will help during the remainder of this project:

End of Life options:
Bending the first-cycle material makes the layers separate. This principle can be scaled up by putting the material through a sheet-forming machine. It is interesting to investigate this finding since it could be a recycling option for this material.

Putting the first-cycle material through a granulater results in a fibrous product. Since this fibrous product retains some of its fibre value, it could be a starting point for making a recycled material.

Boiling the material makes the separation of layers much easier. The layers do not break into smaller pieces; instead, they can be separated entirely.

It should be tested whether it is possible to produce material from the separated layers and the granulate (Appendix 3).

In addition to answering the first few sub-research questions and tinkering activities, the first design criteria have been established based on the findings in the first chapters.

Design criteria:
- The demonstrator will be made of flax fibres in combination with a furan resin.
- The material must be cured in the oven, which restricts the maximum dimensions of the demonstrator product to 1.20m x 1.20m.
- Furan resin is moisture resistant, but product design must incorporate moisture protection, because absorbtion of moisture by flax fibres will lead to swelling and deformation of the product.
- Both flax fibres and furan resin degrade under prolonged UV exposure. The product needs a UV-resistant coating if used outdoors.
- Furan has a good thermal stability in comparison to other bio-based resins. However, flax fibres degrade at high temperatures. Avoid applications where prolonged exposure to temperatures above 150 °C is needed.

03

END OF LIFE OF COMPOSITES

3.1 WHAT IS END OF LIFE?
3.2 END OF LIFE OPTIONS
3.3 SELECTION CRITERIA EOL CHOICE
3.4 EOL CHOICE

3.1 WHAT IS END OF LIFE?

The EoL of a product refers to the final stage of its lifecycle when a product is no longer useful or loses its function. This is when the product will be disposed of, recycled, repurposed or managed otherwise. In a linear economy, a product will be disposed of as waste in landfills or incineration. This leads to resource depletion, pollution, and increased waste, which is unsustainable in the long term. In a circular economy, materials never become waste, and nature is regenerated (The Circular Economy in Detail, 2019).

The butterfly diagram (Figure 9) visualises the continuous flow of materials in a circular economy. This diagram shows different circles; the smaller the circle, the more product/material value is preserved. The smaller loops should be prioritised because it is always the best option to extend the useful life of products and keep the material's value as high as possible for as long as possible; in other words, to postpone the EoL. There are different circular strategies to extend the useful life of products (Joustra, 2022):

Long life: Design products that are durable and reliable in use. When using this strategy, it is important to take safety into account. A product will damage over time, so it needs to be determined how much damage tolerance is acceptable in the product context, as this will determine the product's lifespan.

Lifetime extension: Regular maintenance, repair, upgrades, and adaptations can prolong a product's lifetime.

Product recovery: When a product is broken, refurbishment and remanufacturing might still be possible. Collecting spare parts for lifetime extension or a similar product is also part of this strategy. Refurbished products have shorter delivery times and are cheaper, but assessing the structural state is difficult, especially for composite materials.

These circular strategies are part of the inner circles on the right side of the butterfly diagram and aim to extend the product lifespan. Sharing, reusing, and redistributing products also keep these products/materials in their original shape, which is valuable in terms of sustainability. However, keeping a material/product in these inner circles forever is impossible. Therefore, this thesis will focus on the outer circle of the butterfly diagram, which is recycling.

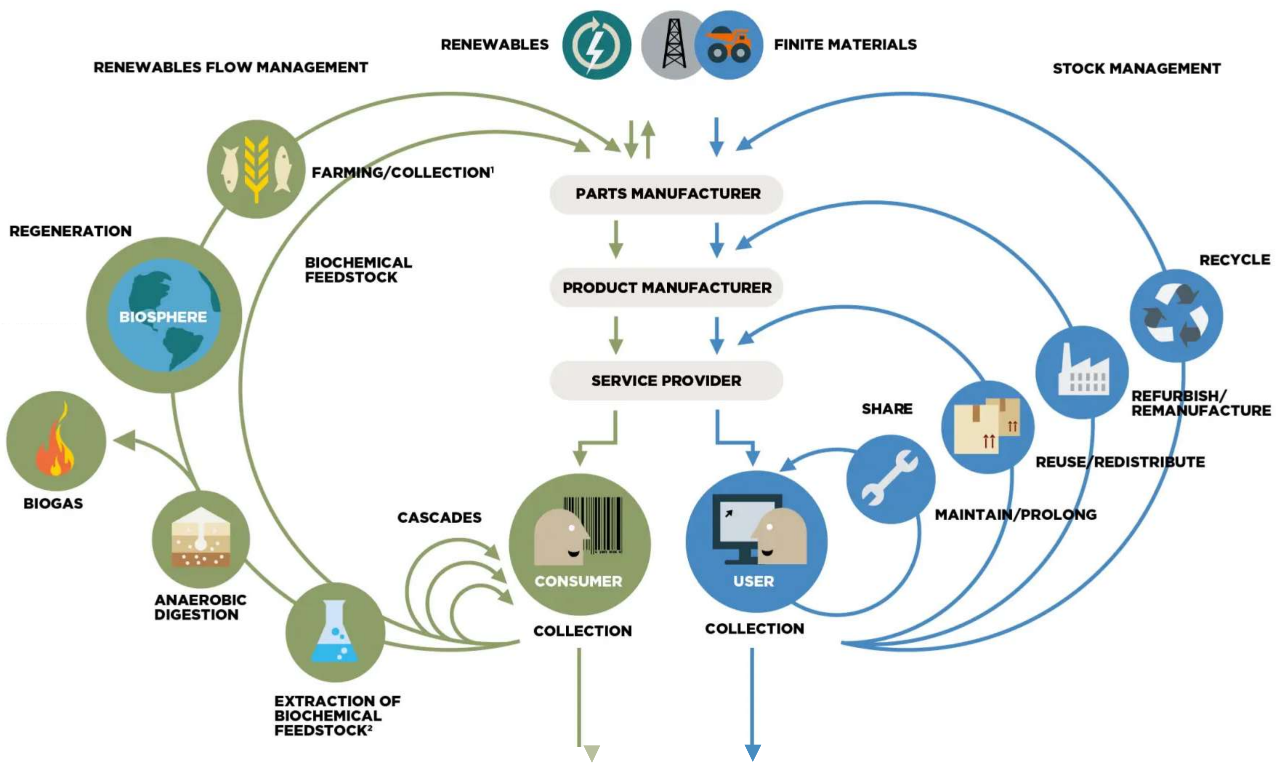


Figure 9: Butterfly diagram (Ellen MacArthur Foundation)

3.2 END OF LIFE OPTIONS

Multiple EoL options are available for composite materials. To select a suitable EoL option for this project, a comprehensive analysis of existing EoL options was done. To structure all findings, a table (Appendix 4) containing all findings was created. The different EoL options are divided into categories that will be explained in this paragraph.

Structural Reuse
Structural reuse involves repurposing, resizing, or reshaping a product. While the original function is discarded, the material's mechanical and structural properties are preserved (Joustra, 2022). To achieve this, detailed knowledge of the initial composite and the ability to assess the structural condition of the used product is essential.

For this project, structural reuse is out of scope because there is no fixed product as the starting point for the first life cycle. The engine cover of an aeroplane is an example for which the original material could be used. However, using this as the starting point for structural reuse would be a hypothetical scenario, which makes it less valuable. Although repurposing, resizing, and reshaping are important considerations in product design, these methods can not be applied endlessly. With each lifecycle, products become smaller or suffer damage, reducing their usability over time. Therefore, this project focuses on what can be done with the material after it has been structurally reused for as long as possible.

Separating layers
The option to separate layers (Figure 10) was found by tinkering with the material (Paragraph 2.5). After tinkering with the material, assumptions and ideas emerged that were tested based on the material drafts. These tinkering for material activities can be found in Appendix 2. During this activity, it was found that it is possible to recycle patches of multidirectional (Figure 10.5) and curved lay-ups (Figure 10.4). Another important finding is that boiling the patches before putting them in the sheetforming machine makes it easier to separate the layers (Figure 10.3). Separating layers is not a recycling method which is used on a large scale. When researching this method, a paper was found written by Justus von Freeden, et al. about a separating layer recycling strategy for continuous fibre-reinforced thermosets based on thermally expanding particles. In this paper, thermally expanding particles are added to the resin of a composite material. When heating the composite material, these particles expand, which induces stress within the material. The stress in the composite material makes it easier to separate the layers. These thermally expanding particles are not biobased, and in terms of sustainability, adding another material to the composite material is undesirable. However, a similar principle can be applied to the flax/furan composite. When flax fibres absorb water, the fibres expand, which can induce stress to ease the separation process of the layers. Boiling the water accelerates this reaction. In Appendix 2 can be seen that putting the material in boiling water seems to have a bigger influence than putting the material in cold water for 24 hours. The method to separate layers should be tested to validate the potential of this method.

Figure 10: Separating layers by putting material through sheet-forming machine (1). Separating without boiling (2), after boiling (3), with a curved lay-up (4), and a with multi-directional lay-up (5)

Mechanical recycling
Mechanical recycling refers to methods that break down material into smaller pieces to make recyclate. This can be achieved by either grinding down the material to roughly separate the fibre and resin fraction or fragmentation, which liberates the fibres from the resin. It should be tested wether it is possible to make a new material of the granulate and how much virgin material should be added.

Thermal recycling
Thermal recycling includes all methods using heat to recover fibres from the matrix or produce energy in the form of oil or gas. The fluidised bed process and pyrolysis recover fibres from the matrix and convert the resin matrices into fuel and gas. However, these two recycling options proved unsuitable for composite materials with flax fibres, due to the high temperatures needed. Flax fibres can not endure the temperatures around 400 degrees Celsius needed for these processes, so fibres can not be recovered this way.

Gasification and hydrogenation will break down the polymer and produce fuel such as oil or gas. These two methods are outside the scope of this project since no material is left to design a new life cycle.

Combustion and incineration produce ash, gas, and heat. Flax fibres absorb carbon dioxide during growth; when the composite material is incinerated, the CO2 is released, but this adds no net CO2 emissions. Many companies claim to be circular because incineration of natural materials is possible. This project strives to retain a higher material value during the next life cycle. However, it is good to understand that the incineration of flax fibres will be possible after multiple lifecycles.

Chemical recycling
Chemical recycling includes methods that use a chemical substance to break down the material into building blocks that can be reused in new products. The matrix is dissolved in a suitable solvent, after which the fibres can be removed from the solvent. The polymer can also be recovered by removing the solvent. However, dissolution is only possible for thermoplastic polymers, and solvolysis is still a very new process, which means there are no commercial applications yet.

Digestion
Digestion is the breakdown of an organic compound into carbon dioxide, methane, water, mineral salts, and new biomass. Just like incineration, digestion can be considered a circular pathway for bio-based products in contrast to petrochemical-based plastics (Ritzen, 2023). Unfortunately, furan is not digestible, which is why this is not an option for flax/furan composite material.
Now that the categories are introduced, Appendix 4 provides a complete overview of EoL options for composite materials. Unfortunately, not all options are suitable for the flax/furan composite material due to the high temperatures used during the process. When flax fibres are exposed to temperatures above 130 °C for an extended period, they will lose their strength (Granta EduPack, 2024). Circular strategies are not EoL options but strategies to prolong the lifetime of the current life cycle. As explained earlier in this paragraph, structural reuse, combustion, incineration, and digestion are out of scope. Dissolution is unsuitable for thermoset polymers, so this is not an option. Solvolysis is a recycling method that is still in the first development phase. No literature is available on applying this method to composite material with natural fibres. As a result, it is challenging to assess whether this process would be suitable for recycling flax-furan composite materials. Additionally, no solvent has been identified that can dissolve furan, and even if such a solvent were discovered, its impact on the properties of flax fibres remains uncertain. Due to these uncertainties, this option is no longer considered a recycling option for this project.

This results in two main EoL options left for this project, separating layers, and mechanical recycling through shredding.

3.3 SELECTION CRITERIA EOL CHOICE

The viability of recycling composite materials is influenced by economic, environmental and technical factors. The circular and environmental incentives are strong, but the economic and technical challenges, such as high costs and low-quality recyclate, limit the widespread application of recycling.

Economic viability
Recycling fibre-reinforced polymers is often difficult to justify based on a purely economic perspective. Recycling methods can be expensive, and virgin materials are relatively inexpensive. This was already mentioned by Åström in 1997 but remains valid today for many composite recycling methods, especially when the recycling process results in materials with lower quality than their virgin counterparts, which limits marketability (van Oudheusden, 2019).

Environmental viability
As explained in the first paragraph of this chapter, in a circular system, materials should be reused and recycled to retain their value for as long as possible. Mechanical recycling can help extend the life of materials, but it often results in lower quality recyclate, complicating its reuse in high-value applications (Van Oudheusden, 2019). Incineration with energy recovery is sometimes preferred over mechanical recycling because it can lead to a net-negative greenhouse gas impact. However, this overlooks the value retention offered by mechanical recycling, which aligns more closely with circular principles (Ritzen, 2023). Maximising life cycles is preferred before incineration as the EoL option.

Technical viability
The main value of recycling composite materials lies in the recovery of fibres. However, the quality of recycled fibres can vary, and if the quality is too low, this reduces the viability of the recycling process (Yang et al., 2012). For recycling composite materials to be viable, the recyclates should provide clear benefits, such as weight savings and reinforcing strength, and they should not introduce new environmental or safety problems (Conroy et al., 2006).

Selection criteria are created to choose the best EoL option for the Eve tile and project.

Minimise CO2 emissions: Eve Reverse's mission is to develop CO2-negative composite material, so CO2 emissions for the different EoL processes should be mapped out.

Maximise material's value retention: Although this project focuses on the outer circle of the butterfly diagram, it is still preferred to use the material in a similar type of product to retain its value

Minimise costs: To make it attractive for external parties to apply a recycling method, the costs for setting up the recycling plant or participation costs should be minimised.

Feasibility: Feasibility can be divided into three categories; the recycling process, the producibility of the product, and the feasibility for this project's time span.

- Recycling process: To be an interesting option for external parties, the recycling process should be feasible, allowing for testing and application within a short timeline. While full-scale methods are not yet required due to Eve-tile's early development, an early-stage exploration of EoL options is valuable.
- Producing products: It should be feasible to produce products with the recyclates. Production processes should be explored to assess this criterion.
- Project feasibility: Facilities should be available during the project's time span to test the recycling process. In addition to the recycling process, producing a demonstrator product using the desired production process should be possible.

Design opportunities: For this project, it is important that the EoL option offers interesting design opportunities. For example, if the EoL option results in a downcycled material that can only be used as a filler material, this will limit the design phase of this project.

3.4 EOL CHOICE

The two remaining EoL options should be compared to select the most suitable EoL options for the Eve-tile within the scope of this project.

Separating layers
Separating the layers of a composite material is not a mainstream recycling method used in the industry. However, the tests performed show the potential to separate the layers of a composite material made from flax in combination with furan (Appendix 3).

Mechanical recycling through shredding
Mechanical recycling is a method applied on a large scale, but primarily for thermoplastic polymers. The tests performed show that it is possible to produce a sample by adding furan resin to the granulate and putting it in a heat press (Appendix 3).

An overview (Table 7) compares the two remaining recycling options based on the selection criteria determined in paragraph 3.3.

	SEPARATING LAYERS	SHREDDING MATERIAL
CO2 emissions	CO2 emissions are uncertain as this recycling method isn't industrially implemented, but its steps are relatively simple.	Mechanical recycling through shredding is generally considered a low-emission method compared to chemical recycling or virgin material production.
Material value retention	Fibres are recovered with minimal length reduction, retaining higher material value. Optimal boiling time and temperature are needed to preserve fibre properties.	Shredding the material reduces the material value retention a lot.
Costs	The process steps are relatively simple, but a recycling plant like this does not exist yet. Setting up this process on a large scale could lead to high investment costs, although the machines needed do exist already.	Because this method is already used in the industry, investment costs to use this method will be relatively low.
Feasibility		
• Process	Cutting → boiling → rolling → sorting. Recycling method does not exist yet, can be interesting to look for applications, but may be less applicable in the short term.	Cutting → shredding Existing recycling process, this makes it easier to recognise for external parties.
• Producing	Putting layers in mould → add resin → compression molding/vacuum in oven.	Bulk compression moulding Sheet compression molding
• Project	If this option is selected, I will not design the recycling method. I will assume it is possible to recover rectangles of one layer and start designing from there.	If this option is selected, making a demonstrator product will require an aluminium mould. This is very expensive, so this could give limitations for making a demonstrator product.
Design opportunities	• Relevant for products that should handle 'a lot of' force, without the need for a safety certificate (it is difficult to analyse the exact properties of recycled fibres). • Tailor made products (by adding extra layers in specific places of the product properties can be tailored to application) • Looking at plywood applications could be interesting inspiration (CurveWorks).	• Properties might be easier to predict because a homogenous mass is created. • Could have thick walls, which could potentially store more CO2. • More complicated shapes are possible by using 3D moulds.

Table 7: Separating layers vs. shredding material

Figure 11 compares the two methods based on the requirements described in Table 7. It is positive if the method is rated towards the outside of the heptagon. This means that when looking at this Figure 11 it is visible that the separating layers method has the advantage that the value retention of the fibres is higher. After applying this method, the following lifecycle product could be recycled through shredding.
An advantage of the shredding method is that it already exists and could be applied in the short term. However, choosing this option might also lead to more predictable and less interesting findings because the method is already applied on a large scale.
This comparison overview and test results were discussed in a meeting with all Eve Reverse employees to determine the most suitable recycling option for the Eve-tile and this project. The employees were most interested in exploring applications for the 'separating layers' method. This method is seen as more innovative, and they are curious about its potential applications. For them, it is not a problem that the recycling method does not exist yet, and they understand that this project is not about designing this recycling method. They also argued the importance of identifying possible applications to assess whether developing a recycling method like this would be worthwhile.

Chapter 4 shows that it is possible to produce a sample by curing the material under vacuum in the oven. This creates more possibilities for this project in terms of creating a demonstrator product.

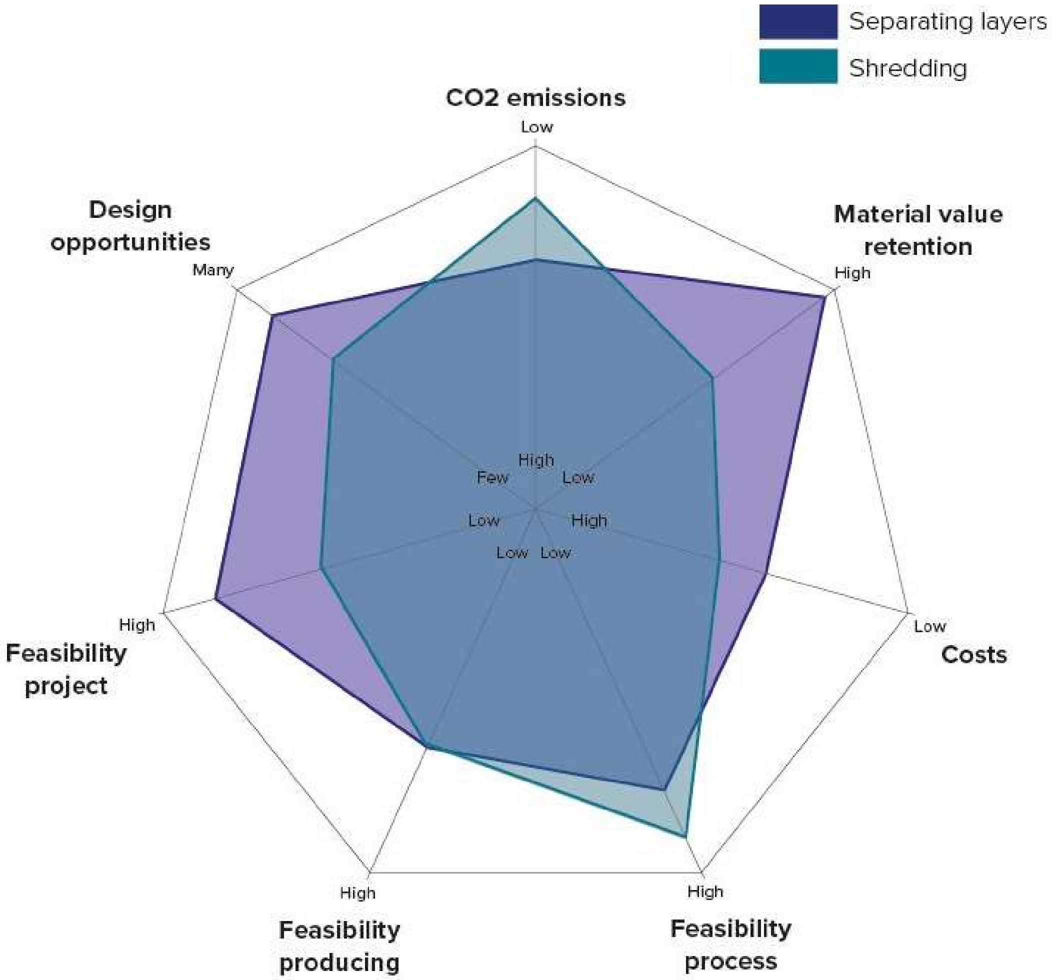


Figure 11: Comparison of separating layers and shredding

TAKE-A-WAYS

Now that the EoL choice is made, more sub-research questions are answered as well.

How are (bio-based) composites recycled currently?
Structural reuse, mechanical recycling, thermal recycling, chemical recycling, and digestion.

What are the EoL options of the Eve-tile in combination with the promising matrix?
After analysing all options, the EoL options are narrowed down to three: separating layers, shredding, and solvolysis. Since there is very little literature about solvolysis in combination with natural fibres, this option is also eliminated.

When is it viable to recycle a bio-based composite?
- Economic: Recycling costs are often high, and costs for virgin material are relatively low. The properties of recycled material are lower than those of virgin material, which makes it difficult to make recycling economically viable. Government regulations that stimulate the use of recycled material can help justify recycling costs.
- Environment: To use a material in the circular system, it is desired to go through as many life cycles before applying incineration as the EoL option.
- Technical: The main value of recycling composite materials lies in the recovery of fibres. The material's value retention should be as high as possible. This means that the recyclate should provide clear benefits, such as weight savings or reinforcing strength.

What are the selection criteria for the best EoL option for this project?
- CO2 emissions should be as low as possible.
- Value retention of the material should be as high as possible.
- Costs should be as low as possible.
- Feasibility of recycling process.
- Feasibility to produce products.
- Project feasibility.
- Design opportunities

The first main research question is answered with these questions being answered.

What is the most suitable EoL option for the Eve-tile composite within the scope of this project?
The separating layers method is chosen for this project. The main reason for this choice is the fibres' higher value retention, which is one of the most important criteria for making recycling viable for composites.

In addition to answering these sub-research questions, more design criteria are established.

Design criteria:
- The demonstrator will be made of a recycled material produced through separation of layers.
- To maximise the value retention of this recycling method, the recycled fibres should have a reinforcing or weight-saving role.
- The demonstrator should not replace something that could be made of a more sustainable material in the first place.
- The product should not need extra reinforcement from other materials because of the deficiency of recycled material.
- The reuse of fibres should not make the recycling of the designed product more complicated.
- The product should have a suitable long service life.
- The product should be cost-effective.

04

MATERIAL EXPLORATION

4.1 MATERIAL ORIGIN
4.2 TINKERING WITH MATERIAL
4.3 TECHNICAL PROPERTIES
4.4 USER STUDIES
4.5 MATERIAL BENCHMARKING

4.1 MATERIAL ORIGIN

4.1.1 FIRST CYCLE MATERIAL

The origin of the flax fibres was discussed in the chapter 2. Furan is 100% biobased, which means it is entirely derived from living organisms. It is produced from a waste stream of sugarcane. The parts of the sugarcane that contain too little sugar to be processed into actual sugar, but still enough to produce alcohol, are used to make the resin. To better understand the furan/flax material, it is important to understand how the material is currently made. This is why a 'Making Process Diagram' is made (Figure 12).

Figure 12: Making process diagram of first-cycle material

4.1.2 RECYCLED MATERIAL

The recycled material is made following the steps in Figure 13.

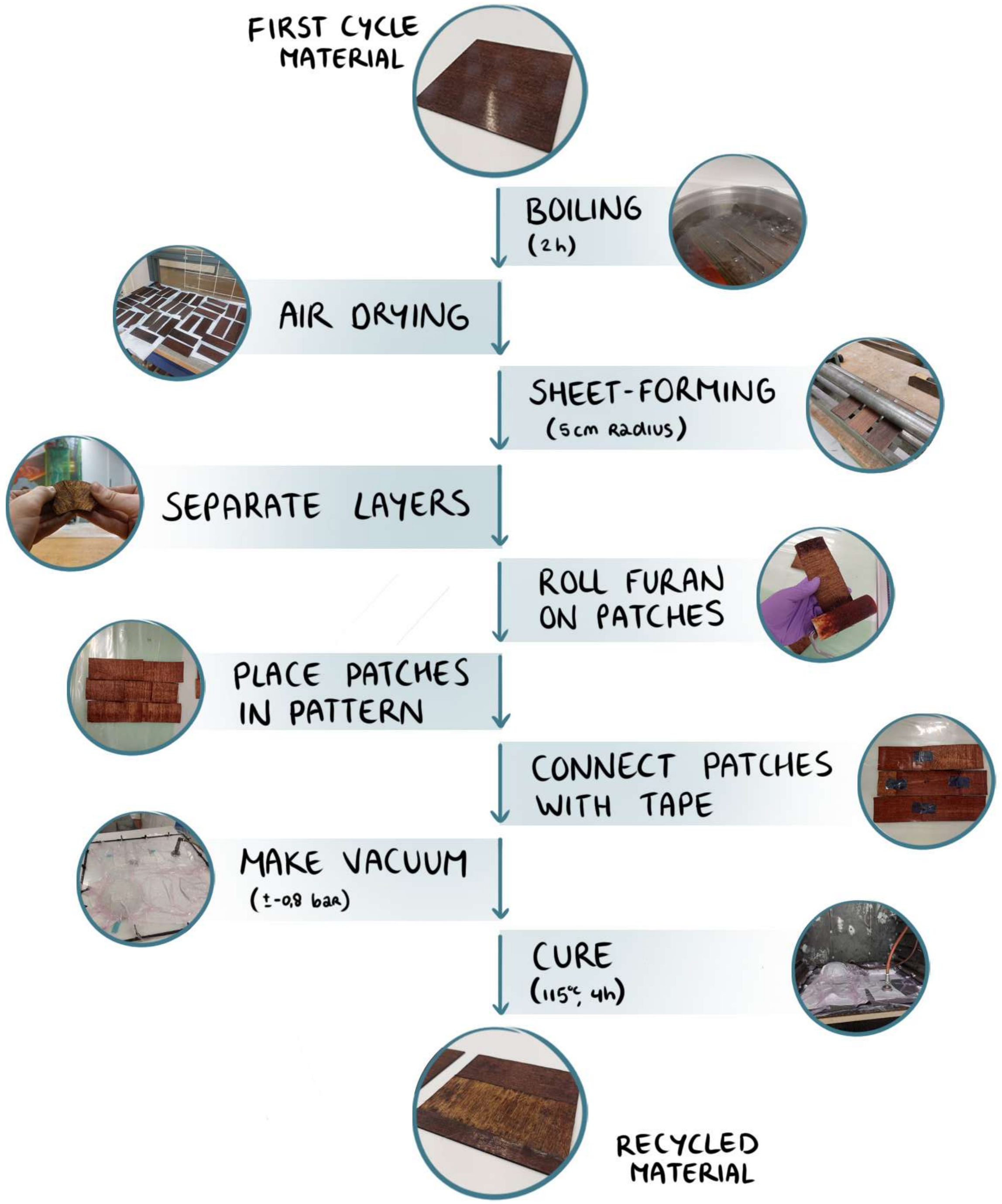


Figure 13: Making process diagram of recycled material

4.2 TINKERING WITH MATERIAL

As described in paragraph 2.5, the MDD method encourages to tinker with the material to gain a better understanding. Therefore, this activity is also done with the recycled material. It is interesting to compare the results of these activities to better understand the differences between the first-cycle and recycled material. Remarkable differences will be discussed in this paragraph.

When bending the first-cycle material, it splits into multiple layers. When bending the recycled material, it breaks immediately (Figure 14). Putting both materials through a sheet-forming machine confirms this finding (Figure 15).

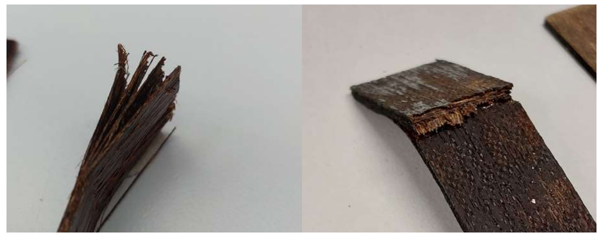


Figure 14: Bending first-cycle (left) and recycled (right).

Figure 15: Sheet-forming first-cycle (left) and recycled (right).

The first-cycle and recycled materials produce a powder with small particles when blended. The particles from the blended first-cycle material are more fibrous, while the blended recycled material look more like flakes (Figure 16). This difference is also observed in the granulates (Figure 17).

Figure 16: Blending first-cycle (left) and recycled (right).

Figure 17: Granulating first-cycle (left) and recycled (right).

Boiling the samples makes both of them softer. The recycled material makes a creaking sound when the samples are bent by hand. It is not possible to completely separate the layers of the recycled material (Figure 18). Putting the recycled material through a sheet-forming machine after boiling might make this possible.

Figure 18: Boiling first-cycle (left) and recycled (right) material.

A complete overview of the tinkering activities, including more pictures of the tinkering process, can be found in Appendix 1.

4.3 TECHNICAL PROPERTIES

Tensile and three-point bending tests are performed to create an overview of the technical properties of the first-cycle and recycled material. Different lay-ups will be tested to compare the properties. Firstly, uni-directional samples of five layers will be tested, this will give the maximal properties because all fibres are oriented in the direction of effort. Secondly, a multi-directional lay-up will be tested to get more realistic values as multi-directional composites are more commonly used in existing products. Lastly, the recycled material will be tested to see what the influence of the recycling process is on the material properties.

The uni-directional, multi-directional and recycled samples are made with flax tape instead of Eve-tiles. This is because a lot of material tests need to be done, and making Eve-tiles is time-consuming at this moment. The main difference between Eve-tiles and flax-tape is that flax fibres in flax-tape are made continuous, and the Eve-tile is made while considering the the finite fibre length of flax.

4.3.1. TENSILE TEST

To determine the tensile properties of the first-cycle and recycled material, tensile tests are performed following ISO 527-4 (Nederlands Normalisatie Instituut, 2023). This standard gives information about test conditions for isotropic and orthotropic fibre-reinforced plastic composites.

The full test plan and results of every individual sample (including pictures) can be found in Appendix 5. This paragraph will summarise and discuss the average tensile test results (Table 8). The test set-up of the tensile test is shown in Figure 19.

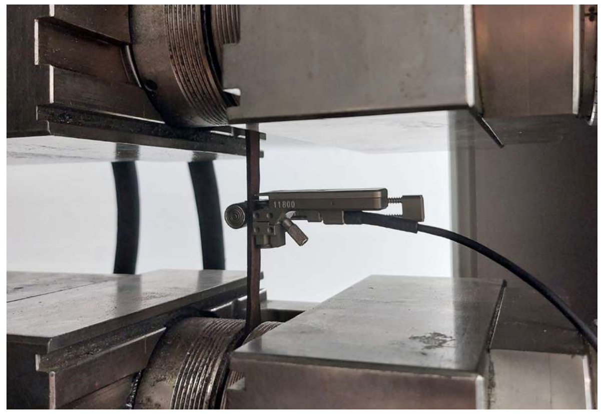
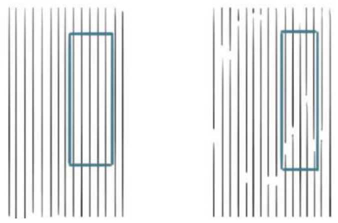


Figure 19: Test set-up tensile tests

Results

The tensile strength of the uni-directional specimens is comparable to those of the samples previously tested at Eve Reverse. The difference in fvf may cause a slight deviation. The fvf is hard to control during a hand-laminating process. Another logical cause for the flax-tape to perform less good than the Eve-tile is that flax tape consists of continuous flax fibres, which means that fibre beginnings and endings are distributed along the entire length of the tape. Conversely, the Eve-tile uses finite flax fibre lengths, resulting in fewer fibre beginnings and endings within one tile:



The Young's modulus of the uni-directional specimens is significantly lower than the values previously tested by Eve Reverse. The modulus is highly dependent on the type of fibres and resin used. The flax tape might have a lower modulus than the fibres used in the Eve-tile. Flax-tape is made of flax fibres from different harvest years to provide more constant properties to their customers. The Eve-tile is made of flax fibres from one harvest, which could mean that the Eve-tiles used for the samples had high quality flax fibres. The quality of harvesting between different years can differ a lot. One of the variables that plays a big role in this is the retting time of the flax fibres. This is the time needed for the fibre to separate from the stem and depends on the weather. Another reason for the Young's modulus to be lower is that the flax-tape might incorporate a different type of binder than the Eve-tile. Variations in the binder type could lead to a less effective interface between the flax and the furan, potentially weakening the matrix and making it more prone to break.

When looking at the results of the multi-directional specimens, the lower values measured for tensile strength and modulus can be related to the 0-90-0-90-0 lay-up. Only three layers of fibres are in the orientation of effort. The multi-directional material is recycled, so it is important to compare the values of the recycled material with the multi-directional values. It is visible that the values have decreased, the tensile strength has decreased by 40,1%, and Young's modulus has decreased by 22,7%. This means that the material's stiffness is largely maintained after recycling, but the maximum load-carrying capacity of the material has decreased. This is visible in Figure 20. The steepness of the graph of the recycled material is comparable with the steepness of the multi-directional material. However, the recycled material breaks under a smaller load than the multi-directional material.

An observation about the test specimens is that a lot of samples broke at the transition from the wide to the small section, which makes it difficult to determine the exact breaking area. Important to note is that if the values were calculated with a larger area, the results would be lower.

	Tensile strength (MPa)	**Specific strength** (MPa*cm³/g)	**Standard deviation** (MPa)	**Young's Modulus** (GPa)	**Specific Stiffness** (GPa*cm³/g)	**Standard deviation** (GPa)	**Fibre volume** (%)	**Resin volume** (%)	**Density (calc.)** (kg/m³)	**Density (meas.)** (kg/m³)***
Eve-tile*	199,76	142,70	23,15	31,19	22,30	2,62	70,44	29,56	1411,32	1106,5
Uni-directional	170,602	125,679	11,394	16,992	12,518	0,318	52,48	47,52	1357,43	1092
Multi-directional	118,705	88,235	6,900	11,657	8,665	0,648	48,44	51,56	1345,32	1099
Recycled	70,152	53,151	9,755	9,009	6,826	0,576	39,95	60,05	1320	1070

Table 8: Results tensile test
**Eve-tile is a uni-directional sample tested before by Eve Reverse.*
*** Calculated based on material properties and dimensions*
**** Measured with densimeter*

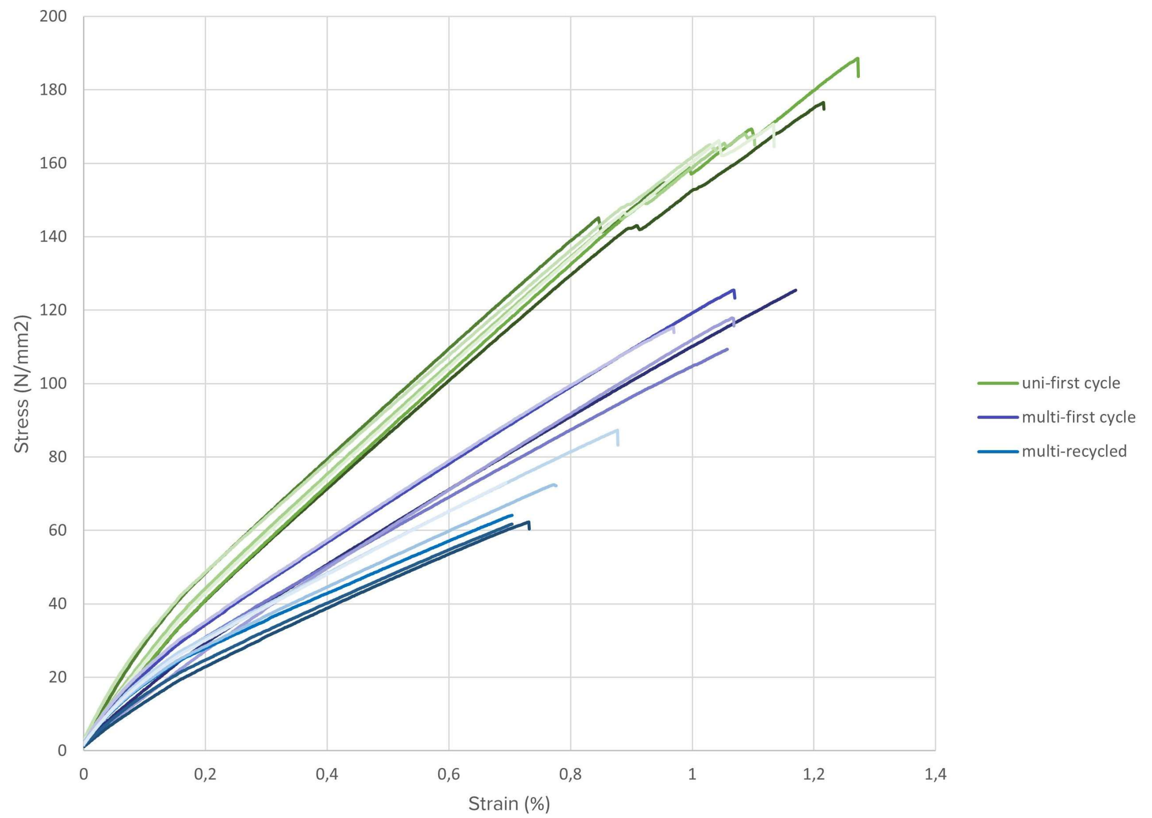


Figure 20: Tensile test results

4.3.2. THREE-POINT BENDING TEST

To determine the flexural properties of the first-cycle material, three-point bending tests are performed following NEN-EN-ISO 14125 (Nederlands Normalisatie Instituut, 1998). This standard gives information about determining the flexural properties of fibre-reinforced plastic composites.

The full test plan and results of every individual sample (including pictures) can be found in Appendix 6. This chapter will summarise and discuss the average tensile test results (Table 9). The test set-up of the tensile test is shown in Figure 21.

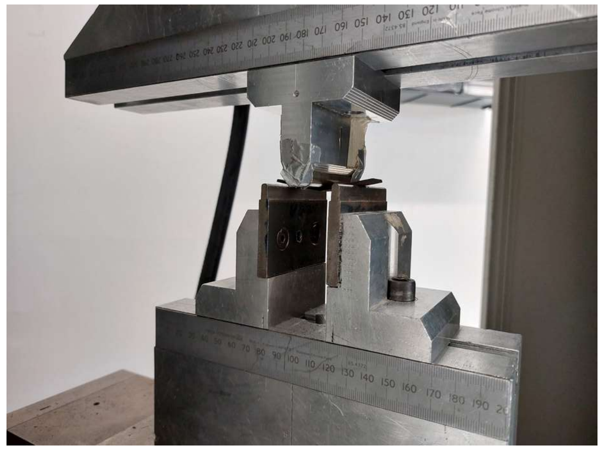


Figure 21: Test set-up three-point bending tests

Results

The values for the flexural strength and modulus of the uni-directional specimens are much lower than that Eve Reverse measured before. Even when compensating for the fvf, the values are much lower than the previously measured values. To compensate for fvf:

$$Pc = Pm * \frac{Vft}{Vfa}$$

Pc = Property compensated
Pm = Property measured
Vft = Fibre volume fraction, target
Vfa = Fibre volume fraction, actual
Values of Table 9 are used for the calculations.

$$\frac{174{,}97}{52{,}47972} * 70{,}44 = 234{,}8505 \text{ MPa (compansated strength for fvf)}$$

This is 58% of the measured value by Eve Reverse.

$$\frac{17{,}625}{52{,}47972} * 70{,}44 = 23{,}6569 \text{ GPa (compansated modules for fvf)}$$

This is 64% of the measured value by Eve Reverse.

An explanation for the lower measured values could be a difference in the sample production process. At the time of production, I had limited experience in this specific type of material fabrication. The samples I produced may contain more air bubbles, which may have weakened the material and made the samples break sooner. However, determining the presence of air bubbles after production is challenging.

The expected density was calculated based on the fibre properties, measured weight, and estimated fvf. In contrast, the density of the samples was also measured directly using a densimeter. The measured values were lower than the expected density, which suggests that air bubbles may be present.

Comparing the two sample types, the Eve-tile samples have a slightly higher measured density (1107 kg/m³ ± 35 kg/m³) than the Uni-directional samples (1092 kg/m³ ± 6 kg/m³). This could indicate that the Uni-directional samples contain more air bubbles. However, the difference is small (approximately 1,4%), making it difficult to draw definitive conclusions. Additionally, the standard deviation of the Eve-tile samples is larger (21,9 kg/m³) compared to the Uni-directional samples (6,1 kg/m³), indicating greater variability in the Eve-tile sample production.

Another factor that adds uncertainty is the accuracy of the expected density calculation. The assumed densities of the fibres and furan may not have been precise, and the volume fraction of each component was difficult to determine. A more reliable approach would be to weigh the samples at multiple stages during the process. This would minimise the assumptions needed to be made and allow for more accurate conclusions based on the measured values.

As expected, the values measured for flexural strength and modulus of the multi-directional specimens are lower due to the 0-90-0-90-0 lay-up. Only three layers of fibres are in the orientation of effort.

Like the tensile specimen, the multi-directional material is recycled, so it is important to compare the recycled values with the multi-directional ones. Both Table 9 and Figure 22 show a decrease in the values. The flexural strength and flexural modulus have both decreased by around 25,5% What is remarkable about the bending test outcomes is that the recycled material has a higher standard deviation, which means that the outcomes have more variation than the tests with the uni and multi-directional material. This is also visible in Figure 22. The blue lines show more variation in both the steepness (indicating stiffness) and the breaking point compared to the green and purple lines. This suggests that recycled material introduces a level of inconsistency in mechanical performance.

Due to this variability, applications requiring strict and consistent safety certifications may not be ideal for this material. The unpredictability in measured values could make it challenging to meet the strict standards needed for such uses.

	Flexural strength (MPa)	Specific strength (MPa*cm³/g)	Standard deviation (MPa)	Flexural Modulus (GPa)	Specific Modulus (GPa*cm³/g)	Standard deviation (GPa)	Fibre volume (%)	Resin volume (%)	Density (calc.) (kg/m³)**	Density (meas.) (kg/m³)***
Eve-tile *	406,90	290,64	54,10	36,80	26,29	2,00	70,44	29,56	1411,32	1106,5
Uni-directional	174,975	128,901	10,577	17,625	12,984	1,252	52,480	47,52	1357,43	1092
Multi-directional	139,998	104,063	4,024	14,622	10,869	0,645	48,441	51,56	1345,32	1099
Recycled	106,097	80,385	25,091	11,045	8,368	2,617	39,95	60,05	1320	1070

Table 9: Results three-point bending test
**Eve-tile is a uni-directional sample tested before by Eve Reverse.*
*** Calculated based on material properties and dimensions*
**** Measured with densimeter*

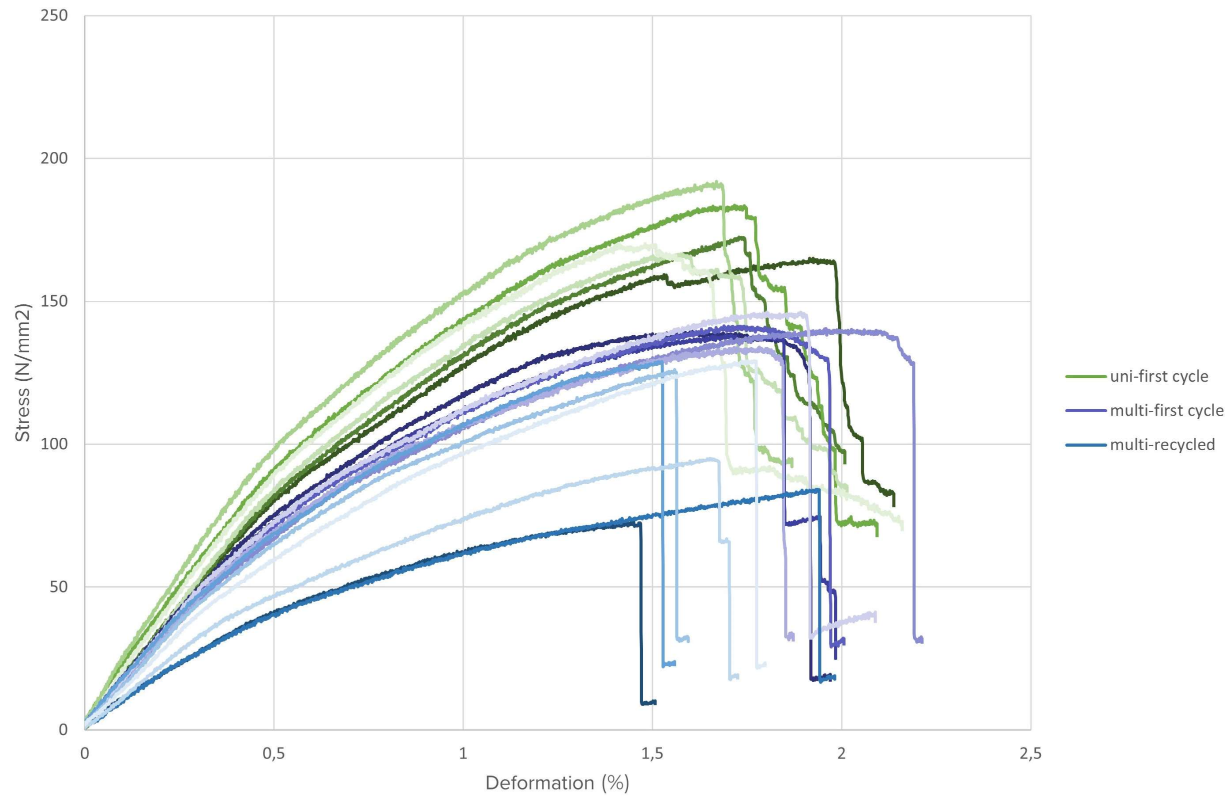


Figure 22: Three-point bending test results

4.3.3 DISCUSSION

When comparing the tensile and flexural strength of the multi-directional material with that of recycled material, we can see that both are reduced after recycling the material. Different reasons can explain this reduction.

The first reason could be that the fvf of the recycled samples is lower because additional furan was added to 'glue' the separated layers back together. Flax fibres have a higher tensile strength and stiffness than the furan resin. A lower fibre volume will result in a lower tensile strength and modulus.

The rule of mixtures suggests that the tensile strength and modulus of the composite are directly proportional to the fvf in the direction of the fibres, so a lower fvf decreases these properties.

$Ec = Ef \cdot Vf + Em \cdot (1 - Vf)$

- Ec = Young's modulus of the composite
- Ef = Young's modulus of the fibres
- Em = Young's modulus of the matrix
- Vf = volume fraction of the fibres

Another reason could be air bubbles inside the sample. Adding (too much) furan resin in between the separated layers can lead to porosity due to air bubbles (as in EoL test, Appendix 3), such defects act as stress concentrators and can reduce the tensile strength and modulus of the material as well.

A third reason for the reduction in properties is that boiling and drying the samples can impact the mechanical properties. Water absorption by the flax fibres leads to fibre swelling, weakening the interface between the fibres and matrix. When the material is dried again and the fibre reduces in size, this can lead to debonding of the fibres with the matrix (Moudood et al., 2018).

The properties of the samples produced and tested by Eve Reverse before this project are higher than the first-cycle material used for the test described in the previous paragraphs. Taking the reduction of properties in percentages, the values measured by Eve Reverse can be scaled down with the same ratio to create theoretical recycled properties.
The tensile strength of the recycled material is 59,1% of the original tensile strength. The Young's modulus of the recycled material is 77,3% of the original Young's modulus. The flexural strength of the recycled material is 75,8% of the original flexural strength. The flexural modulus of the recycled material is 75,5% of the original flexural modulus. It is difficult to explain why the tensile strength reduces more than the other three variables. One reason could be that the tensile strength is more sensitive to fibre imperfections than the other variables.
Recycling the material and glueing the patches back together can introduce imperfections in the material.

See Table 10 for the theoretical recycled properties of the Eve-tile. Based on these values, the tensile and flexural properties of the recycled material are as follows:

Tensile strength: 70,15 - 118,05 MPa
Young's modulus: 9,01 - 24,11 GPa
Flexural strength: 106,10 - 234,86 MPa
Flexural modulus: 11,05 - 23,66 GPa

	Tensile strength (MPa)	Young's Modulus (GPa)	Flexural strength (MPa)	Flexural Modulus (GPa)	Fibre volume (%)	Resin volume (%)	Density (meas.) (kg/m³)
Eve-Tile	199,76	31,19	406,90	36,8	70,44	29,56	1106,5
Uni-directional	170,602	16,992	174,975	17,625	52,48	47,52	1092
Multi-directional	118,705 ↓ -40,9%	11,657 ↓ -22,7%	139,998 ↓ -24,2%	14,623 ↓ -24,5%	48,44	51,56	1099
Recycled	70,152	9,009	106,097	11,045	39,95	60,05	1070
Theoretical value	118,05 (59,1%)	24,11 (77,3%)	308,37 (75,8%)	27,80 (75,5%)	(Percentage of Eve-tile values)		

Table 10: Overview of the test and theoretical values

To better understand what these values mean, a graph plots tensile strength against Young's modulus, to be able to compare the properties with other materials (Figure 23). Additional plots in Appendix 7 illustrate these properties in relation to material density.
Based on this graph it can be seen that the recycled material has a higher strength and stiffness than most woods and plastics, but the strength properties are lower than most composite materials. Materials with comparable flexural and tensile properties are birch wood (measured in longitudinal direction) and ABS with 30% carbon fibre (Table 11).

This means that less material is needed to satisfy a dashboard's required strength and stiffness requirements. However, important to note is that the mechanical properties will be lower when flax/furan is applied in an application due to the overlaps that need to be made. The properties measured are the properties within one patch, instead of a piece of material including overlaps. Additionally, the range of measured values for flax fibres combined with furan resin is broader, which implies that recycling may introduce greater uncertainty regarding the material's actual properties in a given application.

	Tensile strength (MPa)	Young's Modulus (GPa)	Flexural strength (MPa)	Flexural Modulus (GPa)	Density (kg/m³)
Flax/furan (First cycle)	170,6 - 199,7	17,0 - 31,2	175,0 - 407,0	17,6 - 36,8	1092 - 1411,32
Flax/furan (Recycled)	70,2 - 118,1	9,0 - 24,1	106,1 - 308,4	11,0 - 27,8	1070 - 1320
Glass fibre epoxy	300 - 1100	35 - 45	300 - 900	35 - 45	1600 - 1950
Birch wood	122 - 149	14,7 - 17,9	119 - 145	13,3 - 16,3	620 - 760
ABS (injection molding)	42 - 46	2,21 - 2,62	72,4 - 79,3	2,34 - 2,68	1040 - 1070
ABS (30% carbon fibre)	121 - 131	17,2 - 20	165 - 186	12,8 - 17,2	1150 - 1190

Table 11: Comparison of values with different materials (Granta Edupack, 2024)

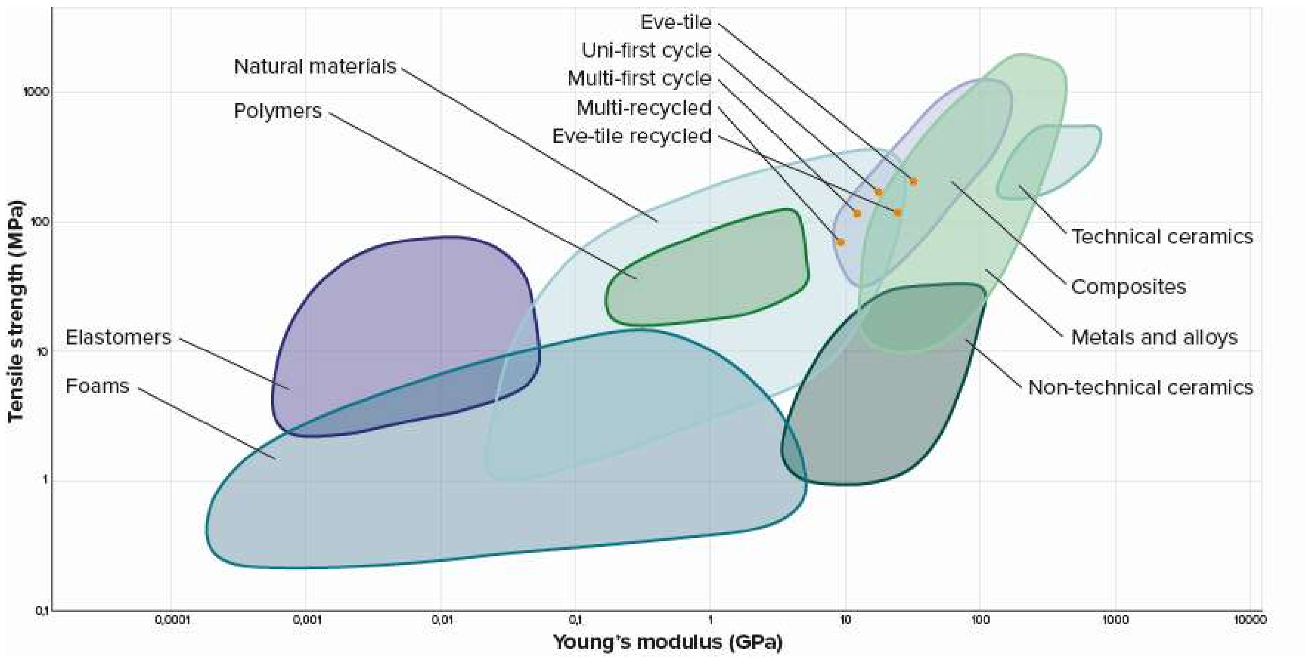


Figure 23: Comparison of tensile strength and Young's modulus with different materials

4.4 USER STUDIES

Recycling often leads to a decline in mechanical properties, but what about the impact on experiential qualities? Do these qualities change as well? And if so, can these changed qualities be used to add new value?

To find out how people perceive the materials on sensorial, interpretive, affective and performative level, the Ma2E4 toolkit is used (Camere & Karana, 2022). This toolkit provides vocabulary and structure, making it easier for participants to explain how they experience a specific material.

4.4.1 METHODOLOGY

This user test will be performed with the first-cycle and recycled material. Both tests are performed at the same moment to maintain consistent contextual variables.
It is important to note that the material given to the participants first was randomly chosen. Two participants started with the first-cycle material, and three with the recycled material. No context about the material was provided to the participants on beforehand.

Set-up
This user test is a one-on-one activity performed in a private room with sufficient natural lighting (Figure 24). Participants' hands were recorded during the sessions to analyse their interactions with the material, and comments were noted.

Participants
The user test is done with 5 participants, this is a small sample size to retrieve qualitative insights. Among the 5 participants were two men and three women, all IDE students between 23 - 27 years old.

Material
The first-cycle material and recycled material are produced following the methods described in paragraph 4.1. The recycled material's square sample is cut using a laser cutter (Appendix 8).


Figure 24: User test set-up

4.4.2 RESULTS

More detailed graphs can be found in Appendix 8.

Performative material qualities
The sample is handed to the participant to freely explore the material, and the participant is asked to describe what the material makes them do.

The way participants handle both samples is quite similar. The main hand movements for both materials are caressing, rubbing, scratching and bending. A difference is that participants are focused on the fibrous section of the recycled sample. They gently touch or pull the fibres but are afraid to loosen them. When bending the material, the recycled sample makes a creaking sound, but Figure 25 shows that both materials are perceived as strong as each other. One participant even said:

(about the recycled material) *"This material could be used for a boat or something, it is coarser, stronger, so an application is suitable that needs this power."* (about the first-cycle material) *"This material is more about its aesthetic vibe. If you want to make something look more natural, you could use this material."*

Sensorial level
The booklet is handed to the participants, they evaluate the material using sensory scales with opposing characteristics.
The blue line in Figure 25 shows the average outcome of the five user tests with the first-cycle material. The green line shows the average outcome for the recycled material. All individual results can be found in Appendix 8.

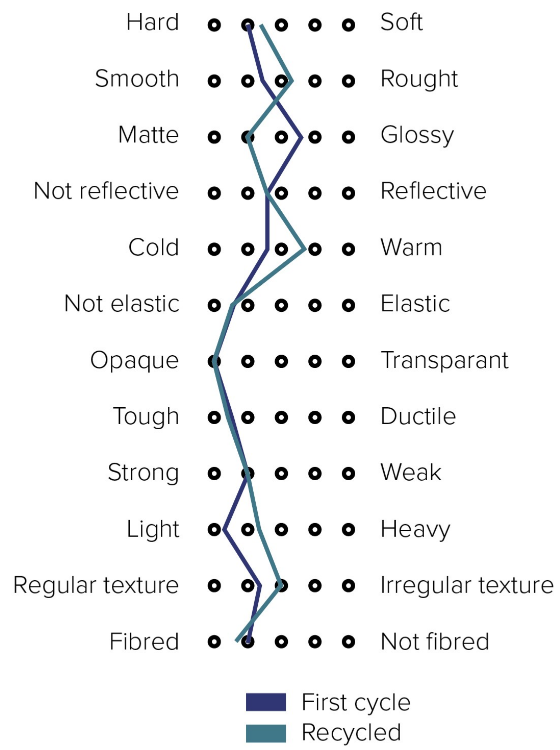


Figure 25: Sensorial scale

The first-cycle material is rated to be opaque, lightweight, and have a regular texture by four out of five participants. The recycled material is rated to be opaque, and four out of five participants rated the material to be more light than heavy and not elastic. It is visible that the average lines of the first-cycle and recycled material show only a small variation. The recycled material is experienced rougher, more matte, warmer, heavier, and more irregular. The graph does not show any big changes on sensorial level after recycling the material.

Emotional level
Participants are asked to select three emotions from an affective vocabulary list (Appendix X) and plot them on a graph (Figure 26), rating their intensity and pleasantness.

First cycle material:
Confidence (4x): The glossy finish makes it look like a finished product/material, which gives confidence in the material.
"It feels like a 'finished' material."
Respect (2x): Participants associate the material with dark brown wood, which reminds them of old furniture that lasts forever, which evokes the emotion of respect.
Boredom (2x): This emotion is evoked because of the same reason as respect. The dark brown wood association is also linked to a very standard and boring look, which is why the emotion boredom is evoked.
Comfort (2x): The material feels smooth and sturdy, which makes the participants feel comfortable.

Remarkable is that participant 4 is the only one that did not mention confidence and wrote down distrust as an unpleasant emotion.
Recycled material:
Respect (3x): Plotted with low intensity, indicating that while the emotion was present, it was not that strong. The handmade or natural appearance of the material evoked this emotion.
"It is weird to feel respect towards a material, but it looks handmade, or natural, which makes me think that this is made for a reason, it is more carefully produced."

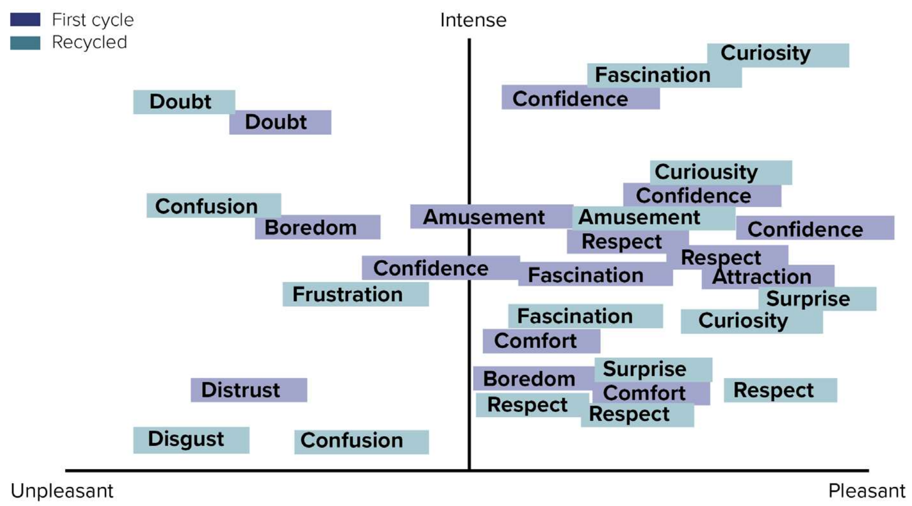


Figure 26: Emotion map

Curiosity (3x), *fascination* (2x), *surprise* (2x): These three emotions are all linked to the fact that there are patches with different textures present in the sample. They are surprised by the different patches, they are curious how it is made, and it fascinates them, which makes them keep touching the sample. *"There is a change, it is not fully regular, so I am more curious now, like where does it come from?"*
Confusion (2x): The fibres that are partly loose confuse two participants, they wonder whether this was on purpose or a mistake.

Just a few emotions recur in both graphs: amusement, respect, fascination and doubt.

Interpretive level
The participants are asked to describe the meaning they associate with the material supported by visual examples presented.

First cycle material:
Nostalgia: The dark brown color reminds participants of the furniture of their grant parents.
Elegance: The glossy finish and dark brown colour give the material a refined appearance.
Handcrafted: The fibres on the top surface create an impression of craftsmanship.
Natural: The visible fibres and the association with wood.
Calm: The aligned fibres and dark colour contribute to a sense of calmness.

Recycled material:
Natural: The patches with different types of fibres visible make that all participants wrote down this meaning.
Handcrafted: This meaning is mentioned by three out of five particpants. The different patches put together make that it has a hand-crafted look.

Quite a lot of meanings recur in both the word cloud of the first-cycle and recycled material (Figure 27). Elegant, nostalgic, frivolous, hand-crafted, natural, and strange are meanings that are associated with both samples. Hand-crafted and natural are the words that are most commonly mentioned. It might be more interesting to look at the words that are different, but these words are not mentioned as often, which makes them less relevant.

Figure 27: Word cloud of results interpretive qualities

Final reflections
The final step of the method is to discuss the most pleasant, disturbing and unique qualities.

"What is the most *pleasant* quality of the material?"

FIRST CYCLE MATERIAL
The pleasant quality that was mentioned most often is the glossy finish. Next to this, pleasant qualities that were mentioned are that the material is strong and elegant, has an eternity-like appearance, and it's natural look.

RECYCLED MATERIAL
The texture is mentioned multiple times as a pleasant quality. Participants mentioned that the material feels soft and comfortable. Next, the warm colour is mentioned, as the contrast between the patches and the fact that it looks natural, sparks curiosity.

"What is the most *disturbing* quality of the material?"

FIRST CYCLE MATERIAL
Two participants mentioned that they find the material standard/boring. Two participants mentioned that the texture looks like it is used because of some misaligned fibres. One participant mentioned the colour to be disturbing.

RECYCLED MATERIAL
The disturbing qualities mentioned are the rough texture, the unfinished appearance, and the fact that the material is perceived as fragile. One participant also mentioned that the material evokes frustration.

"What is the most *unique* quality of the material?"

FIRST CYCLE MATERIAL
Participants mentioned that a lot is going on, and it looks old but modern at the same time. The material is lightweight compared to its look. The handcrafted look and natural appearance (coconut-like) are also mentioned as unique qualities.

RECYCLED MATERIAL
The sample's diversity of looks is noted as unique, along with its contrast, which another participant highlighted. Other mentioned qualities include its shapeability, nature-inspired appearance, and frivolous look.

4.4.3 CONCLUSIONS

The first-cycle material is perceived as luxurious and elegant yet somewhat boring. In contrast, the recycled material is described as unfinished, but its texture and patches spark curiosity, fascination, and surprise. While some experiential qualities go down, new positive qualities have also emerged. In the design process, it is crucial to incorporate these new qualities while minimising the negative ones. The negative qualities, like unfinished and fragile, were mentioned primarily when the participants looked at the side with the open fibres. This could be avoided by using the patches on the side that is not visible to users, or by adding a coating that will seal the open fibres.

4.5 MATERIAL BENCHMARKING

Technical properties
Furan: High mechanical strength, water resistant, heat resistant.
Flax: Good strength/ stiffness to weight ratio, flexible, thermal insolation, moisture absorbtion.

Opportunities
Lightweight, high strength/stiffness.

Constraints
Flexibility of flax in combination with brittleness of furan.

Manufacturing processes
Cure under vacuum in oven, compression moulding, vacuum infusion.

Current applications
Engine cover, traffic signs, wall panels, deck hatches

TECHNICAL CHARACTERISATION

RECYCLED FLAX/FURAN COMPOSITE

EXPERIENTIAL CHARACTERISATION

MATERIAL BENCHMARKING

Key technical qualitities
Fragile vs. strong
Light
Shapeable

Key experiential qualitities
Natural
Curiousity
Unfinished

Design Strategy
CO2 neutral/negative
Circular design

Emotions
Curiousity, respect, fascination, confusion, surprise.
Amusement, doubt, frustration, disgust.

Meanings
Natural, hand-crafted
Sober, frivolous, strange, vulgar, cozy, nostalgic, elegant.

Most pleasant
Colour, natural, texture

Least pleasant
Rough, fragile, unfinished

Association
Wood

Interaction
Curious but hesitant to touch the fibrous part.

Unique
Contrast/diversity, nature immitation, shapeable.

TAKE-A-WAYS

During the tinkering activities, it was noticed that the recycled material was quite brittle. The sample breaks immediately when bending the material or putting it through a sheet-forming machine.

Technical properties of first-cycle material:
- Tensile strength: 170,602 - 199,76 MPa
- Young's Modulus: 16,992 - 31,19 GPa
- Flexural strength: 174,975 - 406,9 MPa
- Flexural Modulus: 17,625 - 36,80 GPa
- Density: 1092 - 1411,32 kg/m^3

The mechanical properties of the recycled material are lower than those of the first-cycle material. A theoretical value is determined by calculating the percentage that the properties decreased. This gives a range of properties of the recycled material.

Technical properties of the recycled material:
- Tensile strength is between 70 - 118 MPa.
- Young's modulus is between 9,0 - 24,1 GPa.
- Flexural strength is between 106 - 318 MPa.
- Flexural modulus is between 11,0 - 27,8 GPa.
- Density: 1070 - 1320 kg/m^3

The material properties of the recycled material are comparable to those of birch wood. Participants of the experiential tests noted that the recycled material also reminds them of wood. Additionally, material benchmarking revealed that the production of layers of recycled patches is similar to the layering process used in plywood manufacturing

Important to keep in mind is that the properties will be lower in reality due to overlaps. The measured properties are within one patch.

Experiential qualities of first-cycle material:
- Gloss & Dark brown: Elegant but strong, luxurious and finished.
- Dark brown: old but modern, boring, nostalgia
- Lightweight compared to its looks.

Experiential qualities of recycled material:
The different fibre patches make the material perceived as natural but also fragile and unfinished. The patches evoke curiosity, fascination, surprise and confusion. Lastly, they make the material look shapeable.

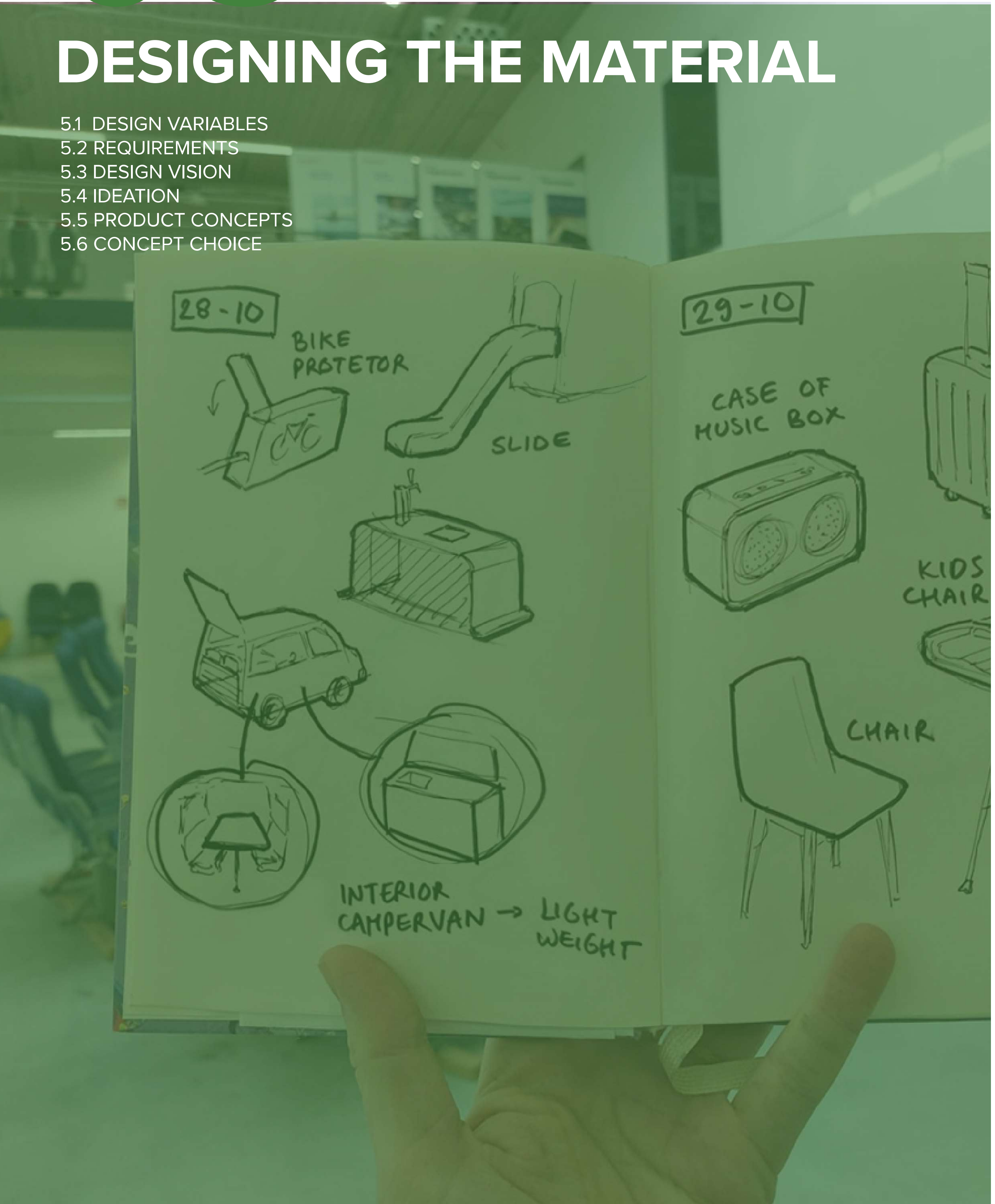
Next to these findings, more design criteria are established.

Design criteria:
- The material can not be used in critical structures requiring a safety certificate. This is mainly because it is difficult to assess whether the first-cycle product already had a loss in properties. The standard deviation is relatively high, indicating a wider variety of measured values.
- The fragile and unfinished look of the recycled material could be avoided by using the patches with a lot of fibres on the side that is not visible to users, or by adding a coating that will seal the open fibres.
- Take into account the technical properties of the recycled material.

05

DESIGNING THE MATERIAL

5.1 DESIGN VARIABLES
5.2 REQUIREMENTS
5.3 DESIGN VISION
5.4 IDEATION
5.5 PRODUCT CONCEPTS
5.6 CONCEPT CHOICE



5.1 DESIGN VARIABLES

A few key design variables need to be defined before deciding what to design with the recycled material. In this paragraph, the pattern of the recycled patches will be determined, and the shapeability of the recycled material will be assessed. These variables will serve as criteria for making the design concept choice.

5.1.1 PATTERN

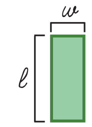
The recycled material consists of smaller patches placed in a mould in a pattern that will keep all the patches together after curing the material in an oven. A few important criteria for this pattern were found when exploring different patterns. Figure 28 shows the final pattern for the recycled patches, different options that were considered can be found in Appendix 9.

When exploring patterns, a brick and fishbone pattern were considered. The downside of the fishbone pattern is that fibres are placed in multiple directions within one layer, and it is difficult to even this out by adding another layer. For the appearance of the application, it could be interesting to use a fishbone pattern. The brick pattern gives an equal distribution of fibre direction because one layer has all fibres in the same direction.

The fibres need to overlap in the direction of the fibre. Eve Reverse does the same when overlapping Eve tiles in a mould. If patches are not overlapped in the direction of the fibre, the chance of breaking between the patches/tiles is big.

By placing layers of patches on top of each other, a material is created with the strength of the fibres in multiple directions. Placing two layers on top of each other can also be done in different ways. The option shown in Figure 28 is preferred because the overlapping areas are not stacked on top of each other, resulting in a more even material thickness.

To be able to make a brick pattern, the ratio between width and length should be:
1 : (2 + 0,5 * overlapping distance).



If overlap is 3 cm on both sides
w = 6 cm
ℓ = 2 * 6 + 0,5 * 6 = 15 cm

If it is desired to retain more fibre length, the patch length could be increased. If the length of the patch is doubled, the ratio becomes 1 : (4 + 0,5*overlap), and if tripled, it becomes 1 : (6 + 0,5*overlap). Tripling the length is preferred over doubling since doubling the length puts the overlapping areas on top of each other. To simplify and limit design options the length is not increased for this project. This means that the ratio 1 : (2 + 0,5*overlap) will be used for the remainder of this project, with the width set at 6 cm.

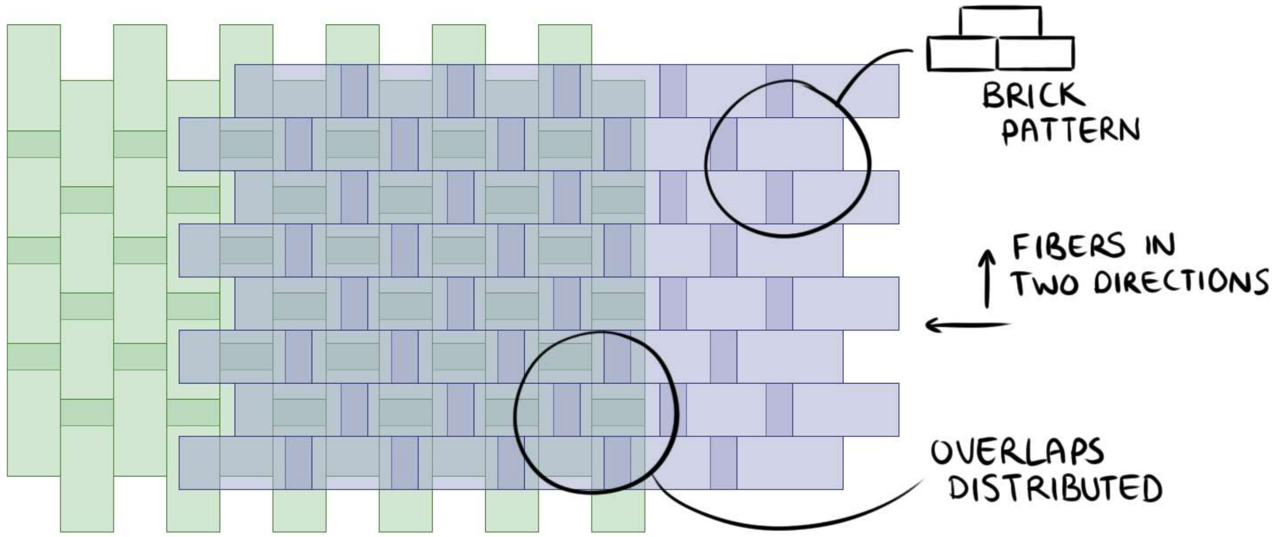


Figure 28: Final pattern of recycled patches

5.1.2 SHAPEABILITY

The shapeability is tested to determine the possible complexity of the shape of the demonstrator. Three shapes were selected: a sphere, half a cylinder, and a conic shape. This way, a single curved shape, a double curved shape, and a curve with changing diameter will be tested.

The recycled material is made as described in paragraph 5.1. The recycled patches are overlapped and connected with a tape (Figure 29). Without the tape, the patches tended to shift out of position during placement, making alignment challenging. See Appendix 9 for pictures of the whole process. The half-cylinder was hollow and made of PVC, which unfortunately melted in the oven, which is why this sample is flat (Figure 30.1). The result is still interesting since the recycled material followed the sharp edge around the PVC part. The melted mould is a single curved shape with a very small diameter. Shaping the material on a single curved shape with a bigger diameter is easier, making it plausible that this is also possible.

The conic shape was hollow, and because of the vacuum, this also collapsed a bit. However, the shape that emerged as a result of this was also interesting because the curve now changes from a round curve to a sharp edge (Figure 30.2). The recycled material followed this shape, with a sharp edge and a round edge with changing diameter.

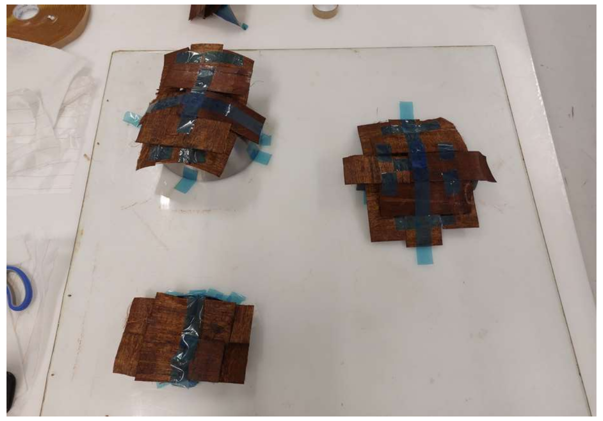


Figure 29: Patches connected with tape

The sphere was the most challenging shape for the material to form around since it is double-curved. Some creases appeared over the length of the fibre patches (Figure 30.3). Creases could be avoided by using patches with a smaller width in double-curved places. The patches on one side did slide over the sphere a bit, so only one layer of material was left there. Small holes arose in these places in between the patches of this one layer.

Figure 30: Shapeability test results

5.2 REQUIREMENTS

A list of requirements is created based on the take-a-ways of every chapter.

1. Production

1.1. It is feasible to produce the demonstrator within the project timespan (Project boundaries).
1.2. It is feasible to produce the demonstrator at the composite lab of InHolland (Facilities).
1.3. The demonstrator is made of flax fibres in combination with a furan resin (Chapter 2).
1.4. The material needs to be cured in the oven, which means that the maximum dimensions of the demonstrator product are 1.20m x 1.20m. (Chapter 2)
1.5. The demonstrator will be made of a recycled material produced through separation of layers (Chapter 3).
1.6. The demonstrator will be made of the recycled patches placed in a brick pattern (Chapter 5).
1.7. The ratio between the width and length of the patches is 1 : (2 + 0,5 overlap), with the width set at 6 cm (Chapter 5).

2. Technical properties

2.1. Furan resin is moisture resistant, but flax fibres' absorption of moisture will lead to swelling and deformation of the product, this means that product design must incorporate moisture protection. (Chapter 2).
2.2. Both flax fibres and furan resin degrade under prolonged UV exposure. The product needs a UV-resistant coating if the application is exposed to sunlight (Chapter 2).
2.3. Furan has good thermal stability compared to other bio-based resins. However, flax fibres degrade at high temperatures. Avoid applications where prolonged exposure to temperatures above 150 °C is needed (Chapter 2).
2.4. Take into account the technical properties of the recycled material (Chapter 4):
- Tensile strength 70 - 118 MPa.
- Young's modulus 9,0 - 24,1 GPa.
- Flexural strength 106 - 318 MPa.
- Flexural modulus 11,0 - 27,8 GPa.

3.Sustainable viability

3.1. To maximise the value retention of this recycling method, the recycled fibres should have a reinforcing or weight-saving role (Chapter 3).
3.2. The demonstrator should not replace something that could be made of a more sustainable material in the first place (Chapter 3).
3.3. The product should not need extra reinforcement from other materials because of the deficiency of recycled material (Chapter 3).
3.4. The reuse of fibres should not make the recycling of the designed product more complicated (Chapter 3).

4. Application

4.1. The product should have a suitable long service life (Chapter 3).
4.2. The product should be cost-effective (Chapter 3).
4.3. Recycled materials have some uncertainty in properties, shown by the high standard deviation in measurements, and prior damage from the first lifecycle material is difficult to assess. This means that the material can not be used in critical structures where a safety certificate is needed. (Chapter 4).
4.4. The fragile and unfinished look of the recycled material could be avoided by using the patches with a lot of fibres on the side that is not visible to users, or by adding a coating that will seal the open fibres (Chapter 4).
4.5. The recycled material can be shaped around a single-curved mould (Chapter 5).
4.6. The recycled material can be shaped in a conic mould (Chapter 5).
4.7. It is difficult to shape the recycled material in a double-curved mould. When a double-curved shape is desired, the radii should be big enough (Chapter 5).
4.8. It should be possible to take the demonstrator to an external location (Eve Reverse).
4.9. The demonstrator product should remain interesting even outside the context of the Ecorunner car (Eve Reverse).

Wishes

W.1. The demonstrator should be an inspiring application to people in the composite industry (Design vision).
W.2. The demonstrator shows as much of the shapeability of the recycled material (Design vision).
W.3. The application is a motivating design challenge for my project (Personal wish).

5.3 DESIGN VISION

With most of the design requirements defined and the technical and experiential characterisation complete, the next step is developing a design vision based on these findings. The design vision will help define the material's role in relation to the product, user, and context.

The main goals that should be incorporated in the design vision are clear, but how to approach the user is still uncertain. The most important goal is to show the EoL potential of the recycled material and that it should be a sustainable choice to use this material (Figure 31).

After writing a few versions of the design vision, it became clear that the goal of this project is to inspire people in the composite industry with this demonstrator product. In this context, the material can make a positive difference. The findings of the experiential tests, that the material sparks curiosity and surprise, can positively contribute to this. The final design vision is:

Demonstrate the end-of-life potential of flax/furan composites by designing an application that uses the material's technical opportunities (and constraints), to inspire the composite industry to integrate biobased composites and recycling principles into the design phase of their products.

Now that a design vision has been created, the ideation phase can start.

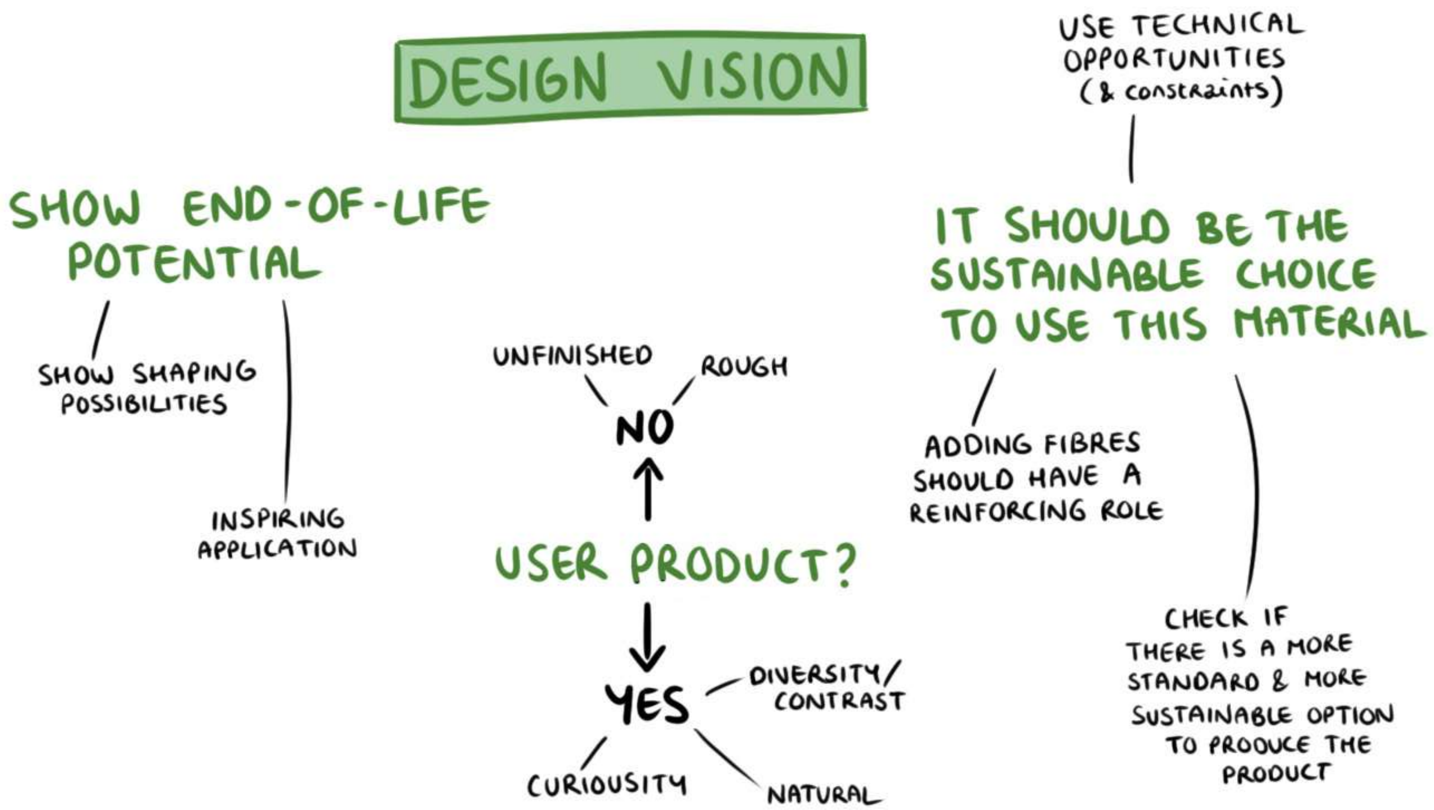


Figure 31: Brainstorm design vision

5.4 IDEATION

5.4.1 INDIVIDUAL IDEATION

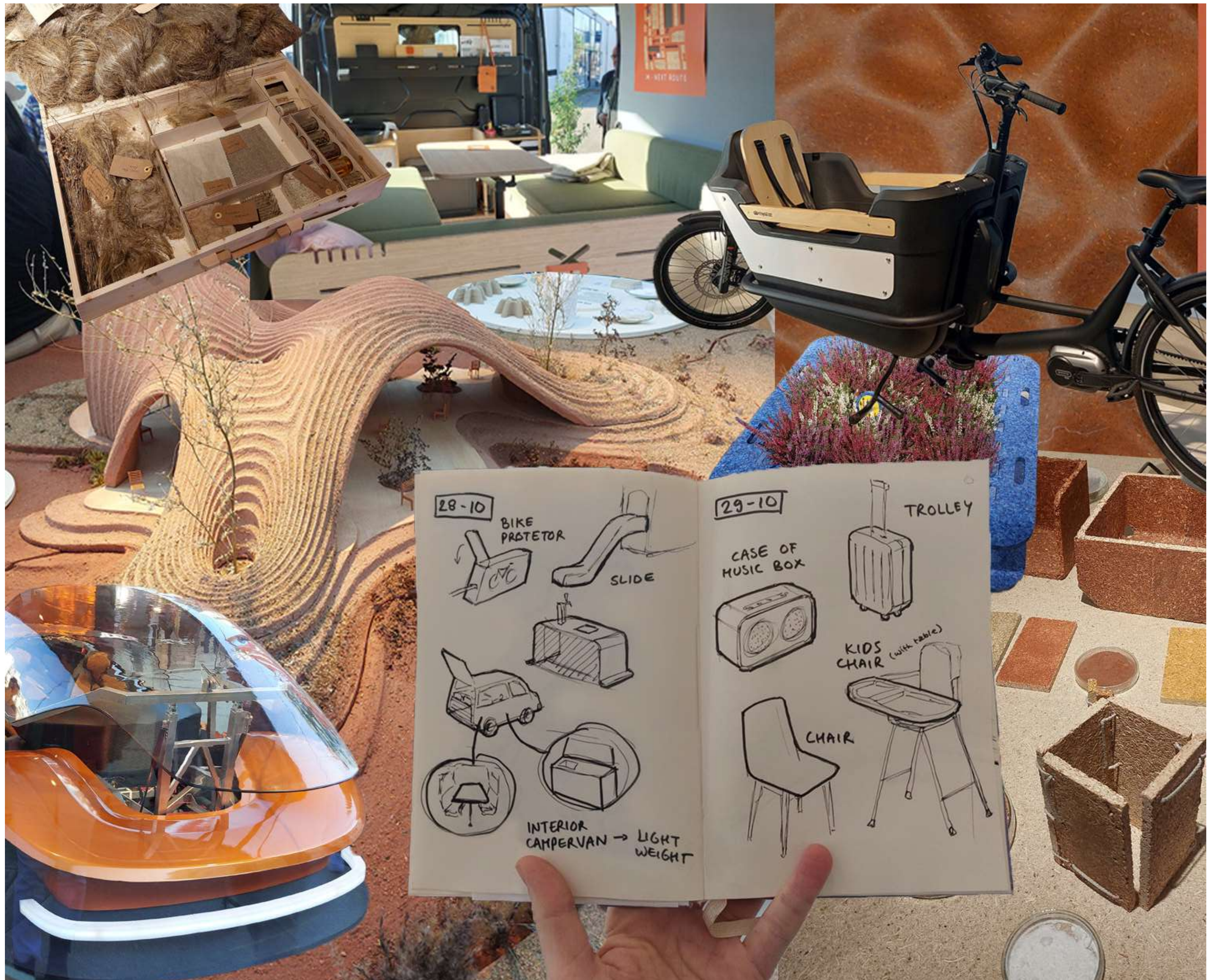
An ideation diary was created to start the ideation phase of this project and generate many ideas. The ideation diary helped to approach the material from a design perspective and to start up the design phase of this project. All ideas that came up were drawn in the ideation diary for twenty days in a row. A complete overview of the ideation diary can be found in Appendix 10.

On the 24th of October, the Dutch Design Week was visited, and inspiration from this day was also drawn in the ideation diary (Figure 32). At the Dutch Design Week, a lot of products were produced with biobased and recycled materials.

- The car of 'Ecomotive' is designed to inspire the automotive industry because their biggest challenge is to maximise the sustainability of cars.
- 'Wad van Waarde' is an initiative to make the the Wadden Sea area plastic free. To achieve this goal, they design and create alternatives for plastic products. One of the materials they work with is flax, and they have also worked with flax residues.
- 'MNEXT' is working on biobased building materials to create nature-inclusive buildings.

In addition to these examples, there were a lot of projects related to sustainable living, green energy, and recycling. Therefore, this day was very insightful.

Figure 32: Impression Dutch Design Week inspiration & Ideation diary



5.4.2 GROUP BRAINSTORM SESSION

A group brainstorm was organised to create a more diverse set of ideas and check the output of the individual ideation. Before the brainstorm session, a detailed plan was made, including different activities and timestamps (Appendix 11), following the guidelines as described in the Delft Design Guide (Van Boeijen et al., 2014).

The group brainstorm took place at the Faculty of Industrial Design Engineering. Four Industrial Design students participated in the group brainstorm (Figure 33). They were asked to sign a consent form at the beginning of the session (Appendix 11). The participants are introduced to the topic, and the goal of this brainstorm session is explained. After a brief introduction, a warm-up exercise is done to get into the mood of drawing and to get familiar with the subject.
During this warm-up exercise, participants are asked to draw/write down products (categories) that have the advantage of being lightweight, have a demand for sustainability, etc. This helps the participants to start thinking in the right direction.

After the warm-up exercise, the design vision of this project is introduced to the participants, together with some opportunities and constraints of the material. With this design vision and material properties in mind, the ideation started. All participants had an A3 paper in front of them, and they drew/wrote down their ideas for four minutes. After four minutes, the sheets of paper are moved to the person on the left. The participants get time to read what is already on the paper, and the four minutes start again. In this way, a large number of ideas are generated.

The ideas generated in the ideation diary and during the group brainstorm are clustered in categories (Figure 35). Based on three important requirements, a part of these ideas is eliminated for this project (Appendix 12).

Figure 33: Group brainstorm

5.5 PRODUCT CONCEPTS

A C-box is created to plot the ideas on shapeability and sustainability (Appendix 13). Based on the C-box, three potentially interesting idea directions are selected (Figure 34).

High Shapeability
The first idea direction is very broad and can be found on the right side of the C-box. All ideas plotted on the right side of the C-box can show the shapeability of the recycled material. This idea direction is less about the application and whether this is realistic or not but purely about showing the shapeability of the material.

Vehicle components
The sustainable advantage of making vehicle components of the recycled material is that the material is lightweight, which is good for the efficiency of vehicles. Next to this, a lot of vehicle components are made of fossil resources. This idea direction also scores high on shapeability because the shapes of these components can be relatively complex.

Office application
The last idea direction focuses on starting the conversation about recycling composite materials. This idea direction is an office application for the Eve Reverse office, but it could also be taken to an event. This idea direction does score lower on the shapeability and sustainability axis, which makes this idea less interesting.

To decide which idea direction has the most potential, a meeting was planned with all employees of Eve Reverse. During this meeting, the three idea directions were presented and discussed. Together, we concluded that vehicle components are the most promising option. This is primarily due to their realistic application, which is more inspiring to professionals in the composite industry. At events like JEC, attendees are more inclined to take an interest in material integrated into a vehicle component rather than something like a tabletop.

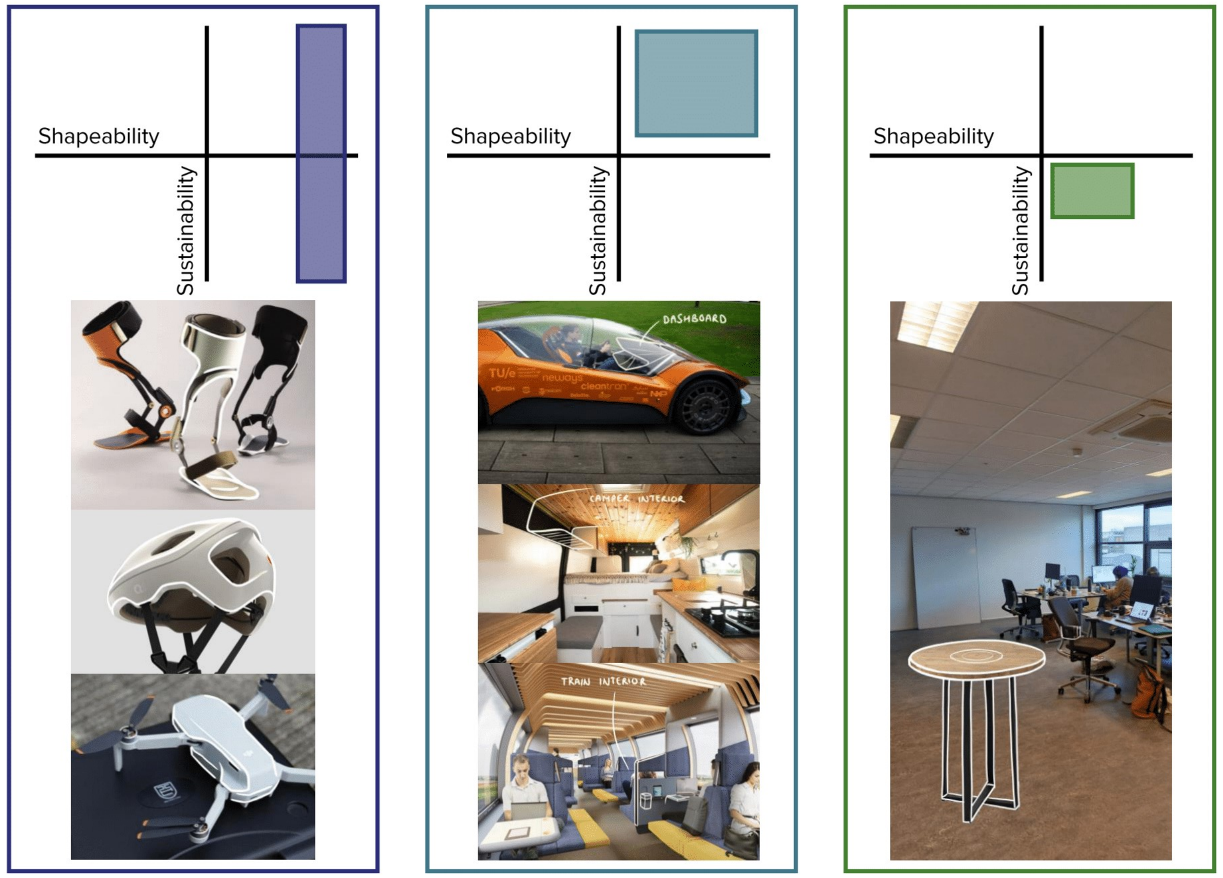


Figure 34: Potential interesting idea directions from C-box

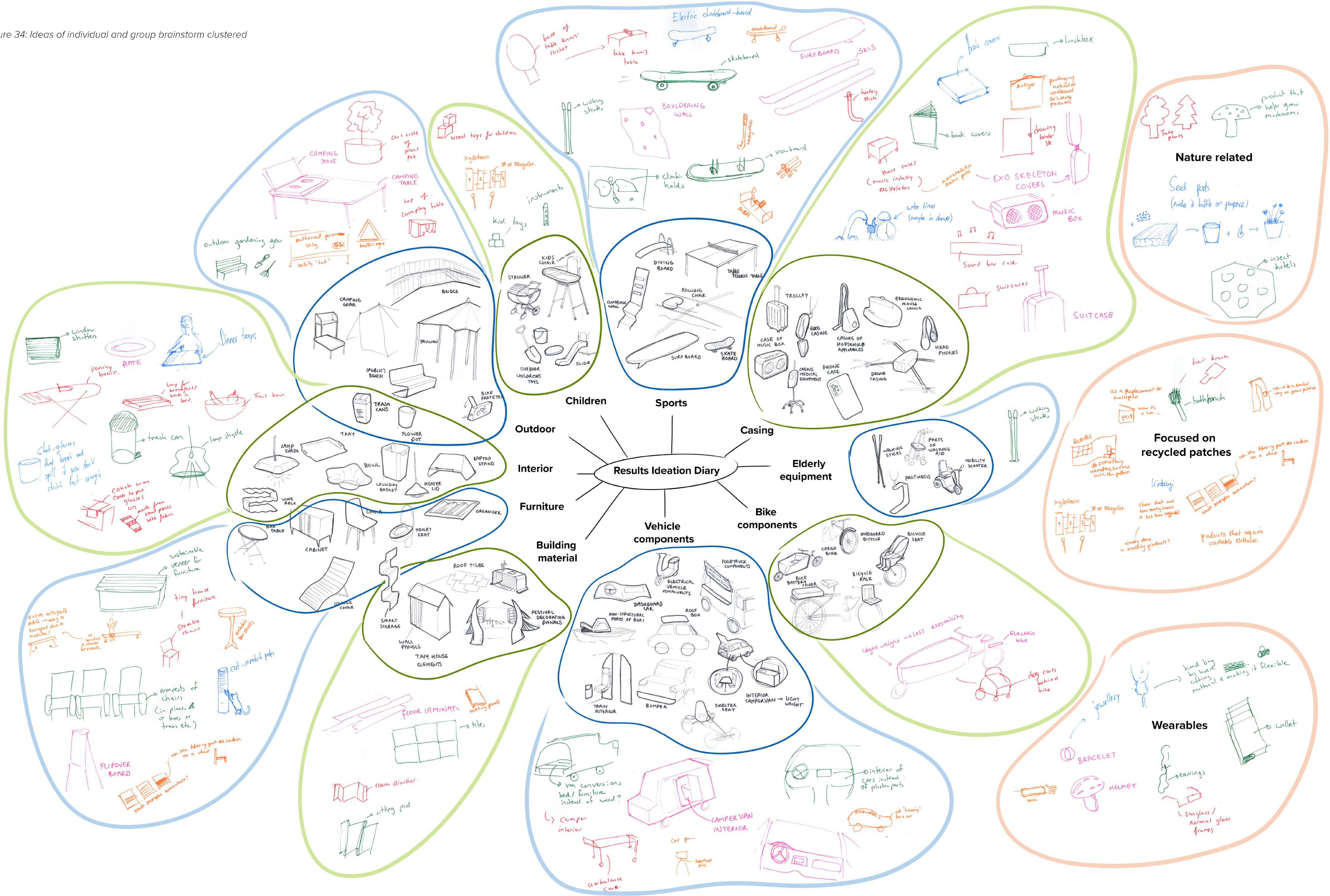


Figure 34: Ideas of individual and group brainstorm clustered

The idea direction of vehicle components was further developed, focusing specifically on interior parts. This decision was made due to the poor UV resistance of flax and furan and the high tendency of flax fibres to absorb moisture. This could be solved by adding a proper coating, but the scope will be narrowed to interior parts for this project. From the C-box, three ideas were selected for further exploration.

The first option that is explored is the interior of car doors. The interior of car doors often have interesting and quite complex shapes. A junkyard is visited to look at different car interiors and to ask for a part that could be used as a mould. The junkyard owner donated the door interior of a Ford Focus (Figure 36). This option would save a lot of time since there is no need to make a mould ourselves.

Figure 36: Car door donated by junyard.

For the second option, Ecorunner, a dream team in the Dreamhall, is visited to ask if they are interested in collaborating on this project. Ecorunner aims to produce a car that inspires the world towards sustainable mobility. This year, they are exploring the option of making the monoshell of their car of biobased fibres, so they were very interested when I told them about this project. Later, the dream hall was visited with a quick drawing of a dashboard in the Ecorunner car (Figure 37). After talking about the possibilities, they confirmed that making a dashboard for their car of the recycled material is possible.

Figure 37: Quick drawing of a dashboard in the Ecorunner car.

The third option explored is the camper interior (Figure 38). Most camper conversions heavily rely on wooden components. To assess the possibilities of using the recycled material, I called an expert who frequently converts vans into campers. She highlighted that one of the main issues with wood is its lack of water resistance, which can be problematic in the damp environment of a camper. Additionally, it would be advantageous to design applications that allow for easy access to electronics, as detaching wood connections often damages this connection. The expert suggested to focus on components that could be adapted for use in commonly converted vans, this ensures a broader applicability and the potential for quick repetition.

Figure 38: Example of wooden camper interior.

5.6 CONCEPT CHOICE

The ideas will be evaluated based on seven criteria to identify the most promising application for the recycled material. These criteria are selected from the list of requirements and cover the most important criteria per category. The criteria are prioritised in order of importance, with the first being the most critical and the last being the least important of these seven criteria.

1. The application of the material should use the technical qualities of the material (Design vision, technical properties).
2. Inspiring application to people in the composite industry (Design vision, application).
3. The application shows the shapeability of the recycled material (Design vision, application).
4. The application is a motivating design challenge for my project (Personal wish).
5. Feasible to produce the part within the project timespan (Production).
6. Feasible to produce at the composite lab of Inholland (Production).
7. There is a sustainable advantage to make the application of this material (Sustainable viability).

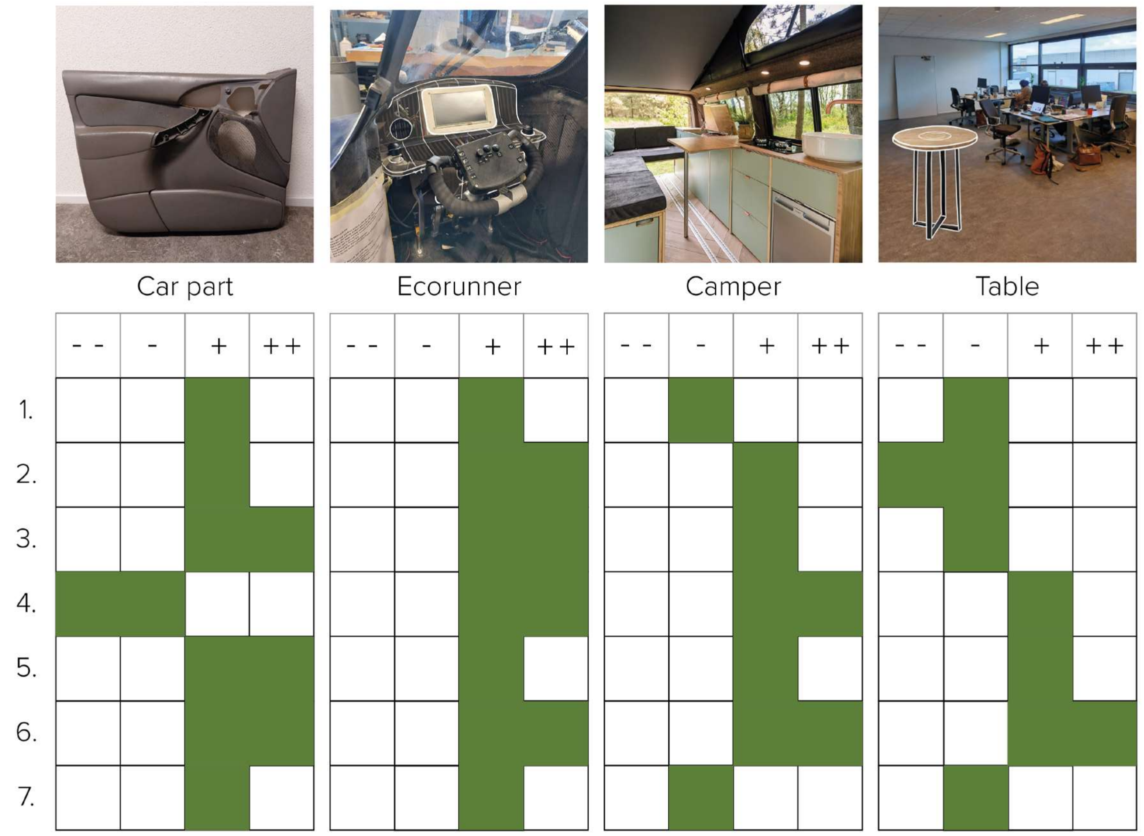


Figure 39: Harris profile

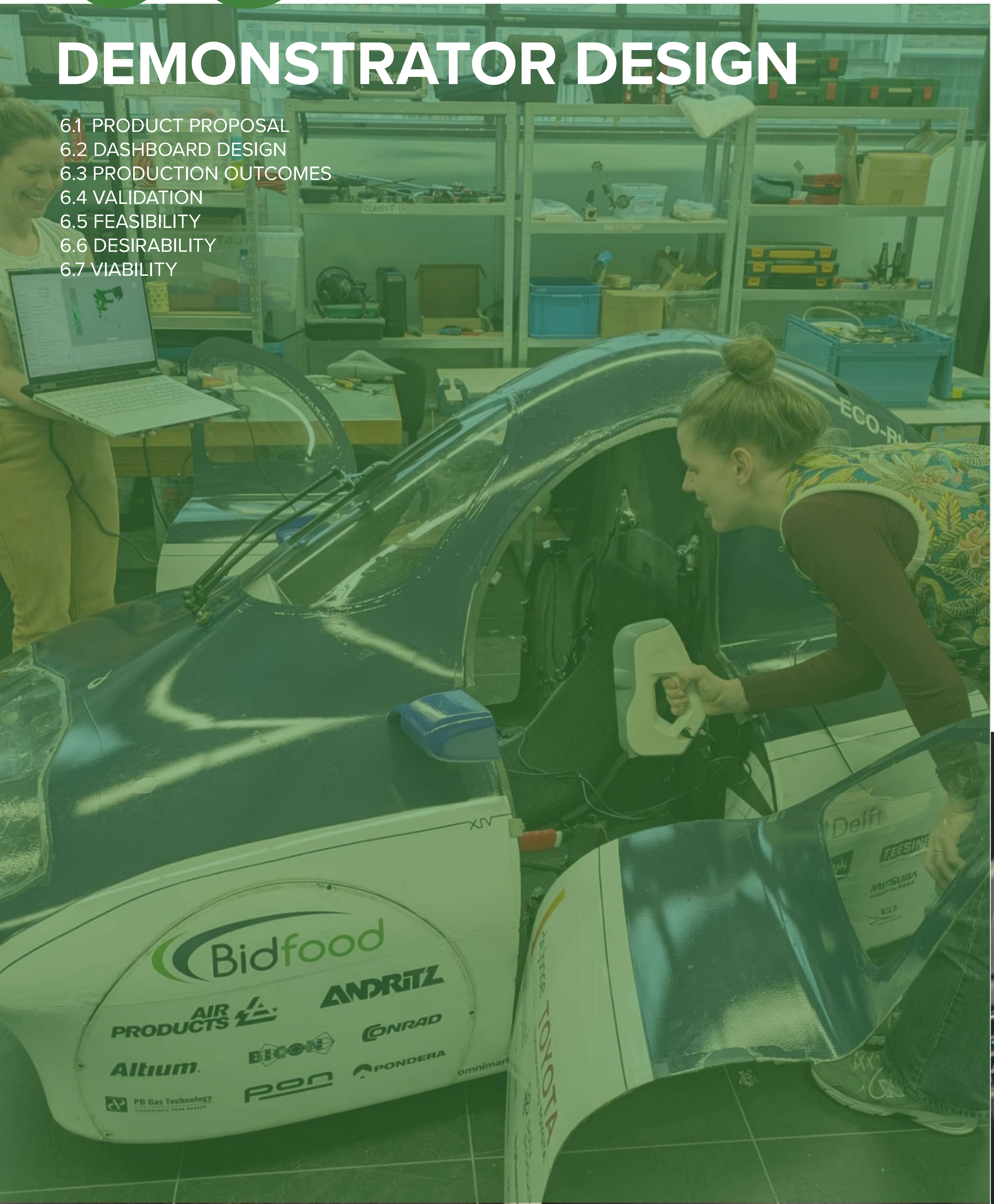
A Harris profile is used to compare the ideas and make any intuitions explicit (Van Boeijen et al., 2014). Because the criteria are ranked according to their importance, it becomes clear which way the tower of blocks would fall.

The Harris profile shows that the dashboard for the Ecorunner car emerges as the most suitable application for the recycled material (Figure 39).

06

DEMONSTRATOR DESIGN

6.1 PRODUCT PROPOSAL
6.2 DASHBOARD DESIGN
6.3 PRODUCTION OUTCOMES
6.4 VALIDATION
6.5 FEASIBILITY
6.6 DESIRABILITY
6.7 VIABILITY



6.1 PRODUCT PROPOSAL

For a very long time, Ecorunner was focused on producing the most efficient car, but since last year, their focus has shifted to producing a street-legal hydrogen-powered car, which means that their car can drive on public roads. Now that their car is allowed on the public road, it becomes more interesting to make it more suitable for public use. Therefore, incorporating a car dashboard is an interesting step towards a more user-friendly car design.

The car dashboard is positioned in front of the driver and is the barrier between the driver and the car's front. The dashboard is the control panel for the driver since it shows relevant information about the car's state and operation. Some of this information is presented on a screen incorporated into the dashboard, and some information is shown with coloured lights. Automotive safety and ergonomics regulations require cars to have an airbag. The airbag for the driver is often incorporated into the steering wheel. The airbag for the passenger seat should be integrated into the dashboard. The Ecorunner car has no passenger seat, so an airbag will not be integrated into the demonstrator dashboard design. Other elements often integrated into a car dashboard are ventilation grills used to circulate the air in the car to regulate the temperature (Figure 40).

Different criteria were found when researching the requirements for the material of a car dashboard. A car dashboard should be long-lasting, the surface should be scratchproof, and the material should be hazard-free, sustainable for vibration, ultraviolet resistant, and lightweight for fuel efficiency. Preferably, the surface should be hand-feel pleasant, and the dashboard should be visually attractive (Shinde & Patel, 2020). Some of these requirements were already included in the list of requirements (paragraph 5.2). The dashboard design will be validated based on these requirements in paragraph 6.4. When looking for the required mechanical properties of an automotive dashboard, a research paper was found written by Salit et al. (2011) that is about a new natural fibre composite material selection process for automotive dashboards using an expert system. This paper states that the required mechanical properties for a car dashboard are:

	Required	Recycled flax/furan
Density (kg/m³)	980 - 1100	1070 - 1320
Tensile strength (MPa)	20 - 30	70 - 118
Young's modulus (GPa)	2 - 6	9 - 24

Table 12: Mechanical properties car dashboard

Looking at the mechanical properties of the recycled material (Table 12), it appears that the car dashboard made of recycled flax-furan composite is overengineered. However, these values do not account for the overlapping areas of the patches. Furthermore, natural fibres are often considered unreliable, making it essential to incorporate a safety margin to accommodate variability in fibre quality and performance.

Figure 40: Car dashboard elements

6.2 DASHBOARD DESIGN

This paragraph shows the different steps required to produce the demonstrator product.

STEP 1

Designing the dashboard

A meeting with Ecorunner was set up to find out whether there were wishes from their side. The Ecorunner car was inspected, and it was decided to design a dashboard for the Eco XIII. This is because the car for this year is still under construction and will not be finished before the end of this project. There are just a few components to take into account, including the steering wheel, two tubes, and a screen.

With this information and a few pictures, I started drawing possible shapes for the dashboard (Figure 41). Designing through drawing is a nice method to come up with new shapes and explore the possible appearances of the dashboard. From these sketches, a few drawings were selected as a starting point for the 3D model.

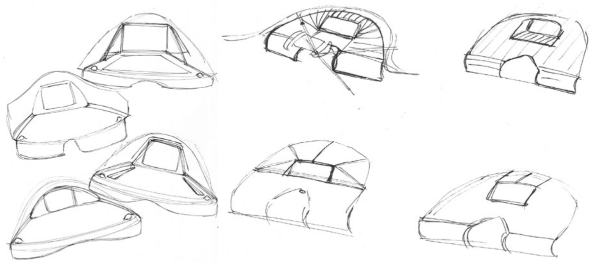


Figure 41: Sketches car dashboard

STEP 2

3D model of dashboard

After a few iterations, a shape was found that would fit the EcoXIII well and incorporates all components. While designing this dashboard, the outcomes of the shapeability tests are incorporated. The shape includes conic shapes, edges with a small diameter and complex double-curved shapes are avoided. The final shape is 3D printed in six parts and glued together. The 3D scan of the inside of the car was very helpful, and because of this scan, the dashboard fitted nicely, and no adjustments to the shape needed to be made (Figure 43).

Figure 43: 3D printed version of dashboard

STEP 3

3D scan of inside of car

To design a dashboard that will fit into the Eco XIII, a 3D scan is made from the inside of the car. This 3D model was used to follow the curves inside the car to design the dashboard (Figure 42).

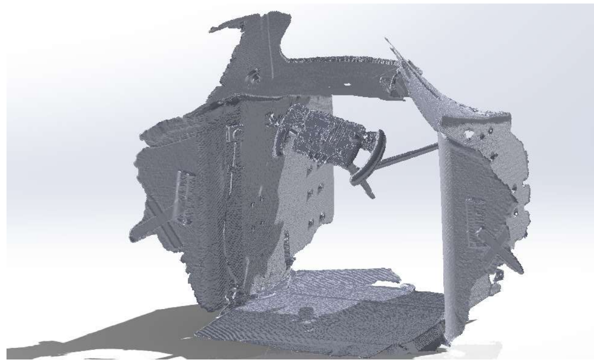


Figure 42: Result of 3D scan

STEP 4

Producing plug

The 3D model of the dashboard is used to print a PLA plug of this shape. The printed plug needs to be post-processed with a few rounds of sanding and filling, to achieve a smooth surface (Figure 44).

Figure 44: Plug

STEP 5

Producing mould

This finished plug is used to produce the mould of high-temperature resistant epoxy and eight layers of glass fibre fabric. This mould is post-processed with micro balloons to achieve a smooth surface. After smoothing the surface, sealer and release agent are added to ensure smooth demolding (Figure 45).

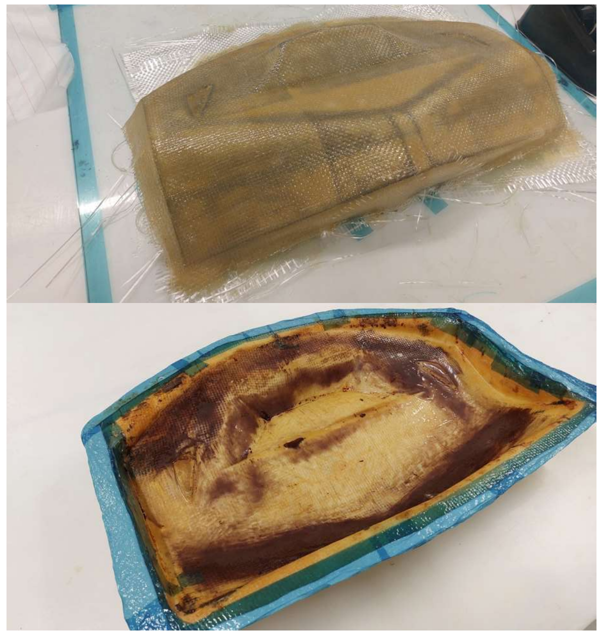


Figure 45: Mould

STEP 6

Preparing material

The first-cycle material is recycled, as described in paragraph 4.1. The patches are measured and cut if necessary to comply with the dimensions of 6 x 15 cm. Furan resin is added (Figure 46) where the patches overlap, after which the patches are placed in the pattern as described in paragraph 5.1.

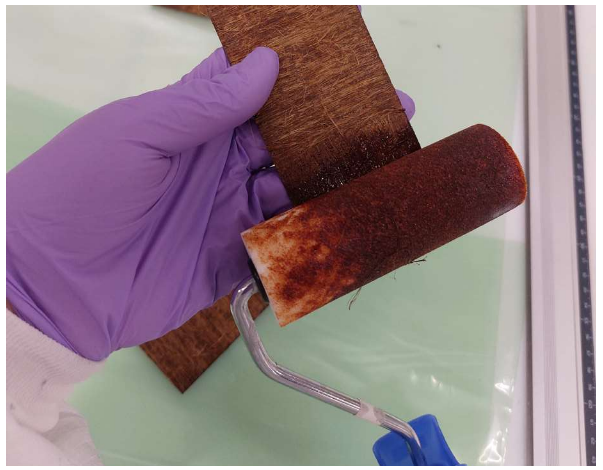


Figure 46: Roll furan on recycled patches

STEP 7

Produce dashboard

The patches are placed in the mould, trying to follow the pattern as well as possible. When all the patches are inside the mould, a layer of peel-ply, release film and breather are added. A vacuum bag is put around the whole product, and a vacuum hose is added to create a vacuum inside the vacuum bag (Figure 47). The vacuum bag is placed in the oven still under vacuum, and the material is cured for 4 hours at 115 °C. After curing, the dashboard is removed from the oven to cool down before demoulding the dashboard.

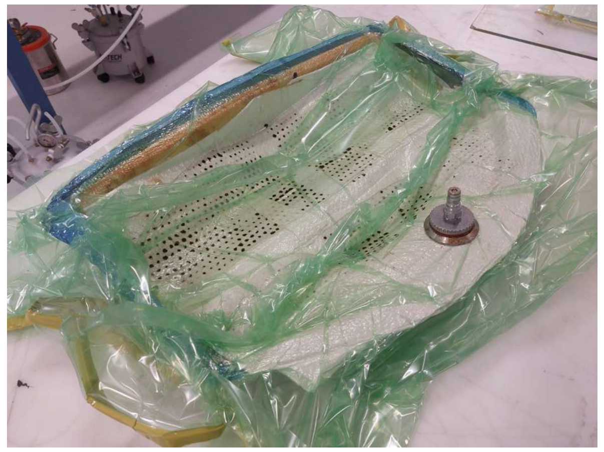


Figure 47: Mould with recycled material under vacuum

STEP 8

Post processing

The 3D printed version of the dashboard is used to draw the dashboard's contours on the recycled material. A dremel is used to achieve the desired shape for the dashboard (Figure 48). The edges are sanded so that they are smoother.

Figure 48: Demonstrator dashboard

6.3 PRODUCTION OUTCOMES

During the exploration phase of this project, a lot of tests were conducted to create a list of requirements (paragraph 5.2). Based on these requirements, several design ideas and assumptions are made. During the production of the dashboard, many of these ideas and assumptions were tested. This paragraph provides further details on the examined variables, including the product's pattern, shapeability, and final appearance.

6.3.1 RECYCLING METHOD

Different batches of first-cycle material are made. One batch was b-staged longer than 16 hours, which gave the material a darker look. For this specific batch, the recycling method did not work as intended. The separated patches broke before complete separation, probably because the material was brittle. The recycling went very smoothly for all other batches, and a lot of recycled material was made this way.

Over time, the patches curled up, probably due to moisture. The curled-up patches were not a problem for production. The outside layers of the laminate are curled up because they are asymmetrical. The middle layers are symmetrical and stayed flat. Some curled-up patches were placed underneath a heavy plate to make them flat again.

It is important to completely airdry the patches before storing them. A few patches were not completely dry before stacking them on top of each other. The moisture caused mould to develop on these patches.

6.3.2 PRODUCTION

It was difficult to follow the pattern as it was intended. The brick pattern in one layer was easy to maintain. Placing the second layer accurately was a challenge due to the complex shape of the dashboard.

Rolling the furan on the patches made controlling the amount of resin added to one patch difficult. Estimating how much resin is added in total is possible, but I am unsure how it is divided over the patches.

A challenging part about the production, compared to placing first-cycle material in the mould, is that the patches do not stick to the mould. The outsides of the patches are dry, which means the patches move around easily when placing the material in the mould. This causes holes and misplacement of patches, which gives a messy look.

To keep the patches in place, heat-resistant blue masking tape was used, this can be removed after the curing process in the oven, but gives limitations for scaling up the production. Removing the tape was sometimes difficult because the patches still moved a bit, and the blue tape was stuck between the two patches.

It was challenging to create a vacuum on the screen section of the mould, likely because the crease had a radius that was too small relative to the depth of the indent. The indent should be positioned closer to the surface if such a small radius is required. Alternatively, if the indent needs to maintain its depth, the radius should be bigger, or the entire indent should be increased in size.

6.3.3 RESULT

The dashboard was produced twice to test whether a few changes would make a difference for the end result. The differences are pointed out in Figure 49. The first recycled dashboard ended up looking better than the second version.

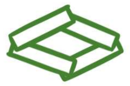
Take-a-ways

- Adding more furan to fill up the uneven area of the overlapping edges is not the solution. This should be solved by looking for a suitable coating.
- The preferred pattern depends on the shape.
- It can be helpful to cut a patch in a specific shape to be able to follow the mould.

Figure 49: First and second version of dashbarod.

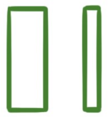
Pattern

The patches did not stay in the right place around the screen. The horizontal patches on the screen moved down, which creates an irregular pattern, this looks messy (Figure 50).



There is a hole because a few patches moved. On both recycled dashboards, the holes are visible around the screen part of the dashboard (Figure 50). When looking at the side of the dashboard, it is visible that the thickness is not even over the whole dashboard. This is due to overlapping areas of patches.

Figure 50: Screen detail of recycled dashboards



The dimensions of the patches were nice to work with for this demonstrator product. When a bigger product is made, the size of the patches could be increased. It helped to cut one patch in the shape of the screen to follow this curve better in the mould.

Take-a-ways

The more complex the shape, the more difficult it is to follow the pattern and the more difficult it is to ensure an even material distribution.

Shapeability

The sharp edge of the screen is difficult to follow for the material. There was air in these places when the vacuum was created. The result is that the edges are more curved than intended.

The indents of the ventilation grills are visible on the surface of the dashboard, which means the recycled material can follow a shape like this (Figure 51). The material could also follow the conic shape with a big radius at the bottom of the dashboard. This is a good example of a small radius close to the surface and a bigger one that can have a bigger indent.

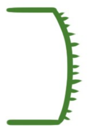
Figure 51: Indent for ventilation grill of recycled dashboards

Take-a-ways

As described before, it was challenging to ensure the vacuum was in the sharp edge of the screen. The result is curved edge. When designing with this specific type of recycled material, it is recommended to use shapes with smoother transitions. The radius of this screen was too small for the depth of the screen. However, the conic shape on the bottom of the dashboard is an example of a shape that would be easy to follow for the material.

Final appearance

The surface of the dashboard is quite rough, which is not what is expected for a car dashboard. The first sample of recycled material for the experience test (paragraph 4.4) had a very smooth surface. This is probably because the patches were perfectly aligned, which was possible because a flat sample was produced. An epoxy and water-based coating have been tested, to see if this would improve the surface. However, it has been decided not to apply a coating to the demonstrator, to show the material as good as possible. The shiny finish of the coating was a bit distracting. A matt coating could be the solution to this problem.



Cutting off the edges with a dremel was easy, but opening up the sides of the dashboard made fibres visible. The edges are sanded to ensure they are less fibrous, but some fibres are still visible on the sides.

Take-a-ways

Now that it is clear that achieving a smooth surface on a more complex shape is not possible, other applications than a car dashboard might be more suitable. For other suitable applications the brainstorm outcomes can be checked in Figure 34. Applying a coating to the sides will help to lock in the open fibres.

Set-up demonstrator

There are different possibilities for the set-up for the demonstrator, depending on the amount of space available and the target audience.

A stand, ventilation grills, steering wheel, and screen are 3D printed to showcase the dashboard with some context. If desired, the screen can be replaced by a phone with a video showing the recycling process (Figure 53). Both the screen and phone can be placed on a 3D printed holder. A poster is designed to give more information about the goal of the demonstrator and the recycling method, and the dashboard in the Ecorunner car is shown (Figure 52). If there is no space for the poster, a small version of the poster can be placed in a different version of the steering wheel, including key information.

In case there is space for two products, a first-cycle product can be placed next to the recycled dashboard to provide more context and make it very clear what type of material is recycled. The dashboard or deck hatch produced with first-cycle material can be used for this (Appendix 14).

Figure 52: Demonstrator with poster in backbround

Figure 53: Demonstrator with phone instead of screen

6.4 VALIDATION

Now that the dashboard is produced, it is time to validate whether all requirements and the design vision have been met.

6.4.1 REQUIREMENTS

The list of requirements is divided in four categories. These will be discussed in this paragraph with the corresponding codes mentioned.

Production
The demonstrator is produced at the composite lab of InHolland (1.2) within the project timespan (1.1). The dashboard is made of recycled flax-furan patches (1.3 & 1.5) with 6 cm x 15 cm dimensions (1.7). The dashboard is cured in the oven, meaning the dimensions are smaller than 1.20 m x 1.20 m (1.4). The only requirement that was difficult to fulfil was following the brick pattern as determined in paragraph 5.1 (1.6). As described in the previous paragraph, using the brick pattern in one layer was easy, but placing the two layers on top of each other was difficult to do as intended due to the complex shape of the dashboard.

Technical properties
A car dashboard is exposed to sunlight through the car windows, and it can also get damp in a car due to temperature changes. A car dashboard is not exposed to temperatures above 150 °C for a prolonged time (2.3). A coating should be applied to protect the dashboard from moisture and UV exposure if the dashboard is used in a car (2.1 & 2.2). For the dashboard as a demonstrator, no coating is applied to show the material as good as possible. The material's technical properties are considered as described in paragraph 6.1 (2.4).

Sustainable viability
The lightweight material is an advantage for the efficiency of the Ecorunner car (3.1). The dashboard is somewhat overengineered and requires no reinforcement from other materials (3.3). It is difficult to assess whether this dashboard is more sustainable than a dashboard produced with virgin material through injection moulding since the recycling process used for the flax/furan dashboard is still in the prototyping stage. However, using recycled material instead of virgin material is good to keep it in the circular loop for as long as possible (3.2). No additional material is added, which makes an EoL option as shredding possible (3.4)

Application
A car lasts, on average, for 15-20 years; therefore, it would be desirable for the dashboard to last for this time. At this moment, it is difficult to assess the material's longevity. Ageing tests could be performed carried out in climate chambers (Shinde & Patel, 2020) (4.1).

Another requirement is that the product should be cost-effective. At this moment, it is most probably more expensive to produce a dashboard of recycled material, partly because the process is still in the prototyping stage and is time-consuming. Also, first-cycle material has not yet been collected, and the supply of first-cycle material is a limiting factor (4.2).

A car dashboard is not a structural component that needs to carry a lot of weight, which is good because it is challenging to guarantee accurate mechanical properties for the recycled material (4.3). There are tests to examine the functionality and reliability that a car dashboard must pass before it can be applied in a car. Examples of these tests are noise, fatigue, tightening torque, impactor collision, and stiffness tests (Shinde & Patel, 2020). There are also aesthetic checks since the appearance of a car dashboard is important. The visibility of the fibres and texture created by the overlapping patches might not be desirable for a car dashboard. The material had some difficulties forming around the screen part of the dashboard, creating some irregularities and giving a fragile look. Applying a smoothing coating could solve this problem (4.4).

The shapeability is stretched to its limits since it was challenging to create the complex shape of the screen as intended. The conic shape on the bottom of the dashboard was also possible for the material and the indents for the ventilation grills (4.5, 4.6 & 4.7).

The demonstrator is lightweight, and the size of the dashboard makes it easy to carry (4.8). A stand is created, including a steering wheel, to make the context of the demonstrator clear when not placed in the Ecorunner car. The picture of the dashboard in the Ecorunner car on the poster also shows the purpose of the demonstrator (4.9).

6.4.2 DESIGN VISION

During this project, the following design vision was created:

Demonstrate the end-of-life potential of flax/furan composites by designing an application that uses the material's technical opportunities (and constraints) to inspire the composite industry to integrate biobased materials and recycling principles into the design phase of their products.

This vision can be split up into different parts. The first part is about demonstrating the EoL potential, which is about showing the material in an application that shows the shapeability of the material. The outcomes of the shapeability tests (paragraph 5.1) are considered when designing the dashboard's shape. Unfortunately, the shape of the screen was a bit too complex, but this is interesting information about the shapeability of the material at the same time.

The second part of the design vision is about the technical opportunities of the material. The material is applied in a car dashboard, providing the necessary strength while remaining lightweight, ensuring it does not compromise the fuel efficiency of the Ecorunner car. The technical properties of the material are higher than required for a car dashboard, but it is challenging to guarantee very accurate properties because the material is recycled. Next to this, natural fibres are not yet perceived to be very reliable and strong. Gaining the trust of potential users by using recycled natural fibres in a car dashboard is a good first step towards building trust in the perception of natural fibres.

The third part of the design vision is about inspiring people in the composite industry to integrate biobased materials and recycling principles into the design phase of their products. Designing a car dashboard for the Ecorunner car is a good start in reaching people in the composite industry since Ecorunner has multiple partners related to this subject and has a good platform for publicity. Ecorunner will make the shell of this year's car of flax fibres, which, in combination with the dashboard made of recycled flax fibres, could inspire professionals to explore this material. Three composite experts were contacted to ask questions about the demonstrator to find out what type of reactions can be expected from industry experts regarding this demonstrator. The participants of these interviews were a lab manager of a composite lab with prior experience as a research engineer at a composite company, a free-lance composite engineer, and a research and design lead at a biobased composite company. The questions and a summary of the answers can be found in Appendix 15. The demonstrator set-up was similar to the set-up in Figure 52.

When the participants looked at the demonstrator, they were curious to learn more about the production and recycling process. The experts were asked what they would design with this recycled material to determine whether the demonstrator inspired them. All three came up with different possible applications for the material, like furniture, wall panels, outdoor applications, and traffic sign boards. It was mentioned that it looks like wood but has the advantage that it can be shaped in curves, that its rough/sturdy look makes it suitable for outdoor applications, and that it could be applied to applications that carry more load than a dashboard since the length of the fibres is retained quite well. The fact that they came up with all these possible applications indicates that the demonstrator is inspiring and sparks new ideas. One of the last questions asked was about concerns or limitations they foresee for this recycling method. The biggest concerns are about recycling costs and the supply of EoL material; therefore, they do not see a business case for the recycling process yet. A concern mentioned before about the recycled material is that it is challenging to guarantee accurate or consistent mechanical properties. It is interesting to hear from the biobased composite expert that they encounter the same problem with biobased first-cycle material. A method needs to be developed to measure the properties of a product when using natural fibres in industry applications because consistency is difficult to offer. It was interesting to hear that this concern does not need to be a limitation, as the same challenge is present in first-cycle biobased composites and recycled fossil-based composite materials.

6.5 FEASIBILITY

6.5.1 FEASIBILITY RECYCLING PROCESS

The different steps of the recycling process are relatively simple, which means that no substantial technical development is needed to set up the facilities. The different steps are cutting the material into rectangles, boiling the patches, putting the patches through a sheet-forming machine, separating the layers, placing the patches in a mould, and curing the product. During this project, it has been proven that the material can be recycled in this way while retaining a lot of its qualities, which is an important factor in the feasibility of the process.

An operational challenge is the availability and supply chain of first-cycle material that can be recycled. Currently, there is no recycling chain for biobased products at the EoL. This is partly due to the perception that biobased materials are already a sustainable alternative, so there are still no large-scale recycling possibilities. This project has investigated EoL options and shows the potential for extending the life cycle of biobased materials. If material is available, one of the more challenging steps in the process will be to assess the structural state of the composite product that will be recycled. It would be very helpful if a material passport would be available of the first-cycle material. The lay-up of the product must be known before cutting, as the material needs to be aligned correctly in the fibre direction for the sheet-forming step. When bending the material with the sheet-forming machine, the fibres of the outside layers should be perpendicular to the bending direction.

For this recycling process to be most successful, a closed-loop production system should be established, where manufacturers encourage customers to return flax/furan-based products at the end of their product life. This approach ensures a predictable supply of recyclable material with a known lay-up, simplifying processing.

While this method retains more fibre value than mechanical recycling through shredding, it may be more complex and require more controlled processing conditions. Additionally, energy consumption, water usage, and potential waste products must be assessed to ensure the process remains environmentally and economically viable. Future research could also explore how many recycling cycles the material can undergo before the quality of the material has reduced too much.

6.5.2 FEASIBILITY DASHBOARD

Paragraph 6.2 & 6.3 show that it is possible to produce a dashboard as a demonstrator product with recycled material. However, changes will have to be made when this dashboard is taken from a demonstrator context to a real-life application. For the integration of this dashboard, connection points need to be created. Car dashboards are often connected to the car with screws. These screws are hidden with small plastic covers with a snap-fit connection. This type of connection is difficult to achieve with the recycled material. To conceal the screws, the dashboard design can include an indent, and a screw cover can be used for a seamless appearance.

The demonstrator product is a dashboard for a car without a passenger seat. To make a dashboard for a standard car, the dashboard needs to be a lot bigger, as almost all cars do have a passenger seat. The stiffness of the material is enough to overcome this width. Dashboards are often made of PVC, PP, PPE, or ABS, and the recycled material has a higher Young's modulus than these plastics. The recycled material also has a higher tensile strength than required for a car dashboard (paragraph XX). The durability and impact strength of the recycled material are unknown. Before producing a car dashboard of the recycled material, gaining more information about these properties is important. A dashboard should last at least as long as the car itself. Impact performance is important for passenger safety and tests are needed to determine whether the material behaves safely under high-impact conditions or poses potential risks, such as splintering. Factors such as heat resistance, sound insulation and UV degradation also need further evaluation.

The production of the demonstrator dashboard has also highlighted challenges in shaping the material. The more complex the design, the harder it becomes to achieve a smooth surface. Since automotive dashboards are expected to have a flawless finish, this limits the design complexity of dashboards made from this material. Optimising the patch dimensions could help mitigate this issue.

When scaling up the production process is desired, the most challenging step is placing the patches in a mould. This could be solved using a pick-and-place method similar to how Fairmat does this (Fairmat, 2024).

6.6 DESIRABILITY

6.6.1 DESIRABILIITY RECYCLING PROCESS

The demand for sustainable product design is growing, especially since Europe's climate policy is to become carbon neutral by 2050 (The European Green Deal, 2021). Next to this, the European Commission has set rules to make the automotive sector circular. The goal is "to prevent and limit waste from EoL vehicles and their components". One of the rules, for example, is "to ensure that at least 25% of plastic used to build a vehicle comes from recycling (of which 25% from recycled ELVs)" (End-of-life Of Vehicles, 2023). These developments indicate that the need for innovative recycling solutions, particularly for biobased materials, will only increase in the coming years.

Some automotive manufacturers have already begun integrating biobased materials into their vehicles. For example, BMW has already started to implement natural fibres in the BMW M4 GT4, incorporating them into the centre console, hood, front splitter, door, trunk, and rear wing contain natural fibres. They use less plastic in this way and, with this, lower CO_2 emissions by 60%. BMW also highlights that switching to natural fibres also reduces weight, which helps make the car more efficient and lower energy consumption (Sustainable Lightweight Construction, 2019). As the use of biobased fibres continues to grow in major brands like BMW, the importance of recycling these materials will also increase.

Exploring different recycling methods containing flax fibres is becoming more important. This project shows that it is possible to recycle a flax/furan composite material, which makes it more attractive to use the flax/furan composite as a first-cycle material. However, adopting biobased materials and recycling methods depends on different factors. Automotive manufacturers will only integrate these new processes if they are cost-effective and if they can market the use of these materials as a selling point.

6.6.2 DESIRABILITY DASHBOARD

The main goal of this demonstrator is to inspire people in the composite industry to incorporate biobased materials and recycling principles in the design phase of a product. Ecorunner and Eve Reverse share part of this mission. Eve Reverse wants "to manufacture truly carbon-negative products", and Eco Runner has the mission "to produce a car, to inspire the world towards sustainable mobility". Ecorunner will produce their monoshell using natural fibres, so they were interested in collaborating with this recycling project. It allows them to get more familiar with natural fibre composites. Additionally, Ecorunner has multiple partners in the composite industry and a strong platform for publicity, making this a good first collaboration to showcase the potential of recycled biobased composites.

This demonstrator shows the possibilities of recycling biobased composites. The material, as presented in the demonstrator, sparks curiosity and, with this, wants to inspire those who design with composite materials. With increasing global attention on the pollution of greenhouse gas emissions and climate impact, governments are setting up regulations and providing subsidies to stimulate sustainable development. Consumer preferences also gradually shift toward greener products (Cheng et al., 2022). These factors drive the desirability of sustainable technologies. However, the desirability of this specific recycled material for a car dashboard remains uncertain. Consumers expect a visually appealing and smooth dashboard surface as an eye-catcher of their car's interior. As currently produced, the demonstrator dashboard has a rough and irregular appearance that is unlikely to meet these expectations. Improvements in processing, surface treatments or coatings could improve its aesthetic appeal, making it more competitive with traditional dashboard materials. In addition, considerations such as durability and ease of maintenance are also critical features. If these challenges can be addressed and natural fibres get a more reliable perception by consumers, this material could become a desirable alternative for interior car parts.

6.7 VIABILITY

The viability of a product refers to the ability of a product to succeed in the market and survive in the long term. Assessing the viability of the recycling process and dashboard is difficult, so this paragraph will mainly be speculative.

6.7.1 WHY IT WOULD SURVIVE

From a technical point of view, the recycling process of flax/furan composites has proven to be effective, with the material maintaining part of the original properties, such as strength and stiffness, after recycling. However, for the process to become viable, it must be scalable to accommodate larger quantities of EoL materials. Regulations from the European Commission about becoming carbon neutral and limiting waste at the EoL of vehicles are good reasons to explore EoL options further, such as separating layers and developing this method further. Funding opportunities from the government stimulate the industry to focus on developing sustainable alternatives for fossil-based materials.

Eve Reverse complements the mission of the European Commission to become carbon-neutral by developing carbon-negative composites. The question is, when is something carbon negative? The Eve-tile is made from flax fibres that absorb CO_2 during its growth. With the help of sunlight and water, the CO_2 is converted into carbon hydrates and oxygen. These flax fibres are used to make biobased composites, which means that biobased composites store CO_2 in the form of CH_2O. If more CO_2 is stored than used during the lifecycle of the composite, it can be said that this biobased composite is carbon-negative. However, a few criteria must be complied with to claim that a product is carbon-negative. One of these criteria is that the removed CO_2 should be stored permanently and not released back into the atmosphere within a short period of time (Nederlands Normalisatie Instituut, 2019). Recycling biobased products helps extend the time that CO_2 is captured in the material. Therefore, this is a good step towards the goal of the European Commission to be carbon neutral.

A Life Cycle Assessment (LCA) should be conducted to assess the sustainable viability of this process. Currently, it is not fair to compare a dashboard made of virgin material through injection moulding with a dashboard produced with recycled flax/furan material. This recycling process is still in the prototyping phase, which is why too many assumptions will need to be made to draw valuable conclusions. Conducting an LCA at a later stage would provide valuable insights into the environmental impact of the process and help establish a clearer picture of its long-term sustainability.

Investment costs for equipment of a first set-up can be relatively low because the processing steps do not require complex technical development. The cost and challenges of scaling up production and ensuring consistent quality across bigger volumes of dashboards will be critical. If the recycling process can be efficiently automated and integrated into existing automotive supply chains, and if the material can be improved to meet the required aesthetic and performance standards, this recycling method could become a viable solution for car manufacturers that want to reduce their environmental impact while meeting sustainability regulations.

6.7.2 WHY IT WOULD NOT SURVIVE

There are different challenges to the recycling process of a flax/furan composite and a dashboard made of this material to survive in the long term. The main obstacle, as already mentioned by the composite experts in paragraph 6.4, will be costs. As long as raw material prices stay as low as they are now, it will be challenging to make recycling more affordable than making a product with virgin material. Virgin materials benefit from established supply chains and economies of scale, decreasing their prices and making them more affordable than recycled materials. Even if recycled flax/furan composites are cheaper in terms of material costs, the overall price of producing a dashboard using this production method could still be much higher than a standard dashboard made from virgin plastic. The recycling and production process of the recycled material is also much slower than the traditional injection moulding method, which produces dashboards in a few seconds. The time required to manufacture a dashboard from recycled material will increase the production costs.

Government subsidies will influence the price of the recycling process. These measures are uncertain and may not be sufficient to close the gap between virgin and recycled materials in the long term. Without persistent government support or a shift in virgin material costs, it will be challenging to make recycled materials economically viable at the scale required for mass production of car dashboards.

The sensitivity of natural fibres to moisture also limits their application in car dashboards. This property can lead to problems such as surface finish, colour defects and deformation (Shinde & Patel, 2020). These drawbacks may affect consumers' perception of the recycled material and make it less attractive compared to traditional plastic dashboards, which may offer more consistent quality and durability. Additional processing steps, such as coating, will also increase production time and thus production costs.

6.7.3 CONCLUDING

The recycled flax/furan material is suitable as a dashboard demonstrator. The application speaks to the imagination since a car dashboard is the focal point of a car's interior. The fact that it is easy to recognise helps to attract attention, and when coming closer, the material evokes curiosity from the viewer. People will be curious to know more about the recycling process, which is exactly what was to be achieved with this demonstrator product.

The recycled dashboard is a suitable addition to the Ecorunner car since both are still in the prototyping phase. Adding a dashboard to the Ecorunner car's interior makes it look more like a passenger car. Additionally, the wooden look of the dashboard gives a warm and inviting aesthetic, offering a more pleasant view compared to the exposed carbon tubes the driver would otherwise see.

However, a car dashboard might not be the most realistic real-world application for this material. The material is over-engineered for this purpose, and the rough appearance is not what people would expect from a car dashboard. The surface finish and the sensitivity of the natural fibres to moisture and temperature create challenges to achieving the smooth, polished look desired in automotive interiors.

Despite these challenges, the material's potential has been proven, and other applications can be explored for the recycled material. When looking at the mindmap on page 56-57 applications like the exterior of a cargo bike, wall panels, or the interior of a self-renovated camper might be suitable for the recycled flax/furan composite material. These applications do not require detailed curves, and it is accepted if they have a rougher appearance. Additionally, these markets might be interested in the material's sustainability, making them promising alternatives for further exploration.

07 CONCLUSIONS

7.1 CONCLUSION
7.2 LIMITATIONS & RECOMMENDATIONS
7.3 PERSONAL REFLECTION

7.1 CONCLUSION

The overarching goal of this project has been to validate the potential of NFRPC's within a circular economy, specifically focusing on the multiple use-cycles of Eve-tiles. By exploring EoL options and designing a demonstrator product, this project contributes to the broader challenge of sustainable composite materials and their recyclability.

To achieve this goal, the combination of flax and furan is selected, and EoL options are explored through desk research and activities of the MDD method. Based on research and material tests, a recycling method was identified: separating the layers of a flax/furan composite through intentional delamination. This method allows the fibres to retain a big part of their value while being applied to a new product. After recycling the material, experiential and technical tests are conducted to discover the interesting properties and characteristics of the material. Based on these findings, requirements are set, and a design vision is created:

Demonstrate the end-of-life potential of flax/furan composites by designing an application that uses the material's technical opportunities (and constraints), to inspire the composite industry to integrate biobased composites and recycling principles into the design phase of their products.

With the requirements and this design vision in mind, an individual and group brainstorm session was started. Finally, it was decided to design a car dashboard for the Ecorunner car.

The production of the demonstrator provided valuable insights into the sustainable potential of recycled composite. Conversations with industry experts confirmed the potential and challenges of implementing this recycled material on a larger scale. While the dashboard demonstrates the feasibility of reusing material made with Eve tiles, concerns remain about production costs and supply of first-cycle material. While these concerns are well-founded, this project aims to explore recycling opportunities early in the material development process. Biobased composite materials will continue to be used in various industries, so it is important to make sure that viable EoL options are in place before large-scale production begins. Waiting for a product's EoL before addressing recyclability can lead to challenges if suitable reuse or recycling methods are not available.

This project confirms the viability of multiple-use cycles for NFRPC's by demonstrating that the lifecycle of Eve-tiles can be extended through the separating layers method. This research shows how recycled biobased composites can be integrated into an industrial application. As recycling methods for composite materials continue to develop, the findings of this project can stimulate further research into sustainable material use.

7.2 LIMITATIONS & RECOMMENDATIONS

Due to the limited time of this project, some areas could use further research and improvements.

Recycling method

- The mechanical properties of the recycled material are lower than the properties of the first-cycle material. It would be interesting to find out which step in the recycling process damages the fibres the most and improve this step if possible, for example, lowering the temperature of the water, reducing the boiling time, or curing the product at a lower temperature.
- The width of the patches was set to 6 cm for this project. This decision was made because it worked, and there was no time to optimise these dimensions. Reducing the width of the patches might make it easier to form more complex shapes. Cutting patches into tailored shapes for specific applications might further enhance flexibility. Another option would be to cut the initial patches in tailored shapes from the first-cycle product before separating the layers. Ideally, first-cycle products could be designed with their EoL application in mind, ensuring easier reuse in future recycling processes.

Real-world applications

- The mechanical properties determined during the tensile and three-point bending tests are based on the recycled properties within one patch. In real applications, these patches overlap to form a larger structure. The influence of overlapping on the mechanical properties is unknown. This could be tested when further developing this recycling method.
- Many composite products have a coating to protect the product from environmental influences and extend the product's lifespan. However, during this project, the impact of such coatings on the recyclability of the product has not been tested. Coatings likely complicate the recycling process. Further research could determine whether certain coatings can withstand the recycling process or whether pre-treatment, such as sanding, is necessary.
- Composites often contain lightweigth core materials to improve the high strength-to-weight ratio even more. Just like coatings, core materials might complicate the recycling process. Further research is needed to determine what type of pre-treatment is necessary.
- The first-cycle material used during this project had no realistic product life. Recycling a material of a product that was used for several years, might introduce new challenges. Developing a method to evaluate the structural integrity of aged biobased composites would provide valuable insights.

Sustainable viability

- A LCA was not conducted, as the recycling method is still in the prototyping phase. However, as the method develops, it will be essential to assess its environmental impact.
- Testing whether this recycling process also applies to other composite materials would be interesting. Setting up a recycling chain that accommodates multiple materials would enhance its viability and scalability.
- The durability of the recycled material has not yet been tested. For a recycled material to be sustainably viable, it is important to assess its longevity. This will determine whether the recycled material can contribute to be a reliable, long-lasting product.

7.3 PERSONAL REFLECTION

As this project is ending, it is valuable to reflect on the personal learning ambitions set at the beginning of this project (Appendix 16).

One of my goals was to learn how to design from a material perspective instead of user wishes by applying the MDD method. It was really interesting to learn about this method and use elements of the method to explore the material. Having little prior knowledge of composite materials worked in my favour, as it allowed me to approach the material with an open mind, free from preconceptions. The MDD method played a big role in the first phase of my project, particularly in the material exploration stage. While creating my design vision and selection criteria, I involved some client and target audience wishes. I realised this when I had already started designing the Ecorunner dashboard. Looking back, I wonder whether the same concept choice would have been made if I had strictly adhered to a MDD approach without considering these user wishes.

Another personal learning goal was to avoid getting stuck in the research phase. The fact that I had to make an early decision on both the material and EoL method helped me to stay motivated and make these choices in time. When making these choices, I had to set clear boundaries and explain these to my colleagues at Eve Reverse to make a well-informed decision. Material testing was part of the research phase of this project, which I enjoyed. Because I enjoyed these activities, I did not feel like I was getting stuck in the research phase. In hindsight, I could have started the ideation phase earlier, parallel to the material tests. These material tests also helped me to achieve another personal learning goal: gaining practical experience with hands-on material testing. I remember my first day at the office when Karel asked me to observe an infusion process with another intern. Standing there wearing a lab coat, safety mask, and goggles, I wondered how I would eventually create my own materials and conduct my own tests. Now, I feel completely comfortable working in the composite lab and using the available equipment. I am grateful for the opportunity to develop these skills during my graduation project.

Working in the composite lab and office at Eve Reverse has been a great experience. I gained valuable insight into what it is like to work at a startup, where I had the opportunity to explore various aspects of the company beyond my specific project. I truly appreciate the freedom I was given to experiment, try new things, and follow my own ideas. Of course, I also experienced some of the challenges that come with working at a startup—from moving offices twice to dealing with a temporary lab closure, which required me to conduct my tests at the Aerospace Engineering composite lab instead. However, these challenges pushed me to stay focused and be creative to achieve my goals.

Finally, in my project brief, I wrote about my ambition to become a designer of products and services that have a positive impact on the environment. Throughout this project, I have learned a lot about recycling, EoL strategies, and sustainable materials. I am very happy that with this thesis project, I could contribute to Eve Reverse's mission of turning emissions into products. If possible, I would like to continue working with sustainable materials in the future.

08

REFERENCES

A

Åström, B. T. (1997). *Manufacturing of Polymer Composites*. http://ci.nii.ac.jp/ncid/BB14760295

B

Busschen, A. T. (2020). Industrial re-use of composites. *Reinforced Plastics, 64*(3), 155–160. https://doi.org/10.1016/j.repl.2020.04.073

C

Camere, S., & Karana, E. (2022, 13 juni). MA2E4 Toolkit - Materials Experience Lab. Materials Experience Lab-.https://materialsexperiencelab.com/index.php/2022/06/05/ma2e4-toolkit-experiential -characterization-of-materials/

Conroy, A., Halliwell, S., & Reynolds, T. (2006). *Composite recycling in the construction industry. Composites Part A Applied Science And Manufacturing, 37*(8), 1216–1222. https://doi.org/10.1016/j.compositesa.2005.05.031

D

Dhahak, A., Cézard, L., Baumberger, S., & Peixinho, J. (2024). Kinetic, Products and Shrinkage for the Pyrolysis of Flax Fibers. *Journal Of Analytical And Applied Pyrolysis, 180,* 106538. https://doi.org/10.1016/j.jaap.2024.106538

E

*End-of-life of vehicles. (*2023, 13 juli). commission.europa. https://environment.ec.europa.eu

Eve Reverse I *natural fibre composites.* (z.d.). Eve Reverse. https://www.evereverse.com/

F

Fairmat. (2024, 30 oktober). *Robotic Solutions - Fairmat.* https://www.fairmat.tech/robotic-solutions/

Fortunato, G., Anghileri, L., Griffini, G., & Turri, S. (2019). Simultaneous Recovery of Matrix and Fiber in Carbon Reinforced Composites through a Diels–Alder Solvolysis Process. *Polymers, 11(6*), 1007. https://doi.org/10.3390/polym11061007

G

Granta Edupack (2024) [Computerprogramma]. Ansys.

J

Joshi, S., Drzal, L., Mohanty, A., & Arora, S. (2003). Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A Applied Science And Manufacturing, 35(3)*,371–376. https://doi.org/10.1016/j.compositesa.2003.09.016

Joustra, J. J. (2022). *Circular Composites* [Doctoral thesis, Delft University of Technology]. https://doi.org/10.4233/uuid:ab19c21b-692a-4dd2-9d78-d62ce447cb4f

K

Karana, E., Barati, B., Rognoli, V., & Van Der Laan, A. Z. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. *International Journal Of Design, 9(*2), 35–54. http://repository.tudelft.nl/islandora/object/uuid:7359026d-57f5-4f63-9835-126c5d23baed/?collection=research

Krauklis, A. E., Karl, C. W., Gagani, A. I., & Jørgensen, J. K. (2021). Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s. *Journal Of Composites Science, 5*(1), 28. https://doi.org/10.3390/jcs5010028

M

Moudood, A., Rahman, A., Öchsner, A., Islam, M., & Francucci, G. (2018). Flax fiber and its composites: An overview of water and moisture absorption impact on their performance. *Journal Of Reinforced Plastics And Composites, 38*(7), 323–339. https://doi.org/10.1177/0731684418818893

N

Nederlands Normalisatie Instituut. (1998). *Met vezel versterkte kunststofcomposieten - Bepaling van de buigeigenschappen* (ISO 14125:1998). https://www.nen.nl/nen-en-iso-14125-1998-en-29040

Nederlands Normalisatie Instituut (2019). *Broeikasgassen - Deel 1: Specificatie met richtlijnen voor kwantificering en rapportage van emissies en verwijderingen van broeikasgassen op* *organisatieniveau* (ISO 14064-1:2019). https://www.nen.nl/nen-en-iso-14064-1-2019-en-255734

Nederlands Normalisatie Instituut. (2023). *Kunststoffen - Bepaling van de trekeigenschappen - Deel 4:Beproevingsomstandigheden voor isotrope en orthotrope met vezel versterkte kunststofcomposieten* (ISO 527-4:2023,IDT). https://www.nen.nl/nen-en-iso-527-4-2023-en-310013

Nigam, M., & Yadav, V. (2019). Linen- the classic fibre for futuristic fashion. *International Journal Of Applied Social Science, 6*(3), 659–667.

P

Pickering, S. (2005). Recycling technologies for thermoset composite materials—current status. *Composites Part A Applied Science And Manufacturing, 37*(8), 1206–1215. https://doi.org/10.1016/j.compositesa.2005.05.030

R

Ritzen, L. (2023). *Sustainability of bio-based plastics in a circular economy* [PhD-Proefschrift, Delft University of Technology]. https://doi.org/10.4233/uuid:ca8b3b1e-41db-4481-a5ab-f4f6d446ed2d

S

Salit, M. S., Mun, N. K., Lok, H. Y., Manab, M. F. A., & Ishak, M. R. (2011). Prototype expert system for material selection of polymeric composite automotive dashboard. I*nternational Journal Of The Physical Sciences, 6*(25), 5988–5995. https://doi.org/10.5897/ijps11.939

Shanmugam, V., Mensah, R. A., Försth, M., Sas, G., Restás, Á., Addy, C., Xu, Q., Jiang, L., Neisiany, R. E., Singha, S., George, G., E, T. J., Berto, F., Hedenqvist, M. S., Das, O., & Ramakrishna, S.(2021). Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C Open Access, 5*, 100138. https://doi.org/10.1016/j. jcomc.2021.100138

Shinde, N. G., & Patel, D. M. (2020). A Short Review on Automobile Dashboard Materials. *IOP Conference Series Materials Science And Engineering, 810*(1), 012033. https://doi.org/10.1088/1757-899x/810/1/012033

Singleton, A., Baillie, C., Beaumont, P., & Peijs, T. (2003). On the mechanical properties, deformation and fracture of a natural fibre/recycled polymer composite. *Composites Part B Engineering, 34*(6), 519–526. https://doi.org/10.1016/s1359-8368(03)00042-8

Sukanto, H. (2021). Carbon fibers recovery from CFRP recycling process and their usage: a review. *Iopscience*. https://iopscience.iop.org/article/10.1088/1757-899X/1034/1/012087

Sustainable lightweight construction. (2019, 5 juli). Bmw-m. https://www.bmw-m.com/en/topics/magazine-article-pool/bcomp-bmw-m-motorsport-.html

T

The circular economy in detail. (2019, 16 september). https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive

The European Green Deal. (2021, 14 juli). European Commission. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

V

Van In, J. B. [Jan Bart Van In]. (2019). Vlas is (terug) in zijn sas. In *Agripress*. West-Vlaanderen Werkt.

Van Oudheusden, A. A. (2019). *Recycling of composite materials* [Student report, Delft University of Technology]. https://resolver.tudelft.nl/uuid:0749ed5c-7aeb-4275-abee-0f904a08ea4d

Von Freeden, J., Erb, J., & Schleifenbaum, M. (2022). Separating layer recycling strategy for continuous fiberreinforced thermo-sets based on thermally expanding particles. *Polymer Composites*, 43(4), 1887–1899. https://doi.org/10.1002/pc.26505

Y

Yan, L., Chouw, N., & Jayaraman, K. (2013). Flax Fibre and its composites – a review. *Composites Part B: Engineering, 56,* 296–317. https://doi.org/10.1016/j.compositesb.2013.08.014

Z

Zhao, X., Copenhaver, K., Wang, L., Korey, M., Gardner, D. J., Li, K., Lamm, M. E., Kishore, V., Bhagia, S., Tajvidi, M., Tekinalp, H., Oyedeji, O., Wasti, S., Webb, E., Ragauskas, A. J., Zhu, H., Peter, W. H., & Ozcan, S. (2021). Recycling of natural fiber composites: Challenges and opportunities *Resources Conservation And Recycling*, 177, 105962. https://doi.org/10.1016/j.resconrec.2021.105962

09

APPENDIX

APPENDIX 1: TINKERING WITH MATERIAL

A.1.1 FIRST CYCLE MATERIAL

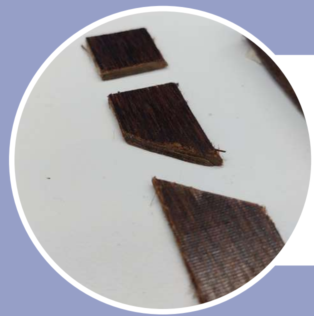
Guillotine scissors

Purpose: Is it possible to cut with guillotine scissors?
Process: The guillotine scissors cut through the sample easily, both along and perpendicular to the fibres. The edges do look a bit rough.
Take-a-ways: For straight lines the guillotine scissors are a suitable option to cut the sample.

Lasercutting

Purpose: Is it possible to laser cut? Will it burn?
Process: The lasercutter made very neat cuts, both along and perpendicular to the fibres. The laser made the furan smell burned.
Take-a-ways: Laser cutting is a very good way of cutting the sample.

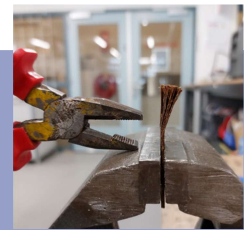
Stanley knife



Purpose: Is it possible to cut with a Stanley knife?
Process: The sample was cut 35 times perpendicular to the fibres. 16 times, 45 degrees to the fibres.
Take-a-ways: It takes a lot of time to cut a sample with a Stanley knife.

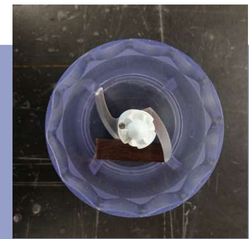
Bending

Purpose: What happens if a sample is bended?
Process: The different layers seperate from each other.
Take-a-ways: It might be possible to use separation of layers as a recycling option.



Blending

Purpose: Is it possible to blend a sample?
Process: It is possible to blend a sample. The result is a powder with some fibrous particals.
Take-a-ways: It might be possible to use the powder to make a new material from it.



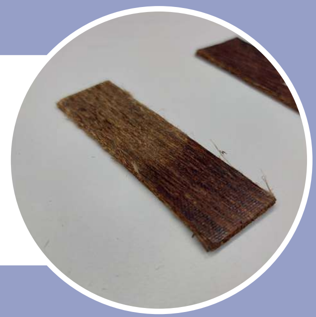
Granulator

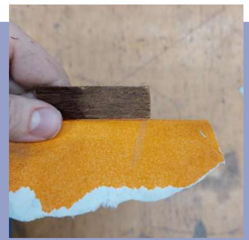
2

Purpose: Is it possible to shred a sample?
Process: The granulator produces consistent particals of around 1 x 4mm.
Take-a-ways: It might be possible to use the granulates to make a new material from it.

Sanding

Purpose: What happens if the sample is sanded?
Process: The matrix is sanded down, the fibres are exposed.
Take-a-ways:
Sanding makes the surface smoother, but the fibres are not protected anymore by the resin.





Sheet forming

3

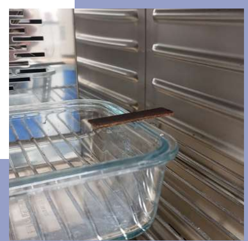
Purpose: What happens if the sample is put through a sheet forming machine?
Process: The layers start to separate from each other.
Take-a-ways: It might be possible to use separation of layers as a recycling option.

Punching a hole

Purpose: Is it possible to punch a hole in the sample?
Process: It is possible to punch a hole, but the sample starts to break in the direction of the fibres.
Take-a-ways: Punching a hole with a punch press uses so much force in a small area, which breaks the sample.

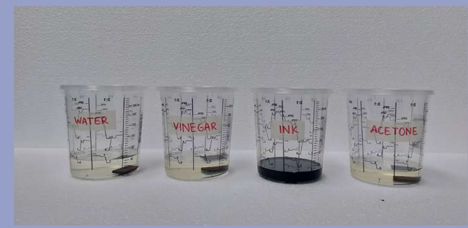
Put in oven

Purpose: What happens to the sample if it is put in the oven for 1 hour at 115 °C?
Process: The sample did not visually change.
Take-a-ways:
Putting the sample in the oven gives no visual results.



Put on hot metal

Purpose: What happens to the sample if it is put on a hot piece of metal?
Process: The sample turned black completely and it is easy to break the sample by hand.
Take-a-ways: Avoid the material from being in contact with a hot piece of material.



Put in water

Purpose: What happens to the sample if it is put in water for 24 hours?
Process: Putting the sample in water for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in water gives no visual results.

Put in ink

Purpose: What happens to the sample if it is put in ink for 24 hours?
Process: The sample is darker because of the ink. This shows that the fibres do take up the ink.
Take-a-ways:
The moisture is distrubed through the whole sample.

Put in acetone

Purpose: What happens to the sample if it is put in acetone for 24 hours?
Process: Putting the sample in aceton for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in acetone gives no visual results.

Put in vinegar

Purpose: What happens to the sample if it is put in vinegar for 24 hours?
Process: Putting the sample in vinegar for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in water gives no visual results.

Boil in water

4

Purpose: What happens to the sample if it is boiled in water for 2 hours?
Process: The sample feels softer and it is possible to peel the layers from each other.
Take-a-ways: Boiling the sample might make it easier to separate the layers.

A.1.2 RECYCLED MATERIAL

Guillotine scissors

Purpose: Is it possible to cut with guillotine scissors?
Process: The guillotine scissors cut through the sample easily. The edges do look a bit rough.
Take-a-ways: For straight lines the guillotine scissors are a suitable option to cut the sample.

Stanley knife

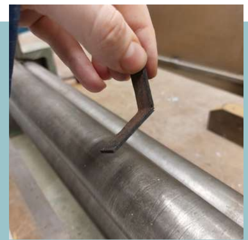
Purpose: Is it possible to cut with a Stanley knife?
Process: It took a lot of cuts to get all the way through the sample.
Take-a-ways: It takes a lot of time to cut a sample with a Stanley knife. The edges do look more straight compared to the guillotine scissors.

Bending

Purpose: What happens if a sample is bended?
Process: When bending the sample with pliers, the sample breaks immediately.
Take-a-ways: The recycled material is very brittle, which is why it breaks immediately.

Sheet forming

Purpose: What happens if the sample is put through a sheet forming machine?
Process: The sample breaks immediately.
Take-a-ways: The recycled material is very brittle, which is why it breaks immediately when put through a sheet forming machine.



Blending

Purpose: Is it possible to blend a sample?
Process: It is possible to blend a sample. The result is a powder with some flaky particals.
Take-a-ways: It might be possible to use the powder to make a new material from it.

Granulator

Purpose: Is it possible to shred a sample?
Process: The granulator produces consistent flakes/ chunks of around 2 x 4 mm.
Take-a-ways: It might be possible to use the granulates to make a new material from it.

Sanding

Purpose: What happens if the sample is sanded?
Process: The matrix is sanded down, the fibres are exposed.
Take-a-ways:
By sanding the sample the surface becomes a bit smoother.

Punching a hole

Purpose: Is it possible to punch a hole in the sample?
Process: It is possible to punch a hole, the edges of the hole look a bit rough.
Take-a-ways: Punching a hole with a punch press in the recycled sample did not make the sample break.

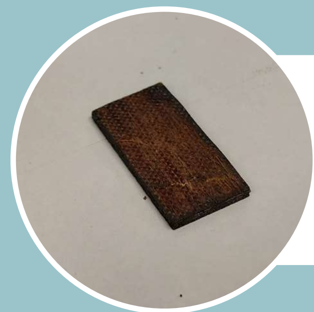
Put in water

Purpose: What happens to the sample if it is put in water for 24 hours?
Process: Putting the sample in water for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in water gives no visual results.

Put in ink

Purpose: What happens to the sample if it is put in ink for 24 hours?
Process: It shows that the fibres do take up the ink. The sample is darker because of the ink.
Take-a-ways: The moisture is distrubed through the whole sample.

Put in acetone



Purpose: What happens to the sample if it is put in acetone for 24 hours?
Process: Putting the sample in aceton for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in acetone gives no visual results.

Put in vinegar

Purpose: What happens to the sample if it is put in vinegar for 24 hours?
Process: Putting the sample in vinegar for 24 hours did not give any visible results.
Take-a-ways:
Putting the sample in vinegar gives no visual results.

APPENDIX 2: TINKERING FOR MATERIAL

After tinkering with the material, assumptions and ideas emerged that can be tested based on the material drafts. This appendix focuses on findings 2 & 4 of paragraph 2.5, testing the feasibility of separating layers of bigger, longer and curved samples, as well as those with a multidirectional lay-up. Additionally, it will be tested whether boiling the sample makes layer separation easier.

Separating layers of longer sample

Aim:
Find out whether it is possible to separate layers of a sample that is longer than the sample used before, to retain even more length of the fibres.

Outcomes:
The big sheet forming machine works better for longer samples. The sample has six layers. It was possible to split up the sample into four layers, of which two still had multiple layers. These thinner parts fit through the sheet forming machine with smaller radii. This made it possible to split up the layers even more. When trying to separate every layer, it started breaking down into smaller pieces.

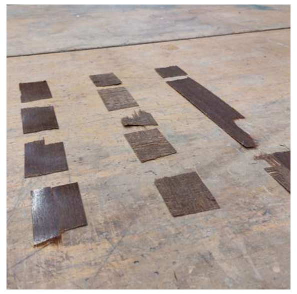



Separating layers of 0-90-0-90-0 laminate

Aim:
It is very common that composite materials are build up with fibres in different directions. Therefor, it is interesting to find out whether it is possible to separate layers from a tile with fibres in multiple directions.

Outcomes:
A sample with five layers was produced (0-90-0-90-0). The sample split in three layers when putting it through a sheet forming machine. The layers that were in line with the bending direction broke but remained attached to the other layers. The sample broke in a few places along the fibre length.






Boiling sample before separation

Aim:
During tinkering with materials, it was found that boiling makes the material softer and more flexible. This test is done to find out whether layers separate more easily when the sample is boiled for two hours on beforehand.

Outcomes:
Boiling the sample before bending it with the sheet forming machine, made it easier to separate the layers. The sample did not break and therefore it was possible to separate the full layers from each other.



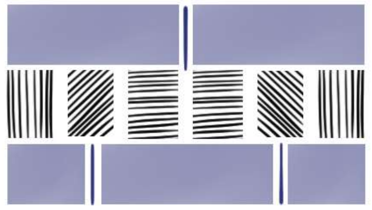
To test what type of material can be recycled, a multidirectional lay-up and curved lay-up will be boiled and put through a sheet forming machine.

Recycling multidirectional lay-up

Aim:
Find out whether it is possible to recycle a material with a lay-up including a 45 degree layer.

Outcomes:
The sample with a 45 degree layer was boiled and put through a sheet forming machine.
The layers did still separate, but not all samples split up at the same point. Some would split up in the middle between the two 0-degree layers (in two pieces) and some would split up on the 45 degree layer (into 3 pieces).





Recycling curved product

Aim:
Find out whether it is possible to separate layers from a curved product.

Outcomes:
After boiling the sample and putting the curved sample through a sheet forming machine, the layers were still easy to seperate. After drying the separated layers did stay in a curve, but the layers are really flexible, so they could be reshaped in a mould.



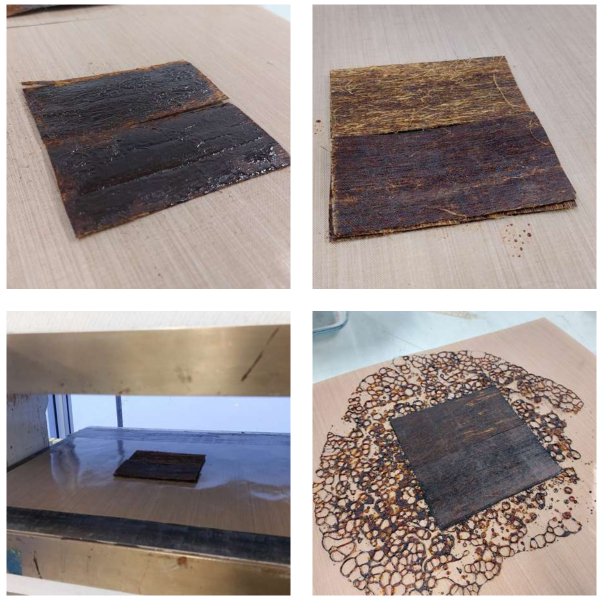
APPENDIX 3: EOL TESTS

The EoL options have been narrowed down to two. As described in the take-a-way section of Chapter 2, a few more tests need to be performed to select the most suitable option for continuing this project. Therefore, in this appendix it will be tested whether it is possible to produce samples of the shredded material and of the separated layers.

Sample of separated layers in heat press

Aim:
Find out whether it is possible to produce a sample of the separated layers of the boiling test.

Outcomes:
The layers are stacked perpendicular, each with a bit of furan resin in between (distributed with a wooden stick). After putting the sample in the heat press at 150°C under 30 kN for 15 minutes, the sample was cured. Excess resin flows out of the sample and bubbles up. The result is a sample of three layers (0-90-0). This test shows the potential to separate the layers of a composite material made from flax in combination with furan.



Granulate with resin in oven

Aim:
Find out whether it is possible to produce a sample from the granulate produced during tinkering with the material by adding furan resin and curing it in the oven.

Outcomes:
Three samples are made with different fibre volumes (20%, 35%, 50%). The mixture with 50% fibre content was very dry when mixing the resin with the granulate. However, it was enough to cure in the oven and produce a sample. The sample with 20% fibre content started bubbling during the curing process (Figure X), so this is too much resin in proportion to fibres. All three samples are very brittle, and it is possible to break them by hand.

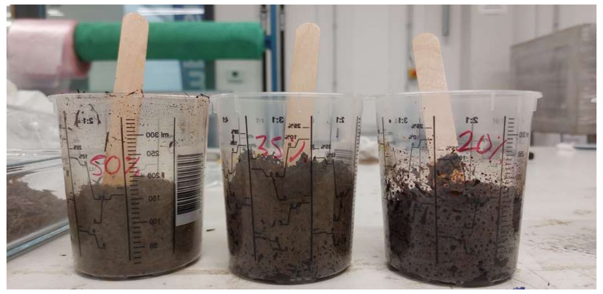


Figure X: First row shows a granulate mixed with furan resin, second row shows the mould prepared with teflon sheet, third row shows the produced sampels after curing in the oven. For each row, from left to right, 50%, 35%, and 20% fibre content.

Granulate with resin in heat press

Aim:
Find out whether it is possible to produce a sample with the granulate produced during tinkering with the material by adding furan resin and curing it in the heat press.

Outcomes:
It is possible to produce a sample in the heat press (150°C, 30kN, 15 min.). The sample feels much stronger than the sample cured in the oven. Adding pressure during the curing process helps to reduce the amount of air within the sample. This makes the sample less brittle, making it more difficult to break it by hand. The excess resin flows out and starts to bubble, which indicates that 35% fibre content was too much resin.

The sample on the first row has a fibre content of 50%. The sample on the second row has a fibre content of 35%.

APPENDIX 4: OVERVIEW EOL OPTIONS

(purple)	Not an EoL option
(light green)	Not suitable for flax/furan composite
(teal)	Out of scope

Category	EoL options	Explanation	Output	Opportunities	Challenges	Resources
Circular strategies	Long life	Design products that are durable and reliable in use.			How much damage tolerance is acceptable for a certain lifespan? (fixed time intervals for replacement? Make it less strong)	(Joustra, 2022)
	Lifetime extension	Maintenance, repair, upgrades, adaptations.				
	Product recovery	Refurbishment and remanufacturing of products.			Assessment of structural state is very important of a refurbished part, but challenging for composites.	
Structural reuse	Repurposing	Using the whole piece of material for another purpose				(Busschen, 2020), (Joustra, 2022)
	Resizing	Using parts of a product for a new purpose				
	Reshaping	Reshaping piece/product to a desired shape	Plate in desired shape		Only possible for thermoplastic matrix	
Separating layers	Based on thermally expanding particles				Thermally expanding particles are added to the resin. Adding another material is not desired in terms of later recycling cycles.	(Von Freeden et al., 2022)
	Sheet forming and glue together	Put material between rollers and 'glue' together with matrix	Separated layers?			
Mechanical recycling	Shredding/Grinding	Sorting, shredding, washing and drying, and reprocessing the composite material.	Depening on the amount of shredding/grinding: Fibrous or powder sized recyclate, mixture of polymer, fibre (and filler).	Fibrous sized recyclate: Can be used to partially replace short fibres, if remainder of virgin fibres are replaced with longer fibres. Not that expensive. Powder sized recyclate: Can be used as filler. Lower density than calcium carbonate filler. Not that expensive.	Recyclate cannot be melted, limiting applications. • Fibrous recyclate: Poor bonding with polymer; larger particles act as stress raisers. • Powdered recyclate: Absorbs more resin, increasing viscosity and reducing mechanical properties.	(Zhao et al., 2021), (Shanmugam et al., 2021), (Sukanto, 2021), (Ritzen, 2023), (Pickering, 2005)
	High voltage fragmentation	Electromechanical process that uses electricity to separate matrices from fibres	Fibres extracted in their original shape as well as matrix pieces in the solution	Relatively low cost, produces fibres of higher quality in comparison with mechanical grinding. In the eperiment of Mativenga temperature treatments of 400C for 2 hours were used, which is too high for flax.	Energy intensive	(Van Oudheusden, 2019)
Thermal recycling	The fluidised bed process	Scrap composites are reduced to ~25 mm and fed into a 450–550°C silica sand fluidized bed. The polymer volatilizes, releasing fibres and fillers, which are carried out as suspended particles. In a secondary chamber, fibres and fillers are separated, and the polymer is fully oxidized.	Fibres that are clean of contaminants and at the same time convert the resin matrices into fuel		Required a high energy supply, degradation of fibre strength and producing gas from resin which endangers humans and the environment. Not sure if possible with natural fibres?	(Pickering, 2005), (Sukanto, 2021)
	Pyrolysis	Heating up the collected recycled plastic without oxygen in a reactor. This rips apart the molecules. The polymer is broken down into smaller molecules and rebuilt again.	Pyrolysis oil, gas (heat), ash, fibres?		Oxygen in polymer will make process less efficitient. At 375C shrinkage of fibres increases a lot.	(Pickering, 2005), (Sukanto, 2021), (Ritzen, 2023), (Dhahak et al., 2024)
	Gasification	Treating polymer with high temperature in a controlled oxygen environment. This is a molecular scrambler. The polymer is broken down into smaller molecules and rebuilt again.	Hydrogen and carbon monoxide (syngas) → Methanol (fertilizer)		Requires very large capital outlays to build all the equipment.	(Ritzen, 2023)
	Hydrogenation	Heating up polymer in presence of hydrogen and catalyst at 350-400C.	Polymer is liquefied and filtered to yield naphtha or oil.			(Ritzen, 2023)
	Combustion	Combustion is a chemical reaction in which substances react with oxygen, producing energy.	Energy is produced in two forms as light energy and heat energy. Incombustible material (fibres)	Incombustible material material can be incorporated in cement.		(Pickering, 2005)
	Incineration	Destruction of something through burning	Ash, flue gas and heat	Incinerating natural fibres adds no net CO_2, as plants absorb CO_2 during growth, which is released on combustion. Thus, NFR composite incineration provides carbon credits and reduces global warming impact.		(Sukanto, 2021), (Joshi et al., 2003), (Ritzen, 2023)
Chemical recycling	Dissolution	The recovery of a polymer through its dissolution and precipitation in a suitable solvent/non-solvent, without any alteration to its molecular structure.	Dissolution → cleaning → Precipitation → Extrusion = New polymer granulates with similar properties like the virgin material.	Any additives or contaminants in a plastic can be removed, achieving high recovery rates with homogeneous products while being able to selectively recover specific polymers from mixed plastic waste	Dissolution requires large amounts of solvents and non-solvents, which are currently not bio-based. Dissolution is also energy intensive as it often requires temperatures above 100 °C. Only possible for thermoplastic polymers	(Ritzen, 2023), Contact with CreaSolv
	Solvolysis	The cleavage of a polymer by a solvent such as water or alcohol, often in the presence of a catalyst. Polymer is dissolved in a solvent, solution is purified and the polymer can be recovered by removing solvent. Polymer chain remains intact.	Fibres (damaged?) + Polymer	In contrast to dissolution and mechanical recycling, solvolysis can also recover thermoset polymers. No commercial application yet.	High costs arise from the complex liquid residues of solvolysis, requiring expensive separation for valorization. This is due to the thermosetting nature of amine-cured epoxy matrices, which resist solubility and reworkability.	(Ritzen, 2023), (Krauklis et al., 2021), (Fortunato et al., 2019)
Digestion	Anaerobic	The breakdown of an organic compound by microorganisms in the absence of oxygen to carbon dioxide, methane, water and mineral salts of any other elements present (mineralisation) plus new biomass.	CO_2 and H_2O		Under aerobic conditions, polymers biodegrade into CO_2 and H_2O, adding no compost value and losing all functional plastic value. This should be a recovery option only if the plastic is destined for nature and proven to fully disintegrate.	(Ritzen, 2023)
	Aerobic	The breakdown of an organic compound by microorganisms in the presence of oxygen to carbon dioxide, methane, water and mineral salts of any other element present (mineralisation) plus new biomass".	Methane		In uncontrolled anaerobic conditions, polymers produce methane, which can be released into the atmosphere, where it is a potent greenhouse gas.	(Ritzen, 2023)

APPENDIX 5: TENSILE TEST

A.5.1 TENSILE TEST PLAN

ISO 527-4/1B/2
Test performed on: Test: 01-11-2024

Material type, source and manufacturer
Fibres: L-Flaxtape-200 by EcoTechnilin located in Valliquerville, France
Resin: Furolite C-series by TransFuransChemicals located in Geel, Belgium.

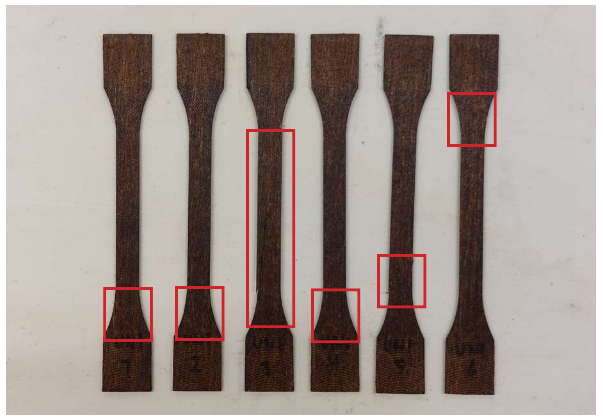
Production of material
The first-cycle material is made following the method described in paragraph 4.1. In short, prepregs are made of flax-tape with furan and B-staged in the oven at 50°C for 16 hours. Plies are put together both uni-directional and multi-directional (0-90-0-90-0), put under a vacuum and cured in the oven for 4 hours at 115°C. For the recycled material, this first-cycle material is recycled as described in paragraph 4.1. The mutli-directional material is recycled. Which means that the recycled material has 3 layers in the direction of effort and 2 layers perpendicular to this direction. The recycled patches are "glued" back together with a little bit of furan and cured in the oven again for 4 hours at 115°C.

Test specimen
Multiple specimen types have been tested to make sure the specimen will not break at the clamps. Due to the relatively low tensile properties, the dogbone shape specimen (type 1B, ISO 527-4) worked the best for this material. The samples are made in the dogbone shape by laser cutting. For both types of samples (multi and uni-directional) 6 test specimens are made. One multi-directional specimen broke at the clamps due to a wrong grip length (70 mm), the results of this specimen will be left out when analysing the results.

Test set-up
Tests are performed on a Zwick/Roell ZMART.PRO with hydraulic grips, at room temperature. To measure the strain a clip-on extensometer is used. The machine settings are fixed conform the ISO 527-4 standards, except for the grip length. Different length were tested, the best results (breaking in the middle) was achieved when using grip length of 85 mm.

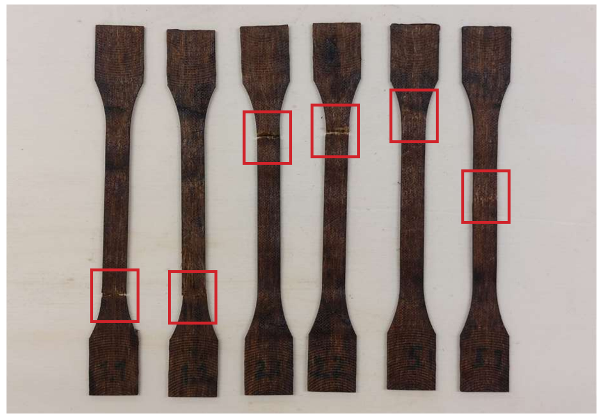
- Gauge length: 10 mm
- Gripping separation at start: 85 mm
- Testing speed: 2mm/min
- Pre-load: 50N

A.5.2 TENSILE TEST SPECIMENS INCLUCING BREAKING LINES



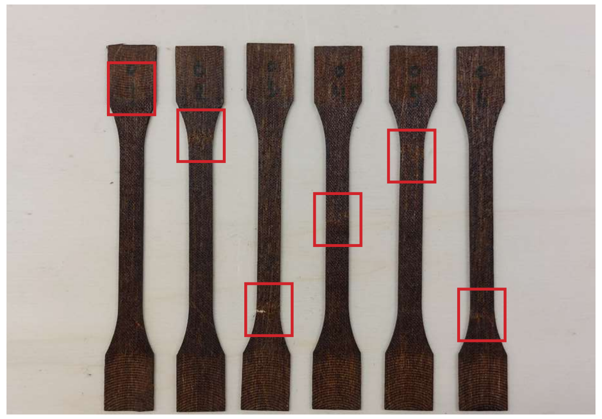
Uni-specimens with break lines marked

Uni-directional specimen:
UNI1, UNI2, UNI4 & UNI6 broke at the transition from the wide to the small part of the dogbone shape, but did not break completely. UNI3 broke diagonally along the small part and UNI 5 broke fully in the middle of the specimen.



Recycled specimen with break lines

Multi-directional specimen:
Specimen O1 will be rejected because it broke at the clamps as a result of using a 70 mm grip length. The multi-directional first-cycle specimens all broke with straight lines. O2, O3, O5 and O6 broke at the transition between the wide and small part of the dogbone shape, only O3 broke all the way through. O4 broke in the middle of the small part, which is the desired place for the specimen to break. It is nice that at least one of the specimens broke at this place, so we can use it as a reference.



Multi-specimen with break lines marked

Recycled specimen:
1.1, 1.2, 2.1, 2.2 and 5.1 broke at the transition from the wide to the small part of the dogbone shape, all of them broke completely. 5.2 broke in the middle, which is the desired place for the specimen to break. It is nice that at least one of the specimens broke at this place, so we can use it as a reference. As long as the other samples give comparible results, it is fine that they did not break exactly in the middle.

A.5.3 INDIVIDUAL RESULTS PER SPECIMEN OF TENSILE TESTS

Tensile test results per specimen:

	Minimum	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	b	h	A_0	Weight
	N	MPa	MPa	MPa	%	%	mm	mm	mm²	g
uni1	3037,42	16904,5		176,543	1,21578	1,22332	9,3	1,85	17,205	3,44
uni2	2465,76	17207,8		154,705	0,95441	0,99506	9,16	1,74	15,9384	3,25
uni3	3121,95	17068,7		188,592	1,2719	1,27234	9,3	1,78	16,554	3,431
uni4	2890,67	17191,3		168,013	1,08597	1,10287	9,3	1,85	17,205	3,428
uni5	2670,89	16387,3		165,053	1,02936	1,08094	9,3	1,74	16,182	3,209
uni6	2952,86	17193,1		170,706	1,13407	1,14332	9,3	1,86	17,298	3,452
O3	2227,18	12176,2		125,496	1,06746	1,11036	9,39	1,89	17,7471	3,609
O2	2178,98	11635,2		125,434	1,17014	1,1802	9,39	1,85	17,3715	3,664
O4	1941,12	10551,3		109,377	1,05793	1,10724	9,39	1,89	17,7471	3,47
O5	2103,22	12008,8		117,887	1,06556	1,05662	9,39	1,9	17,841	3,706
O6	2046,45	11912,2		115,333	0,96885	1,03548	9,29	1,91	17,7439	3,634
1.1	1390,69	8753,96		62,3068	0,73144	0,75665	9,3	2,4	22,32	4,576
1.2	1395,87	8542,07		61,767	0,70376	0,75077	9,3	2,43	22,599	4,529
2.1	1222,19	8436,52		64,1065	0,70352	0,79509	9,3	2,05	19,065	4,222
2.2	1381,09	8878,26		72,4414	0,77127	0,84527	9,3	2,05	19,065	4,337
5.1	1745,62	9643,52		87,3031	0,87703	0,95626	9,3	2,15	19,995	4,06
5.2	1459,32	9801,57		72,9843	0,69361	0,76449	9,3	2,15	19,995	4,087

APPENDIX 6: THREE-POINT BENDING TEST

A.6.1 THREE-POINT BENDING TEST PLAN

NEN-EN-ISO 14125/ClassIII/1
Test performed on: 12-11-2024

Material type, source and manufacturer
Fibres: L-Flaxtape-200 by EcoTechnilin located in Valliquerville, France
Resin: Furolite C-series by TransFuransChemicals located in Geel, Belgium.

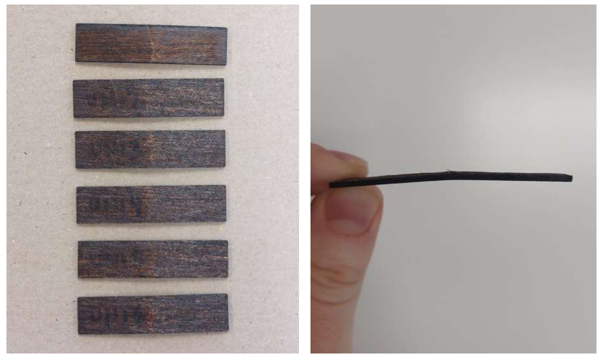
Production of material
The first-cycle material is made following the method described in paragraph 4.1. In short, prepregs are made of flax tape with furan and B-staged in the oven at 50°C for 16 hours. Plies are put together both uni-directional and multi-directional (0-90-0-90-0), put under a vacuum and cured in the oven for 4 hours at 115°C. For the recycled material, this first-cycle material is recycled as described in paragraph 4.1. The mutli-directional material is recycled. Which means that the recycled material has 3 layers in the direction of effort and 2 layers perpendicular to this direction. The recycled patches are "glued" back together with a little bit of furan and cured in the oven again for 4 hours at 115°C.

Test specimen
Based on table 4 of NEN-EN-ISO 14125 the Class III specimen is used for this test. The samples are made in this shape by laser cutting. For both types of samples (multi and uni-directional) 6 test specimens are made.
The recycled samples are made by boiling the first-cycle material for two hours and drying the boiled material overnight. The boiled samples are put through a sheet forming machine to separate the layers. As expected the sample splits into three layers, with the 90-degree layers divided on the 0-degree layers. These layers are glued back together using furan resin and cured again under vacuum in the oven for 4 hours at 115°C
(Pictures were taken of all different layers to see whether breaking lines can be linked to breaks in the individual layers.)

The thickness requirements as described in NEN-EN-ISO 14125 are not met. Following the standard the thickness can not exceed the tolerance of +/-2% of the mean value. Due to limited materia,l the uni-directional samples have a thickness between -4,1 and +3,5% of the mean value and the multi-directional samples have a thickness between -8,6 and +6 %.

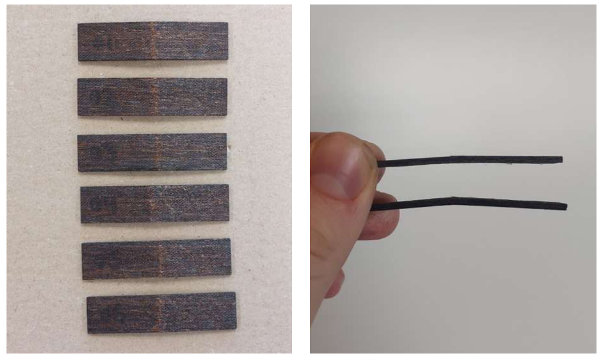
Test set-up
Tests are performed on a Zwick/Roell ZMART.PRO with hydraulic grips, at room temperature. The machine settings are fixed conform the NEN-EN-ISO 14125 standards.
Specimen length: 60 mm
Outer span: 40 mm
Testing speed: 1mm/min

A.6.2 THREE POINT BENDING SPECIMENS INCLUDING BREAKING LINES



Uni-specimen three-point bending tests

Uni-directional specimen
In the middle of the specimens is a slight breaking line visible due to the force that the loading pin has put on the specimen. The breaking line is visible on the bottom side of the specimen. The breakingline is most visible on specimen UNI1, UNI3 and UNI4. From the side of the specimen a slight bend is visible (Figure X).



Multi-specimen three-point bending tests

Multi-directional specimen
The breaking lines on these specimens are more visible than on the unidirectional specimen. Only specimen O4 shows the breaking line a bit less clear than the other multi-directional specimens. When looking from the side a slight bend is visible, which is a bit more bent than the uni-directional specimens.

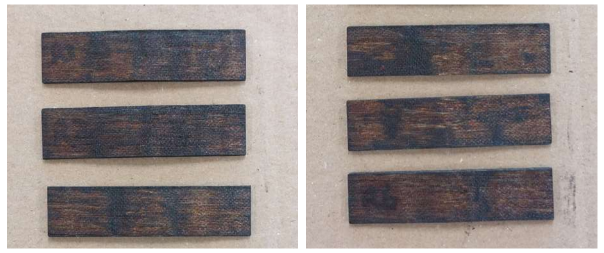


Figure X: Recycled specimen three-point bending tests

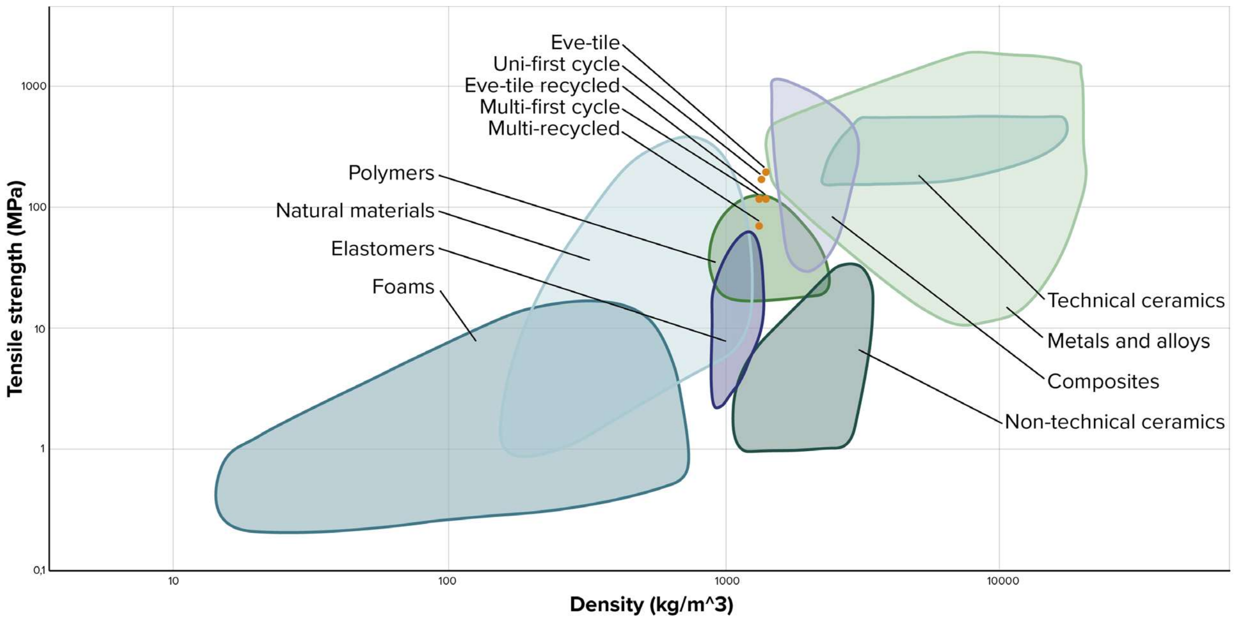
Recycled specimen:

Due to the dark color caused by the furan resin, the breaking line is not really visible on the pictures. When looking very closely a breaking line is visible on specimen R1, R2, R5 and R6. R2 even shows a breaking line on both sides of the specimen.

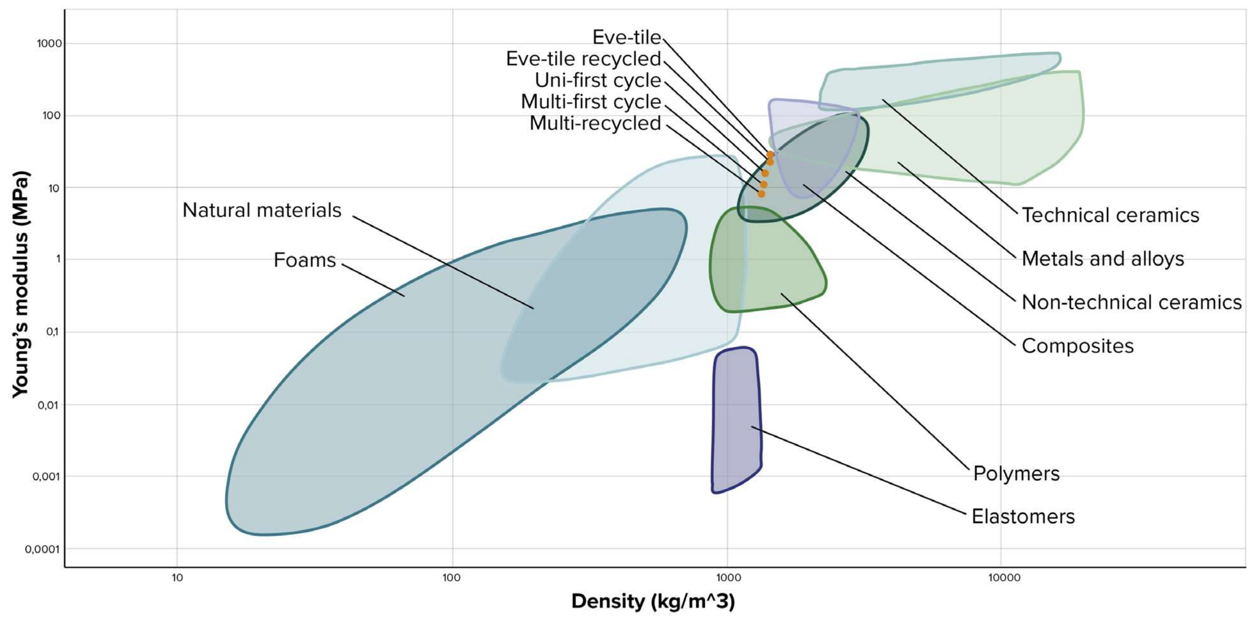
A.6.3 INDIVIDUAL RESULTS PER SPECIMEN OF THREE POINT BENDING TESTS

	E_m	F_{max}	f_m	l_1	t	b	a	weight	volume	volume
	N/mm²	N	N/mm²	mm	mm	mm	mm2	g	mm3	cm3
uni1	16245,56	128,561	165,05483	40	1,78	14,75	26,255	1,528	2434,56	2,43456
uni2	16526,13	134,812	172,49617	40	1,78	14,8	26,344	1,533	2552,94	2,55294
uni3	17548,66	130,417	183,56674	40	1,7	14,75	25,075	1,505	2707,61	2,70761
uni4	19739,82	128,464	191,94277	40	1,65	14,75	24,3375	1,498	2831,16	2,83116
uni5	17570,7	125,757	166,5867	40	1,75	14,79	25,8825	1,56	2463,82	2,46382
uni6	18120,76	115,612	170,20394	40	1,66	14,79	24,5514	1,508	2517,32	2,51732
O1	15419,4	121,597	139,56992	40	1,88	14,79	27,8052	1,695	2064,24	2,06424
O2	15038,67	120,669	138,31753	40	1,88	14,81	27,8428	1,677	2048,48	2,04848
O3	14239,58	108,021	141,37528	40	1,76	14,8	26,048	1,586	2092,35	2,09235
O4	13646,12	106,094	140,53981	40	1,75	14,79	25,8825	1,557	2078,58	2,07858
O5	14410,26	86,5302	133,9394	40	1,62	14,77	23,9274	1,465	1978,28	1,97828
O6	14980,71	110,254	146,24808	40	1,75	14,77	25,8475	1,63	2160,08	2,16008
R1	8008,492	75,9762	73,094902	40	2,05	14,84	30,422	1,717	1084,73	1,08473
R2	8251,34	87,1599	84,194896	40	2,05	14,78	30,299	1,698	1244,4	1,2444
R3	13979,71	125,86	128,84556	40	1,99	14,8	29,452	1,733	1906,91	1,90691
R4	13728,31	131,019	126,1352	40	2,05	14,83	30,4015	1,837	1870,58	1,87058
R5	10316,08	103,235	95,031187	40	2,1	14,78	31,038	1,784	1404,56	1,40456
R6	11986,96	134,198	129,28269	40	2,05	14,82	30,381	1,779	1915,97	1,91597

APPENDIX 7: PLOTS



Tensile strength against density of different material categories, to compare it with Eve tile and recycled material.



Young's modulus against density of different material categories, to compare it with Eve tile and recycled material.

APPENDIX 8: EXPERIENCE TESTS

A.8.1 TEST PLAN EXPERIENCE TESTS

1. Performative level
Ask the participant to freely explore the material. Then ask him/her to describe what the material makes them do.

2. Sensorial level
Ask the participant to explore the material with her/his senses and rate it with the sensorial scale provided.

3. Affective level
Ask the participant to describe which emotions the material elicits to them.
Then show him/her the affective vocabulary.
Ask them to select few emotions (min 3.) among these and place them on the map.

4. Interpretive level
Show the interpretive vocabulary to the particpant.
Ask him/her to select 3 meanings that describe their associations with the material and write them on the template.
Show 3 related interpretive picture sets to the participant.
Ask him/her to associate 2 pictures for each word, without considering the material (only the meaning of the word).

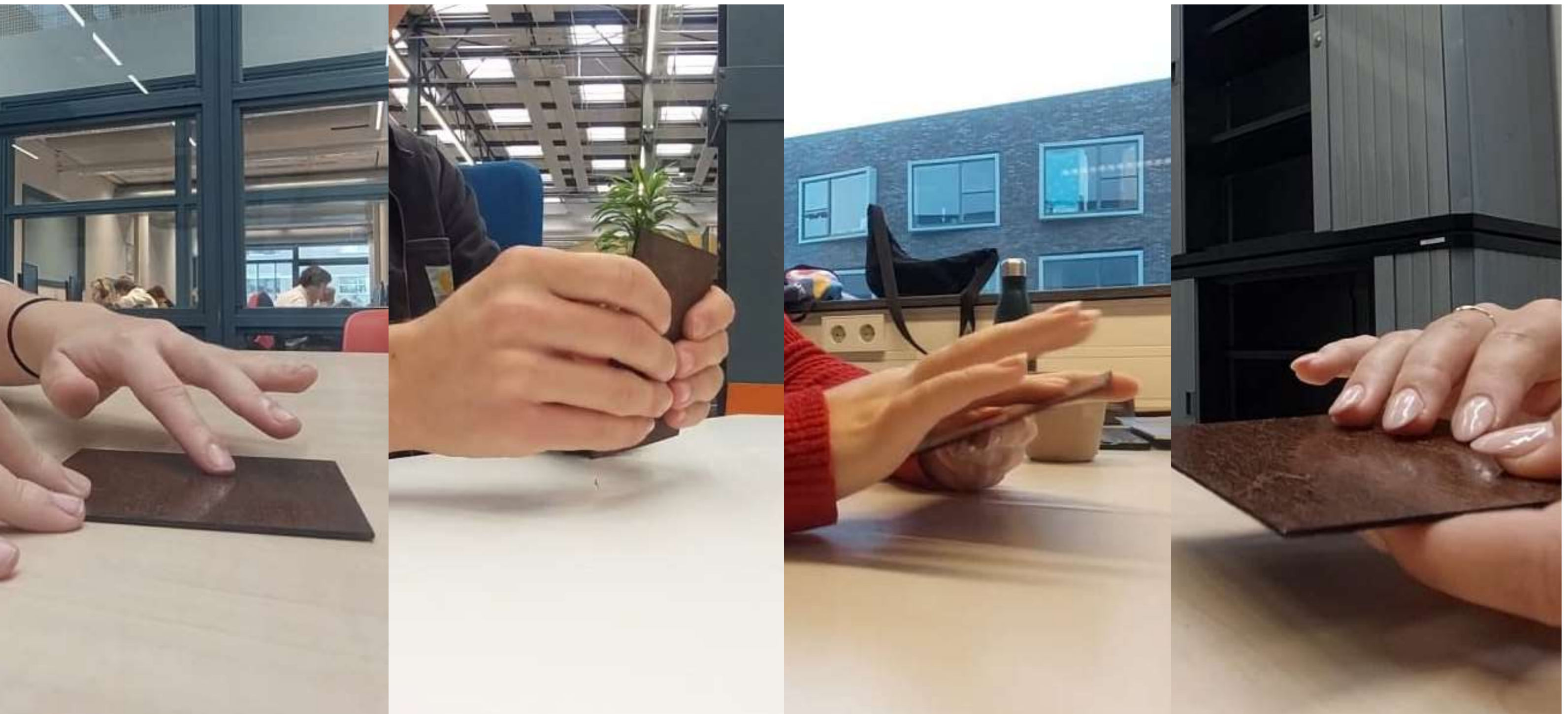
5. Final reflection
Ask the participant the last three questions. Use this level to deepen your understanding of their experience, asking the 'whys' behind their answers and taking notes of other comments they make about the material.

When the participant has seen both materials:
Ask the participant for what type of appliciation they envision these materials and whether this is different for the two materials.

A.8.2 MATERIALS FOR EXPERIENCE TESTS

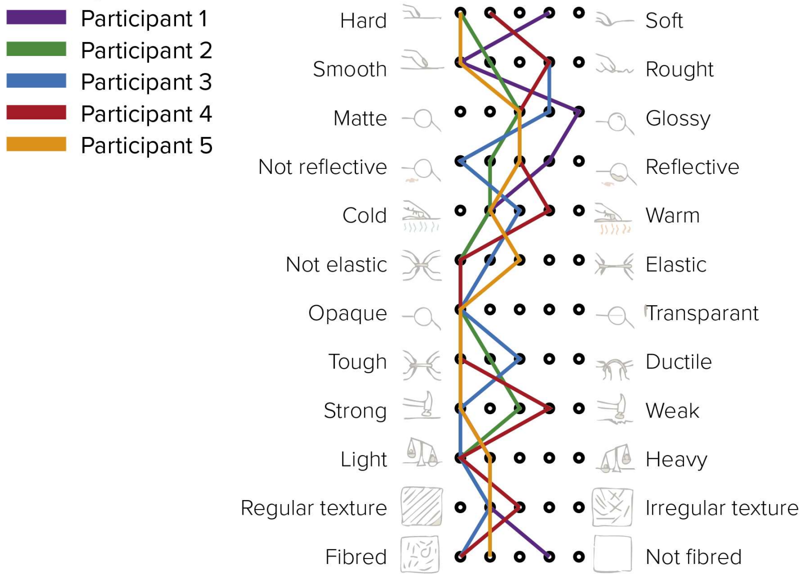
On every picture the sample on the left is the first-cycle material and the sample on the right is the recycled material.

Screenshots of videos experience tests

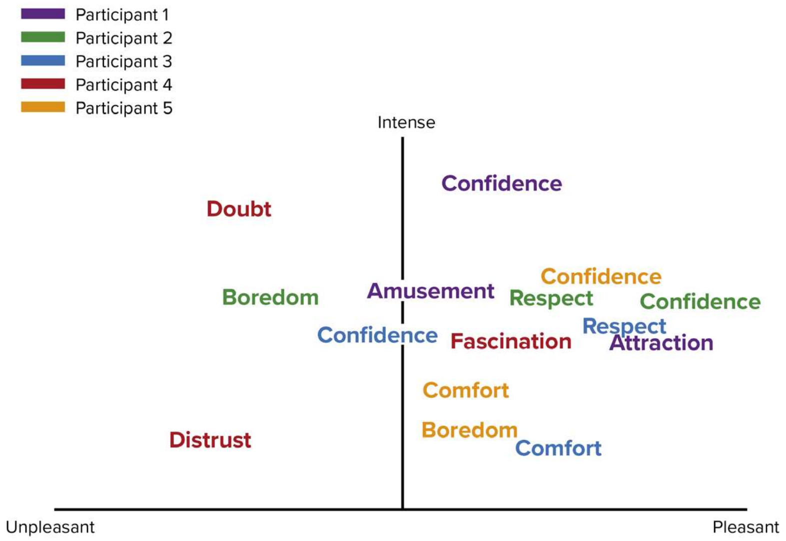


A.8.3 MORE DETAILED RESULTS OF EXPERIENCE TESTS

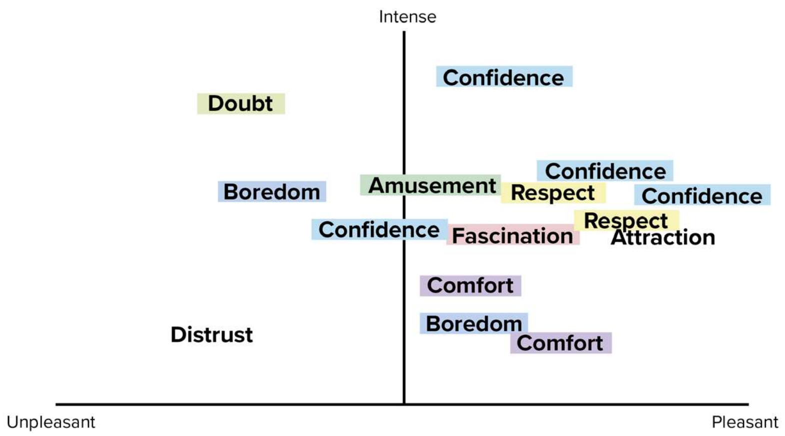
First cycle



Sensorial scale, individual outcomes

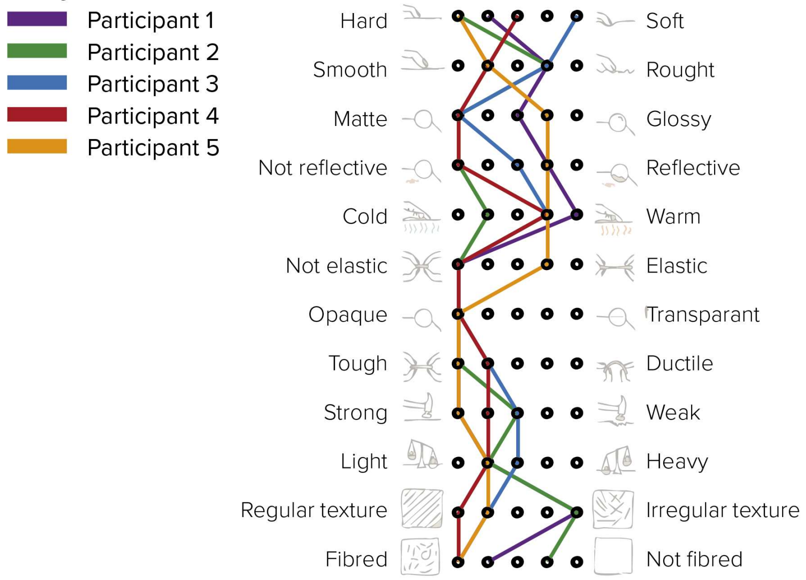


Emotion map, individual outcomes

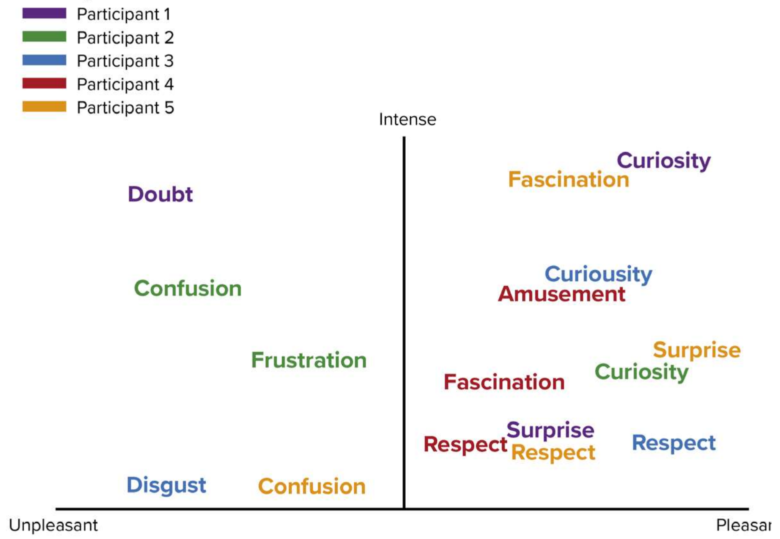


Emotion map, words colour coded

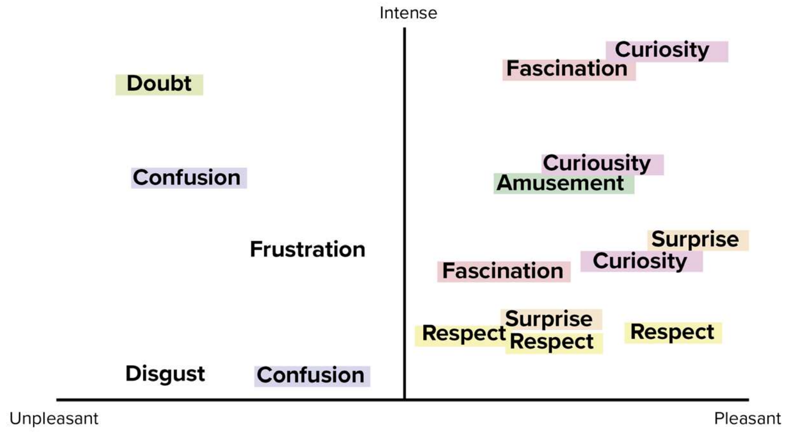
Recycled



Sensorial scale, individual outcomes



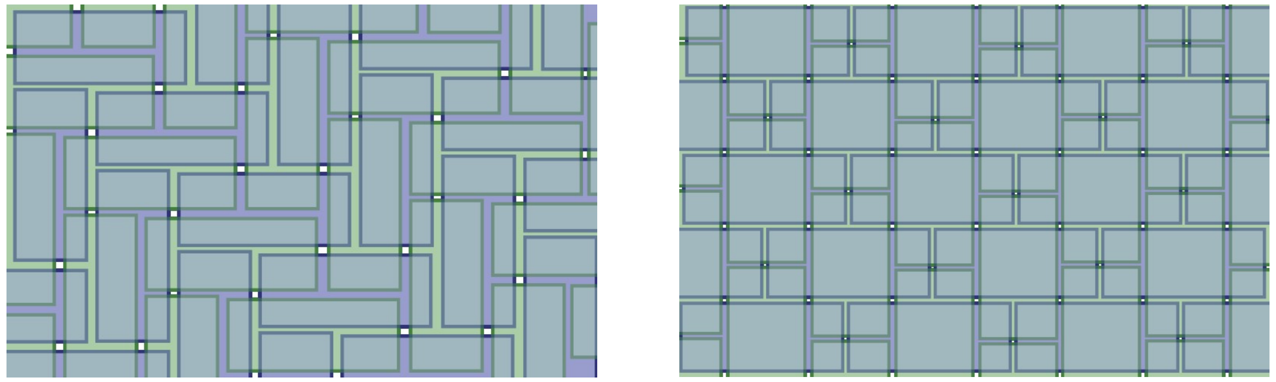
Emotion map, individual outcomes



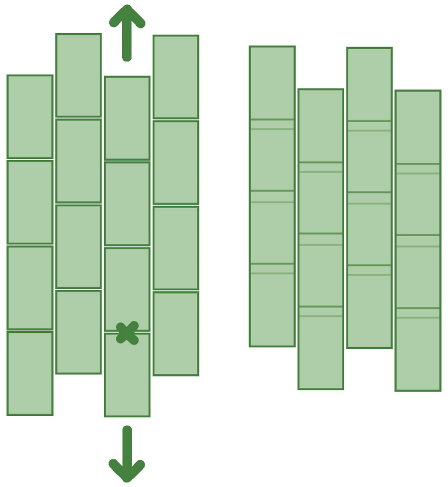
Emotion map, words colour coded

APPENDIX 9: DESIGN VARIABLES

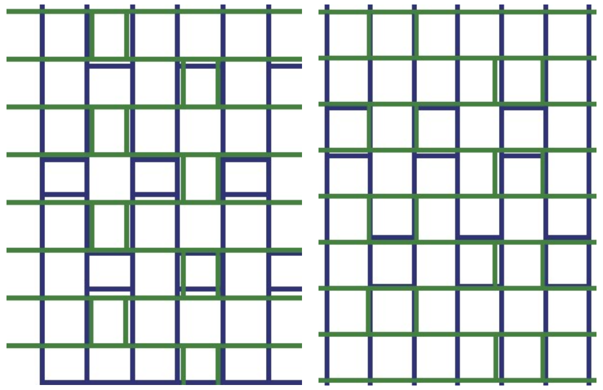
A.9.1 PATTERN OPTIONS



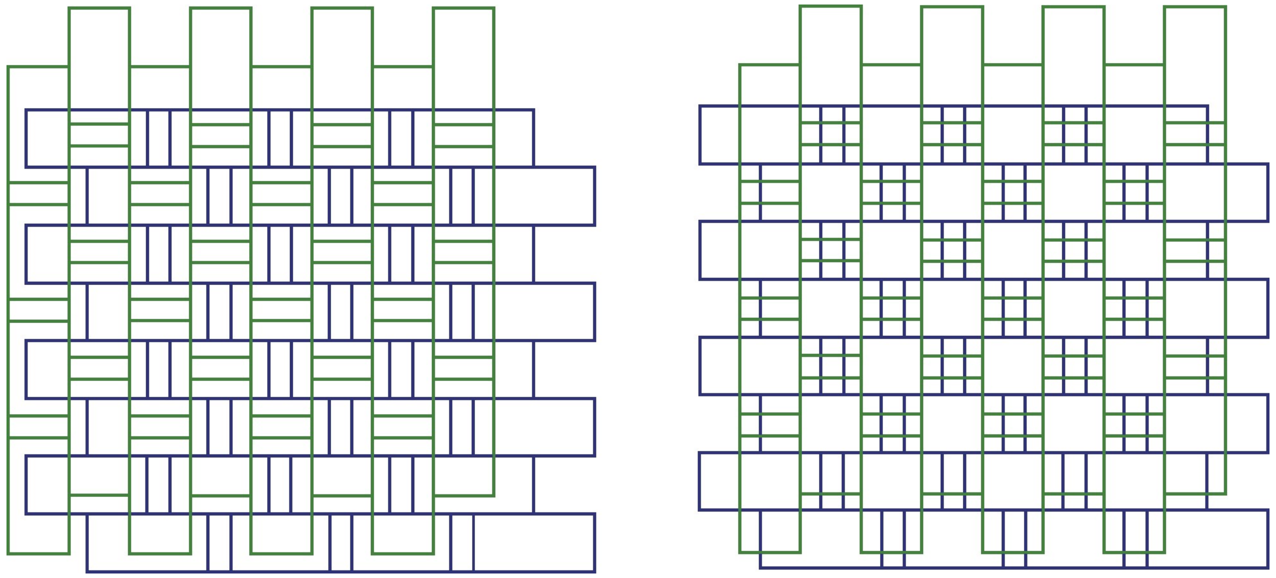
Fishbone and brick pattern



Overlap in fibre direction is necessary



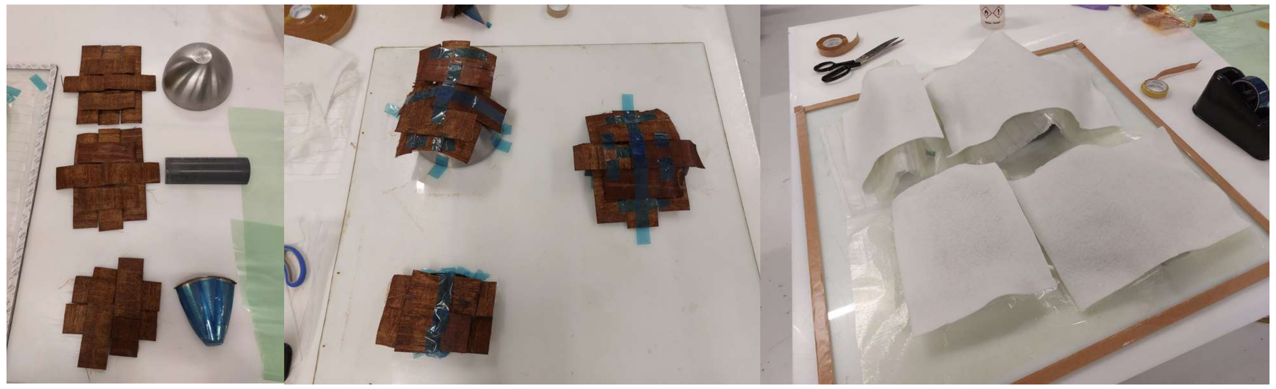
Doubling and tripling the pattern



Two possible overlapping patterns

A.9.2 SHAPEABILITY PROCESS PICTURES

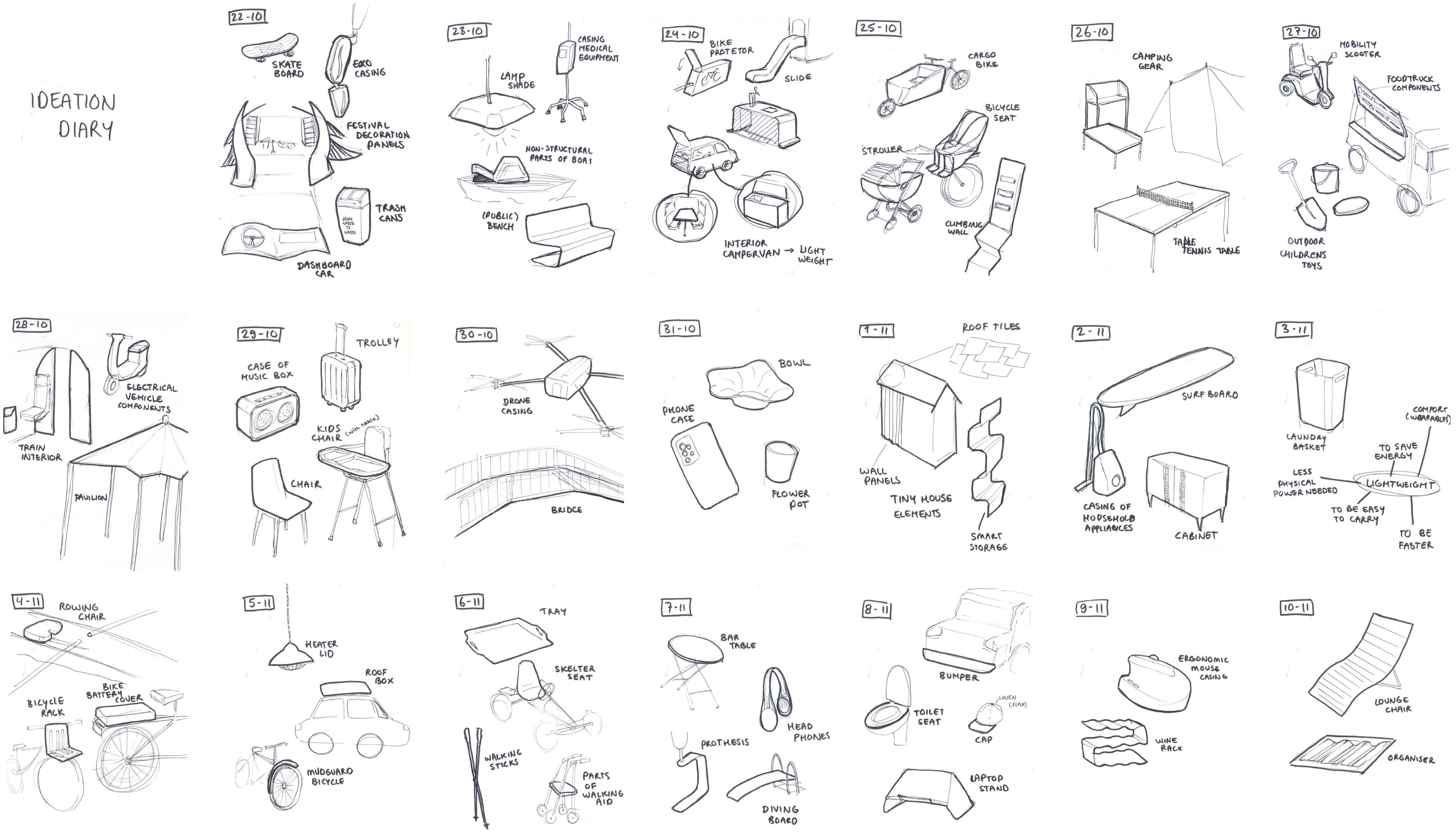
Preparing patches



Placing patches on shapes

Cure furan in oven

APPENDIX 10: IDEATION DIARY



APPENDIX 11: GROUP BRAINSTORM

A.11.1 CONSENT FORM

Consent to participate in brainstorm session and to use the outcomes of the brainstorm session.

I agree to participate in the brainstorm session conducted by Lica Boot as part of her graduation project about finding an application for recycled bio composite material.

I understand that the information collected and photos taken during the brainstorm session are for research purposes only. Information will not be used for any other purpose and will only be accessible to those involved in Lica Boot's graduation project. All personally identifiable data will be anonymized before being reported.

I understand that participation in this session is voluntary and I agree to immediately raise any concerns or areas of discomfort during the session if necessary.

Please sign below to indicate that you have read and you understand the information on this form and that any questions you might have about the session have been answered.

Name participant:

Signature:

Date

11-11-2024

A.11.2 GROUP BRAINSTORM PLAN

1. Welcome + Consent form (5 min)

2. Why Brainstorm (5 min)
- Ideation phase of the process, individual project, good to include people from outside the project to come up with as many ideas as possible. Which brings me to the 4 rules
- 4 rules: There are no bad ideas, write down everything you can think of, combine ideas, quantity over quality

3. Introduction (5 min)
- Bio Composite material
- Tekening composite met uitleg dat het reinforcement/fibre heeft en matrix/resin Matrix binds reinforcments together, protects fibres from outside. Fibres carry most of the load Bio omdat mijn composiet gemaakt is van: flax/furan
- Je kan een composiet zelf taileren naar waar het sterk moet zijn doordat je lagen in een mal legt. Lagen kunnen met vezels in 1 of meerdere richtingen liggen
- Aerospace, rail, automotive, and sporting goods industries are increasingly attracted to this class of materials due to their excellent specific stiffness, strength, ease of manufacture, non-corrosion, resistance to chemical attack, and performance tailoring capacity.
- Recycled material after separating layers
- Difficult to promise high quality after recycling --> geen producten met hoge safety standaarden
- Productieproces: In een mal onder vacuum in de oven.

4. Warm up (10 min)
- Products that have an advantage of being lightweight
- Products with a demand for sustainability
- (Parts of) products that require to be stiff
- Interesting shaped (parts of) products that can be shaped in a mould

5. Ideation (30 min)
Show the EoL potential of a recycled flax/furan composite by designing an inspiring application that uses the technical oportunities (& constraints) of the material and sparks curiousity from the user.

Opportunities:
Relatively low weight compared to stiffnes
Biobased recycled material

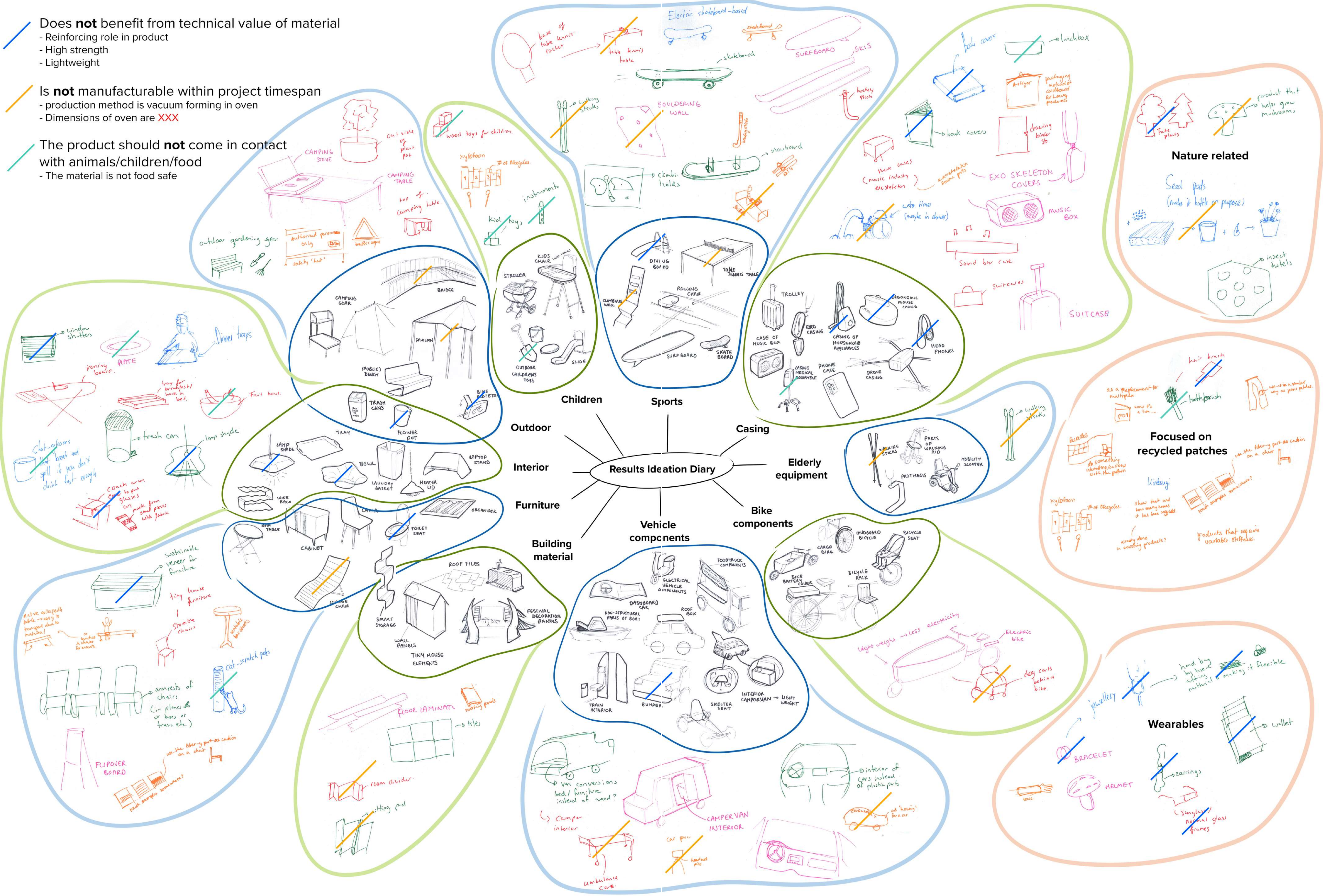
Constraints:
Flexibility of fibres cannot be used due to brittleness of matrix
Production method: Vacuum in oven
Not in structural parts with high safety demands due to recycled material

APPENDIX 12: ELIMINATION IDEAS

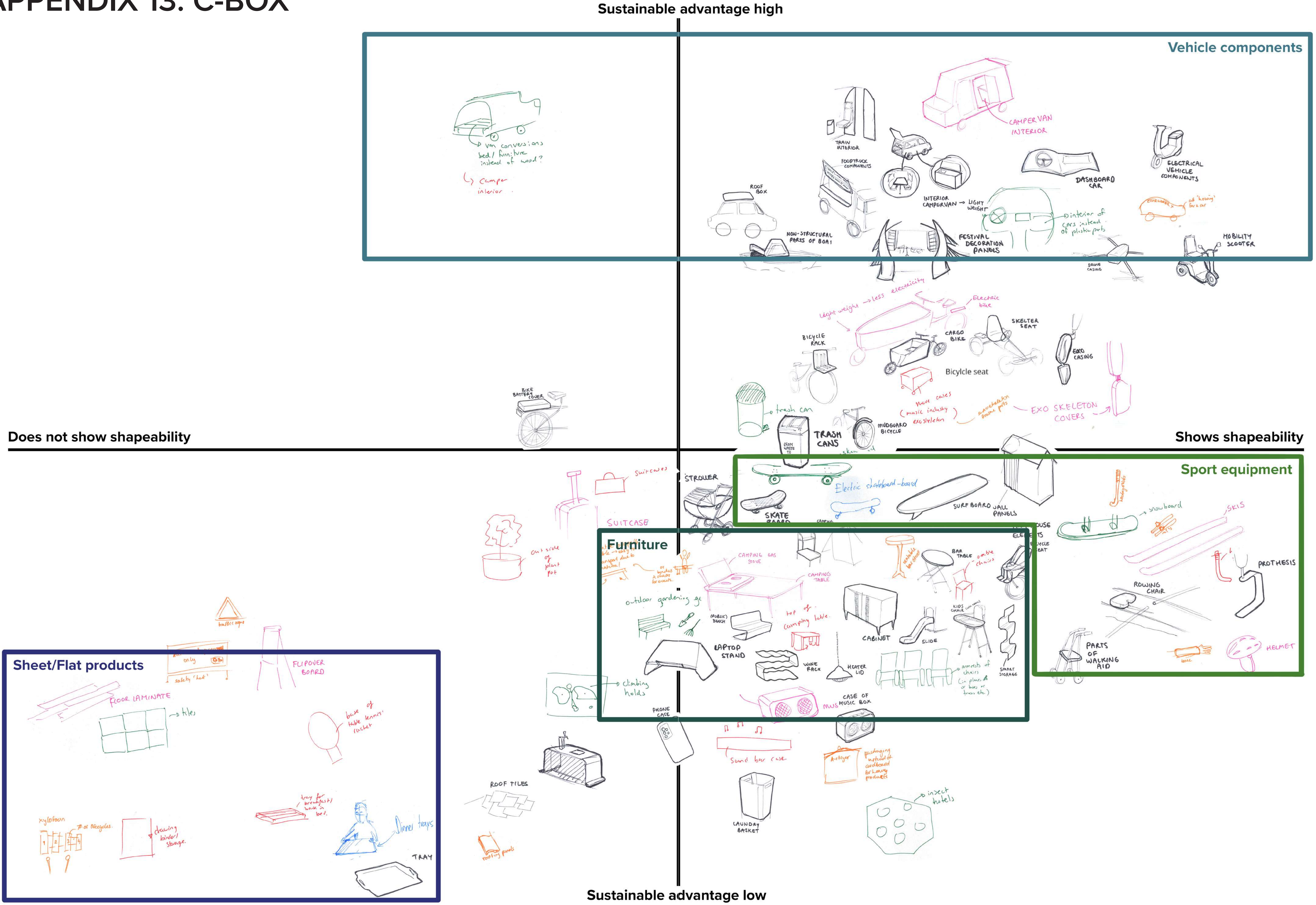
Does **not** benefit from technical value of material
- Reinforcing role in product
- High strength
- Lightweight

Is **not** manufacturable within project timespan
- production method is vacuum forming in oven
- Dimensions of oven are XXX

The product should **not** come in contact with animals/children/food
- The material is not food safe



APPENDIX 13: C-BOX



APPENDIX 14: FIRST-CYCLE MATERIAL

Dashboard produced with first-cycle material.

Deck hatch made of first-cycle flax/furan, next to a bundle of flax and the dashboard produced with recycled flax/furan.

APPENDIX 15: INTERVIEW SUMMARY

A.15.1 QUESTIONS

Is this dashboard inspiring to people in composite industry?

Does it inspire them to incorporate recycling of composites into their design process?

Demonstrator + poster
Observe reaction without explanation

General
- What is your profession?
- Do you design/have you designed with composite materials?
- Do you design/have you designed with biobased composite materials?
- What is the first thing you notice when seeing this demonstrator product?

Find out whether it inspires them
- What do you think this demonstrator is about?
- What do you think the goal of this demonstrator product is?
- Does this demonstrator raise any questions?
- (context, material, model?)
- What would you design with this recycled composite material?
- Do you think about the EoL of the products that you design?

Explanation recycling method
- Have you seen a recycling method like this before?
- What do you think about the recycling method?
- Do you think this recycled material can be used for other applications?
- What do you think limitations are of the recycling method?

Explanation goal of demonstrator
- Is this message clear?
- What could be added to make it more clear?

A.15.2 SUMMARY CONVERSATIONS

First reaction
- Wilt het aanraken, tikken, kloppen, wat voor materiaal?
- De patches zijn niet helemaal strak, jammer als je dit als dashboard hebt en daarnaar zit te kijken. Baksteen patroon, in verstek. Niet elke patch heeft dezelfde vorm/kleur.
- Naden zichtbaar, patches lopen niet door in elkaar. Kleur is erg donker. UV licht zal het lichter kunnen maken.

Professional background
- Lab manager at Inholland, before worked at Airborne as research and design engineer.
- Free lancer composite engineer.
- Research and design lead at company that develops innovative and ecofriendly composite materials.

What is your experience with composite materials?
- Bridges, wind turbine blades, ambulances. wind turbine blades. All types of moulds. I like to visit the JEC to learn about new technologies. Never worked with biobased materials.
- Varies from chairs to boats of 20/30 meters long. Worked with flax ones to produce a canoe.
- Mostly construction and automotive at this moment.

First thing you notice about demonstrator:

I hadn't immediately noticed the fibres in it. If you had asked me I would have said it is wood with an epoxy coating. It looks like solid wood.

What do you think the demonstrator is about?
- To show what kind of shapes you can make with natural fibres. This dashboard shows that it could be used as a car interior.
- Reflax indicates recycling flax. Using the material. Using reusable flax patches for products.
- Small part made of sustainable material. Visible part in a car so from a commercial point of view. A bottom plate of a car could perhaps also be made of this material, but then it would not be visible to the customer.

Does this demonstrator raise any questions?
- How did you make it? With a mould? Why did you decide to use patches? Does this help with the strength of the product? What kind of impact can the product have? Does it still need a coating?
- How is it made? How did you get these patches? Can you buy those somewhere? What is the mechanical data of the product? Can it be more than a cosmetic product?
- What are technical test values of material? What type of clients is interested in this material? Curious to see an LCA of the recycling method. Did you look into regulations about the uptake of CO_2 and did you think about EoL? Did you think about safety regulations?

Do you see other applications for the material?
- Furniture industry like a table. Wall panels, I thinkt there are many more possibilities, It looks like wood but it has the advantage that it can be shaped in a curve. The application could be both decorative and practical.
- It depends on the technical qualities, but different types of interior parts could be made of this material. Something that does not need to carry too much load. Maybe outdoor applications because it looks rough/sturdy.
- If you can retain this length of the fibres it is a shame to make an interior part of the material. Maybe an application that needs to carry more load. Something like traffic signboards.

APPENDIX 16: PROJECT BRIEF

Personal Project Brief – IDE Master Graduation Project

Name student Lica Boot **Student number** 4,832,272

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

Project title Finding applications for the Eve tile over multiple life cycles

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

Introduction

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

Eve Reverse is a young startup founded by experienced composite, materials, and industrialization specialists. They want to fight climate change by developing technology to manufacture truly carbon-negative products. Focussing on products with more CO2eq embedded than emitted during manufacturing and with a long lifetime to store the CO2 for decades.

Eve reverse has developed the Eve-tile. The Eve-tile is a fibre preform consisting of scutched flax which is processed in a uni-directional tile including a natural stabilizing agent to prevent fibers from splitting apart. The Eve-tile embraces the finite fiber length of natural fibers, thereby reducing the energy required to make fibers continuous, by eliminating processing steps like drawing, spinning, or weaving. Individual Eve-tiles are stacked in a mold with overlapping edges after which a resin is added, and the mold is closed.

There are three types of tiles, the Eve dry tile (a natural fiber preform without matrix), the Eve prepreg (partial cured tile with biobased thermoset matrix), and Eve thermoplastic (plate with thermoplastic matrix). My thesis will focus on the Eve dry tile in combination with a promising polymer, which will be determined before, or in the first phase of my graduation project.

The material qualities of a product made from the Eve-tile still need to be studied, as well as the end-of-life options. If performance tests show positive results and suitable applications are identified, the Eve tile could be an important step towards the development of low-emission fiber preforms, paving the way for CO2-negative composites.

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

introduction (continued): space for images

image / figure 1 Flax, tile and application.

image / figure 2

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

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

Increasing environmental and sustainability awareness has motivated companies to use biobased composite materials for various applications. While implementing biobased materials into your design can seem sustainable and serve as an effective marketing tactic, it is not always the most environmentally friendly option. The actual environmental impact depends significantly on how these biobased composites are used. Incorporating biobased composities into a design may result in a shorter product lifespan or complicate recycling efforts. Therefore, it is crucial to consider the type of products in which we use biobased composites and to keep in mind their end-of-life options.

With this graduation project, I will find a suitable application for the Eve-tile and expolore promising end-of-life options for this fiber/resin combination.

To find out whether the Eve-tile is a step towards valuable CO2-negative composites, it is important to test the material properties. Based on the results of these tests, suitable applications can be explored and end-of-life options can be investigated.

Assignment

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

Create a demonstrator product, and investigate end-of-life options to validate the potential of the Eve-tile, developed by Eve Reverse, in the circular economy.

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

In the first phase of this project I will analyse the Eve Dry Tile and research possible end-of-life options. To be able to validate the potential of the Eve-tile, I will start by testing the performance of the material produced with Eve-tiles and try out different recycling methods on the material. When I have a full understanding of the material, I can start looking for suitable applications, and make prototypes to test my assumptions. When I have a full overview of the end-of-life options, I will select the most promising ones, and find suitable applications for the end-of-life material.

I am planning on using elements of the Material Driven Design Method to be able to fully understand the material and design suitable applications.

I will conclude my graduation project with a demonstrator product to showcase the potential of the Eve-tile over two life cycles.

Project planning and key moments

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

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

Kick off meeting	29 aug 2024
Mid-term evaluation	22 okt 2024
Green light meeting	17 dec 2024
Graduation ceremony	30 jan 2025

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

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

Comments:

Motivation and personal ambitions

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

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

I do not want to become a designer of products without a function that only contribute to unnecessary material consumption. I aspire to design products that have a positive impact, are well-designed, and are minimally harmful to the environment. The goal of Eve Reverse to create carbon-negative products therefore appeals to me, and I am eager to contribute to this mission. Additionally, I am curious what it is like to work at a startup and hope to experience this during my graduation project.

Although I am not experienced in the material-driven design method, I am eager to learn how to apply it and understand its influence on my design process. This method is very different from my previous design projects, which were based on client or user wishes. Another personal learning ambition is to avoid getting stuck in the research phase. For this project, I aim to apply an iterative approach, alternating between research and practical tests and prototypes.

Integrated Product Design

February, 2025