A valuable application for shredded composite material from wind turbine blades

Tjits Tuinhof

MASTER THESIS
Delft, June 2018

A valuable application for shredded composite material from wind turbine blades

MASTER THESIS
Delft, June 2018

AUTHOR
Tjits Tuinhof
Integrated Product Design
tjitstuinhof@gmail.com

CHAIR
Prof. dr. ir. Jansen, K. M. B.
Professor Emerging Materials
Industrial Design Engineering
Delft University of Technology

MENTOR
Ir. Joustra, J. J.
PhD candidate Circular Product Design
Industrial Design Engineering
Delft University of Technology

DELFT UNIVERSITY OF TECHNOLOGY
Faculty of Industrial Design Engineering
Landbergstraat 5
2628 CE Delft
The Netherlands

Preface

This graduation thesis is the final deliverable of my Master's degree Integrated Product Design at the Delft University of Technology. Six months ago, I was at the start of this project, which is commissioned for Jelle Joustra, a PhD candidate at the Delft University of Technology. He is a part of the European EcoBulk project which is aiming to demonstrate how composite material can be a part of the circular economy. As a designer, I have a strong incentive to develop products that can contribute to a cleaner environment. For this reason, this project was a good fit for me and a problem I was motivated to tackle. It provided me of very valuable learning experiences and it was the perfect way to conclude my study time in Delft.

Throughout this project, many people were a great help to me. I would like to thank my supervisory team for supporting me during this project. Kaspar, for sharing your knowledge on composite materials and production techniques and inspiring me to execute many practical tests. Jelle, for helping me organize my thoughts and insights in our weekly meetings and providing me of valuable information and materials to facilitate my project.

In addition to this, I would like to thank the EcoBulk project and Virol for providing me with test materials. Professor of Circular Product Design Ruud Balkenende, Willem Böttger from NPSP, Barend Ubbink from ARN and Menno Gravemaker for thinking along with the challenges that I came across during the project. Ella and the students and supervisors from the Circular Design Lab for their feedback and support. InHolland Composites, Hukseflux and the Resource & Recycling lab, Precision and Microsystems Engineering department and Applied Labs at the TU Delft for letting me use their production and testing facilities. The employees of the "PMB" for answering all my prototyping questions. Luïsa for helping me with material testing and Suzanne for leading my creative session.

Lastly, I would like to thank my family and friends who supported me and believed in me during this journey. My parents, brother and sister for always being there when I need help and motivating me when that was necessary. My uncle Frans for sharing information on the wind turbine industry. My (old) roommates in Delft, and later also in Rotterdam, for listening to my graduation stories and cheering me up with sweet words and fun activities. Nienke, Sarah, Marit, Marijke, Emma, Ineke and Sophie for making me feel happy and appreciated when I ever felt down. Marieke, Josephine, Marjolein, Lynn, Helen and Piek for occasionally sharing a workspace with me and giving me motivation. Josien, Josephine and Govert for the coffee breaks when I needed someone to talk to. And lastly, Dirk, my teacher, and the fellow students at my meditation school to facilitate a place where I could learn to empty my head and take life as it comes.

I hope you enjoy reading my graduation thesis!

Executive Summary

INTRODUCTION

The wind energy industry is growing significantly, which causes an increase in the number of decommissioned wind turbines as well. After a life span of 20 to 25 years (Mishnaevsky et al., 2017), a wind turbine is outdated and will no longer be used. The blades consist mainly of fiber reinforced thermoset polymers which are difficult to recycle. For this reason, most blades currently end up in landfill or incineration which is a waste of this high value material. One option for recycling is shredding the material and reusing this. Usually, this results in significant down-cycling of the material. In this graduation thesis, the shredded composite material is evaluated and a design is made of a valuable application. With this design, it is aimed to demonstrate its recycling possibilities within the circular economy to positively influence the environmental impact of the wind turbine blades.

To get a better understanding on the aspects of value creation, value types have been developed. These types were used to evaluate in which way value is achieved in certain applications. The value types are functional, emotional, economic, symbolic and sustainable value.

ANALYSIS

To collect background information on the topic, a general analysis was executed on composite materials and on the design and current end-of-life scenarios of wind turbine blades. Additionally, market research was done to get a grip on the current developments in the field of composite recycling. To gain knowledge on the content of the shredded composite material, two batches were analyzed. Microscopic images were made and the moisture and glass fiber content were calculated using a drying and burn-off test. This showed that variations appear between the different material supplies. Lastly, the material properties of the shredded composite were determined. In order to do so, literature research is enriched with material tests on extrusion profiles including shredded composite. On these profiles, burn-off, three-point bending and tensile tests were executed. It turned out that larger fibers can still deliver reinforcement, however often most mechanical properties are decreased by the addition of the shreds.

From the analysis, it was concluded that instead of functioning as reinforcement and filler material, the shredded composite has other characteristics that should be exploited to achieve value, such as its appearance and water resistance. In addition to this, the most potential is seen in focusing on achieve functional or sustainable value.

CONCEPTUALIZATION

The design vision describes that the shredded composite should be a helpful addition to the new application and should not be hidden. This vision was used, together with the during this research formulated requirements and wishes, to function as guideline and evaluation criteria for the generated ideas. Material samples were created as inspiration for the idea generation. In addition to this, thermoplastic was selected as the most appropriate material to include the shredded composite in the new application, due to the high recyclability.

The selection of the most valuable ideas concluded in four idea directions:
- beams as replacement of wood,
- addition to plastic housings,
- small windmills,
- grip or texture on material surfaces.

Eventually, it was concluded that, from the evaluated possibilities, the most valuable idea is using the shredded composite in the housing of an electrical car charger. This product demonstrates how the shreds can be reused in a thermoplastic material and has a symbolic link with the wind energy industry.

EMBODIMENT

The electrical car charger can be produced by pressing shredded composite between two layers of thermoplastic sheets. This resulting sheet of material can be vacuum formed in the desired shape. The shape restrictions are mainly determined by the flexibility of the shredded composite. For the shreds to be sufficiently flexible, the maximum thickness should be 1 mm. However, this does require a sieving procedure when shredding the composite.

The thermoplastic material that is used in the design is polyethylene terephthalate (PET). This material has properties that suits the use context and provides a good bonding to the shredded composite.

With the shape of the design, it is aimed to radiate environmental friendliness and a link with wind turbines. The shredded composite is used to create different textures (smooth and bumpy) on both housing parts. In addition to this, LED light is integrated in the design to highlight the shreds inside the material. Within the design, the appearance, structure and story behind the shredded composite is mainly used to create value.

The developed product can again be recycled into new applications. However, the shredded composite will be part of a cascading model in which the fiber size will decrease with every recycling procedure.

EVALUATION

A prototype was created to evaluate the production method. From this, it can be concluded that it is possible to develop a housing with shredded composite with these production techniques.

CONCLUSION

The final design shows the possibilities of recycling the composite material in a thermoplastic housing. With this application, especially symbolic and sustainable value is achieved. The design is only reusing a small amount of the total supply of composite waste and is therefore not an all-encompassing solution to the problem. Additionally, mechanical recycling does cause significant down-cycling of the high value material. Therefore, it is best to replace the thermoset polymer composites with a better recyclable material, until a recycling procedure turning the fibers and resin back into raw materials is fully developed.

Glossary

ACRONYMS

FRP	Fiber reinforced polymer
FRPC	Fiber reinforced polymer composite
GFRP	Glass fiber reinforced polymer
HDPE	High-density polyethylene
OSB	Oriented strand board
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PETG	Polyethylene terephthalate glycol-modified
PP	Polypropylene
SC	Shredded composite
WTB	Wind turbine blade

TERMS

Circular economy	An economic system where products and services are traded in closed loops or cycles aiming to retain as much value as possible of products, parts and materials.
Composite	Material that is composed of two or more materials which can still be individually identified.
Matrix	The component of a composite in which the fibers are embedded.
Recyclate	Material sent to, and processed in, a waste recycling facility.
Shreds	Fractions that are produced by mechanical recycling a material.
Thermoplastic	A polymer that becomes moldable above a specific temperature and solidifies upon cooling.
Thermoset	A polymer that is irreversibly cured from a viscous liquid.

Table of Contents

Introduction

As an introduction to the topic of this thesis, background information and the assignment of the project are described in this section. In addition to this, the method used to approach this research and design project is explained.

Chapter 1
Introduction

With natural resources becoming scarce, more and more sustainable options are developed to replace these materials. For the energy production, wind energy is one renewable solution that is expected to grow in the upcoming years. According to Wind Europe (2017a) wind power covered 10.4% of the EU's electricity demand in 2016. They expect the share of electricity in the EU generated by wind power to be 21.6 – 37.6 % by 2030, depending on potential conditions that can influence the wind energy deployment (Wind Europe, 2017b).

This growth can be seen as a positive development for the fight against the amount of CO_2 emissions. However, considering a wind turbine's life span of 20 to 25 years (Mishnaevsky et al., 2017) and widespread use of modern materials in blades, such as composites, since the mid-1970s (Joncas, 2010), the challenges concerning recycling these turbines are currently faced. When taking the expected growth in the wind power industry into account, this amount of decommissioned wind turbines is only going to increase. Research on the environmental impact and uncertainties on how to recycle the different components coming from a turbine shows that the blades are the largest issue (Andersen, Borup and Krogh, 2007) (Figure 1).

This is caused by the material that is used in the blades, which is primarily glass fiber reinforced polymer (GFRP). The most common materials in other parts of the wind turbine, such as the tower, are steel, iron and copper. For these materials, recycling options are well developed and they have commercial value (Andersen, Bonou, Beauson and Brøndsted, 2014). For composites such as GFRPs, a viable and well-developed recycling method is unfortunately not yet existing. Because of this, most blades currently end up in landfill or incineration (Wind Europe, 2017c). Also, in other industries, such as aviation and automotive, they make widely use of fiber reinforced polymers (FRP). According to Wind Europe (2017c), the construction sector in which the wind power industry is included associated with 34% of Europe's glass fiber production. This is equivalent to 363 million tonnes of this material. Based on the expected growth in the wind power industry and the trend to increase the blade size of wind turbines (Mishnaevsky et al., 2017), the amount of FRPs produced will simultaneously increase. With the fact that wind turbines have a limited life span, this logically means that the amount of these composites being discarded will also largely rise in the upcoming years. To ensure that this high value material is not becoming waste and to optimize the environmental benefits of this type of renewable energy, it is of great importance that recycling options are further developed.

In this graduation project, the potential of fiber reinforced thermosetting polymers that are shredded into smaller fractions and particles is evaluated to find a valuable application for this material. The focus will be on composites from wind turbine blades, but it is aimed to develop a generalized solution that will also be suitable for similar composites from other industries. With the final design, valuable reuse of recycled composite material is demonstrated to stimulate the recycling of this resource and reduce its environmental impact.

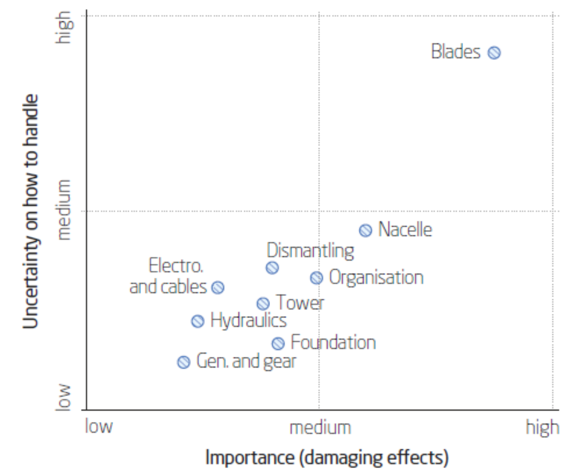


Figure 1 - Assessment of the environmental impact and uncertainties of recycling wind turbines

Chapter 2

Assignment

When evaluating the opportunities for recycling the GFRP in wind turbine blades, the available methods can be divided into three groups: mechanical, thermal and chemical (Beauson, Lilholt and Brøndsted, 2014). Mechanical recycling involves shredding and grading the wind turbine blades into smaller pieces, which results in a powder or fibrous fragments consisting of multiple materials. With thermal techniques, the glass fiber and, to some extent, polymer resin can be redeemed by processing them at temperatures between 300 and 700 °C. The last category consists of processes that recover glass fibers and polymer resin with the use of supercritical fluids. The glass fiber remnants from all these methods could be reused in new composites although the residual mechanical and geometrical properties differ.

In this graduation assignment, the focus will be on the mechanical recycling method of wind turbine blades. According to multiple studies (Mishnaevsky et al., 2017; Andersen, 2015), shredding the composite material results in a significant down-cycling of the high value material, because currently the residues are mainly used as a filler. However, Andersen et al. (2014, p. 97) makes several recommendations for future research:

“There is a need to know more about the potential markets for products made from recycled materials. There are established markets for scrap steel and alloys, but there is limited knowledge about the market for secondary products from wind turbine recycling, such as composite matrix materials derived from blades.”

Also, Meira Castro et al. (2014) states that mechanically recycled FRP waste remains “mired by the scarceness of cost-effective end-use applications and clearly developed recycling routes (logistics, infrastructures and recycling facilities) between waste producers and potential consumers for the recyclates”.

This report shows the research and design project that is done to continue closing this knowledge gap. This includes material research on the shredded composite material and on the new composites that can be obtained with these recyclate which will be used to design a valuable application for the material. The basis of the research lies in the belief that it is only possible to develop valuable applications for the shredded composite if more knowledge on the properties and limitations of the obtained material is developed. This knowledge can also be valuable for evaluating the current design of composite materials to enable better recycling.

With this project it is aimed to create an application that maintains the highest value to the composite material. This application should ensure the turbine blades of an end-of-life scenario that fits the circular economy principles, keeping the following definition in mind (Het Groene Brein, 2016):

“A circular economy is an economic system where products and services are traded in closed loops or ‘cycles’. A circular economy is characterized as an economy which is regenerative by design, with the aim to retain as much value as possible of products, parts and materials. This means that the aim should be to create a system that allows for the long life, optimal reuse, refurbishment, re-manufacturing and recycling of products and materials.”

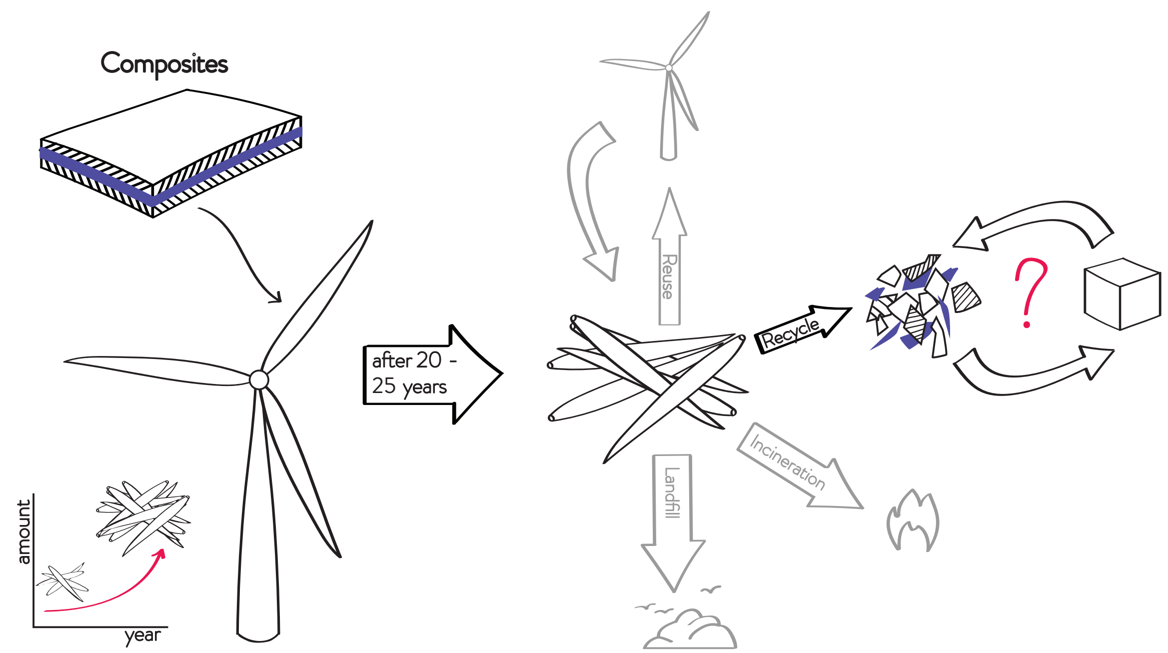


Figure 2 - Visualization of the context of the project

Chapter 3

Method

A design project typically starts with a user need or defined problem for which suitable solutions are created. In this project, the starting point is a waste material which requires a slightly different approach.

For the overall process of the project the general design model of Pahl and Beitz can be followed (Figure 3) (Roozenburg and Eekels, 2001). However, the detailing stage that follows the embodiment and consists of the realization of the product, is not included in this project. During the three main phases in the process (analysis, conceptualization and embodiment) basic design cycles will appear (Van Boeijen, Daalhuizen, Zijlstra and Van Der Schoor, 2013).

During the analysis phase, the shredded composite will be evaluated on its characteristics and potential directions for the recycling of the material will be identified. To get an understanding of the mechanical properties, extrusion profiles including the shredded composite will be used for material testing. The results of the analysis will be used to find valuable search areas for designing a new material and application including the shredded composite.

Valuable applications will be explored in the conceptualization phase. In literature, different methods are described to find a suitable application for a specific material. The method Material Driven Design (Karana, Barati, Rognoli and Zeeuw van der Laan, 2015) is focusing on the material experience and methods developed by Landru, Bréchet and Ashby (2002) have more emphasis on the technical properties of the material. Depending on the defined search areas, suitable aspects will be used from these methods to find a valuable application.

In the last phase, the embodiment phase, the chosen application will be further developed together with the material. For the design it is important that the material properties and limitations are further explored and that a suitable production method is selected.

Within this process, multiple frameworks are defined to facilitate the evaluation of the findings on the level or type of value that they achieve. These frameworks will be explained in the following section.

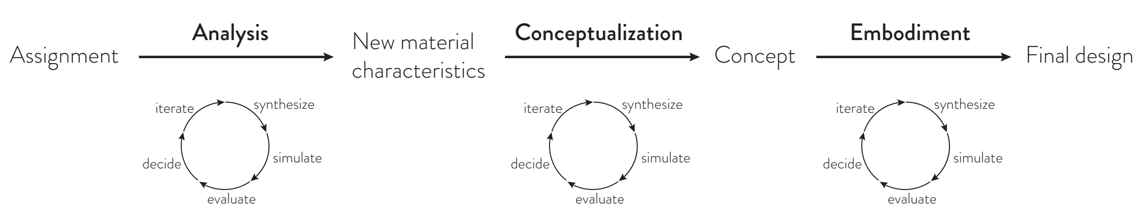


Figure 3 - Design model

FRAMEWORK 1: WASTE HIERARCHY

When looking at the waste hierarchy in Figure 4, defined by the European Waste Framework Directive (2008/98/EC) (Wind Europe, 2017c), the prioritizing of the waste treatment is visible. The category on which this project is focusing is "Recycle", in which the following subdivision can be distinguished (Halliwell, 2006; European Commission, 2011):

- Primary recycling: converting the waste into a material that has equivalent properties to those of the original material.
- Secondary recycling: converting the waste into a material that has inferior properties to those of the original material.
- Tertiary recycling: converting the waste into chemicals and fuels.

This project will focus on mechanical recycling, which belongs to secondary recycling. A decrease in properties will occur due to the reduction in the fiber size when shredding the material. When considering the material utilization and the remaining material value, it is preferred to succeed with the highest possible level of recycling (Halliwell, 2006). For this reason, a solution with the highest retained properties within the secondary recycling level will be searched.

FRAMEWORK 2: VALUE TYPES

To be able to design a product that has value for its customer, it is important to have a closer look at the types of values that can be achieved (Mulder, 2012):

- Functional value: it brings convenience, solves a problem or is better, easier, more extensive.
- Emotional value: it is enjoyable or attractive, feeling of devoting towards it because of nostalgia, advice by others.
- Economic value: it is time, energy or money saving or innovative.
- Symbolic value: it provides status or represent something.
- Sustainable value: it is beneficial to the environment, made of recycled material, can be recycled after use.

The end value, which is also discussed by Mulder, is neglected because the other types are projected in it. Sustainable value is added because of the growing importance of this aspect for customers and the large role it plays in this project. This division of values will be used during the project as a framework to develop and evaluate ideas and help shape a commercially interesting material and application from the shredded composite by excelling on at least one of these value types.

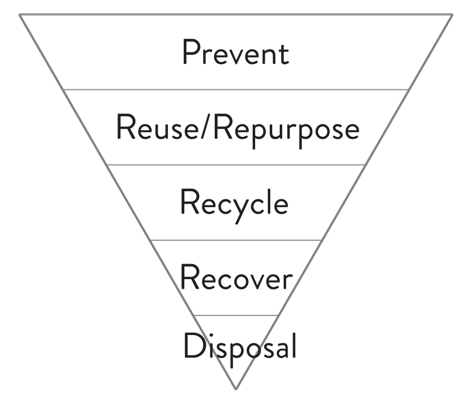


Figure 4 - Waste hierarchy

Analysis

The analysis started with gaining general knowledge on composite materials and the design and current end-of-life possibilities of wind turbine blades. After this, market research was executed to find out in which applications shredded composite material is used. In addition to this, material and literature research is done on the shredded composite and extrusion profiles including shreds to learn about the properties. These analyses concluded in a list of strengths and weaknesses of the shredded composite and opportunities and threats for the to be designed application. In this section, the results of the analysis phase are discussed.

Chapter 4

Composite Materials

A composite is a material that is composed of two or more materials. These are combined in such a way that they do not blend into each other and that the different materials can still be identified. The primary materials have their own strengths which often results in a composite with unique and favorable properties (Royal Society of Chemistry, 2006). The broad range of possible compositions and geometries within the composites enables them to be designed with a perfect fit for a specific application.

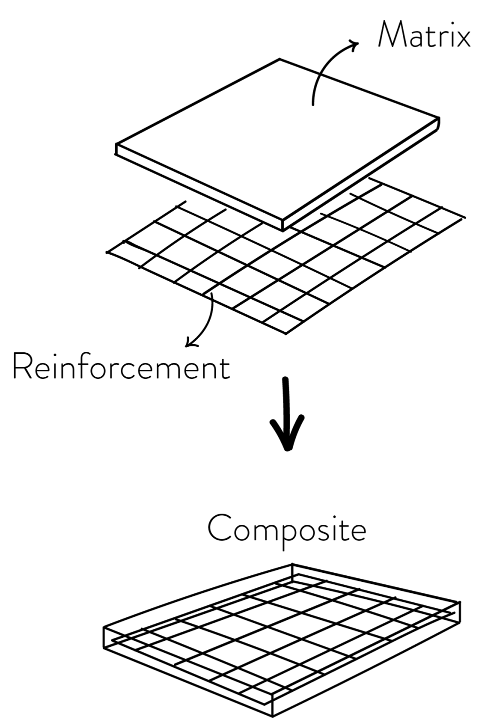


Figure 5 - Reinforcement and matrix

COMPOSITION

Within the composite one material acts as the binder, also known as matrix, that surrounds and keeps the fragments of the other material, the reinforcement, together (Figure 5) (Royal Society of Chemistry, 2006).

CLASSIFICATION

Composites can be classified in multiple ways, based on their matrix or reinforcement. For matrix materials the most common classes are Polymer Matrix Composites (PMC's), Metal Matrix Composites (MMC's) and Ceramic Matrix Composites (CMC's). Reinforcements are classified on their type and orientation as visible in Figure 6 (Otani and Pereira, 2014; "Seminar on composite application in aerospace", 2015).

Probably the best-known composite is concrete. Concrete belongs to the large-particle composites with both matrix and reinforcement being ceramic materials: cement (matrix), gravel and sand (reinforcement) (Callister, 2007). To make the concrete even stronger, metal reinforcement is often used. Interesting to know is that composites also exist in nature, for example bones and wood. They consist of multiple materials that are strongly bound together (Royal Society of Chemistry, 2006).

PROPERTIES

As an inevitable result of the broad range of composite types, the properties of composites differ for each compound. However, in general it can be stated that the main aspects that determine the properties of a composite are (Callister, 2007):

- The properties of the matrix and reinforcement materials and their relative amounts
- Geometry of the reinforcement, namely the particle sizes, shape, distribution and orientation
- The bond between the matrix and the reinforcement
- For structural composites, the properties also strongly depend on the geometrical design of the materials.

Important aspects of composite materials are the level in which they are homogeneous and isotropic. If a material is homogeneous, the properties of the material are the same in each point. If this is not the case, the material is heterogeneous. Isotropic applies when the properties of the material are not depending on the direction. In case the properties do differ for different directions within the material, it is defined as anisotropic.

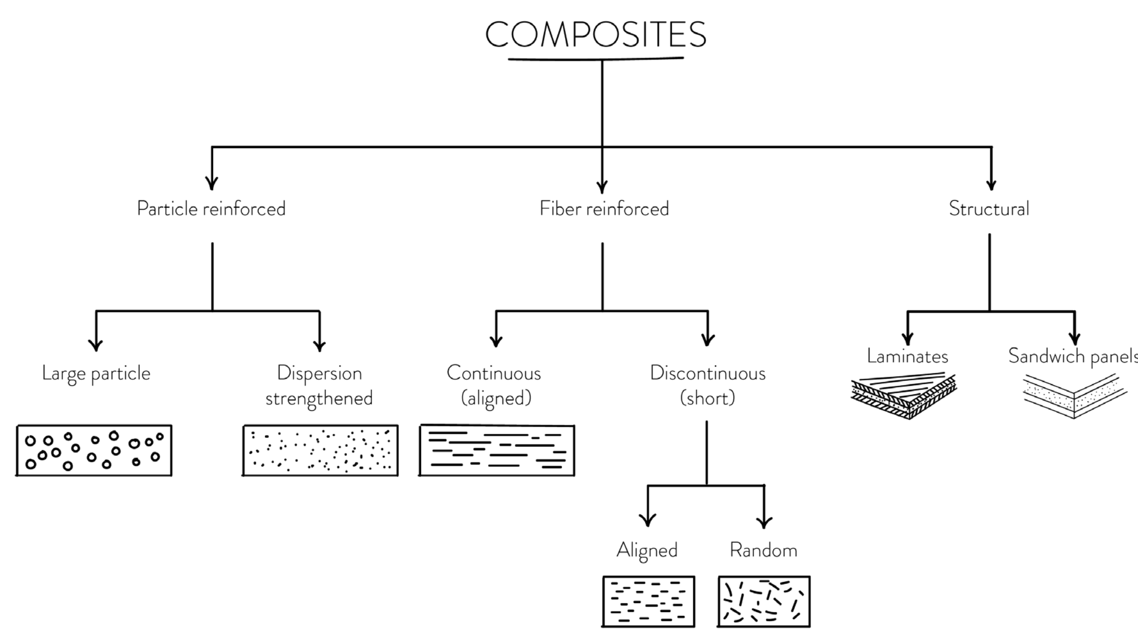


Figure 6 - Classification of composites based on reinforcement

Chapter 5
Wind Turbine Blades

Wind turbines are optimized to work with a high efficiency and to generate as much energy as possible. Having large blades is one important aspect of this optimization. This requires that the blades are made of a both strong and light material that can resist fatigue loads. FRPs are a perfect fit for this application because of their unique characteristics and their flexibility to be customized to a specific application (Royal Society of Chemistry, 2006). For these reasons, this composite material is the main material in wind turbine blades.

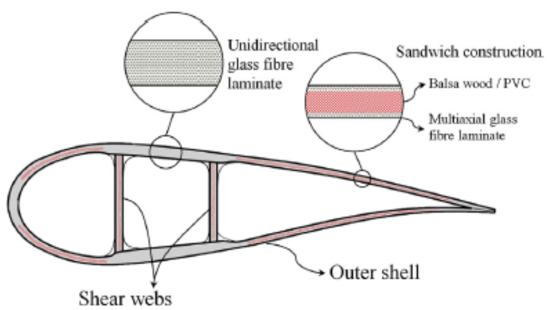


Figure 7 - Common design of wind turbine blade (Beauson, Madsen, Toncelli, Brøndsted and Ilsted Bech, 2016)

Although the material composition varies between blade types and manufacturers, a generalized design of a wind turbine blades is visible in Figure 7 and Figure 8. As visible in the figures, the fiber reinforced polymer composites (FRPC) in blades are laminated and at some places sandwiched with core material and therefore belong to the structural group in Figure 6. The laminates themselves consist of individual sheets with long, continuous fibers or short, random fibers. The used materials are often (Wind Europe, 2017c):

- Laminates of FRP:
  - Reinforcement: mainly glass fiber, but could also be carbon, aramid or basalt. The fibers often taken up 60-70% by weight of the FRP.
  - Matrix: most often a thermoset such as epoxy, polyester, vinyl esters and polyurethane. 30-40% by weight of the FRP consist of matrix material.
- Core material: balsa wood or foams such as polyvinyl chloride (PVC) and polyethylene terephthalate (PET)
- Coating of polyethylene (PE) or Polyurethane (PUR)

When looking at the variety of materials that are used in the wind turbine blade industry, it seems that a standard for the FRP composition is not existing. However, Mishnaevsky et al. (2017) state that E-glass fiber, a specific type of glass fiber, is most often used as reinforcement in combination with a polyester or epoxy resin matrix. For these last two materials, polyester was initially the most common material, but with the increase in blade size epoxy resins took over. This is caused by the improved mechanical properties of epoxy in comparison to polyester.

Currently, the development of using carbon fibers in the blades is getting started. This material can cause a decrease in weight with an increase of mechanical properties, but the material costs are higher than for glass fiber.

In future developments within the wind energy industry, the recyclability of the blades is calling for more attention. This could mean that eventually the blades will be made of an improved recyclable material or that a well suitable recycling method will be developed for the current material. However, until that moment is reached, many blades will already be decommissioned that need a proper end-of-life scenario. According to Speksnijder (2018) the first wind turbine blades with thermoplastic composites, which is better recyclable, might be operating in 2030, which means that by 2050 these thermoplastic blades will be decommissioned. Until then, the recycling of thermoset blades will be a problem that has not found a suitable solution yet.

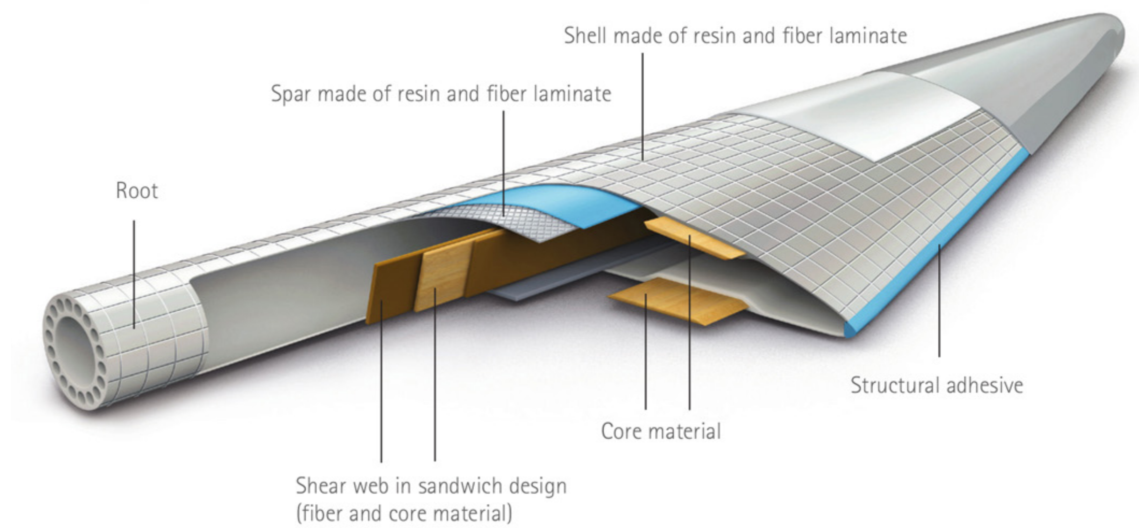


Figure 8 - Common design and material use for wind turbine blades (adapted from Grunewald, 2014)

Chapter 6

End-of-Life Scenarios

After approximately 20 to 25 years, an operating wind turbine will be decommissioned. By this time, the wind turbine has reached its designed lifetime and the developments on more efficient designs have probably made the wind turbine outdated. When it is taken down, the materials could be reused or recycled. However, the large issue with recycling the blades is caused by the FRPCs that it consists of. These composites are made of thermosetting polymers which cannot be melted and therefore cannot be deformed into a new shape. Also, separation of the compounds is difficult. Currently, a few end - of - life options are existing for the turbine blades, which will be discussed in this chapter. The waste hierarchy of figure 4 will be used to categorize the different end - of - life possibilities.

RE-USE

The best option for the decommissioned blades from a sustainable point of view is fully re-using them. Most often, the blades are still able to be reused after their lifetime. However, the developments in material and design cause that the older blades are not suitable anymore for the mature markets. These older turbines can be sold for re-use to less developed markets, such as Eastern Europe and Latin America (Andersen et al., 2014).

RE-PURPOSE

Some blades are reused on a small scale in other markets. An example of this is SuperUse Studios that used old blades to design a playground (SuperUse Studios, 2008) (Figure 9) and a camping (SuperUse Studios, 2011) (Figure 10).

RECYCLE

Mechanical recycling, such as grinding and shredding, is located in the secondary recycling category. ERCOM is an example of a company that reused shredded composite into sheet and bulk molding compounds (Papadakis, Ramírez and Reynolds, 2010). The composites are currently often used in cement production by incinerating the composites and using the residue in cement plants. This is considered tertiary recycling, because the composite is used as a fuel (Papadakis, Ramírez and Reynolds, 2010). Pyrolysis and fluidized bed thermal process are also considered tertiary recycling. With both processes, the matrix material breaks down in liquids or gas and is separated from the fibers under a temperature of around 500 °C (Pickering, 2006). After these processes the glass fiber typically has a reduction in its strength. One example of a company that is reusing the fiber residue obtained from pyrolysis is ReFiber ApS, which is developing insulation material from this (ReFiber ApS, 2004) (Figure 11).

RECOVER

Incineration with energy recovery is fitting inside the recovery group. For glass fiber reinforced composites, the incombustible glass will remain as residue after burning, which causes an efficiency of only 10 to 30% (Papadakis, Ramírez and Reynolds, 2010).

DISPOSAL

Two options that fall in this category are landfill and incineration without energy recovery. The cheapest option is landfill, but the legislation on the waste that is allowed to go to landfill has become stricter in many countries. As a result, materials with a high organic content are banned which also concerns blade waste which has an organic content of 30% (Cherrington et al., 2012).

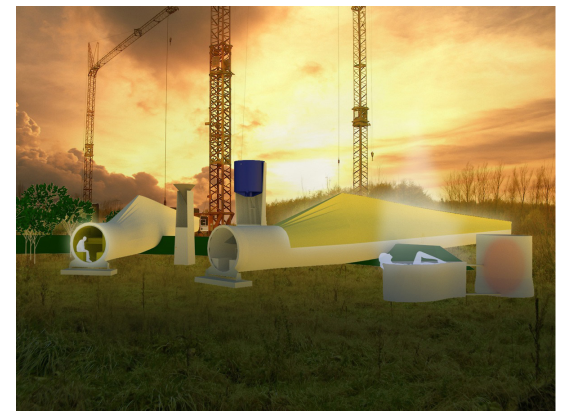


Figure 9 (top) - Wikado
Figure 10 - ReWind camping
Figure 11 (bottom) - ReFiber insulation material

Chapter 7

Market Research

To get a grip on the products that are produced with shredded GFRPs, a market analysis was done. The applications that were found were clustered in different product categories and will be shortly explained in this chapter.

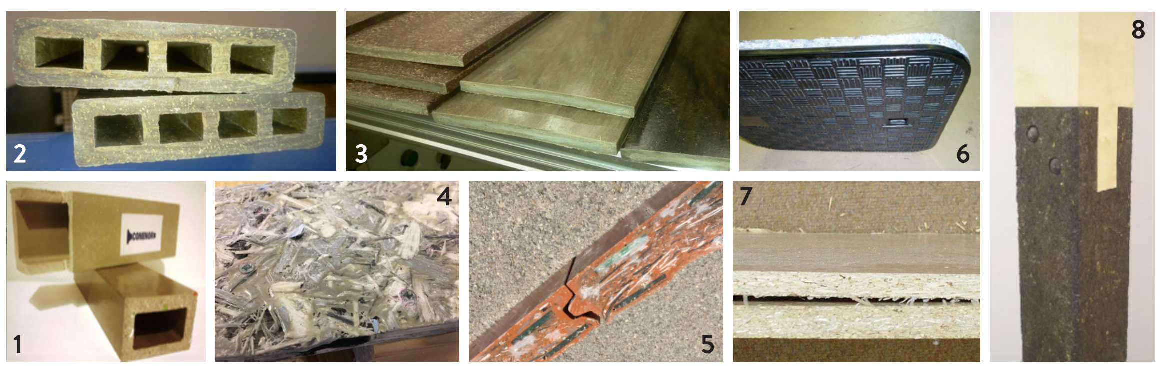
CONSTRUCTION AND INFRASTRUCTURE

Most applications that were found are building materials. The Finnish extrusion company Conenor produces extrusion profiles with wind turbine blade (WTB) waste, wood and polypropylene (PP) or high-density polyethylene (HDPE) [1] (Uribe, 2017). They also developed decking boards [2] and panels [3] (Conenor, 2017). Conenor claims that the HDPE variants are stronger and stiffer than virgin HDPE.

The Dutch research and education institution Windesheim has been doing research in recycling shredded composite and developed oriented strand board (OSB) made of fiber reinforced plastic [4] (Bouwmeester, 2017). This OSB is more moisture resistant than wooden OSB and tests show that it could be a potential application for the shredded composite. They also produced canal retaining walls made of larger strokes of composite waste [5] (Ten Busschen, 2016).

Conroy, Halliwell and Reynolds (2006) discuss current waste management options for composite waste. They mention several developed applications, such as artificial wood made from ground fiberglass composite waste, wood flour and HDPE [8]. An increase in E- and flexural modulus was detected together with a decrease in impact strength due to the addition of glass fiber waste. They also point out the strength improvement that could be made when using the recyclate fiber in asphalt. Other applications that they discuss are particleboards [7] and manhole covers [6].

Reprocover, a Belgium recycling company, is also producing manhole covers, valve chambers and



other construction products of ground glass fiber thermoset polymer composites waste and clean waste fibers from production (Job, 2013).

Lastly, an English building products company named Hambleside Danelaw is developing thermoplastic composites by adding recycled short glass fibers to PP building products, which increases the strength and stiffness [9] (Job, 2013). The costs are reducing, because of the substitution of PP.

CEMENT AND CONCRETE

A widely known application for shredded composite is cement production. Neocomp in Germany and Holcim in Switzerland are two companies that do this [10]. The remaining ashes from the incineration process of shredded composite, which contain silica, are used as a substitution for natural sand (Holcim, 2017). Mixt Composites Recyclables (M-C-R) in France is using a similar method, but is also selling the longer fibers from the recyclate to function as a substitute for PP fibers in cement floors to limit cracking (Job, 2013).

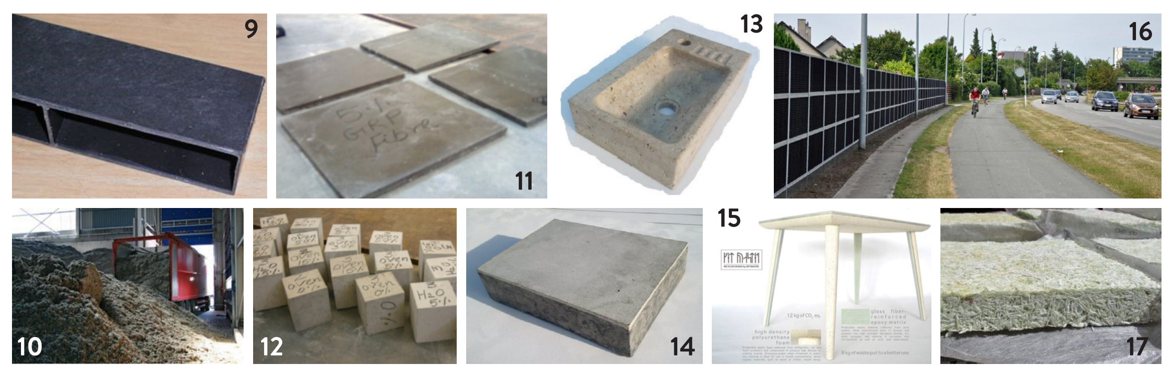
BeAware is a project that is also investigating opportunities to recycle GFRP waste into concrete composites. They showed that it can partial replace fine aggregate and that the fibers can significantly improve the quality of concrete products [11] [12] (BeAware, n.d.).

FURNITURE AND SANITARY

The Dutch company Extreme Eco Solutions is experimenting with the production of a material that looks like natural stone [13] [14]. With this material, they are aiming to enter sanitary, infrastructure and construction markets as well as the funeral industry. Another company, GETWasted, produced a table from the composite waste [15] (GETWasted, 2014).

ACOUSTIC AND THERMAL INSULATION

Miljøskærm (2018) has achieved to develop acoustic insulation of good quality from the shredded glass fiber polymer composites and claims that the material could also be used for thermal applications [16] [17].



Evaluation Market Research

When looking at the results of the market research, there seems to be quite a wide market for shredded composite. However, despite these applications, many still claim that no valuable solutions exist for the waste. Meira Castro et al. (2014) state that many of the tried experiments with shredded composite waste "have not succeeded for one or both of the following reasons: a) tendency of the recyclate addition to negatively affect the mechanical properties of final composite; and b) negative cost balance, where mechanical recycling and sorting operational costs outweighed the market value of the virgin product (chopped glass fibres and calcium carbonate)". To get a better understanding of the situation, it could be useful to identify the perspectives in which is already experimented with the waste material. Therefore, the applications were categorized based on the defined value types explained in Chapter 3 - Method and the function of the waste in the new material.

VALUE TYPES

The products found in the market research were categorized based on the five defined value types. One product can achieve multiple types of values, which means that some applications can be found in more than one value category. The placement of each application was estimated with the help of the available information on that specific product. Often this information is delivered by the producing company itself, which means that it should be handled with a critical attitude.

In Figure 12 the categorization can be found. It is visible that little applications are achieving symbolic or emotional value and that the focus is on the economic, sustainable and functional values within the current products.

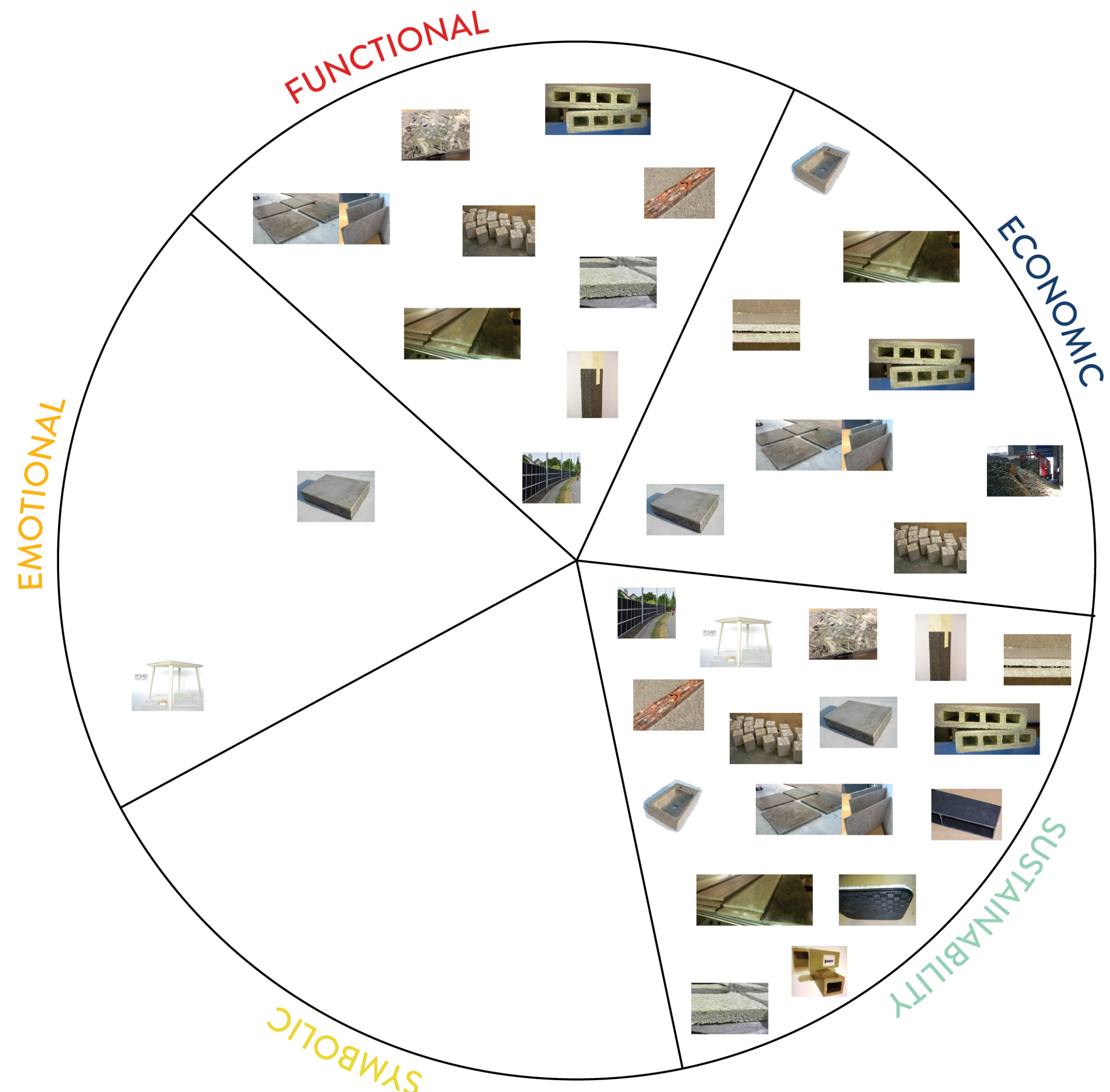


Figure 12 - Categorization on value types

FUNCTION

The different applications for the shredded composite can also be categorized on the type of function that it performs in the new product (Figure 13). When looking at the applications on the current markets, the following categories were distinguished.

Reinforcement

The function that the shredded composite performs has a correlation with the size of the shredded recyclate. As visible in the examples that were mentioned within the market research, some companies accomplished to produce a material with shredded composite that has improved strength and stiffness because of the fibers. In these products, the shredded composite can be seen as reinforcement.

Filler

Grinded composite waste can be used as filler in many materials and products. When this is done, the product is purely benefiting from the volume that the material occupies. ERCOM was a recycling company that used grounded recyclate in new sheet molding compound but had to stop doing that in 2004. The chosen approach reduced the value of the material to that of calcium carbonate, which is a filler material that can be purchased at a very low cost (around 200 Euros/ton) (Job, 2013). This made it difficult to create an economically valuable business case. However, M-C-R is currently executing a similar process for automotive parts with the environmental benefit as their motive for recycling (Job, 2013).

Other functionalities based on characteristics

Next to adding strength and volume, other characteristics of the shredded composite could be used within a new product. When evaluating the products from the market research, it became clear that characteristics such as acoustic and thermal insulation, water resistance, light-weight, aesthetics and silica content could also be usefully exploited.

CONCLUSION

The market research shows that several companies are already trying to recycle the shredded composite. Most of these products are achieving economic, functional or sustainable value. Emotional and symbolic value are areas that are not focused on by most. In addition to this, it can be concluded that next to functioning as reinforcement and filler material, the other characteristics of the shredded composite could also be exploited in the new application.

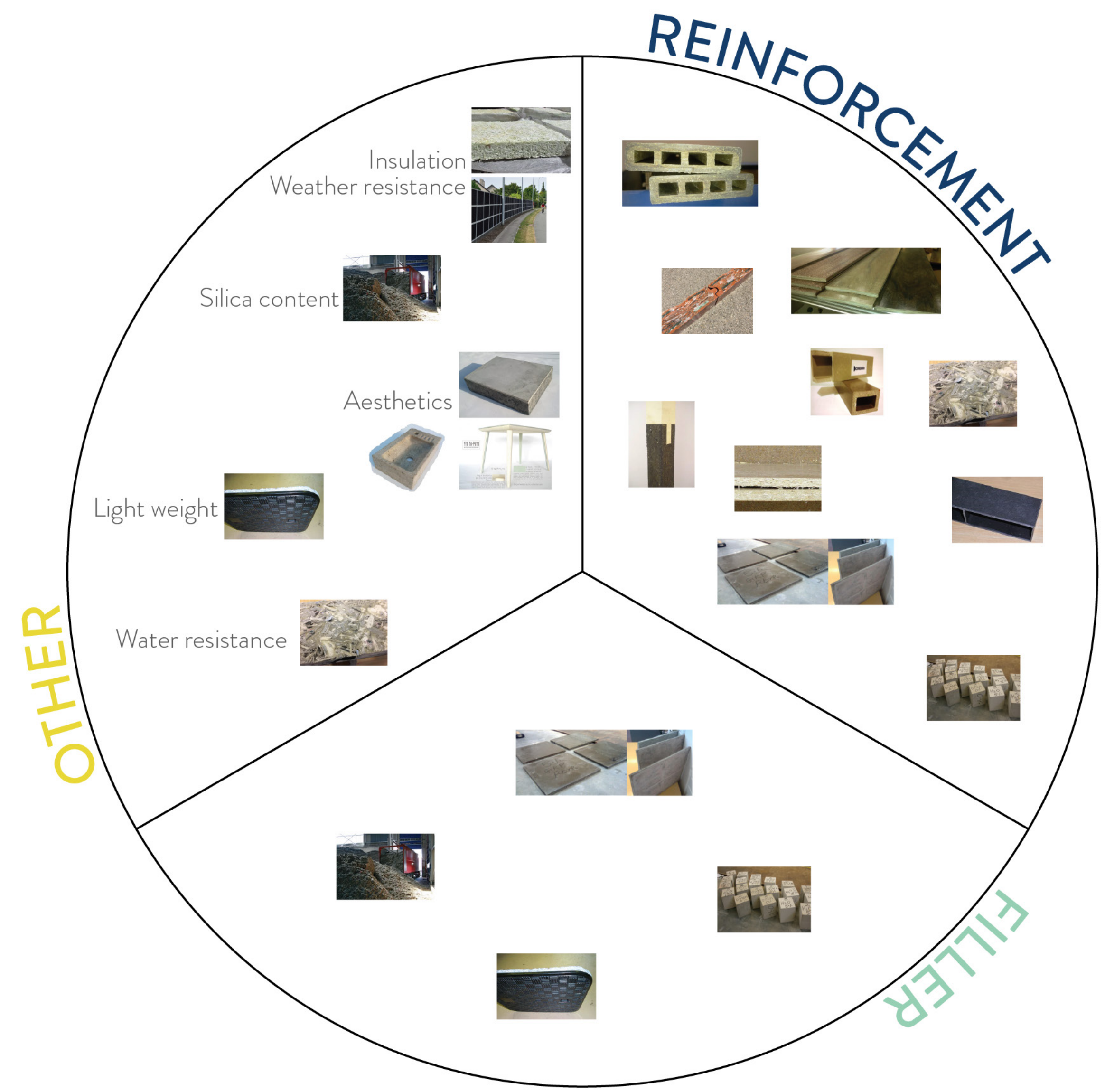


Figure 13 - Categorization on function

Chapter 8

Batches of Shreds

Two batches of shredded wind turbine blades were obtained, one from Korsnäs in Finland (referred to as shredded composite (SC) 1) and one from Demacq in the Netherlands (referred to as SC2). To identify the differences that may appear between the supply of wind turbine blades, the two batches were evaluated. First, the shreds were analyzed with the bare eye and the microscope. Secondly, a moisture content test was done on SC2 after which the samples were again viewed under the microscope. Lastly, a burn - off test was executed to remove the thermoset matrix to be able to analyze the glass fiber residue. The results of these analyses will be explained in this chapter.

VIEWING THE SAMPLES

The content of the batches of shreds seems to be quite different when they are compared with the bare eye. The color of the batches is differing: SC1 (Figure 14) has a white color and SC2 (Figure 15) is more brownish. However, it is visible that both batches at least consist of glass fiber and foam. SC2 seems to consist of additional materials such as unexpected plastics and electronic wires as well.

To get a closer look at the batches, both were analyzed with a microscope. Results are visible in Figure 16, Figure 17 and Appendix 1 and also show differences in the appearances of the batches. The different materials (fibers, matrix material and foam) are clearly recognizable in SC1, which is more difficult in the SC2. Additional materials seem to be present in this batch.

Figure 14 - SC1

Figure 15 - SC 2

MOISTURE CONTENT

The SC2 batch appeared shiny under the microscope, which could mean that the shreds are wet. To calculate the amount of moisture in the SC2 batch, three samples were dried in an oven at 105 °C for 1 hour. The samples were placed in glass or porcelain cups. The weight of the cups and the samples were determined before and after the test to calculate the moisture content in the samples. The resulting average amount of moisture present in the batch of shreds is 22.6 wt%. An elaborate description of the test can be found in Appendix 2.

Analyzing a dried sample under the microscope shows that the glistering surface has disappeared and the fibers are easier to recognize (Figure 18).

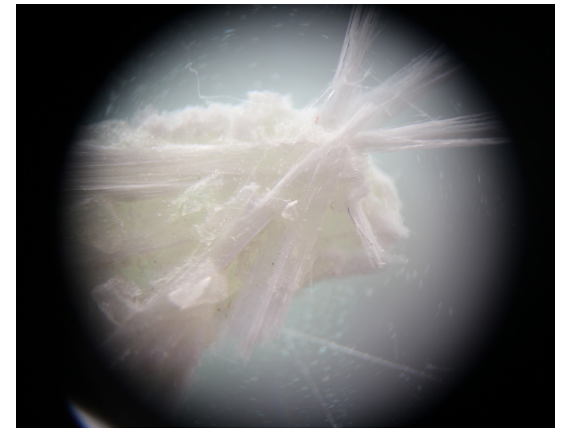


Figure 16 – SC1 under the microscope

Figure 17 – SC2 under the microscope

Figure 18 – Dried SC2 under the microscope

BURN-OFF TEST

A way to get a better grip on the content of the shreds is to find out what the amount of glass fiber is within different samples. This was done with a burn-off test. In this section this test and its results are shortly explained. For more extensive results of the test Appendix 3 can be consulted.

Five samples of both SC1 and SC2 were used in the burn-off test (Figure 19 and Figure 20). For this test, the samples were placed in porcelain cups, of which the weight was determined beforehand, and were heated in an oven at around 570 °C (ASTM International, 2002). At this temperature, the thermoset matrix material and foam are burned off from the samples. The oven was programmed to increase its temperature as quick as possible to 570 °C after which it would keep the temperature stable for one or two hours. After the one or two hours, the oven stopped heating and slowly cooled down. The samples and cups were weighted before and after the test.

From the results, it is visible that the average amount of residue after the burn-off test is 55.2 wt%. The amount of glass fiber present in SC1 seems to be a bit higher than in SC2, however this is hard to conclude with a limited number of samples. The main material in this residue is expected to be glass fiber, because the other materials are supposed to be burned off during the test.

The samples were analyzed with the microscope after this burn-off test of which images are visible in Figure 21 and Figure 22. The SC1 batch resulted in clean-looking glass fibers. In the SC2 batch, dusty material is visible together with clean-looking glass fibers. The dust could be glass fiber as well, but then grinded into powder. The brownish color is still present in the dusty material, which could also mean that it is some type of pigment.

CONCLUSION

From the different tests that were done conclusions can be drawn on the two batches of shreds. Firstly, the batches consist of an average of 55.2 wt% glass fiber. Secondly, on the microscope images it can be seen that the SC2 has a brownish color, which is probably caused by wood or foam. After the burn-off test, this brownish color is still present which could refer to a pigment in the foam. It is also visible that additional materials are present in SC2, such as wires or plastics. Thirdly, a 22.6 wt% of moisture is present in the SC2 which gives the shreds a different appearance in comparison with the SC1 batch.

Figure 19 – Sample 1 to 5 before the burn-off test

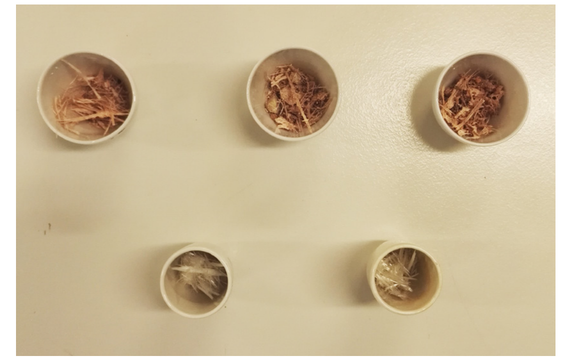


Figure 20 – Sample 1 to 5 after the burn-off test

Figure 22 – SC 2 after burn-off test

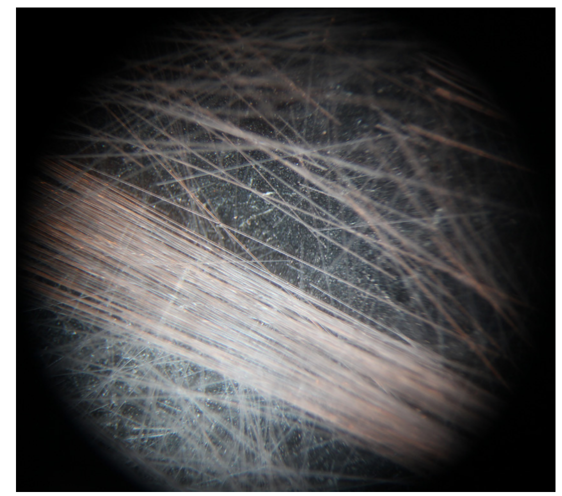


Figure 21 – SC1 after burn-off test

Chapter 9

Material Properties

To be able to reuse the shredded blades, it has to be combined with a binding material which will result in a new composite. Mechanical properties of this new composite material are hard to determine upfront. Amongst others because the bond between the used matrix material and the shreds is of great influence on this. Therefore, every composite should be tested to get a good idea of its characteristics. However, with the large amount of possible binding materials, this is a time-consuming task. To still be able to get an understanding of the properties of the shredded composite within a new application, material tests were done on two composites to determine their mechanical properties. The results are combined with literature research on mechanical and other material properties to get an idea of the characteristics that can be achieved with the shredded composite.

MECHANICAL PROPERTIES OF THE PROFILES

The composite materials that were analyzed are two types of extrusion profiles that consist of shredded composite from batch SC1, wood snippets and respectively recycled PP and virgin HDPE. The weight fractions of the content of the profiles are visible in Table 1. All profiles were labeled with the names PE 1 to 3 and PP 1 to 3 to be able to distinguish them throughout the material tests.

Cross section

The profiles were cut in half and sanded to get a better look on the fibers inside the material (Figure 23). The resulting surface was analyzed with a microscope. The wood fibers are clearly visible due to their brown color, but the shredded composite is more difficult to identify. When comparing the cross section of the profile in the extrusion direction and the direction perpendicular to that, it was expected to see fibers in one direction as rounds or ovals on the surface and in the other directions as lines. This would have meant that the fibers are orientated parallel to the extrusion direction. Because the fibers are hard to identify on both cross sections, it is hard to tell which orientation the fibers have within the profiles. This could mean that the fibers are randomly oriented.

Burn-off test

To get a better idea of the dimensions of the fibers that are inside the profiles, a burn-off test was done on different samples of the PE and PP profiles. In this section, the test and the results are discussed.

For further information, Appendix 4 can be consulted.

In these burn-off tests, the thermoplastic material was removed from the samples, as well as the wood snippets, foam and the thermosetting epoxy or polyester that is stuck on the fibers. Three samples of the PE and PP profiles respectively were used and placed in porcelain cups. They were heated in an oven to 570 °C (ASTM International, 2002) for 1 or 2 hours. The samples and cups were weighted before and after the test to evaluate the amount of the glass fiber residue. The end results from the burn-off tests can be found in Table 2, which shows that the average amount of residue is 10.3 wt%.

In addition to glass fiber, the residue contains powder which color corresponds to the color of the original profile (Figure 24). This could mean that the residue also contains pigment. When the amount of residue from the burn-off test was compared with the content information delivered the production company (Table 1), it is visible that the amount is lower than expected (10 wt% instead of 12 wt%). This can be caused by the presence of moisture in the shredded composite prior to the extrusion process which influences the weight.

The residues were analyzed with a microscope to have a closer look at the fibers that are inside and to identify the content of the residue. In Figure 25 the sample number 8 with residue from a PE profile is visible. On these microscopic images, several fibers were assigned with their length and thickness. Sample number 9, that originates from a PE profile, and sample 14, originating from a PP profile, were analyzed under the microscope as well. All resulting

PROFILES	
Material	*Weight fraction [%]*
Shredded WTB of which:	20
- Fibers	12
- Matrix	8
Wood pellet	40
PP/HDPE	30
Additives	10

Table 1 - Content information of the profiles

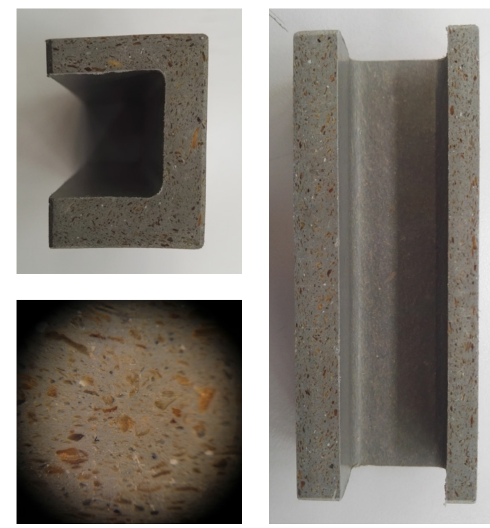


Figure 23 – Cross sections (top left and right) and microscope image of a cross section (bottom left)

images can be found in Appendix 5.

One particle of the powder present in the residue was analyzed closely to identify what material it is made of. With different lighting it became visible that it is made of a material that reflects the light (Figure 26). When comparing this with a glass fiber in the same lighting, the resembling appearance made clear that a large chance exists that they are made of the same material. This could mean that the powder in the residue is grounded glass fiber.

It is visible in the microscopic images that the length and the thickness of the fibers differ in all samples. The fiber lengths are varying from particle size until a few millimeters. The largest fiber measured in this sample was 5 mm, but this does not mean that no larger fibers are present in other samples. The thickness has an average value of 22 μm in these samples.

Density

The densities of the profiles' materials were determined by measuring the weight of six samples per material with decided dimensions. The samples were produced with milling machinery which resulted in fairly constant dimensions for length, width and thickness. This resulted in an average density for the PP composite of 1.14 gram/cm^3 and of 1.20 gram/cm^3 for the PE composite. Elaborate results can be found in Appendix 6.

The densities were also calculated based on theory to compare this with the measured value. For this calculation, the rule of mixtures (Nijhof, 2006) is used which states that the sum of the densities of the separate materials within a composite multiplied with their volume fractions describe the density of the composite. The densities of these materials are based on theoretical information of the materials (Borealis, 2008; Prospector, 2018; AZO Materials, 2018; CES EduPack, 2017; European Wood 2018a; European Wood 2018b; Pilling, n.d.). More information on these values can be found in Appendix 7. The calculated values for the density of the composites are 0.785 for the PP profiles and 0.799 for the PE profiles (Appendix 10). The difference with the measured values could be caused by the additives present in the profiles which are simplified in the calculations or by the use of theoretically values that do not fully correspond to the reality.

Strength and stiffness measurements

The profiles were analyzed with a bending and tensile test to identify the mechanical properties. The approach and results of both tests are discussed in this section.

Three-point bending test

For the three-point bending test, a previously done test by the company Muovipoli was followed to be able to compare their results with the obtained test results (Muovipoli, 2017). In their test, Muovipoli tested extrusion profiles including shredded composite with different compositions (Conenor, 2018). A specimen with the dimensions of 160 x 15 x 8 mm was cut from the side of the profile which thickness is approximately 8 mm. These test specimens were bent in a three-point set-up with the striking edge and supports having a radius of

	wt% residue
PE profiles	10,0
	9,9
	10,8
PP profiles	10,9
	10,6
	9,5
average	*10,3*
% variation	*7,6*

Table 2 - Residue percentage after burn-off test

Figure 24 – Residue of PP (top) and PE (bottom) profiles

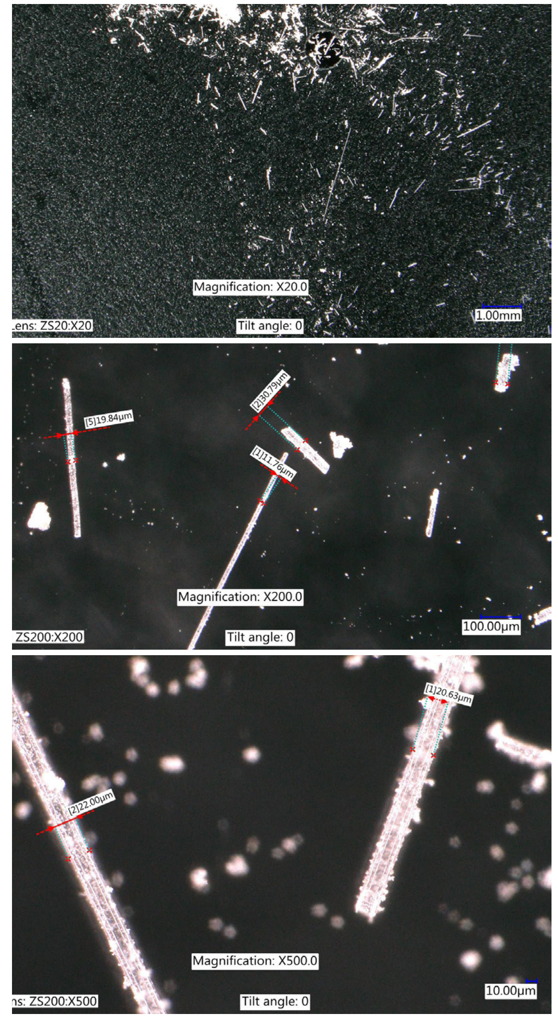


Figure 25 – Microscopic images of residue material

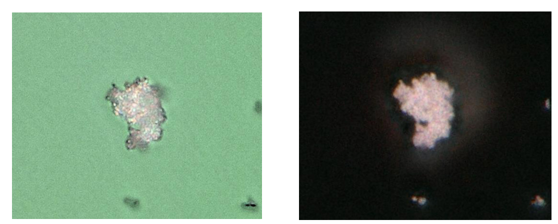


Figure 26 – Images of powder in residue

5 mm, a support span of 128 mm and a deflection rate of 2 mm/min. The bending force was applied to the side of the specimen corresponding to the outside of the profile.

These test guidelines were followed for this test except for the radius of the striking edge, which has a diameter of 6 mm, and the support span, which is 127 mm. From the three PE (PE1 to PE3) and three PP (PP1 to PP3) profiles that are available for the test, three test specimens per profile (B1 to B3) were created. With a milling machine the test specimens were cut to the correct dimensions. Only the thickness was kept to the original thickness, which sometimes slightly differed from 8 mm due to inconsistency in the profiles.

The results from the bending test are visualized in Figure 27 and Figure 28 and elaborate results can be found in Appendix 8. The average measured values for the flexural strength and flexural modulus are compared with unreinforced PP and PE to see which differences occur. The values for unreinforced PP and PE are taken from literature (MakeItFrom.com, 2018a; MakeItFrom.com, 2018b; CES EduPack, 2017; MakeItFrom.com, 2018c; MatWeb, 2018). However, in order to correctly compare these with the measured values, the test method and preparation of the samples must be identical. For this reason, it would be best to carry out a similar test for all materials. However, in this research the results are compared to those found in literature which means that the conclusions should be handled with caution.

Tensile test

For the tensile test, three test specimens (T1 to T3) from two PE (PE1 and PE2) and two PP (PP1 and PP2) profiles were exposed to an axial force until their breaking point. By ASTM D3039/D3039M-17 general geometry requirements are given for the test specimen. Recommendations for the dimensions are also listed, but these may vary as long as the requirements are met. Based on these requirements, test specimens were milled with dimensions of 90 x 10 x 6 mm. The test specimens were cut out of one side of the profile which thickness comes closes to 6 mm. The head displacement rate that is used for the test was 2 mm/min.

For the test specimen, it is important that they break at a point within the support span. When the specimen breaks at the point where the supports are clamping the material, the measured stress at break is influenced by the clamping. To make sure that the samples are breaking at the correct place tabs are often included in the shape of the test specimen. In this test, these tabs were not created because of the. The results of the test showed that tabs were not necessary because all specimens except one broke on the correct place (ASTM International, 2017).

The results from the tensile test are visualized in Figure 29 and Figure 30 and elaborate results can be found in Appendix 9. The average measured values for the tensile strength and E-modulus are compared with unreinforced PP and PE to see which differences occur. The values for unreinforced PP and PE are taken from literature

(MakeItFrom.com, 2018a; MakeItFrom.com, 2018b; CES EduPack, 2017; MakeItFrom.com, 2018c; MatWeb, 2018; Borealis, 2008; Prospector, 2018). Similar to the bending test, the conclusions should therefore be handled with caution.

Discussion

From the results, it can be seen that the flexural modulus is strongly increased by the addition of the wood snippets and shredded composite. It rose from 1300 to 2808 MPa for PP and 1274 to 3026 MPa for PE. The flexural strength of PP has decreased from 31 to 17.5 MPa. For the PE composite, a similar effect is seen for the flexural strength which dropped from 37 to 26.5 MPa.

When looking at the results from the tensile test, a reduction is also visible in the E-modulus and tensile strength in respect to the unreinforced thermoplastics. The PP composite has dropped from 1300 to 854 MPa for the E-modulus and from 33 to 10.5 MPa for the tensile strength. For the PE composite, a decrease from 1200 to 945 MPa

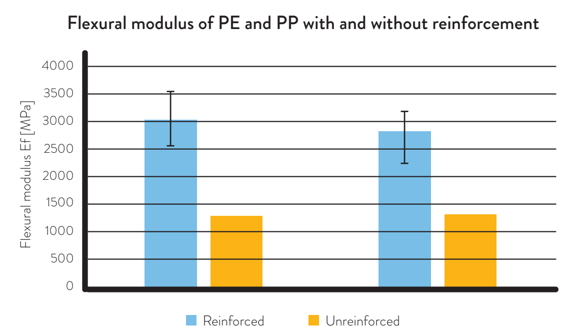


Figure 27 - Flexural modulus of PP and PE

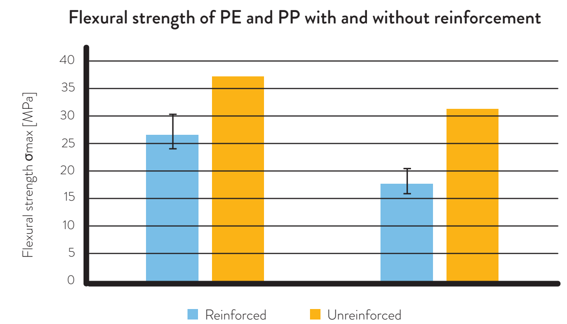


Figure 28 - Flexural strength of PP and PE

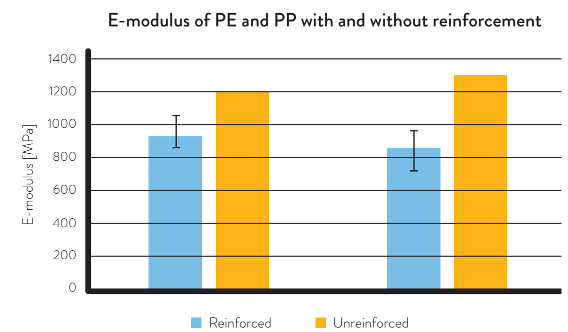


Figure 29 - E-modulus of PP and PE

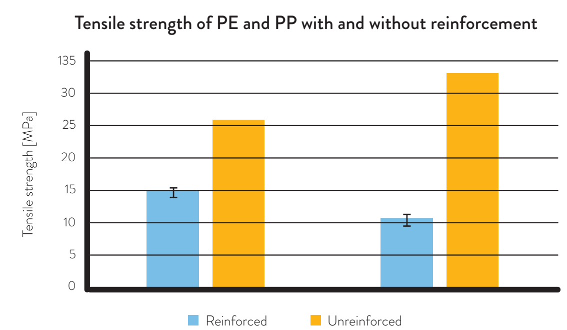


Figure 30 - Tensile strength of PP and PE

occurred for the E-modulus together with a drop from 26 to 14.9 MPa for the tensile strength. When comparing the results to the bending test done by Muovipoli, it can be seen that the flexural strength of the PE composite rises to 36.2 MPa when an addition 40% composite waste is used instead of wood snippets. In contrast to this, the flexural modulus is reducing to 2410 MPa with the use of more composite waste.

Conclusions

The experiments with the profiles have led to multiple findings. However, it is not possible to draw a conclusion that is generally valid for all PE and PP profiles, because only limited samples have been tested and the results are compared to values found in literature instead of similar testing. Therefore, the conclusions have to been handled with caution.

The shredded composite and wood snippets seem to have an influence on the properties of the material. The flexural modulus is improved by the addition, but the tensile strength, flexural strength and E-modulus are negatively influenced. This means that the composite materials are less stiff than unreinforced PP and PE when exposed to axial tension and stiffer for flexural load, but less strong in both situations. The shredded composite and wood snippets are called reinforcement in the tests, but it can be concluded that it is not functioning as such. The variations in the measured properties shows that the materials are slightly heterogeneous. However, the deviations are not significantly higher than in other heterogeneous materials.

As explained in Chapter 4 - Composite Materials, homogeneity and isotropy are important aspects of a composite material. The differences between the flexural and tensile strength and between the flexural and E-modulus measured in the tests show the heterogeneity of the materials. If the material would have been homogeneous, the flexural properties should have been the same as the tensile properties. The isotropic or anisotropic nature of the material is harder to establish. Particle reinforced composites are often isotropic, because the particles have no dominant dimension and therefore no specific direction (Nijhof, 2006). However, the shredded composite in the profiles consists both of glass particles, short fibers and wood snippets of which the orientations are not determined with certainty. This makes it hard to conclude if the material is isotropic. Tensile tests should be done with test specimen perpendicular to the extrusion direction to get a better idea on this.

When plotting the material with CES EduPack 2017, it can be seen that the profiles are located at the bottom of the plastic group (Figure 31). When looking at the location of the profiles in relation to the separated materials within the profiles, they seem to have lower values than expected (Figure 32). Ideally, the composite material should be based in between its content materials, because it represents the combination of their properties. In Appendix 11, charts of other properties and a more elaborate explanation can be found.

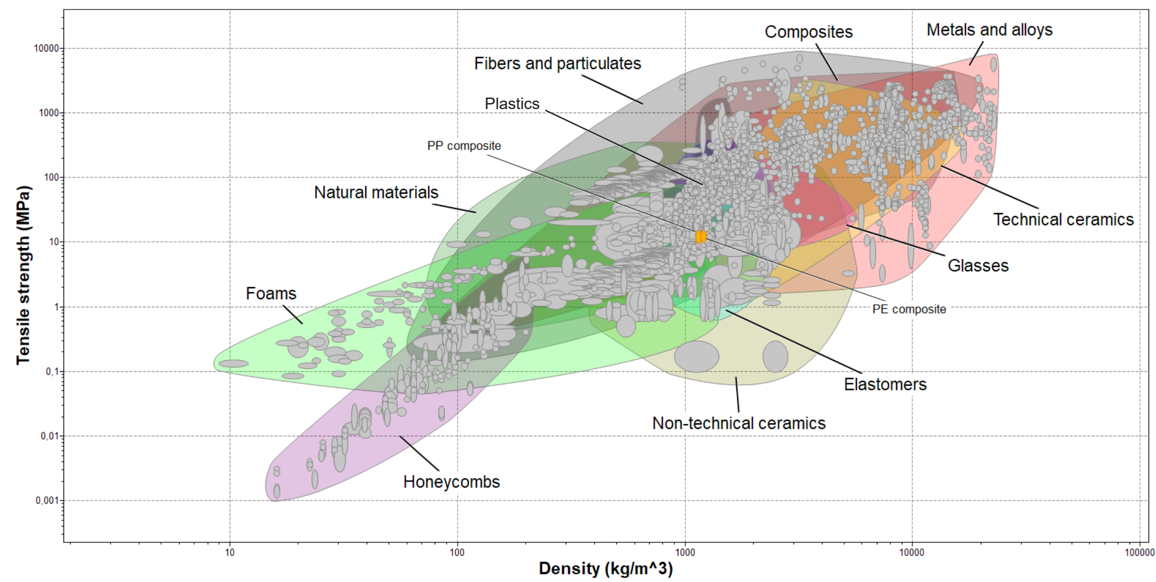


Figure 31 – Tensile strength - density chart

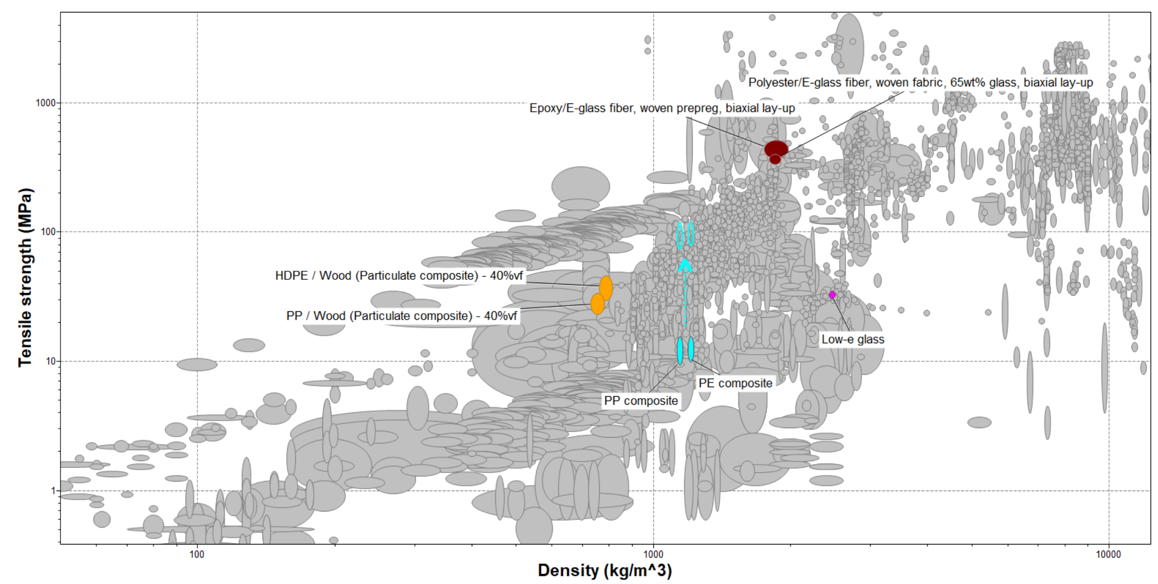


Figure 32 – Tensile strength - density chart for the composite materials, with indication of the expected location of the composite

LITERATURE RESEARCH ON MECHANICAL PROPERTIES

By testing the profiles, one possible composite with the use of shredded wind turbine blades was analyzed on its resulting properties. However, more options for reusing shredded composite are available. To get a broader understanding of the mechanical properties that can be achieved in different reuse scenarios, literature research was done.

When coarse shredded composite is used as replacement for fillers, a reduction in mechanical properties is generally found according to Pickering (2006). This is caused by the weaker bond between the shreds and the new matrix material. The material testing done in this project shows similar results. Palmer, Ghita, Savage and Evans (2009) studied the effect of a partial replacement of virgin glass fiber with coarse and fine shredded composite into a polyester resin including calcium carbonate filler. The results showed that most flexural properties were slightly lower than for the material filled with only virgin glass fibers.

Windesheim has executed research in using coarse fibers from composite material waste with a new polyester or epoxy matrix into wooden OSB (Bouwmeester, 2017). The bending stiffness and strength of the new OSB turned out to be higher than those of wooden OSB. Large fibers for which the optimal orientation is determined promise the highest mechanical properties.

A study on the use of around 10, 20 and 30% of fine, coarse and as received shredded composite into a new polyester matrix shows that the stiffness was larger than pure polyester and became higher as the fiber content raised (Beauson et al., 2016). The strength however decreased in comparison with pure polyester, but did raise together with the fiber content.

The influence of fine and coarse shredded composite in polymer concrete is evaluated by Meira Castro et al. (2014). Their research shows that using up to 12% recyclate as replacement of sand aggregate causes an increase on both flexural and compressive strength. It can be seen that samples with coarse fibers have slightly better mechanical properties compared to these with fine fibers.

In the study of Kouparitsas, Kartalis, Varelidis, Tsenoglou and Papaspyrides (2002) fibers with a length of at least 3.5 mm are reused into PP and compared with similar samples filled with virgin glass fibers. It became clear that not much differences in mechanical properties occurred between the samples.

Conclusion

Different findings are presented that do not give a coherent image of the mechanical properties of reused shredded composite. From the studies, it seems as the shredded composite can still deliver reinforcement to a matrix material. Mainly the stiffness is increased with the use of shreds. Research also shows that coarse recyclate can deliver more reinforcement than fine particles.

OTHER PROPERTIES

Next to the mechanical properties such as density, tensile strength and E-modulus, more properties of glass fiber epoxy/polyester composite could be useful for a new application. Therefore, these materials were evaluated on several properties in Appendix 12 (Granta Design, 2017; Epoxy Floors, 2015; AcoustaFoam, n.d.; The Engineering Toolbox, 2004a; The Engineering Toolbox, 2004b; NetComposites, n.d.). These characteristics of glass fiber, epoxy and polyester were used to give an indication of the characteristics of the shredded composite. This concludes in multiple relevant characteristics of the material, which are shown on the right.

The shredded composite seems to have a lot of similarities with virgin glass fiber. To make sure that the application makes use of characteristics that specifically belong to the shredded composite, it can be useful to highlight the distinctions between these two materials. The largest difference between the materials is the rough and anisotropic appearance of the shreds. Additionally, shredded composite is a little lighter because of the addition of thermosetting resin. These differences could be exploited in the new application.

The defined material properties were also set across potential markets to see in which markets the various properties would be useful (Appendix 13). This shows that the appearance, resistance to water and abrasion and light-weight characteristics of the material have the most potential in different markets. For this reason, these characteristics are focused on in the continuation of the project.

Appearance
The shredded composite has a unique appearance: it is translucent, glistering and has an anisotropic and rough surface.

Electrical isolator
The shredded composite is good in isolator for electrical current.

Chemical resistance
The resistance against chemicals of the material is good.

Water resistance
The material has an excellent resistance to water.

Light-weight
The material is light-weight, especially with regard to its strength.

Abrasive resistance
The material is abrasive resistant.

Chapter 10
Evaluation

The aim for this project is finding a valuable application for the shredded fiber reinforced thermoset polymer composites. With the evaluation from literature and the results from the analysis, a suitable direction for the continuation of the project are selected.

Currently several companies are reusing the shreds, however a fee is still required to dispose the blades. This means that the current applications are not valuable enough to give the material positive financial value. This is expected to be caused by the following aspects:

- The shreds negatively influence the properties of the new material (Meira Castro et al., 2014). This is also visible in the evaluation of the mechanical properties of the profiles.
- The application is not cost-efficient when the shreds function as filler or reinforcement within the material, because they cannot compete with filler material such as calcium carbonate or reinforcement such as chopped fiber glass (Job, 2013; Meira Castro et al., 2014).

Bouwmeester (2017) is also describing the case of ERCOM which tried to use composite waste car components into new car components. This project had to be stopped because it was financially not profitable. Bouwmeester concludes that we can learn from this project that the material should have a clear added value in the end product, which makes the choice of the product crucial.

Next to these first evaluations found in literature, the results from the analysis conclude in a list of strengths and weaknesses of the material and opportunities and threats for a valuable application. This list can be found on the next page. The aspects on the list can each lead to a type of value, which is indicated with a dot.

CONCLUSION

When taking the list of strengths, weaknesses, opportunities and threats into consideration, the most potential is seen in creating an application that achieves functional or sustainable value. Some other value types, such as economic and emotional, have larger threats and less opportunities and are therefore less favorable to focus on when designing. However, this does not mean that other value types cannot be achieved or should not be considered throughout the project.

Next to the value type, the function of the shredded composite in the new material is also of great importance for the continuation of the project. When evaluating the list with results, the focus will be on giving the shredded composite a function in the end product that fits its other material properties, apart from functioning as reinforcement or filler. When the shredded composite would only be used as reinforcement or filler, it would be difficult to compete with calcium carbonate and virgin glass fiber. The defined material characteristics from Chapter 9 - Material Properties, namely appearance, resistance to water and abrasion and light-weight, will therefore be focused on when finding an application for the material.

STRENGTHS

- Sustainable due to reusing waste material
- Larger fibers can be used as reinforcement
- Water resistant
- Electrical insulation
- Appearance: Glistering, translucent, fibrous and rough surface
- Strong and light-weight
- Abrasive resistance
- Chemical resistance
- Low, even negative, costs
- Origin of the material appeals to the imagination

WEAKNESSES

- Differences in the composition of the supplied shreds, which can have influence on its properties.
- Prediction of the mechanical properties is hard.
- The material supply includes impurities.
- The material can negatively influence the mechanical properties.

OPPORTUNITIES

- Sustainability is of growing important in all industries.
- Making the material visible and using this instead of trying to hide it. If it is hidden, it could be every material so it does not provide added value.
- Products that do not have to carry lot of load.
- Replacement of a more expensive material.
- Products that have a link with the origin of the recycled material can create more value.

THREATS

- Virgin chopped fibers are cheap.
- Filler material such as calcium carbonate is cheap.
- Lots of waste material already used in infrastructure and building industry.
- Niche markets might not meet the amount of supplied material.

Emotional value

Functional value

Economic value

Sustainable value

Symbolic value

Conceptualization

With the determined focus, a design vision is written. This vision is used as a guideline for generating and selecting ideas, together with the requirements and wishes that were determined in this project. Material experiments were done to function as inspiration for the ideation. To generate a full set of ideas, several brainstorm methods were executed. The resulting ideas were evaluated and eventually one idea was selected for the continuation of this project.

The above described steps are discussed in this section.

Chapter 11
Design Vision

To give direction to the design, a design vision is drafted. This vision is used, together with the requirements and wishes explained in the next chapter, to select appropriate concepts that achieve value for the shredded composite.

The vision consists of two elements. The first element is about the function of the shredded composite in the new application. For the material to have real value, it should be a helpful addition to the application instead of a disturbance. This is something that should be aimed for in the design. The material will be a helpful addition if at least one of its characteristics is usefully deployed in the application.

The second element of the vision is about the visibility of the shredded composite in the new application. Meetings with experts and the market research show that a lot of recycled material is used in the infrastructure and building sector. In this case it is often used as a filler material and does not necessarily provide a functional addition to the application. The recycled material is sometimes placed in between two layers of virgin material to be sure that the outside appearance of the product is not affected by the recyclate. This causes that the value of the recycled material is rather low and it gives the impression that it should be hidden.

For recycled material to get a higher value, it should not be hidden but the aesthetic value of the material should be used. When these characteristics of the recyclate are used, it cannot just be replaced by any other waste material. Also, with the current exhaustion of resources, recycling should become more and more the standard for waste management. This means that it will be used increasingly in the future in our products and people should learn to appreciate imperfections occurring in recycled material. For this reason, it is aimed in the design of this project that the shredded composite is visible and that its visibility provides added value to the design.

In Figure 33, an impression is given of how the recycled material can be made visible without being a disturbance (D'Werk Plaats, 2018; Pinterest, n.d.; Better Future Factory, 2016; Preat, 2012; Pure Joy, n.d.; Mohawk Group, n.d.; Super Local, n.d.).

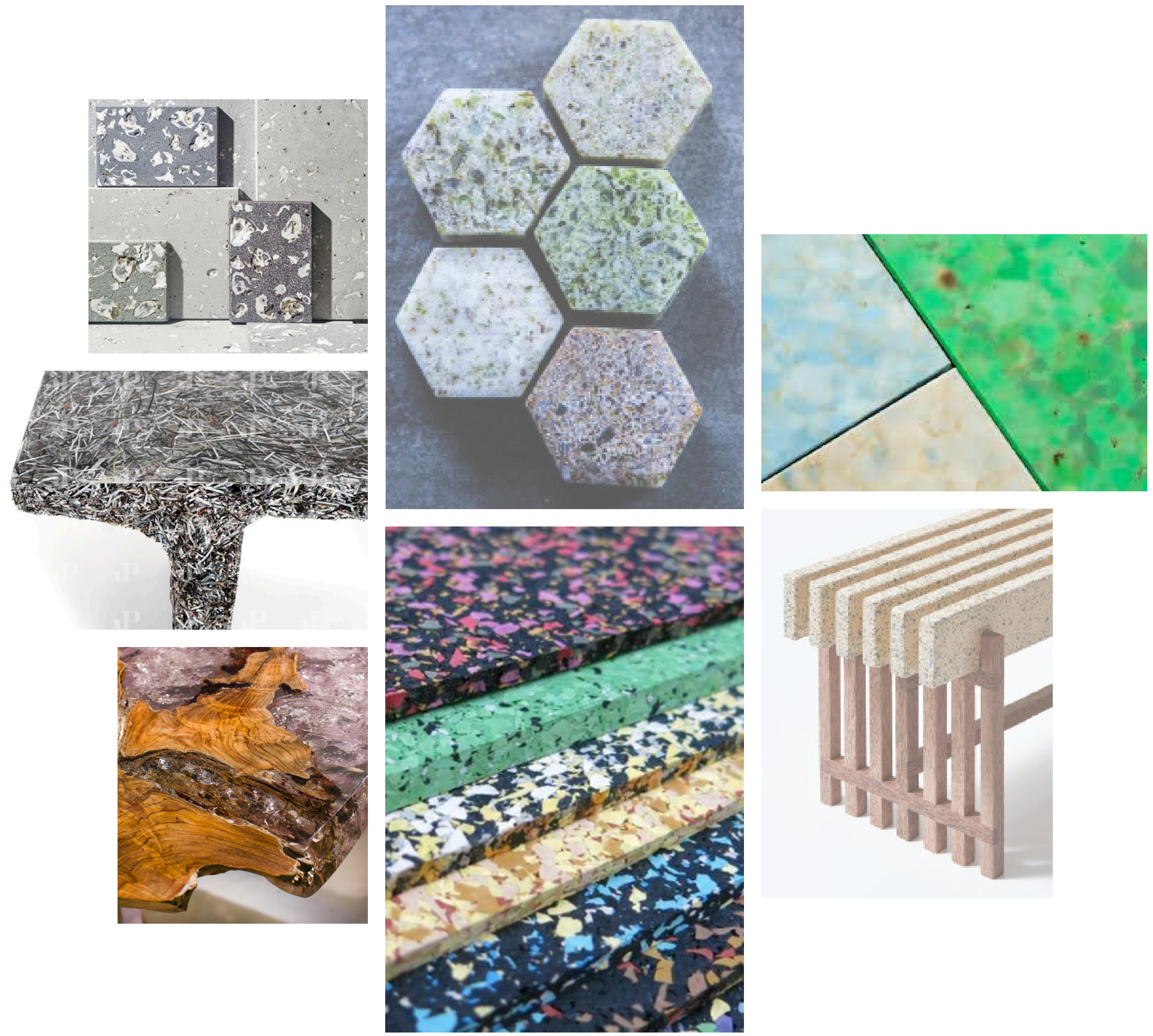


Figure 33 - Impression of aesthetic use recycled material

Chapter 12

Requirements and Wishes

The design of the new application should meet several requirements, which were determined with the help of the executed analysis. In addition to this, multiple wishes for the design were formulated which can be used to score the ideas and concepts on their relevance. The most important ones of these requirements and wishes are described in this chapter. The complete list can be reviewed in Appendix 14.

REQUIREMENTS

As concluded from the analysis, the design should evoke functional and sustainable value for the user. The shredded composite should have a role in achieving this value and should therefore be a useful addition to the design. The specific characteristics of the shreds determined in Chapter 9 - Material Properties, namely water and abrasive resistant, light-weight and appearance, can be used to achieve this. By doing this, it is ensured that the material is not only used as filler or reinforcement.

Another important topic within the requirements is the safety concerning the use of the shredded composite. The material can be irritating for the human skin and should also not end up in nature, because it is not biodegradable. This means that the shredded composite should not undesirably detach for the product. Selecting a matrix material that does not fall apart is therefore crucial.

The last most relevant requirement is about the end-of-life situation of the newly designed product. To facilitate a circular life cycle for the product, it should be possible to recycle it after its use. This is therefore an important criterion for the matrix material that is selected. In addition to this, the end-of-life of the product should also be controllable to make sure that the product will end up in the right place to actually be recycled afterwards.

WISHES

It is favorable for the design if all value types would be achieved for the user. Although this is unlikely, it is something to strive for. Another wish for the design is that the shredded composite is substituting an endangered, expensive, less good or unsustainable material resource. If this is the case, the product will positively change with the addition of the shredded composite and will increase the material's value.

It is also favorable to use the shredded composite as large as possible in the design. When the shreds are large, their characteristics can be used in the most optimal way and the most value can still be achieved.

Several wishes are formulated concerning the market in which the new application will be located. In a conversation with an expert in recycling from the recycling company ARN, an example came to the table in which the buyer of the recycled product was also the supplier of the recyclate. This is favorable because this company has a responsibility towards recycling the material and has therefore an incentive to buy the products made of their recycled material. For this reason, it can be beneficial if a similar construction can be found for the shredded composite from wind turbine blades.

Another wish regarding the market is a need for sustainable alternatives. If this is the case, a higher value will be attached to using recycled resources instead of virgin ones. An example of a market that pays extra attention to sustainable alternatives is the government. Additionally, the size of the market should fit the amount and variation in the supply of the composite material. Lastly, the product can get a higher value if a link between the end product and the origin of the composite material exists, because this has an influence on the symbolic value of the product.

Chapter 13

Experimenting

Eventually the shredded composite should be added to or covered with a new material in order to reuse them in a new product. Some experiments were done with the help of Luisa Jacobse, a graduate of the Design Academy Eindhoven with knowledge of material experiments. These material samples were created to get a feeling for the effect of the shredded composite within a new material and to deliver inspiration for the idea generation of a suitable application.

Samples were created of the shredded composite in combination with several matrix materials: concrete, thermosetting resin and latex. In addition to this, the recyclate was covered and stuck between flexible plastic sheets which were melted together with heat. Images of the several samples are visible in this chapter, together with a short description of their content.

From these experiments several observations can be obtained. First, the shredded composite is translucent which provides an interesting effect when the matrix material is transparent. The amount of light that is allowed to pass differs throughout these samples, which can be beneficially used in the design. Secondly, it was visible that in the concrete samples, the shredded composite only shows when it is located at the top of the sample. The outer surfaces of the samples that were covered by the mold are smooth and do not show the recyclate. Thirdly, the shredded composite provides an anisotropic character to the flexible latex. This means that the axial deformation in the direction of shreds becomes limited. This effect also occurs when the shredded composite is stuck between the layers of plastic.

***Latex** with random oriented shredded composite*

***Latex** with vertical oriented shredded composite*

*Shredded composite **covered in plastic***

***Resin** with random oriented shredded composite*

***Resin** with vertical & horizontal oriented shredded composite*

***Resin** with random oriented shredded composite and pigment*

*Shredded composite in between **layers of plastic***

***Concrete** with random oriented shredded composite*

***Concrete tile** with particle sized shredded composite*

Chapter 14
Ideation

Ideas were generated with the results of the analysis kept in mind. To achieve functional and sustainable value with the new application, ideas were developed with a focus on the specific characteristics of the shredded composite material. Several ideation techniques were used to come up with a full set of valuable ideas. In this chapter, the different activities are explained.

With the defined characteristics, namely water and abrasive resistant, light-weight and appearance, as a starting point, suitable applications were generated. In order to do so, one characteristic was focused on at a time and associations were made with current applications in which this characteristic would be helpful. This follows the line of thinking described by Landru, Bréchet and Asbhy (2002) in which they explain methods for finding applications for materials. One of these methods is called "Optimised Matching of Design Requirements", in which the material properties are compared with requirements of certain applications to find matches. This corresponds to the frame of mind with which applications were found in relation to the characteristics of the shredded composite. For example, focusing on abrasive resistant resulted in finding applications such as grip on boat decks and floors.

A second method they describe, "Parasitical Substitution", compares the material properties

with those of similar materials in order to see if the new material can replace and excel the current material used in an application. This way of thinking was applied to find possibilities for substituting less sustainable materials and formulating applications accordingly. Tropical hardwood is an example used with this method to find applications in which shredded composite could replace this material. This resulted in applications such as railway sleepers and park benches.

In addition to this, a creative session was held to generate ideas with a larger group of people (Figure 34). In this group, students and graduates of different backgrounds were present. This was done to have a broad spectrum of angles of approach from the participants and to come up with a wide range of ideas. The session was led by a student, Suzanne van Beek, specializing in creative facilitation. The goal of the session was to generate many ideas which could function as inspiration for the project. For this reason, divergent topics were used to brainstorm on using the Brainwriting and How-tos ideation methods (Van Boeijen, Daalhuizen, Zijlstra and Van Der Schoor, 2013). The material characteristics and material samples made were used as a starting point for these brainstorms. After generating ideas, they were classified based on the C-box method (Van Boeijen, Daalhuizen, Zijlstra and Van Der Schoor, 2013) in which they are located on their level of feasibility and innovativeness. From this classification, the participants could select their most valuable ideas (Figure 35). In groups of two, they then combined these ideas into a concept which was the ending point of the session. A more elaborate description of the creative session can be found in Appendix 15.

The most relevant ideas resulting from these methods can be found in Appendix 16. These ideas were evaluated afterwards to select the most valuable ideas. This process is explained in the next chapter.

Figure 34 - Flower association in creative session

Figure 35 - Selecting the most valuable ideas in creative session

Chapter 15

Idea Selection

In order to select the most promising ideas, the matrix material to which the shredded composite is added was first determined. This desicion was used to eliminate the ideas that were not suitable for this matrix material. Secondly, the vision and requirements and wishes were used to select the most valuable ideas. The main decisions in this process (Figure 36) are described in this chapter.

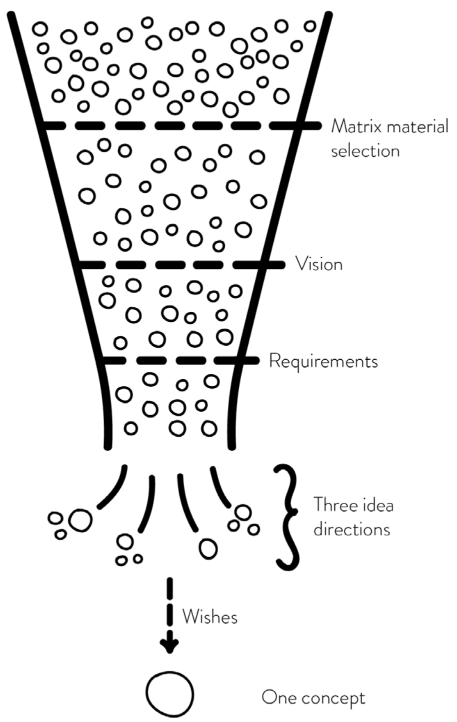


Figure 36 - Visualization of the selection process

SELECTING THE MATRIX MATERIAL

The matrix material to which the shredded composite is added needs to be determined, it has a large impact on the characteristics of the final material and the role that the shredded composite will play in this.

A brainstorm and literature research were done to determine a range of possible matrix materials. The most promising materials were selected on three requirements:

1. The material does not disintegrate undesirably in the following use conditions:
   - Contact with water
   - Under forces occurring with normal use
2. The material is recyclable without the need of additional material.
3. The material is producible on a large scale when including shredded composite.

These requirements can be found back in the program of requirements and wishes in the "General – Matrix material" subsection in Appendix 14 and a more elaborate selection explanation is given in Appendix 17. The matrix materials that were included in the evaluation are: thermoset, clay, rubber, concrete, chalk, alginate and thermoplastic. Lastly, the option of wrapping the shredded composite with a flexible fabric was also evaluated. Glass and metal were not taken into consideration, but the high temperatures at which these materials need to be processed make them unsuitable to contain shredded composite. The thermoset will burn off the composite and the glass fiber will melt into the matrix material, which means the shredded composite will not maintain its current form.

The resulting evaluation can be found in Table 3. It is visible that a thermoplastic matrix is best suitable based on these requirements. This is caused by the high recyclability of the material, which means that the material can easily be heated and transformed in a new shape. For most other materials, some amount of new matrix material is needed to be able to recycle it. Thermoplastics also protects the shredded composite from ending up in the environment or causing health problems, because they do not easily disintegrate.

EVALUATING THE IDEAS

After the matrix material was determined, the first selection of ideas was executed by rejecting all ideas that were not suitable for a thermoplastic matrix material. After this, the remaining ideas were put next to the criteria resulting from the vision and rejected if one was not met. These criteria were (Appendix 14, subsection "General – Vision"):

- The product benefits from the specific characteristics of the shredded composite, namely water and abrasive resistant, light-weight and appearance.
- The shredded composite is visible in the product.

	Thermoset	*Clay*	*Concrete*	*Rubber*	*Chalk*	*Alginate*	*Thermo-plastic*	*Wrapping*
1. Material does not disintegrate undesirably	✓	×	✓	✓	×	×	✓	×
2. Recyclable without additional material	×	×	×	×	×	×	✓	✓
3. Producibility with SC on large scale	✓	×	✓	✓	✓	✓	✓	✓

Table 3 - Selection of matrix material

The reduced amount of ideas were once more evaluated with the help of the remaining general requirements from Appendix 14, excluding the vision and matrix material specific requirements. If an idea did not meet a requirement, it was automatically rejected. It became visible that all ideas fulfilled the requirement on sustainable value, because the same material is used as a starting point. The selection resulted in ten valuable ideas for the shredded composite (Figure 37).

These ten ideas were scored on a scale of 1 to 5 on the wishes from the program of requirements and wishes (Appendix 14 and 18). In Table 4, the scores are visible. When evaluating the ideas, four idea directions became visible through grouping the ideas:

Idea direction 1: replacement of wood
The first direction is about creating a beam from the shredded composite which can replace a wooden beam. With this beam multiple constructions can be build such as a market stall, park bench and beach house.

Idea direction 2: addition to plastic
The second direction is using the shredded composite within a product that is normally already made of plastic, for example a charging point for electrical cars, train interior and the housing of a smart thermostat. The addition of the shredded composite creates a valuable link with the origin of the material.

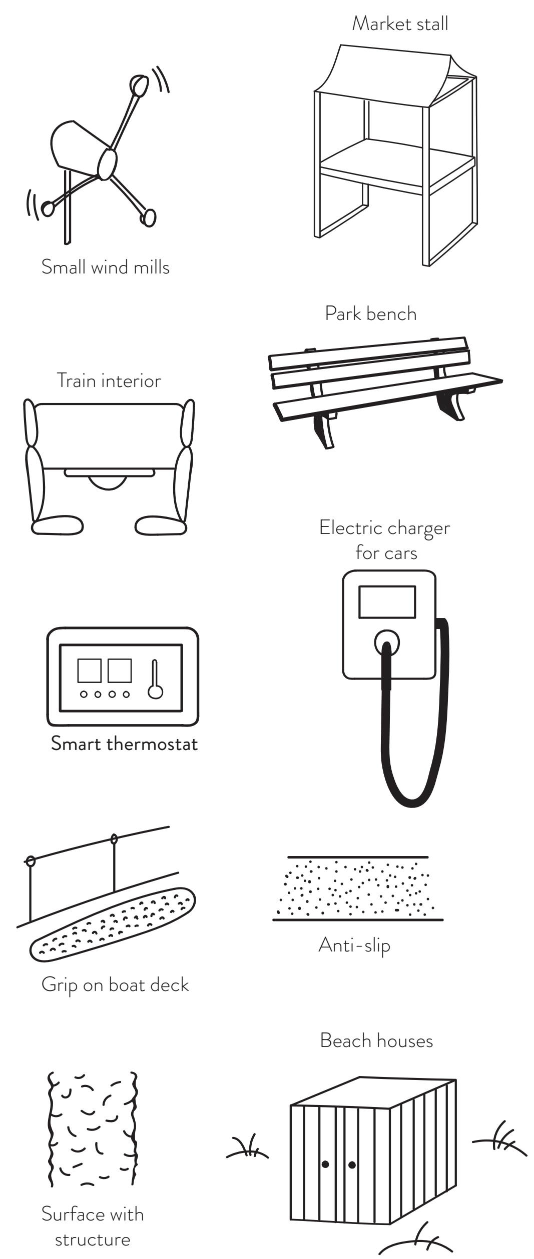


Figure 37 - Ten most valuable ideas

Idea direction 3: small windmills
The third idea direction is focusing on creating a small windmill from the shredded composite that can be used locally for producing energy.

Idea direction 4: delivering texture
The last direction is using the structure of the shredded composite to provide grip or to change the surface texture of a material.

	Idea direction 1			**Idea direction 2**			**Idea direction 3**	**Idea direction 4**		
	Market stall	*Beach houses*	*Park bench*	*Train interior*	*Smart thermostat*	*Charging point electrical car*	*Small wind mills*	*Grip on boat deck*	*Surface with structure*	*Anti-slip*
Functional value	2	3	2	2	2	3	2	3	2	3
Economic value	1	1	3	2	2	2	3	2	2	2
Sustainable value	5	4	5	5	4	4	4	3	3	3
Symbolic value	2	3	1	3	3	5	4	1	1	1
Emotional value	1	3	3	2	2	1	1	1	3	1
Substituting material	2	2	2	3	3	3	4	2	2	2
Quantity	3	3	2	4	2	4	3	3	4	4
Size shredded composite	5	5	5	3	2	3	3	2	2	2
Market	1	1	1	1	5	5	3	2	1	1
Sustainable market	2	3	5	5	5	5	5	2	3	3
Link with origin	1	3	2	3	5	5	5	3	1	1
Total	**25**	**31**	**31**	**33**	**35**	**40**	**37**	**23**	**24**	**24**

Table 4 - Evaluation of ten most valuable ideas

CONCLUSION

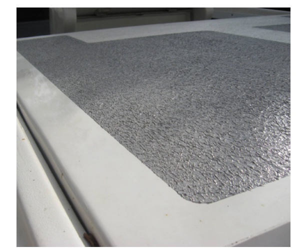
From the evaluation of the ideas, it is visible that the second and third idea directions are the most promising. However, while sharing these directions with the supervisory team the conclusion was drawn that the small wind mills have to carry a large amount of load. The shredded composite is not be able to facilitate this. Therefore, after reconsideration this idea direction is rejected based on the requirement that states that the product should not be carrying a significant load. This means that the second idea direction is the most valuable.

In the second idea direction, the shredded composite is used within a product which will evoke a link with the origin of the material by using its appearance characteristics. This enlarges the symbolic value that is attached to the product. Within this direction the focus will be on designing a charging point for electrical cars, because this idea scored highest on the wishes. By designing this product, an approach is shown for producing a thermoplastic housing including shredded composite which opens a broad range of possibilities for other design projects.

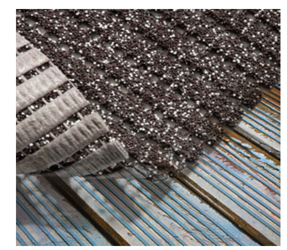
IDEA DIRECTION 1

IDEA DIRECTION 2

IDEA DIRECTION 3



IDEA DIRECTION 4



Embodiment

The electrical car charger is further elaborated on in this section. Firstly, product research was done to get an idea on the chargers that are currently sold. Secondly, the production method and thermoplastic material were determined. This resulted in design guidelines that were used to shape the design. Lastly, the charger is developed focusing on the shape, function and preparation of the shredded composite, production method, recycling of the product and business aspect of the material.

Chapter 16

Product Research

To find out what kinds of electrical car chargers are on the market currently and what material they are made of, a short market research was executed. In this research, chargers of different brands were listed together with their location of use, material, price and dimensions (Appendix 19). The relevant results from the analysis will be explained in this chapter.

Within the electrical car chargers on the market, three different types of chargers were found. These types are associated with their place of use, namely at home, at work or in public spaces (Figure 38). It became clear that the chargers used at home are smaller and subtler in comparison with the robust public chargers. The work chargers often have two outputs just as the public chargers, but their appearance is often closer to that of home chargers. The chargers used in parking garages can be both work or public chargers and are therefore not defined as a separate type.

When looking at the material used in the different types of chargers, it can be concluded that home and work chargers are more often made of a thermoplastic material, namely polycarbonate (PC) or a combination of PC and acrylonitrile butadiene styrene (ABS). The chargers that are meant for public spaces are produced from stainless steel. This is probably done because the public charger have a higher chance to be exposed to large forces and unintended use. Using thermoplastics in this type of charger will not be sufficient because of the lower mechanical properties. For this reason, the focus will be on designing a charger for home or work use in this project.

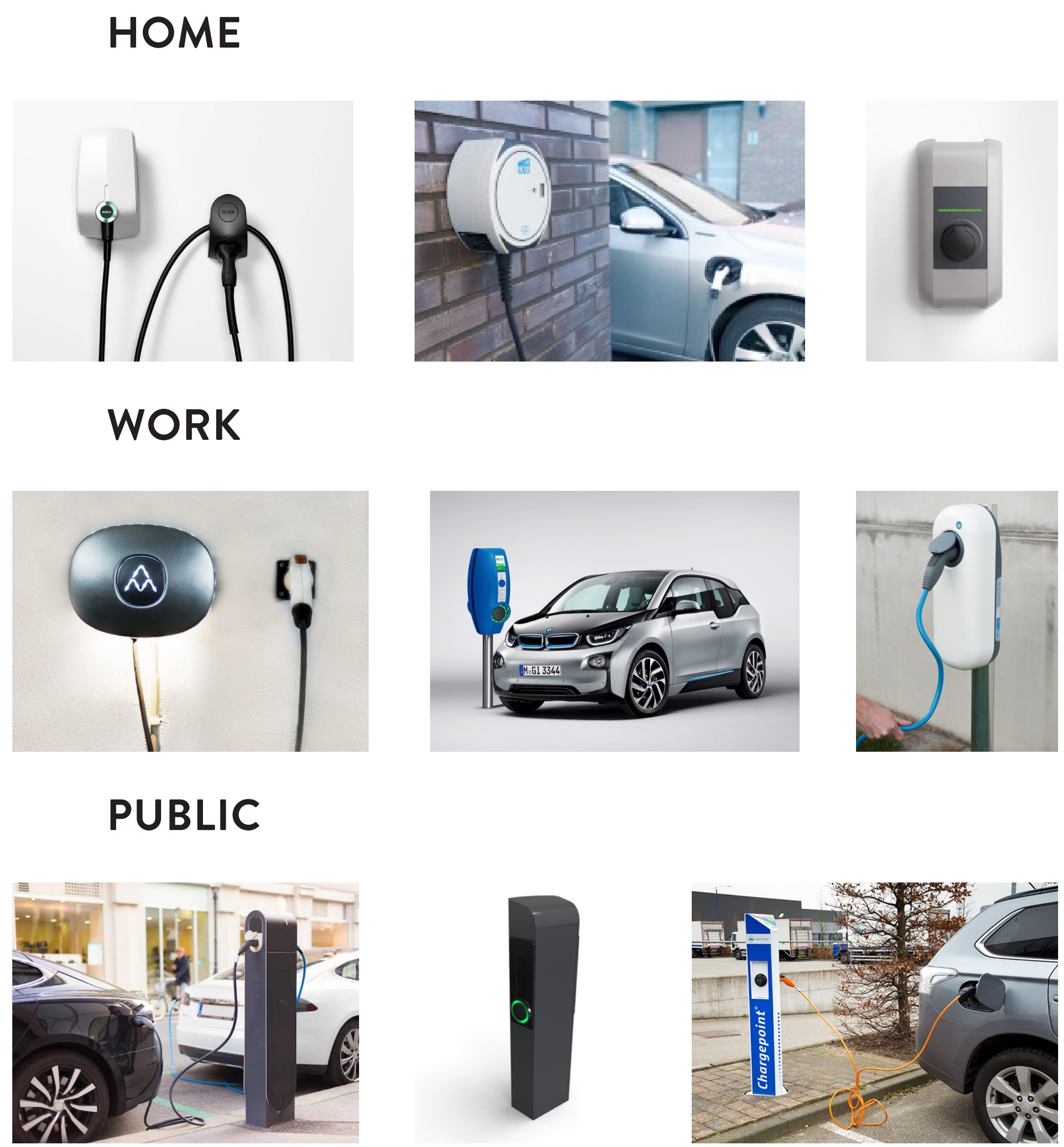


Figure 38 - Home, work and public chargers

Chapter 17
Production Method

The way of producing the thermoplastic composite including shredded wind turbine blades is a crucial aspect of the design of the electric car charger. The shape requirements of the selected production method will have a leading role on the shape of the electric car charger. In this chapter, different methods will be evaluated and the most suitable one for a fiber length of approximately 3 to 5 cm will be selected. This fiber length is desirable to make the shredded composite clearly visible in the material.

SELECTION PRODUCTION METHOD

One important aspect of molding thermoplastic composites is the length of the reinforcement (Brent Strong, 2008). With short fibers, traditional thermoplastic production methods can often be used to produce the thermoplastic composite. However, with longer fibers the methods sometimes require adjustments or unique methods need to be used. The production techniques that are used for thermoset composites are often not applicable for thermoplastics. Thermoset composites are processed by wetting out the fibers by for example transferring the thermoset resin through a fiber mat. Due to the higher viscosity of thermoplastics and the loose shredded composite as used in the electrical car charger, this is not possible because the material would push the fibers away.

Extrusion, injection molding and thermoforming are examples of traditional production methods for unreinforced thermoplastics. Extrusion and injection molding can be used for short fiber reinforced plastics (about 0.1 to 0.6 cm) (Brent Strong, 2008). Longer fibers will not fit the ejection nozzle or will be degraded by the screw which is included in the process. This screw is necessary to shear the heated plastic and lower the viscosity before injecting. When looking at the extrusion profiles, the fiber length within the profiles is also limited. This means that using this production method will result in too short fibers. Also the use of thermoforming for reinforced thermoplastics can be complicated. This is caused by the reduction in elongation that occurs by the presence of the fibers. However, if the fibers are a few centimeters in length and the volume fraction is not too high, this method could be considered and experimented with.

Another thermoplastic production method is compression molding, in which the material is shaped in a mold under pressure. A downside of this method is that melting the plastic and mixing this with the shredded composite is difficult. Usually, a screw would be used to facilitate this mixing procedure. However, this is not possible because of the degradation in fiber size that will occur. A similar process that uses matched die molds has more potential for shaping thermoplastic composites due to the use of thermoplastic sheets and will be explained below.

Stretch forming, flow forming, flexible die forming and hydroforming all make use of matched die molds (Åström, 1997; Brent Strong, 2008). The processes start with sheets of thermoplastics in which the fibers are already processed. These sheets are heated in an oven after which they will be placed in a cold mold that is closed to shape the sheets. In stretch forming, the sheet is tightly clamped while being pressed to make sure that the fibers stay in their determined place. With flow forming, the sheet is less tightly or not clamped so movement of the fibers is tolerated. Flexible molds can also be used in this production process, which is called flexible die forming. With hydroforming, this flexible die is backed with a hydraulic reservoir. These matched die molds methods seem to be sufficient for sheets with the shredded composite.

It can be concluded that matched die molding or thermoforming are production methods that could be suitable for this project. However, for these techniques thermoplastic sheets including the shredded composite should first be produced. The production of these sheets requires melting plastic sheets and pressing shredded composite between or on them with a heated press. The difference between the matched die molding and thermoforming lies in the number of molds that is used. For thermoforming, one mold is used over which the material is shaped. Due to this, only the out- or inside surface of the product can be influenced. With matched die molding, both surfaces will be in contact with a mold and can therefore be controlled.

For the continuation of the project thermoforming, specifically vacuum forming, will be selected as the production method to be used (Figure 39). This production method has lower investment costs because only one mold is necessary in the process. For the product, the inner surface will also be of less importance which makes it sufficient to use only one mold in the production process.

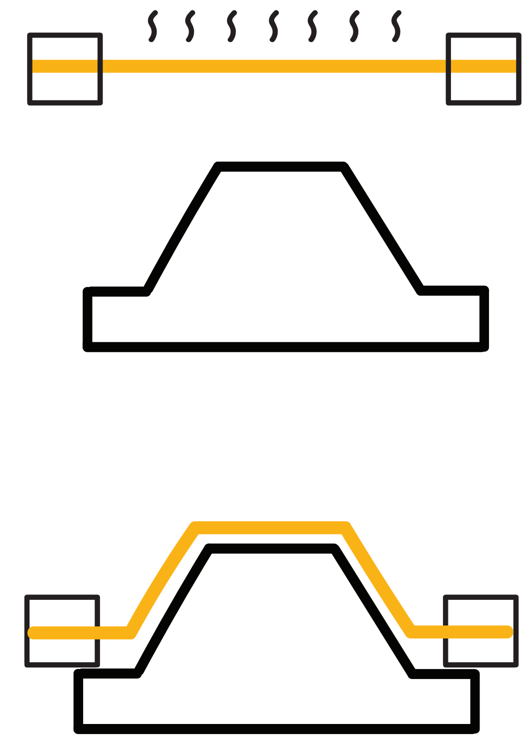


Figure 39 - Thermoforming process

TESTING PRODUCTION METHOD

To validate the selected production method, multiple tests was done. First, sample sheets were produced with various methods to identify the best technique for this. Secondly, two sheets were thermoformed to analyze the challenges that occur during this process. Elaborate information on and pictures of all samples can be found in Appendix 20.

Producing the sheet

Sheets were produced with a variety of equipment, namely an oven, t-shirt press and heated press. Within every test, thermoplastic polyethylene terephthalate glycol-modified (PETG) sheets were heated with or without shredded composite between the layers. During these tests, it was aimed to produce a sheet with as little air bubbles and impurities as possible.

In the oven test, sheets were heated to a minimum of 145 ˚C in a simple metal mold. A weight of 8.4 kg was placed on the heated sheets during or after heating. The resulting sheets contained many air bubbles and had a rough surface due to the metal mold (Figure 40). From the tests it could be concluded that:

- 160 ˚C is sufficient for melting the sheets,
- More pressure might be necessary to create a sheet without air bubbles,
- The surface of the mold has a large influence on the appearance of the sheets.

After this, a t-shirt press was used to develop several sheets. The samples were heated to 160 ˚C after which the press was closed and pressure was applied. The resulting sheets had a reasonable smooth surface, but air bubbles were found between the layers of plastic (Figure 41). From the test it was concluded that:

- Placing the sheets between baking paper causes the material to become translucent. A smooth material such as metal will make the sheets transparent,
- Air bubbles emerge between the sheets around large fibers,
- When one side of the press is less rigid than the other, the fibers will stick out on this side. This will cause the surface to be less smooth on this side.

Lastly, a heated press of the brand Fontijne Presses was used to produce sheets under a pressure of 30 kN. The press was first heated to 160 ˚C before the pressure was applied on the sheets. Afterwards, the press was cooled down to 60 ˚C before releasing the pressure and removing the sheets. The resulting sheets had a smooth surface and only little air bubbles were found within the material (Figure 42). From these samples it was concluded that:

- Using dried shredded composite gives no different result than using undried shreds,
- When a sufficient amount of pressure is applied, a smooth sheet can be created with only little air bubbles,
- The press has several scratches on the contact sheets. Smooth metal molds should be used to create a smooth surface,
- The thickness of the sheet is decreased by the applied pressure. When a specific thickness should be obtained, a mold should be used.

To fully remove the air bubbles from the material, a good combination should be found between the temperature and the applied pressure. However, this study is not included because it is not in the scope of the project.

Thermoforming the sheet

A sheet from the oven test was vacuum formed to test the challenges that might occur during this process. The result showed that vacuum forming

is definitely possible with the material (Figure 43). However, some shreds were not flexible enough to bend according to the molds. This caused impurities in the final part.

Figure 40 (top) - Sample from oven test
Figure 41 - Sample from t-shirt press test
Figure 42 (bottom) - Sample from heated press test


Figure 43 - Vacuum formed sample

Chapter 18

Thermoplastic Selection

After deciding which production method will be used, it is also possible to further define which type of thermoplastic will be applied. To facilitate this selection, several requirements were determined on which the different plastics are evaluated with the help of CES EduPack (2017) Level 2. In this chapter, the selection process and results will be explained.

As a starting point, the requirements for the matrix material (see Appendix 14, subsection "Final Design – Matrix material") were determined. First of all, the matrix material should be recyclable to facilitate a sustainable end-of-life situation for the product. Secondly, the product is used outside the user's house which means that the product should be resistant against UV radiation and water and should be able to function between temperatures of -50 and 50 ˚C. Between this temperature range, the product will be suitable in a large number of countries (Meteolink, n.d.). Thirdly, the material should be transparent or translucent to make sure the shredded composite will be visible. Lastly, the moldability of the material should be high to make production process possible.

Next to these requirements, the adhesion of the shredded composite to the thermoplastic is a crucial aspect in the material selection. If the shreds are not adhering well to the thermoplastic, the material will easily break, even if the plastic has good mechanical properties. For this reason, the adhesion is more important than the mechanical properties of the plastic. The level of adhesion is influenced by the way that the two materials interact with each other. The polarity of a material is an important aspect of this interaction.

If a material is polar, it means that it has a negative or positive charge (Plastic Notes, n.d.). In comparison to this, a material is non-polar if it has no charge. This charge is caused by a carbonyl or hydroxyl group present in the structure of the plastic (Khan Academy, n.d.). Materials that are polar can form strong bonds with other polar materials by the polar attraction (Mereco, n.d.).

Epoxy and polyester, that are covering the shreds, are polar materials so it is desirable that the thermoplastic is also polar to form a strong bond between the materials.

To find out about the polarity of the thermoplastics, the plastics that met the other requirements were evaluated on their structure. If a carbonyl or hydroxyl group is present within the plastic, it can be assumed that the plastic is polar and will therefore maintain a strong bond with the shreds. The materials that met this and the previous explained requirements are: Polyamides (PA), Polycarbonate (PC), Polyethylene Terephthalate (PET), Polyhydroxyalkanoates (PHA) and Polymethyl Methacrylate (PMMA).

These plastics were evaluated on a closer level to see which plastic would be the most appropriate for the application. For this, the wishes listed in Appendix 14 subsection "Final Design – Matrix material" were used. These wishes were determined considering the use context of the product, which makes it for example important to withstand normal use and impact forces and contact with certain fluids and greases. In Appendix 21, the values for relevant properties of the plastics can be found such as yield strength, flammability, machinability and resistance to diesel, gasoline and lubricating oil. By identifying the values that are not or less sufficient for the application, the most appropriate plastics were identified. This results in the plastics PET, PA and PC as the most suitable types. PET has the most beneficial characteristics and therefore this material will be primarily used in the design (Figure 44 (Plasticoop (n.d.)).

When an opaque plastic is required, other plastics could also be used. Several characteristics of the material, such as the polarity and the UV resistance, can be influenced with the help of additives.
This means that the material is not necessarily insufficient if it falls short on these characteristics.

The thermoplastic resource that is used in the design is preferred to be recycled instead of virgin.

Figure 44 - PET sheets

Chapter 19

Design Guidelines

The production method and the shredded composite gives several restrictions to the design of the electrical car charger. In this chapter, these restrictions will be explained to set up guidelines which can be used in the final design. In addition to this, the minimal dimensions of the charger will be determined.

SHAPE RESTRICTIONS

When vacuum forming, several requirements should be met. In addition to this, the shreds have a great influence on the shape restrictions as well.

Vacuum forming requires a male or female mold (Figure 45). The type of mold that is used will determine which surface of the product will be shaped. This means that, when a female mold is used, higher details can be achieved on the outside surface. However, this process is usually more expensive because a more advanced mold should be developed (Universal Plastics, 2014). The minimal radius that can be used on a male mold is 0.8 mm (Universal Plastics, 2014). For a female mold this value of 0.4 mm. In addition to this, the shape should have slightly tapered walls to facilitate easy demolding of the product. Negative drafts, also named undercuts, are only possible in thin parts (under 1 mm thickness) and only with small dimensions (Universal Plastics, 2014). In this case, the product can be released from the mold by the flexibility in the material. To facilitate larger undercuts, moveable components should be added to the mold.

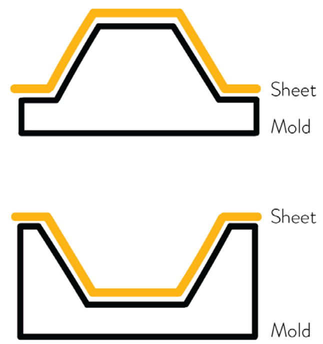


Figure 45 - Male and female mold for vacuum forming

Another aspect that should be kept in mind with vacuum forming is the thickness of the material. By drawing the material onto the mold, the thickness decreases compared to the original sheet. The depth of the draw in the shape has influence on the amount of reduction in the wall thickness. When the shape and the aimed wall thickness are known, the required thickness of the original sheet can be determined. A second important aspect that should be kept in mind is about the shape of the mold. It is important that the mold is at least 1 cm higher than the intended shape. This will make it easier to process the shaped part afterwards.

Next to the requirements given by the production method, the shredded composite inside the thermoplastic sheets also have a large influence on the possibilities when shaping. The flexibility of the shreds is actually determining the minimum angle that can be present in the shape. However, this only applies when a shred is located at the place of the bend. In case no shredded composite is present at the place of the bend, no additional limitations have to be considered. The flexibility and the location of the shredded composite are therefore important. However, taking this into account is difficult because the flexibility differs for each shred and the locations are not easy to control. When analyzing a batch of shreds, it can be concluded that shreds with a maximum thickness of 1 mm are sufficiently flexible. Controlled shredding and sieving could therefore be beneficial to produce thin shreds. However, clear guidelines for the shape of the design are not possible to compose due to the inconsistency within the shreds. It can only be stated that larger bends have a higher success rate and therefore sharp corners should be avoided at much as possible.

Figure 46 - Charger with fixed output (left) and detachable output (right)

DIMENSIONS

The minimum dimensions of the charger's housing are defined by the components inside the product. Analyzing the components in detail is not in the scope of the project. However, to get an idea about the size that the housing should have, the dimensions of currently existing chargers were analyzed. In Appendix 19, the dimensions of the chargers for home use are listed. These dimensions were evaluated to find the average values (Appendix 22). This results in an average length, width, thickness and volume of 360, 221, 135 mm and 14 dm^3 respectively.

Significant differences are visible between the dimensions of the chargers. The results of the evaluation have shown that the chargers with a fixed output require a smaller charger than the ones with a detachable output (Figure 46). The type of output used will therefore also have an influence on the possible dimensions of the housing.
When deciding on the dimensions, the minimum dimensions of the chargers that are currently on the market (Appendix 22) are kept in mind to make sure that a realistic design will be developed. The minimum length, width, thickness and volume are 160, 150, 52 mm and 2,2 dm^3.

Chapter 20
Final Design

In this chapter, the different aspects concerning the final design of the charger are explained. Firstly, the design and the reasoning behind it are discussed. Secondly, considerations on the shredded composite, recycling of the product and the business model are further explained.

Figure 47 - Material sample: PET sheet with shredded composite

DESIGN

The shape of the charger should represent the vision and aimed value of the shredded composite. Additionally to this, the design should show what is possible with the recyclate to inspire others to use this material. In order to do so, the message that should be conveyed by the product needs to be defined. This is used to create guidelines for the shape functioning as inspiration while designing.

Message to convey

As described in the vision in Chapter 11 - Design Vision, the product should show that recycled material does not have to be hidden but that the recycled material can be a valuable addition to a product. In this product, the shredded composite evokes a link with the wind energy sector. in addition to this, people that own an electrical car are often environmentally oriented. This product should radiate a similar message by processing the shredded composite visibly and creating a shape that strengthens the link with wind turbines.

Shape guidelines

Short brainstorms were executed to find associations for the material and the message that needs to be conveyed. These outcomes were used to set up the most important qualities that the product should evoke. These were transferred into shape guidelines to use while designing. The results are described below.

The use of recycled material clearly shows imperfections which highly contrasts virgin materials. These imperfections make the material interesting and underline that every product is unique. Additionally, the plates with shredded composite give a natural appearance which is remarkable because no natural materials are used (Figure 47). Despite this fact, the shreds seem to be associated with straw. In addition to this, the to be conveyed message describes that the shape should strengthen the link with the wind turbines and that the overall product should radiate environmental friendliness. This concludes in the following qualities that the product should evoke: imperfection, environmental friendliness and a link with wind turbines.

These qualities can be translated into shape guidelines by thinking of associations around these topics. Imperfection can be represented by asymmetrical shapes. When thinking of products that evoke environmental friendliness, natural materials are often included. Materials found in nature also contain imperfections and have organic, asymmetric shapes. In addition to this, textures are often present on these materials. To facilitate a link with the wind turbines, the associations made in the creative session held during the ideation were evaluated together with the shape of the wind turbine (Figure 48 (Naplesbay, n.d.)) (Appendix 23). From this, one can conclude that minimalistic, organic and round shapes, possibly with one sharp edge, represent the form language of a wind turbine. Using round shapes also suits the production possibilities defined in Chapter 19 – Design Guidelines. Together, these shape

Figure 48 - Wind turbine

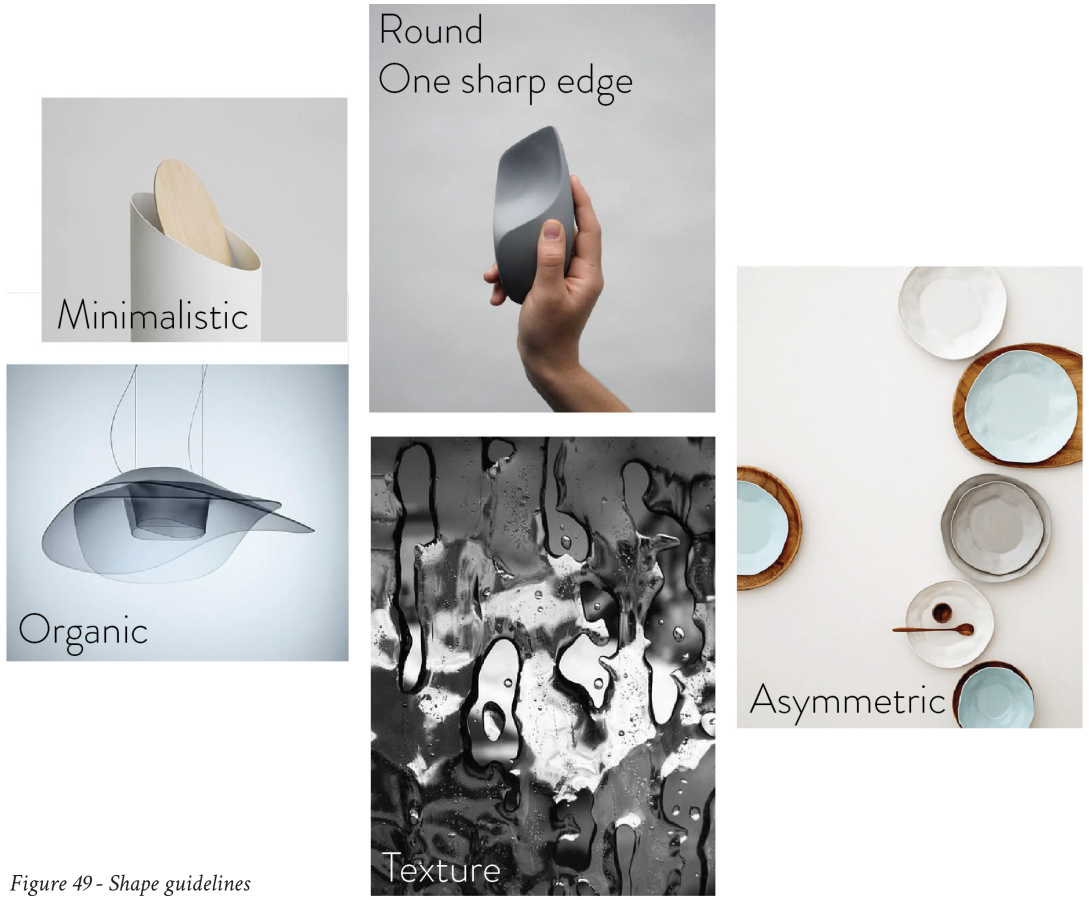


Figure 49 - Shape guidelines

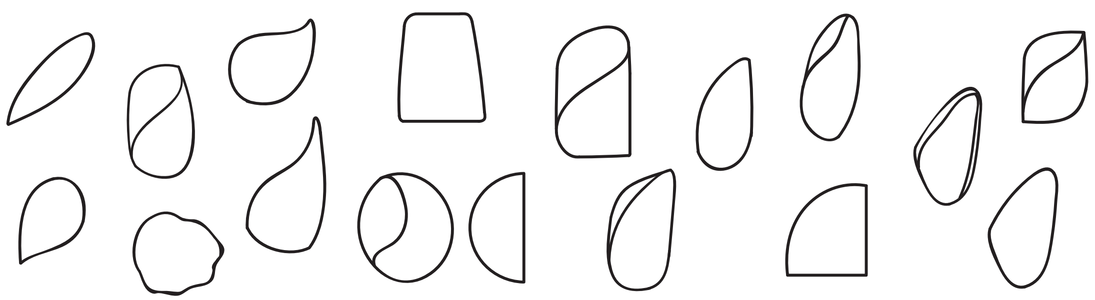


Figure 50 - Ideation shapes

guidelines form the starting point for designing the electrical car charger (see Figure 49 (Shumaker, 2012; Palomba Sarafini Associati, 2009; Austin, 2009; Énola, 2016; Takeuchi, 2018)).

Ideation shapes

With these form guidelines, ideation on possible shapes was performed. Sketches and clay models were developed to evaluate the shapes (Figure 50 and Appendix 24). Eventually, a final shape is created which is visible in Figure 51. Although the shape does not include a sharp edge, it complies with the shape guidelines and the three corners have a link with both the three blades of a wind turbine, and the triangle shape present in a blade.

Final design

The selected shape was developed into the final design of the charger. An overview of the design can be found in Figure 53 (render in use adapted from EV Company (n.d.)).

The design consists of two housing parts. The back housing will be connected to the wall and the inside components are placed in this part. The front housing can then be put onto this to protect the content of the product. Between the two halves, a LED strip is present to shine on the edge of the bottom housing. This will cause the fibers inside the material to light up (Figure 52). The thickness of the material is 2 mm and allows for enough transparency to let the light go through. The light is used to indicated when the car is fully charged.

The power supply and output are located on the bottom. The output cable will be fixed, which causes that the dimensions of the charger can be smaller, as explained in Chapter 19 - Design Guidelines. This is done because the production possibilities for developing the prototype do not allow for a larger shape.

The recycling process of the shredded composite, including the production of the charger, is illustrated in Figure 54. After shredding the

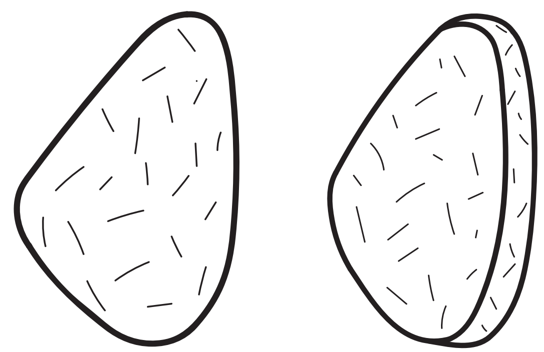


Figure 51 - Final shape in 2D (left) and 3D (right)

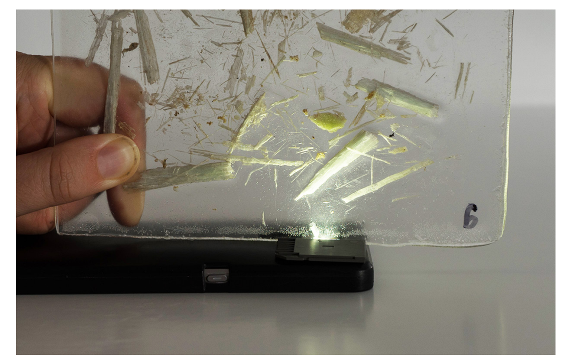


Figure 52 - Light shining inside the material

Figure 53 - Final design

composite, sheets need to be produced. This can be done by heating two sheets of plastic with shreds in between. When the plastics are heated sufficiently, they will be pressed to create one sheet. Secondly, the sheet is shaped into the desired part with the vacuum forming method. With this production technique, the sheet will again be heated and pulled over a mold to shape it. Thirdly, the parts need to be machined to remove unnecessary material and create the holes for the cables and screws.

The two parts of the housing both have different appearances: one is fully transparent and the other is partly white. This last housing part can be produced by pressing the shredded composite in between two sheets of plastic of which one is transparent and the other is opaque. It is important to make sure that these sheets consist of the same plastic type. Therefore, it is necessary to make use of another plastic than PET because this type of plastic is mainly transparent. PC could be a replacing plastic that is both available in transparent and opaque white.

In addition to the color, the texture is also differentiating between the housing parts. The back housing has a bumpy texture that is caused by the shredded composite, while the front housing's surface is smooth. This is done to illustrate the different possibilities the material has to offer. To

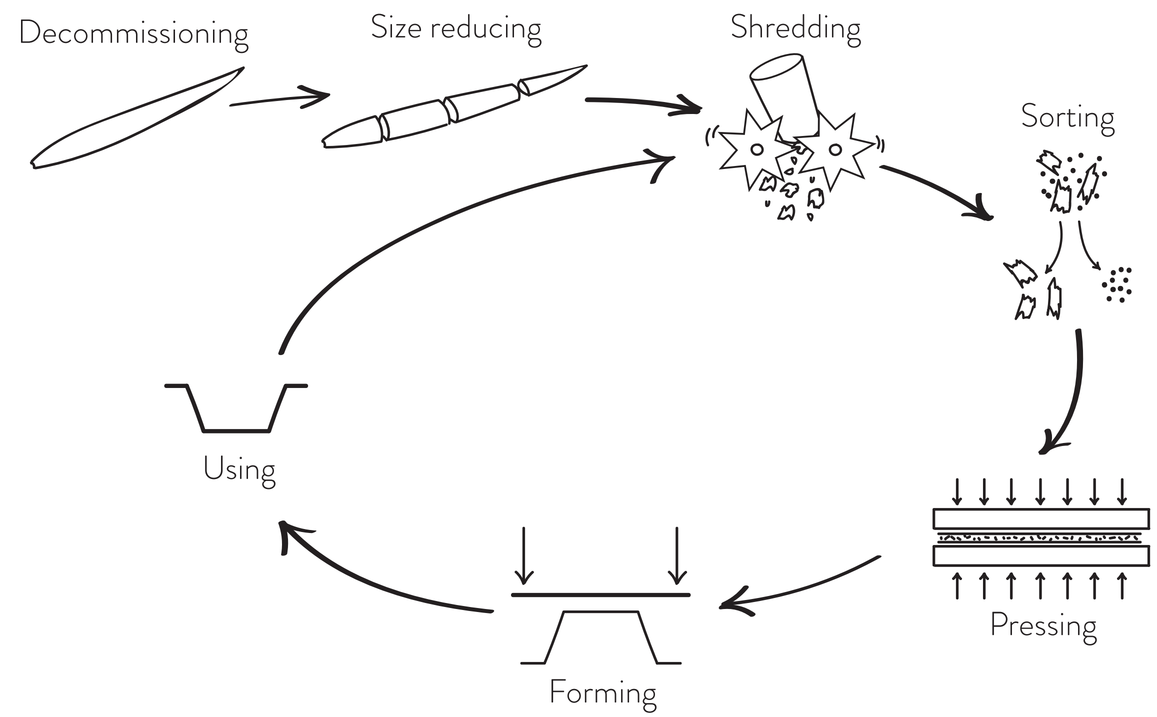


Figure 54 - Recycling process of the wind turbine blade

facilitate this, the production method needs to be slightly adjusted for both parts. When vacuum forming, one surface is in contact with the mold. When a male mold is used, the inner surface touches the mold causing the shredded composite to create a bumpy texture on the outer surface of the part. When using a female mold, the textured surface will be on the other side and the outer surface will be smooth.

SHREDDED COMPOSITE

The shredded composite is an important component of the design. Therefore, the different aspects concerning the recyclate, such as the function, preparation and used quantity of the shreds in the new product, are highlighted in this section.

Function

Applications for the shredded composite have been found by looking at the specific characteristics of the material and thinking of ways to beneficially deploy these. In this design, the focus is especially on showing the shreds and with this creating a symbolic link between the wind energy industry and the product. This means that the appearance of and the story behind the material are used. Other ways in which the shreds can be useful in the design have also been evaluated to fully exploit the potential of the material, which is explained below.

The determined characteristics of the material, appearance, light-weight, electrical isolation and water, chemical and abrasive resistance, are considered within the chosen application. However, adding the shredded composite to a thermoplastic matrix causes that most characteristics become less relevant. The thermoplastic material will be in direct contact with the environment, placing the most demands on the characteristics of this material. Because of this, the water, chemical and abrasive resistance and electrical isolation properties of the shredded composite cannot be usefully deployed. The light weight is also less relevant, because the thermoplastic material that is normally used in electrical car chargers has an even lower density. For these reasons, the appearance of the material is the most useful characteristic to exploit. In addition to this, the shredded composite may deliver strength and/or stiffness to the material. Due to the random placement and size of the shreds, this reinforcement is highly anisotropic. In order to conclude whether or not the shreds lead to reinforcement, material testing should be done.

A brainstorm was done to find ways to use the appearance of the shredded composite in the design. The results can be seen in Appendix 23. As described in the preceding section, it is eventually chosen to use the shredded composite to create a texture on one housing part. By doing this, it demonstrates how the material could provide grip on a surface. In addition to this, the LED light that shines into the material causes the shreds to light up and glister, which highlights its aesthetic qualities.

Preparation

The size of the shredded composite within the product was determined to be approximately 3 to 5 cm. However, as explained in Chapter 19 – Design Guidelines, the thickness is especially important for the producibility of the material. For this reason, the thickness of the shreds should not exceed 1 mm.

To make sure that the shredded composite has a thickness of 1 mm, the shredding process needs to be controlled. The larger shreds should continue the shredding process until they have the correct size. A sieve can be placed inside the shredder to make sure that the shreds only exit the shredder once they have a certain size. However, it could happen that a shred fits through a hole in the sieve but that the thickness or length is more than 1 mm and 5 cm respectively (Figure 55). A sieve with rectangular holes with the width of 1 mm could also be used (Figure 55), but many shreds might then not leave the shredder due to a wrong orientation.

The small particles of foam, wood and shreds, which are always produced during the recycling process, should be separated from the recyclate. This can be done with the use of a sieve.

Another method to sort the shreds is with the use of air. The thinner shreds have a lighter weight and could therefore be blow away from the other heavier shreds. The foam could also be separated out of the shredded composite with a similar method. All these methods will probably not ensure a completely sorted material, but they might be sufficient enough. However, experiments should be done to see which process is best suitable.

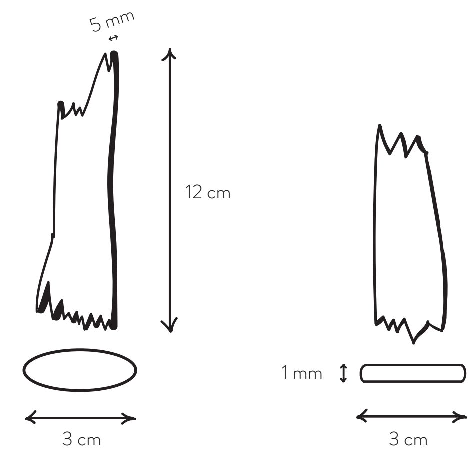


Figure 55 - Difficulties with the size of the sieving holes

Quantity

In the material used for the product, the volume fraction of the shredded composite is approximately 20% which equals around 30 grams. It was shown while building the prototype (Chapter 21 - Prototype) that the material can still be thermoformed with this quantity. Higher volume fractions might also be possible, but experiments on the production of the product should first be executed to ensure this.

The amount of waste from WTBs worldwide is expected to be nearly 50.000 tonnes in 2020 (Froese, 2016). When looking at the number of chargers that can be sold, one can conclude that it is expected that in 2020 20% of the newly bought vehicles in the Netherlands will be electrical (Ernst & Young, n.d.). This means that 100.000 people will buy an electrical vehicle in that year. If 5% of these people will buy the electrical charger with shredded composite, 5.000 chargers will be sold in the Netherlands. Even when it is considered that the charger would be sold in the developed continents, Europe and North-America, the amount of shredded composite that is being recycled is not incredibly high. However, when the material will be used in more products, the impact will rise.

RECYCLING OF THE PRODUCT

The charger could be part of a service model offered by energy suppliers such as Eneco and Nuon. These companies own the wind turbines and therefore have an incentive to reuse the composite material. For example, the chargers can be developed by Eneco with the waste of their wind turbine blades and provided to their customers who own an electrical car. When doing this, Eneco will keep the ownership over the product. Whenever the product is broken, it will return to Eneco in order for them to repair or recycle it.

When reparation is not possible, the product should be recycled. Electrical devices are normally shredded after which the different materials are separated as much as possible (Recycling Platform, n.d.). If the thermoplastic material with shredded composite ends up in this process, it will be difficult to separate it from the other thermoplastics. Therefore, it would be better to first disassembly the product. To facilitate this, temporary connections such as screws and snap-fits should be used in the design.

After disassembly of the product, the shredded composite material could be handled separately. Similar to other fiber reinforced thermoplastics, the material could be shredded in flakes (not smaller than 1 cm) and re-processed with for example compression molding (de Bruijn, Vincent & van Hattum, 2016; Vincent, n.d.). The flakes could also be again pressed into a sheet and thermoformed. After one recycling procedure, the shredded composite will be slightly degraded but the material will still be visible within the plastic.
The flakes can be used to create new charger housings, but can also be used in other products. However, it should be made sure that the material will again be recycled separately from other plastics. To facilitate this, the product should be collected by the production company when it is discarded or a material passport should be provided for the product. This will make sure that the recycling company knows which material is included in the product and how it should be processed.

After the material has been through multiple recycling cycles, the shredded composite is probably significantly reduced in size. With this decline in size, a decrease in mechanical properties often occurs, meaning that the material will be part of a cascading model in which it will be slightly down-

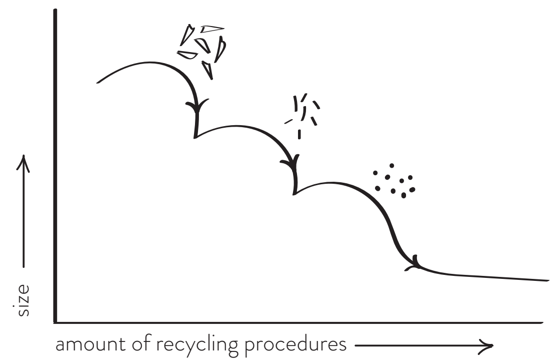


Figure 56 - Cascading model

cycled with every recycling procedure (Figure 56). Eventually, the material will contain short and particle-sized shredded composite which will only function as filler material inside the plastic. Material testing should be done to determine the strength of this obtained material, but it is expected that it could be sufficiently used for non-structural applications.

BUSINESS ASPECT OF THE MATERIAL

The electrical car charger is an example of a product in which the material with shredded composite can be used. To showcase why this material should be used by companies, some attention will be paid to the business aspect of the material.

The main unique selling point of the material is that it is reusing a waste resource. Within this material, the waste can be recycled and does not end up in landfill or incineration. The thermoplastic including the shredded composite can again be recycled afterwards, making this material a reasonably responsible choice for companies.

Additionally, the end-of-life situation of thermoset composites is becoming a more important subject, because it is increasingly used in for example the automotive and wind energy sector. When companies are reusing this material, it can create positive publicity for the company and awareness for the recycling problem. The products from which the shredded composite originates, such as wind turbine blades and airplanes, appeal to people's imagination which can have a beneficial influence on this publicity and awareness.

These advantages are mainly focused on the image of the company who is using the recycled material. However, also from a financial point of view the material could be beneficial to use. As Appendix 12 describes the costs for the shredded composite are expected to be relatively low (0,10 Euro/kg). This is significantly lower than the price of common thermoplastics such as PET and PP. For this reason, it can be financially advantageous to add shredded composite to plastic products as done in the electrical car charger.

One downside of using the material is the expected investment costs concerning the shredding of the composite. A suitable shredder with sewing and sorting process must be installed and it should be made sure, due to health and safety issues, that the glass fibers are not released to the surrounding. However, once these facilities are developed, large amount of material can be processed at low cost.

Evaluation

To evaluate the design and the production procedure, a prototype was made. In this section, it is described which steps were taking for developing this prototype and points for improvement are discussed.

Chapter 21
Prototype

To evaluate the design, a prototype was created. While making this prototype, the production method was evaluated further and challenges were identified. In this chapter, the prototyping steps will be explained. The process is divided in three sections: production of the sheets, forming of the sheets and finalizing of the prototype.

Figure 57 - Polishing the metal plates

Figure 58 - A final sheet produced in the heated press

PRODUCTION OF THE SHEETS

From the production tests described in Chapter 17 - Production Method, it was concluded that the heated press from Fontijne Presses develops the smoothest sheets. Therefore, this press was used to produce the prototype sheets.

To make sure that the surface of the material would become smooth, two polished metal plates were placed between the material and the press (Figure 57). The press was heated to 160 ˚C, after which a pressure of 30 kN was applied to the material for 2 minutes. After this, the press was cooled down to 60 ˚C before releasing the pressure and removing the produced sheet.

Two final sheets need to be produced: one for the front housing part and one for the back housing part. The back housing should contain a texture from the shredded composite. To facilitate the realization of this texture, thicker shreds were used in the sheet for the back housing. Eventually, multiple sheets of PETG were produced with shredded composite in between or on top of the layer(s) (Figure 58). The sheets were developed originating from sheets with a 1 and 2 mm thickness or form one with 3 mm thick.

FORMING OF THE SHEETS

The sheets with the largest thickness were vacuum formed into the desired shape. To facilitate the difference in texture between the two housing parts, one hard and one soft mold was used. With the soft mold it was expected that the shredded composite would push into the mold and a smooth outer surface would be created. In contradiction to this, the hard mold would push the shreds to the outside and a textured outer surface would be developed.

To produce the molds, the shape of the two housing parts was milled from foam. This foam mold was used for vacuum forming the front housing part. The hard mold for the back housing part was made of plaster. A plastic sheet was first vacuum formed with the produced foam mold. This thermoformed sheet could then again be used as a mold for the plaster. The final molds and the material after vacuum forming can be seen in Figure 59 and Figure 60.

FINALIZING THE PROTOTYPE

After forming the sheet, the shape was cut out. The shredded composite that could not bend between the base plate and the mold were sticking out of the material (Figure 61). These were manually heated and bent into the correct position.

After this, the inside of the front housing part is painted white. In the final design, the material used for this part should be made of one transparent and one colored sheet, instead of two transparent sheets.

Holes were created in the back housing part to facilitate a connection to the wall and to let the electronic wire of the LED strip go through. The foam molds were painted black to function as padding inside the housing parts. A connection was created between these foam molds to keep the housing parts together.

The LED strip was placed on the outside edge of the front housing part to shine through the material of the back housing part.

Figure 59 - A foam (left) and plaster (right) mold

Figure 60 - The thermoformed sheet

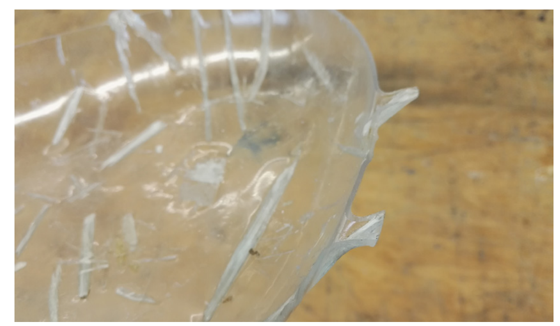


Figure 61 - Shredded composite sticking out of the part

Chapter 22
Evaluation Prototype

While making the prototype, the production of the product was evaluated and challenges were identified. In this chapter, the final result of the prototype is visible (Figure 62) and process of developing the prototype is reflected on. This reflection is divided into similar sections as Chapter 21 - Prototype.

PRODUCTION OF THE SHEETS

The production of the sheets was sufficient, but some points for improvement could be implemented. Firstly, the polished metal plates should have the same size as the press. In the prototype, the plates were slightly smaller which caused the material to be pushed outside of the platess (Figure 58). Due to this, the thickness of the sheets became less than intended.

Secondly, transparent thermoplastic sheets were used to develop the material of the front housing part. For further development it would be necessary to test with one transparent and one color sheet. This will make it unnecessary to paint the part afterwards.

Thirdly, to further reduce the amount of air bubbles between the layers of plastic, more experiments should be done. Eventually with the correct combination of temperature and pressure, the air bubbles could be completely removed from the material. Additionally, in order to develop sheets with a specific thickness a metal mold should be used.

FORMING OF THE SHEETS

A soft and a hard mold were used to produce one housing part with a smooth surface and one with a bumpy surface. Thicker shredded composite was also processed in the material of the back housing part to facilitate this texture. However, the result was not completely as expected because both surfaces eventually contained a bumpy texture. In the final design, a male and a female mold should be used to create these different textured as explained in Chapter 17 - Production Method.

Some difficulties emerged when forming the material. The corner between the mold and the base plate was sharp and not every shredded composite was flexible enough to make this bend. In the final design, the mold should be produced with a few centimeters spare height. When this is done, the part can be cut out of the material a few centimeters above the sharp corner.

FINALIZING THE PROTOTYPE

When finalizing the prototype, especially the LED strip caused some challenges. The back housing part should actually have a mininum thickness of 2 mm to facilitate the light to shine inside the material. The LED strip should therefore be located exactly on top of the edge of the material in the final design.

Figure 62 - Prototype

Conclusion

Finally, in this last section the design is evaluated on the formulated assignment and the composed frameworks and vision. The results from the project are concluded in final design guidelines that can facilitate others to reuse shredded composite material. Additionally, recommendations are given for the development of the charger, for further research on recycling of composites and for the design of wind turbine blades. This thesis ends with a personal reflection on project.

Chapter 23
Evaluation Design

In this chapter, the assignment formulated at the start of the project is evaluated to determine to what extent it is fulfilled. In addition to this, the final design is assessed with the help of the frameworks defined in Chapter 3 - Method and the vision explained in Chapter 11 - Design Vision.

EVALUATION ON THE ASSIGNMENT

The assignment for this project was to find a valuable application for shredded composite of wind turbine blades. Currently, this high value material is significantly down-cycled, landfilled or incinerated. With the last two options, the material resource is wasted. The aim of the project was to show how the material can be reused by finding an application that maintains the highest value of the material. While doing this, guidelines (which are presented in the next chapter) were determined to enable others to use the shredded composite material in new products.

The final design will be evaluated on two important aspects of the assignment: the shredded composite and the circular economy.

Shredded composite

The amount of composite waste originating from wind turbines is large and the design was aimed to fit this supply size. However, as explained in Chapter 20 - Final Design, only a limited amount of the shredded composite will be reused in this electrical car charger. This could be improved by increasing the size of the charger. In the design, the dimensions are relatively small because the production facilities for the prototype did not allow for larger dimensions. When the product would be realized, different production equipment could be used which would increase the amount of shredded composite used in the product. In addition to this, the volume fraction of shreds within the material could also be enlarged.

Despite these optimizations, only a small part of the total supply of shredded composite is used. The residual shreds could be used in products with similar thermoplastic housings, such as kitchen appliances. In these products, the link with the origin of the material would be less relevant but the texture and sustainable aspects of the material could be exploited. In addition to this, the shredded composite may deliver strength and stiffness. In order to draw any conclusions in this regard, material tests need to be executed.

For the current design, the shredded composite is sieved and the particle sized shreds are separated. The particle sized recyclate has a brownish color and can be used as a filler material similar to the shredded composite used in the design after several recycle cycles, as proposed in Chapter 20 - Final Design. In order to find suitable applications for this, further research should be done on the mechanical properties that can still be obtained with this filler material. However, when using the shreds as filler material, the value of the material is low as explained in Chapter 10 - Evaluation.

Lastly, a wish for the project was to find an application that is not only applicable for composites from wind turbine blades but also for other types of composite waste. The final design is using the link between the product and the wind turbines, which makes it more difficult to apply this design to other composite waste streams. However, the process and determined guidelines can be used to come up with suitable applications for other types of composite waste. In addition to this, the project shows the possibility to create thermoplastic plate material with shredded composite and thermoforming this into a new product. This procedure can be used for all composite material and for many applications. The design of the charger can therefore inspire others to reuse composite waste.

The circular economy

When evaluating the end result of the project, it may be called into question if this solution is truly the most sustainable. For example, a thermoplastic product might be easier to recycle when shredded composite is not included. However, when evaluating the environmental friendliness of products, many different parameters can be considered which are often not all met. This project was mainly focused on preventing the shredded composite from becoming waste and processing the material into a new application. When taking this perspective, it can be concluded that a more sustainable end-of-life situation has been developed for the composite material.

Another aspect of the assignment was focused on developing an application that fits the circular economy principles. This requirement had a significant influence on the selection of the matrix material to which the shredded composite would be added. With the thermoplastic matrix, it is ensured that the product can be recycled after its use and that the resources are not wasted.

EVALUATION ON THE FRAMEWORKS

As stated in Chapter 3 - Method, the recycling process of composite material described in this project belongs to secondary recycling. It was mentioned that the highest value can be maintained if the retained properties of the new material are as high as possible. When evaluating the project, it probably did not result in the highest retained properties of the material when considering its strength and the characteristics determined in Chapter 9 - Material Properties. Due to the choice for a thermoplastic matrix material and the decision to not focus on using the material as reinforcement or filler, only few material properties are used in the final design. The thermoplastic material fully covers the shredded composite and has several characteristics that are similar to those of the shreds. This made it difficult to beneficially exploit the characteristics of the shredded composite. However, the recyclability of the matrix material was an important aspect in the selection and made thermoplastic material the most favorable choice.

This does not mean that no value is achieved within the final application. When considering the value types, it can be seen that the waste hierarchy framework is mainly focused on functional value. With the final design, mainly sustainable and symbolic value is achieved by reusing waste material and creating a link with the wind energy industry. Functional value, which was determined as focus together with sustainable value, is limitedly accomplished by using the appearance and texture characteristics of the material in the design. As previously described, it became clear during the project that beneficially using the specific characteristics of the shredded composite was difficult due to the thermoplastic material. After learning that it can be beneficial to create a link to the origin and the supplier of the material, the focus shifted more towards symbolic value. From the market research in Chapter 7, it was concluded that no current solutions are achieving this type of value which means that this design can deliver a new perspective to the current market of reusing composite material.

EVALUATION ON THE DESIGN VISION

The vision to handle the shredded composite as a visible and wanted addition instead of hiding it is met in the final design. The shreds are clearly visible in the material and cooperate with the shape of the product to convey the message as described in Chapter 20 - Final Design. In addition to this, light is used to highlight the shredded composite in contrast to the thermoplastic material to show that recyclate can dominate in a product without being a disturbance.

CONCLUSION

Finding a valuable application for shredded composite material is a complex assignment, because significant down-cycling of the material is occurring. Several aspects are influencing the complexity of the problem, namely:

- considering the safety aspects in regard to the glass fiber,
- enabling the recycling the new product after its use,
- using the specific characteristics of the shredded composite in a beneficial way,
- matching the amount of composite waste material.

These aspects are influencing each other which causes difficulties when aiming to fulfill them

all. Despite this, the project concludes in a value application for the shredded composite that focuses on the safety aspects regarding the glass fiber and the recyclability of the new product. Using the specific characteristics of the material in a beneficial way was aimed for in the design and is partially met by using its appearance and structure.

Chapter 24

Final Design Guidelines

The insights that were obtained during the project are used to set up final design guidelines. These guidelines can allow others to design with and find valuable applications for the shredded composite material. In addition to this, specific guidelines for developing products with the sheet material and thermoforming process, as used in this project, are described.

FUNCTION

- Use of the shredded composite should be beneficial to the product instead of being a disturbance, for example as structural/ reinforcing or weight saving role (Conroy et al., 2006).
- Making the material visible and using its appearance can be more valuable than trying to hide the recyclate.
- The shredded composite should not be used as filler material without adding any characteristics to the product, because of the more cost-efficient filler options.
- The product including the shredded composite should not have to carry a lot of load.

CHARACTERISTICS

- The larger the fibers, the more strength and stiffness it can give to the material.
- When the shredded composite is functioning as reinforcement, the product should not have to be reinforced with an additional material or made thicker to compensate for some deficiency caused by inclusion of shredded composite (Conroy et al., 2006).
- Variation in the properties caused by the varying content of the supply should be considered when designing.
- Keep the material large. The smaller the material, the less (mechanical) properties remain.
- The shredded composite has specific characteristics such as the appearance and structure, electrical isolation, chemical resistance, water resistance, light-weight and abrasive resistance. These characteristics could be usefully exploited in a new material.

SAFETY

- The product should not pose environmental problems or health and safety problems in use, e.g. abrasion, wear related loss of glass fibers, or during cutting and drilling (Conroy et al., 2006).
- The matrix material in which the shredded composite is included should not undesirably disintegrate.

SUSTAINABILITY

- The product should not be a substitute for something which is actually made from a more sustainable material in the first instance (Conroy et al., 2006).
- The new product including shredded composite should be able to be recycled itself and the end-of-life situation should be controllable.
- The life cycle of the new product should have a length that fits the material and recyclability of the material used.
- It is favorable if the shredded composite replaces an endangered, expensive, less good or unsustainable material resource.

VALUE TYPES

- The different values types (emotional, functional, economic, sustainable and symbolic value) can be used to get a grip and evaluate on the value achieved by a product or material.

MARKET

- It is favorable if the buyer of the product is also the supplier of the waste material. They have an incentive to buy the product with recyclate.
- If the market in which the product is functioning attaches value to sustainable alternatives, more interest in the product will exist.
- It can be valuable to reuse the shredded composite in a product that has a link with the origin on the composite material.

THERMOFORMING

- It is possible to create thermoplastic sheets containing the shredded composite. These sheets can be formed into a desired shape.
- Different textures (smooth or bumpy) can be created with the shredded composite using of a male or female mold.
- The shredded composite has a large influence on the angles that can be present in the part.
- The shredded composite should have a maximum thickness of 1 mm to be sufficiently flexible.
- Sharp corners should be avoided in the design.

Chapter 25

Recommendations

This research and design project is an addition to the studies that are done on the recyclability of thermoset polymer composites. However, this topic is extensive and this report does not describe an all - encompassing solution. Therefore, several recommendations for further research will be discussed in this chapter. The topics will be divided in different sections regarding the electrical car charger, recycling of shredded composite and the design of wind turbines.

ELECTRICAL CAR CHARGER

To further develop the electrical car charger, several detailing steps need to be taken. First, the production should be tested on a larger scale to:

- find the most appropriate method to shred and sort the composite,
- find the correct temperature and pressure combination for pressing the sheets,
- investigate how one sheet can be produced from two sheets with different colors,
- decide which specific production method is best suitable for this material and for the development of the smooth and bumpy texture,
- determine how the machining actions can be automated.

Secondly, the material sheets that are obtained from the production process should be tested with the three-points bending and tensile test to get an idea of the mechanical properties. Similar tests should be done with sheets that do not contain shredded composite in order to compare them equally. From the obtained results, it can be concluded if the shredded composite still delivers reinforcement to the material. Thirdly, the design should be further detailed, amongst others on the connections and the inside housing for the components.

Lastly, the environmental impact of the product can be evaluated in comparison with a similar product that does not contain shredded composite. This will give insights into the environmental friendliness of the material. With these insights, further recommendations can be done on the improvement of the design and on the way the shredded composite can be recycled best.

RECYCLING OF SHREDDED COMPOSITE

The electrical car charger is one application in which the shredded composite can be reused. However, addition research and design projects could be executed to come up with a broader range of products in which the material can be used. Within these projects, the focus could be on searching for more applications for the sheet material described in this project. In addition to this, it could be useful to further investigate other material and production possibilities. However, it is recommended to keep the recyclability of the new product in mind in order to make sure that it is not additionally contributing to the recycling problem.

In addition to this, research and material tests should be executed on composites including the particle-sized shreds as a filler material. It will be difficult to financially compete with other filler materials, such as calcium carbonate, as explained in Chapter 7 - Market Research. For this reason, it is necessary to identify which benefits the shredded composite can have in comparison with other materials. If no advantages can be found, the incentive for companies to use the shreds as filler material should be based on environmental aspects.

WIND TURBINES DESIGN

Based on the findings of this project on recycling of composite material, several recommendations can be made regarding the design of wind turbines.

It is useful if more information on the content of the wind turbine blades is available. With the batches of shreds that were obtained in this research, it was uncertain which materials it was composed of. Material passports can provide this information. In these passports, the specific content materials can be specified which will simplify the determination of the characteristics of the recyclate and consequently facilitate the reuse.

Although this project shows a suitable way to recycle shredded composite waste into new products, it should be highlighted that eliminating the fiber reinforced thermoset polymer composites is the best solution to further limit this recycling problem. Unless a recycling procedure is developed in which the fibers and resin can be turned back into raw materials, the end-of-life situations conclude in significant down-cycling of the high value material.

For this reason, it would be best to replace thermoset polymer composites with a better recyclable material. A thermoplastic matrix material would be a possible replacement, because this material can be melted and reshaped. Therefore, it would be recommended to further invest in research on facilitating the use of this material instead of thermosets.

Chapter 26

Personal Reflection

In this chapter, I want to personally reflect on the process I went through during this graduation project. In this reflection, I am evaluating challenges that I encountered along the way and the personal developments that I experienced.

At the start of the graduation project, I did not foresee the process as it turned out to be. Based on previous experiences, it is always possible to develop certain expectations for the challenges you will encounter along the way. However, it always turns out to be slightly different than envisioned, which is logical for such a project. At the start of this project, it was difficult to create a detailed plan for the steps I was going to take and for the focus I was going to apply. When being forced to figure this out individually, I was eventually able to develop an approach with which I felt content. However, as mentioned above, the process always changes along the way when new insights are obtained. Experiencing that it is fine to let go of intended steps and to be able to make adjustments to the plan of approach along the way was a very educative part of the project. Although this plan of approach changed throughout the project, it turned out to be very helpful to dwell on it extensively in the beginning.

Throughout the project I noticed that it is important to stay focused on the scope of the assignment. Many challenges exist around a complex problem as the one handled in this project. This causes that it is easy to get carried away and lose track of the bigger picture. To make sure I stuck to the right direction, it was helpful to discuss my progress with my supervisors, and to sometimes zoom out and write down the steps I had taken and the ones I was intending to take.

These many challenges regarding the topic sometimes also caused me to feel unsatisfied. When you are focusing on solving a problem, it can be difficult to accept that not all aspects of the problem can be addressed when only limited time is available. However, zooming out and keeping track of the bigger picture facilitated that I could understand which aspects were most relevant to develop a coherent story. This made sure that I feel satisfied with the end result of the project, although additional research is still required.

A similar urge was also visible in the decision making throughout the project. I have a tendency to sort out every detail before feeling able to make a decision. However, often it is not feasible to collect a complete overview of information due to the time limitation. This made it often difficult to take a decision on important moments in the process. Discussing this with others often made it possible to zoom out and see what was really important for the continuation of the project. Often it turned out that detailed information was not necessary to be able to make well-founded choices.

In addition to this, I learned to enjoy asking others for input and help if needed. I am often afraid to be a burden to others when I need help on a certain topic. Therefore, I tend to try and solve things on my own. However, throughout the project I tried to step out of my comfort zone and reach out to others, for example when organizing the creative session. Eventually, I experienced that others are often willing to help out and that they are also flattered when you ask them. This made it everytime easier to approach someone.

To conclude, this graduation project was also a helpful process for my personal development. Prior to the project, I was nervous for executing a design project individually as opposed to in a group. Due to the large amount of group work during my studies, I was uncertain about my qualities as a designer while working on my own. Along the way, I came across many situations in which I was uncertain about my capabilities. Although I still have a many possibilities to improve on this, I learned to not run from these challenges. Once I accepted the challenge and started working on it, it often turned out that I was able to handle it. Experiencing this has helped me to increase my confidence, which is very valuable for my further development as a designer and a person in general.

References

A. Brent Strong (2008) *Fundamentals of Composite Manufacturing: Materials, Methods and Applications* (Second edition). Dearborn: Society of Manufacturing Engineers

AcoustaFoam (n.d.) *Acoustic Insulation*. Retrieved on 9th of March 2018 from http://www.acoustafoam.com/products/acoustic-insulation/

Andersen, N. (2015) *Wind turbine end-of-life: Characterisation of waste material* (Student thesis). Faculty of Engineering and Sustainable Development, University of Gävle, Sweden

Andersen, P. D., Bonou, A., Beauson, J. and Brøndsted, P. (2014) *Recycling of wind turbines*. DTU International Energy Report 2014: Wind Energy – drivers and barriers for higher shares of wind in the global power generation mix, 91-97. Retrieved from http://orbit.dtu.dk/files/102458629/DTU_INTL_ENERGY_REP_2014_WIND_91_97.pdf

Andersen, P. D., Borup, M. and Krogh, T. (2007) Managing long-term environmental aspects of wind turbines: a prospective case study. *International Journal of Technology, Policy and Management, 7*(4), 339 – 354

ASTM International (2002) *ASTM D2584-94 Standard Test Method for Ignition Loss of Cured Reinforced Resins*. Retrieved from https://doi.org/10.1520/D2584-94

ASTM International (2017) *ASTM D3039/D3039M-17 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. Retrieved from https://compass.astm.org/EDIT/html_annot.cgi?D3039+17

Åström, B. T. (1997) *Composite Sheet Forming, Chapter 2 - Thermoplastic Composite Sheet Forming: Materials and Manufacturing Techniques*. Amsterdam: Elsevier Science B.V.

Austin, O. (2009) *Ice* [picture]. Retrieved on 15th of June 2018 from https://www.flickr.com/photos/51054039@N02/4691488836/

AZO Materials (2018) *E-Glass Fibre*. Retrieved on 7th of March 2018 from https://www.azom.com/properties.aspx?ArticleID=764

Beauson, J., Lilholt, H. and Brøndsted, P. (2014) *Recycling solid residues recovered from glass fibre-reinforced composites – A review applied to wind turbine blade materials*. Journal of Reinforced Plastics and Composites, 33(16), 1542-1556

Beauson, J., Madsen, B., Toncelli, C., Brøndsted, P. and Ilsted Bech, J. (2016) *Recycling of shredded composites from wind turbine blades in new thermoset polymer composites*. Composites: Part A, 90(2016), 390-399

BeAware (n.d.) *Applications of GRP waste in concrete composites*. Retrieved on 4th of February from http://www.bre.co.uk/filelibrary/pdf/rpts/BeAware_GRP_Waste_in_Concrete_Briefing_Document__D3.9.2.pdf

Better Future Factory (2016) *New Marble* [picture]. Retrieved on 20th of June 2018 from https://materia.nl/material/new-marble/

Borealis (2008) *Polypropylene BB125MO*. Retrieved on 27th of May 2018 from https://www.arcopolimeri.com/UserFiles/files/ProdottiPlastics/Borealis%20BB%20125%20MO%20tech.pdf

Bouwmeester, J. (2017) H*ergebruik van thermohardende composieten – Hergebruik in de vorm van vlokken*. Retrieved from https://www.windesheim.nl/~/media/files/windesheim/research-publications/hergebruikindevormvanvlokkenkiemvang4.pdf

Callister, W. D., Jr. (2007) *Materials Science and Engineering: An Introduction*. New York: John Wiley & Sons, Inc.

Cherrington, R., Goodship, V., Meredith, J., Wood, B.M., Coles, S.R., Vuillaume, A., Feito-Boirac, A., Spee, F. and Kirwan, K. (2012) Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe. *Energy Policy, 47*(2012), 13-21

Conenor (2017) *Recycling thermoset FRP-waste*. Retrieved on 2nd of February from http://www.conenor.com/recycling-thermoset-frpwaste/

Conroy, A., Halliwell, S. and Reynolds, T. (2006) Composite recycling in the construction industry. *Composites: Part A, 37*(2006), 1216-1222

Davallo, H., Pasdar, M. and Mohseni, M. (2010) Mechanical properties of Unsaturated Polyester Resin. *International Journal of ChemTech Research, 2*(4), 2113-2217

De Bruijn, T. A., Vincent, G. A., & Van Hattum, F. W. J. (2016) *Recycling of long fibre thermoplastic composites by low shear mixing*. In B. Vangrimde (Ed.), SAMPE Europe Conference 16 Liege: Liege, Belgium, 13–15 September 2016 (pp. 540-546). Liege, Belgium.

D'Werk Plaats (2018) *Oesterplat* [picture]. Retrieved on 20th of June 2018 from https://www.material-lab.co.uk/journal/surface-design-show-material-directions/

Énola (2016) *Cerámica Hecha Arte* [picture]. Retrieved on 15th of June 2018 from http://blog.enola.es/ceramica-hecha-arte/

Epoxy Floors (2015) *Properties and Characteristics of Epoxy Resins*. Retrieved on the 9th of March 2018 from http://www.sanantonioepoxy.com/properties-and-characteristics-of-epoxy-resins/

Ernst & Young (n.d.) *Elektrische mobiliteit in 2020, volop kansen in Nederland*. Retrieved on the 16th of June 2018 from http://www.urgenda.nl/wp-content/uploads/Elektrische_mobiliteit_in_2020.pdf

European Commission (2011) *Plastic Waste in the Environment – final report*. Retrieved from http://ec.europa.eu/environment/waste/studies/pdf/plastics.pdf

European Wood (2018a) *Spruce*. Retrieved on 7th of March 2018 from http://jp.europeanwood.org/en/living-with-wood/selected-european-wood-species/spruce/

European Wood (2018b) *Pine*. Retrieved on 7th of March 2018 from http://jp.europeanwood.org/en/living-with-wood/selected-european-wood-species/pine/

EV Company (n.d.) *HALO - Charge Amps* [picture]. Retrieved on 21st of June 2018 from https://evcompany.eu/laadpalen/laadpalen/halo-laadpaal-elektrische-auto/

Froese, M. (2016) *Reaching retirement: Recycling aging turbine blades*. Retrieved on 16th of June 2018 from https://www.windpowerengineering.com/mechanical/blades/recycling-wind-turbine-blades/

GETWasted (2014) *Facebook page*. Retrieved on 4th of February from www.facebook.com/getwasteddotdk/

Granta Design (2017) CES Edupack 2017, database for materials.

Grunewald, S. J. (2014) *New 3D printing material mimics light weight balsa wood for use in wind turbine construction*. Retrieved on 19th of January 2018 from https://3dprintingindustry.com/news/3d-printing-material-light-weight-balsa-wood-29265/

Halliwell, S. (2006) *End of Life Options for Composite Waste. Recycle, Reuse or Dispose?*. National Composites Network. Retrieved from https://compositesuk.co.uk/system/files/documents/End%20of%20Life%20Options.pdf

Het Groene Brein (2016) *What is the definition of a circular economy?* Retrieved on 2nd of February from https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/definition-circular-economy/

Holcim (2017) *Disused Rotor Blades can now be utilized in Cement Production*. Retrieved on 2nd of February 2017 from http://www.holcim.com/de/referenceprojects/disused-rotor-blades-can-now-be-utilized-in-cement-production.html

Job, S. (2013) *Recycling glass fiber reinforced composites – history and progress (part 1)*. Retrieved on 4th of February from https://www.materialstoday.com/carbon-fiber/features/recycling-glass-fibre-reinforced-composites/

Joncas, S. (2010) *Thermoplastic Composite Wind Turbine Blades: An Integrated Design Approach* (thesis). Delft University of Technology, Delft

Karana, E., Barati, B., Rognoli, V. and Zeeuw van der Laan, A. (2015) Material Driven Design (MDD): A method to design for material experiences. *International Journal of Design, 9*(2), 35-54

Khan Academy (n.d.) *Functional groups*. Retrieved on 16th of May 2018 from https://www.khanacademy.org/science/biology/properties-of-carbon/hydrocarbon-structures-and-functional-groups/a/functional-groups

Kouparitsas, C.E., Kartalis, C.N., Varelidis, P.C., Tsenoglou, C.J. and Papaspyrides, C.D. (2002) Recycling of the fibrous fraction of reinforced thermoset composites. *Polymer Composites, 23*(4),682 - 689

Landru, D., Bréchet, Y. and Ashby, M. F. (2002) Finding Applications for Materials. *Advanced Engineering Materials, 4*(6), 343- 349

MakeItFrom.com (2018a) *Unfilled PP Homopolymer*. Retrieved on 7th of March 2018 from https://www.makeitfrom.com/material-properties/Unfilled-PP-Homopolymer

MakeItFrom.com (2018b) *Polypropylene Random Copolymer*. Retrieved on 7th of March 2018 from https://www.makeitfrom.com/material-properties/Polypropylene-Random-Copolymer

MakeItFrom.com (2018c) *Unfilled HDPE*. Retrieved on 7th of March 2018 from https://www.makeitfrom.com/material-properties/Unfilled-HDPE

MatWeb (2018) *Overview of materials for High Density Polyethylene (HDPE), Extruded*. Retrieved on 7th of March 2018 from http://www.matweb.com/search/datasheettext.aspx?matguid=482765fad3b443169ec28fb6f9606660

Meira Castro, A. C., Carvalho, J. P., Ribeiro, M. C. S., Meixedo, J. P., Silva, F. J. G., Fiúza, A. and Dinis, M. L. (2014) An integrated recycling approach for GFRP pultrusion wastes: recycling and reuse assessment into new composite materials using Fuzzy Boolean Nets. *Journal of Cleaner Production, 66*(1 March 2014), 420-430

Mereco (n.d.) *What makes epoxy resin good adhesives? Why do they bond so strongly to surfaces?*. Retrieved on 16th of May 2018 from http://www.mereco.com/resources/ask-the-doctor/what-makes-epoxy-resins-good-adhesives-why-do-they-bond-so-strongly-to-surf

Meteolink (n.d.) *Weer records Nederland en de wereld*. Retrieved on 18th of May 2018 from http://www.meteolink.nl/weer-records-nederland-en-de-wereld/

Miljøskærm (2018) *Recycling of Fiberglass / Composite Materials.* Retrieved on 4th of February from http://miljoskarm.dk/english/

Mishnaevsky, L., Jr., Branner, K., Nørgaard Petersen, H., Beauson, J., McGugan, M. and Sørensen, B. F. (2017) Materials for Wind Turbine Blades: An Overview. *Materials 2017, 10*(11), 1285

Mohawk Group (n.d.) *Recycled rubber* [picture]. Retrieved on 20th of June 2018 from https://www.pinterest.co.uk/pin/56646907792948629/?lp=true

Mulder, P. (2012) *Waardepropositie creëren.* Retrieved on 29th of January from https://www.toolshero.nl/marketing-modellen/waardepropositie/

Muovipoli (2017) *Mechanical testing of WPC-profiles.* Retrieved on the 8th of March 2018 from https://static1.squarespace.com/static/5330780de4b025b2a08440a4/t/58e0d1586b8f5b410f650ca3/1491128666432/170118+report.pdf

Naplesbay (n.d.) *Rotorbladen Windmolen* [picture]. Retrieved on 21st of June 2018 from http://www.naplesbay.info/rotorbladen-windmolen.shtml

NDT Resource Center (n.d.) *Composite Structures.* Retrieved on 15th of January from https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/composite_class.htm

Neowa (2017) *Associated company neocomp gmbh.* Retrieved on 2nd of February 2017 from https://www.neowa.tech/references/neocomp-gmbh-1/

NetComposites (n.d.) *Glass Fibre/Fiber.* Retrieved on 13th of May 2018 from https://netcomposites.com/guide-tools/guide/reinforcements/glass-fibrefiber/

Nijhof, A.H.J. (2006) *Vezelversterkte kunststoffen: Mechanica en ontwerp.* Delft: VSSD

Nuwer, R. (2014) *What is the world's scarcest material?.* Retrieved on 11th of March 2018 from http://www.bbc.com/future/story/20140314-the-worlds-scarcest-material

Otani, L. B. and Pereira, A. H. A. (2014) *Elastic Moduli characterization of composites using the Impulse Excitation Technique* (technical report). Retrieved on 15th of January from https://www.researchgate.net/publication/276288705_Elastic_Moduli_characterization_of_composites_using_the_Impulse_Excitation_Technique

Owens Corning (2011) *Glass Fiber Reinforcement Chemical Resistance Guid*e. Retrieved on the 9th of March 2018 from http://www.owenscorningindia.com/ocindia/composites/pdf/oc_chemical_resistance_guide_edition.pdf

Palmer, J., Ghita, O.R., Savage, L. and Evans, K.E. (2009) Successful closed-loop recycling of thermoset composites. *Composites: Part A, 40*(2009), 490 - 498

Palomba Sarafini Associati (2009) *Fly Fly* [picture]. Retrieved on 15th of June 2018 from http://www.palombaserafini.com/it_IT/fly-fly/

Papadakis, N., Ramírez, C. and Reynolds, N. (2010) *Chapter 16 - Designing composite wind turbine blades for disposal, recycling and reuse.* Management, Recycling and Reuse of Waste Composites, Woodhead Publishing.

Pickering, S.J. (2006) Recycling technologies for thermoset composite materials – current status. *Composites: Part A, 37*(2006), 1206-1215

Pilling, J. (n.d.) *Mechanical – Thermal properties of selected fibres/matrices.* Retrieved on 7th of March 2018 from http://www.mse.mtu.edu/~drjohn/my4150/props.html

Pinterest (n.d.) *Recycling glass* [picture]. Retrieved on 20th of June 2018 from https://nl.pinterest.com/pin/95490454569703321/?lp=true

Plastic Notes (n.d.) *Polymer Polarity.* Retrieved on 16th of May 2018 from http://plasticnotes.blogspot.nl/2009/11/polymer-polarity.html

Plasticoop (n.d.) *Apet Sheet Pet Sheet Clear and Colored Glossy Embossed Matte Max 2100mm Instead of Cheap Polycarbonate Sheet Acrylic* [picture]. Retrieved on 21st of June 2018 from http://www.plasticoop.com/products/apet-sheet-pet-sheets-clear-and-colored-glossy-embossed-matte-max-2100mm-instead-of-cheap-polycarbonate-sheet-Acrylic-817753.html

Praet, J. (2012) *Shredded High Bench* [picture]. Retrieved on 20th of June 2018 from http://www.jenspraet.com/projects_shredded_2012_high_bench.html

Prospector (2018) *Lupolen 5261 Z.* Retrieved on 27th of May 2018 from https://plastics.ulprospector.com/datasheet/e45839/lupolen-5261-z

Pure Joy (n.d.) *Kitchen countertop* [picture]. Retrieved on 20th of June 2018 from https://www.trendir.com/unusual-kitchen-countertops/

Recycling Platform (n.d.) *Elektrische apparaten.* Retrieved on 17th of June 2018 from https://www.recyclingplatform.nl/recycling-processen/elektrische-apparaten

ReFiber ApS (2004) *We develop recycling technology for composites.* Retrieved on 4th of February 2018 from http://refiber.com/technology.html

Roozenburg, N. F. M. and Eekels, J. (2001) *Productontwerpen, structuur en methoden.* Utrecht: Uitgeverij Lemma BV

Royal Society of Chemistry (2006) *Composite materials* (chapter 4.3.1 of Inspirational Chemisty – Resources for modern curricula). Retrieved on the 11th of January 2018 from http://www.rsc.org/Education/Teachers/Resources/Inspirational/resources/4.3.1.pdf

Schumaker, S. (2012) *Hand Tool – Ice Cream Scoop* [picture]. Retrieved on 15th of June 2018 from http://www.coroflot.com/scottberkley/Hand-Tool-Ice-Cream-Scoop

Seminar on composite application in aerospace (May 2015) Retrieved on 15th of January from https://www.slideshare.net/rjrishabhjain/seminar-on-composite-application-in-aerospace-engg

Speksnijder (2018) *Reuse of Wind Turbine Blades In a Slow Traffic Bridge* (Master Thesis). Retrieved on 12th of May 2018 from https://repository.tudelft.nl/islandora/object/uuid%3A5af53410-1be0-43e0-9a6d-2e438b1865f9?collection=education

Super Local (n.d.) *Trending Terrazzo* [picture]. Retrieved on 20th of June 2018 from www.super-local.com

SuperUse Studios (2008) *Wikado*. Retrieved on 6th of February 2018 from http://superuse-studios.com/index.php/2008/10/wikado-2/

SuperUse Studios (2011) *ReWind Camping*. Retrieved on 6th of February 2018 from http://superuse-studios.com/index.php/2011/06/re-wind-camping/

Takeuchi, S. (2018) *Swing Bin* [picture]. Retrieved on 15th of June 2018 from https://www.kickstarter.com/projects/1349205551/swing-bin

Ten Busschen, A. (2016) Windesheim onderzoekt hergebruik composiet. *Jachtbouw Nederland, 6*(December 2016), 20 - 21

The Engineering Toolbox (2004a) *Epoxy – Chemical Resistance*. Retrieved on 13th of May 2018 from https://www.engineeringtoolbox.com/chemical-resistance-epoxy-d_786.html

The Engineering Toolbox (2004b) *Polyester – Chemical Resistance*. Retrieved on the 9th of March 2018 from https://www.engineeringtoolbox.com/chemical-resistance-polyester-d_784.html

The Wood Database (2018a) *Norway Spruce.* Retrieved on the 7th of March 2018 from http://www.wood-database.com/norway-spruce/

The Wood Database (2018b) *Scots Pine*. Retrieved on the 7th of March 2018 from http://www.wood-database.com/scots-pine/

Universal Plastics (2014) *Thermoforming Design Guidelines.* Retrieved on 13th of June 2018 from http://www.universalplastics.com/wp-content/uploads/2014/03/UP-Design-Guide-v1.2.pdf

Uribe, J. (2017) *What would Don Quixote recycle?*. Retrieved on 2nd of February from http://ecobulk.eu/public/news/what-would-don-quixote-recycle

Van Boeijen, A. G. C., Daalhuizen, J. J., Zijlstra, J. J. M. and Van Der Schoor, R. S. A. (2013) *Delft Design Guide*. Amsterdam: BIS Publishers

Vincent, G. (n.d.) *Recycling*. Retrieved on 17th of June 2018 from https://tprc.nl/research-overview/recycling/

Wind Europe (2017a) *Wind in power – 2016 European statistics*. Retrieved from https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2016.pdf

Wind Europe (2017b) *Wind Energy in Europe: Scenarios for 2030*. Retrieved from https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf

Wind Europe (2017c) *Discussing paper on managing composite blade waste*. Retrieved from https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf

TU Delft