STRUCTURAL REUSE APPLICATIONS OF WIND TURBINE BLADES

MASTER THESIS INDUSTRIAL DESING ENGINEERING TU DELFFT

Sammie van der Vinne

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Structural reuse application of wind turbines blades.

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Sammie van der Vinne
Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Chair: Dr. Ir. Jelle Joustra
Mentor: Dr. Soroush Aghaeian

SUMMARY

This thesis showcases applications for structural reusing wind turbine blades. Wind turbine blades are extremely difficult to recycle and thus reuse avenues are being researched to extent the useful lifetime of these blades. The goal of this thesis is to generate applications that utilise segments cut from wind turbine blades. This goal is approached in four steps: end of life, wind turbine blade design, cutting strategies and applications.

The first part focuses on the end of life of wind turbine blades. Analysing current and future waste management solutions that have been explained trough the lens of a waste hierarchy. Showing why reuse is a better option than current solutions and how this thesis fits into the entire reuse landscape.

The second part analyses wind turbine blades to better understand the design philosophies behind them and how this influences the reuse of wind turbine blades. It was found that the design, materials and the state of blade all influence reuse strategies.

The information found these first two parts is then used to generate the possible cutting strategy, cutting pattern and applications in the final two parts off this thesis.

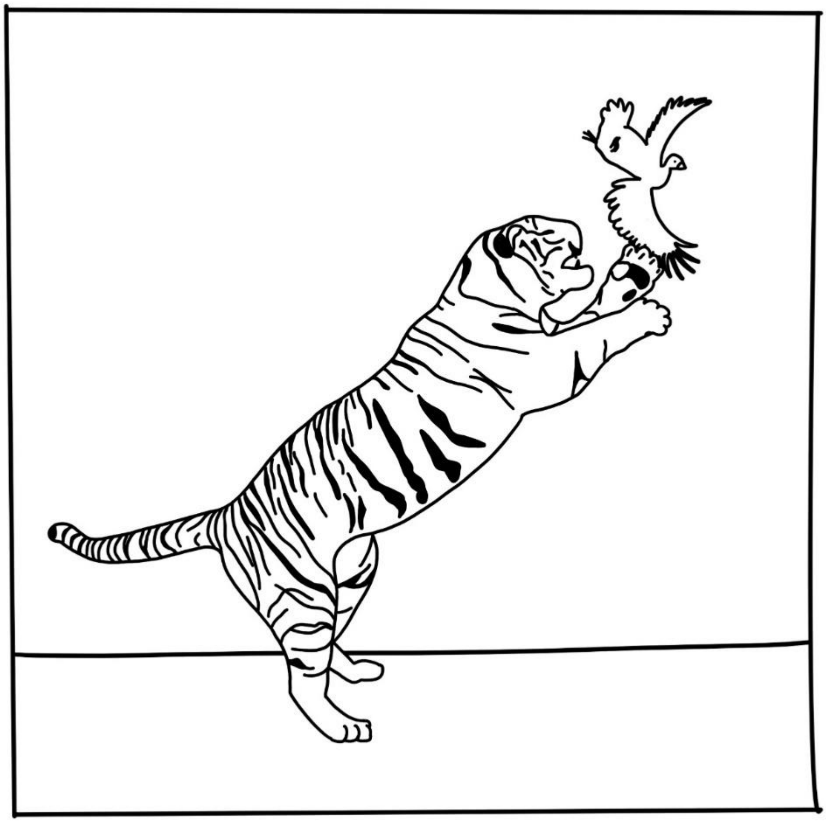
The third part ideated on a possible cutting strategy showcasing what steps should be taken to reuse wind turbine blades. Looking into the logistical and processing difficulties.

The last part uses all the information found and combines the knowledge to create a cutting pattern and a proposal for an applications. A cutting pattern using rectangular or triangular segments and simple beams was created that is used to create a concept of an adventure park.

PREFACE

This thesis is made as part my graduation project for the Integrated Product Desing master of the faculty of Industrial Design Engineering at the TU Delft. This thesis showcases the skills I have learned while studying here and is the end of a long journey.

I want to start by thanking my supervisory team, family and friends for helping me getting trough this long journey. It has had its ups and downs, but the most important thing I have learned is that one cannot know everything and we shouldn't always wonder "why, why, why".



Drawing recreated from a picture by Andrey Gudkov (2019).

"Tiger got to hunt, bird got to fly;

Man got to sit and wonder 'why, why, why?'

Tiger got to sleep, bird got to land;

Man got to tell himself he understand."

— Kurt Vonnegut, Cat's Cradle

TABLE OF CONTENTS

ABBREVEATIONS

CFRP	Carbon fibre reinforced polymer.
EOL	End of life.
FRP	Fibre reinforced polymer.
GFRP	Glass fibre reinforced polymer.
HAWT	Horizontal axis wind turbine.
LCA	Life Cycle Assessment.
MW	Mega Watt.
TRL	Technology readiness level.
VAWT	Vertical axis wind turbine.
WT	Wind turbine.
WTB	Wind turbine blade.
UD	Uni-directional.

INTRODUCTION

Windmills and their modern counterparts the wind turbine have been a staple of our landscape for decades and with more effort being put into renewable energy their numbers will only rise. The Netherlands has planned to obtain 75% of its energy needs from wind by 2030 (windopzee..nl, n.d.) But what happens to these wind turbines after their service life is ended. Around 94% of a wind turbine can be recycled (Schleisner, 1999) but there are difficulties with the remaining 6%. The wind turbine blades are one of the challenges, they are made of a composite sandwich of glass fibre reinforced polymer (GFRP) with a light wood or foam in between. It is possible to recycle such a monstrous hybrid[1] but this is a difficult endeavour. An interesting alternative is to repurpose or reuse the old blades.

RESEARCH GOAL

Reusing old wind turbine blades is a difficult task. They have a double curved aerodynamic shape and their are plethora of different versions in use today. This often leads to the reuse of entire blades or the usage of large segments. A possible interesting direction is a system that strategically cuts smaller segments out of the blades that can be used to build multiple structures. Structural reuse through segmentation is such a reuse strategy (Joustra et al., 2021). The goal of this project is to design applications and research if it is possible to design a cutting strategy suited for multiple models of wind turbine blades. Making it possible to build larger structures from smaller cuts (segments) of a wind turbine blade. These structures could then be taken apart and be built into something new. This could make it easier to reuse old wind turbine blades possible lowering the environmental load that is connected to the end of live of a wind turbine.

This results in the following research goal:

Identify structural reuse applications for wind turbine blades and develop a cutting strategy that can be used to cut standardized elements from multiple wind turbine blade models. Then demonstrate the cutting strategy with a possible structure.

[1] The combination of technical and organic materials is considered a monstrous hybrid when looking at the definition given in Cradle to Cradle (Braungart & McDonough, 2002, p.99).

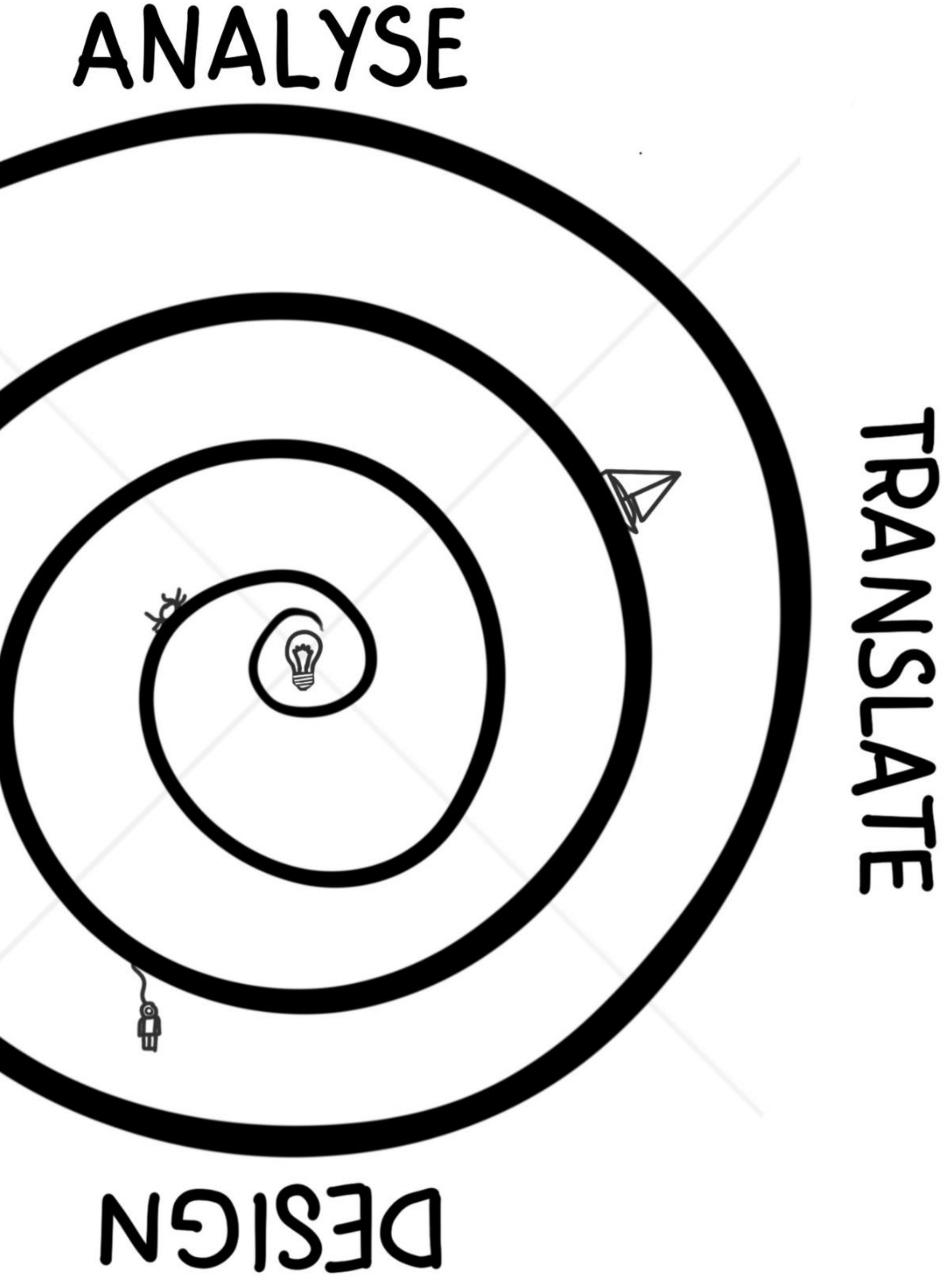
This research goal is then subdivided into five research questions.

1. What are current and possible future end of life solutions for wind turbine blades?
2. How does the composition and build-up of wind turbine blades influence a possible application and cutting strategy?
3. How can wind turbine blades be strategically cut to ease structural reuse solutions?
4. What applications can be identified to structurally reuse wind turbine blades?
5. How can a structural application be designed/ made by repurposing wind turbine blades?

APPROACH

The goal of this project will be to show a non- blade specific cutting strategy that can be used to make structures as a way to reuse old wind turbine blades. This goal will be attacked by answering the five research questions of the previous page and any possible other question that might arise. This project will be approached using a Research trough Design methodology with critical journaling (reflecting reporting method) as a way to keep track of work. Desing tasks will be used as an input for later research and research will be used as input for design tasks. Going through a cyclic design spiral depicted on the right.

The cyclic design spiral can be explained as a design process that starts of as wide as possible and slowly goes into detail, with the goal of finding its way to a final design in the middle of the spiral. There are four phases that will get repeated as often as is necessary. It starts of with analysing and researching information. Trying to learn anything useful and to understand the subject better. The next phase is the translate phase, it exist to generate conclusions and questions. The learnings of this phase are than translated in the next phase into design tasks. The design tasks can be very broad this includes for example: brainstorming, drawing, prototyping (high-fi and low-fi), etc. Then the next translate phase has the same goal but now to find tasks for the next analysis phase. And we are back at the analysis phase going into a new cycle but with a better idea of what is going on and with more precise questions to research. This approach is a simplified version of the basic design cycle explained in the Delft Desing Guide (van Boeijen et al., 2014, p. 19). But with the added goal of going through multiple design cycles, each one more homed in on the final design.


ANALYSE
TRANSLATE
DESIGN

READING GUIDE

This thesis is divided into five parts it starts with an analysis of the problem space and ends up with a proposed applications of structural reuse trough segmentation. Each part will try to find an answer to one of the five research questions that were given in the previous chapter. The goal of part one and two is to explain the problem space to any one that has never heard about wind turbine blades. It will thus be a broad analysis that will miss some nuance of certain subjects, you are recommended to look at the referenced sources to go into a deeper dive if a subject sounds interesting to you. This analysis isn't only useful to better understand the problem space but will also be used to find factors of influence that can steer the cutting strategy and structural reuse applications. Part three and four will propose possible cutting strategies and applications, showing the design steps and reasoning behind decisions. The last part, part 5, will be a conclusionary part with the conclusion, recommendations and limitations of this thesis.

Part 1: The end of life of wind turbine blades, will analyse the current waste management strategies using a waste hierarchy as a lens. The goal is to better understand the problem space of wind turbine blades and how reuse fits into the current waste management strategies landscape.

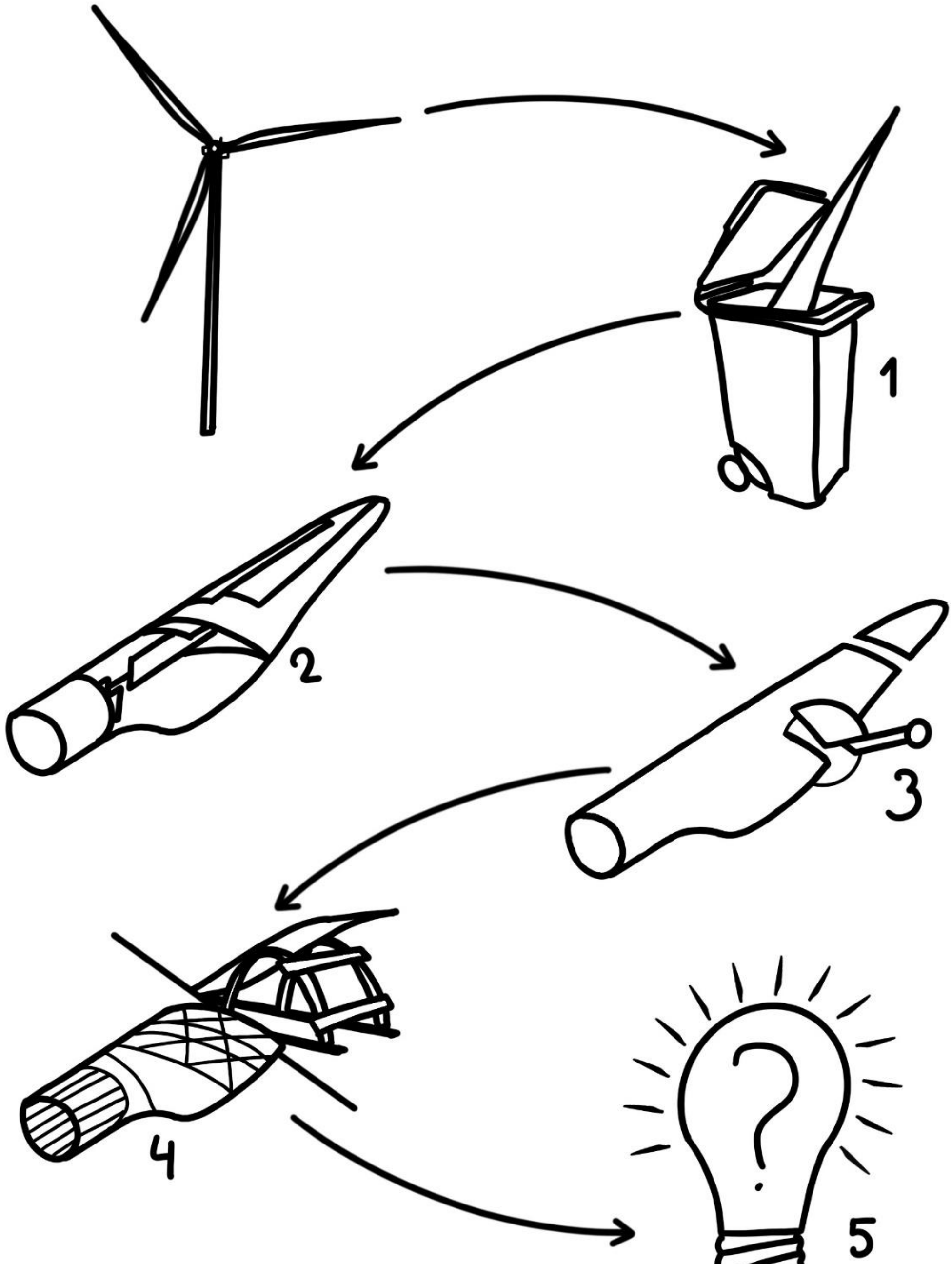
Part 2: Understanding wind turbine blades, will analyse the design of wind turbine blades. The goal is to better understand the segments and their properties that will be used in reuse steps, this is done by analysing the shape, the materials and the state of wind turbine blades.

Part 3: Cutting strategies, will ideate on possible cutting strategies. The goal is better understand the system around the structural reuse trough segmentation of wind turbine blades. This is done by analysing factors of influence and the resulting criteria and then propose possible cutting strategy.

Part 4: Reuse applications, will ideate on possible applications and cutting patterns. The goal is to end with a concept that showcases a cutting pattern usable for multiple applications. This done by going trough ideation phases and using the factors of influence and criteria of part 3 to hone down to one application.

Part 5: Conclusion, will finalize this thesis by giving a conclusion, recommendations and limitations.

But before we go into the depth of knowledge that can be found about wind turbine blades we will first learn a bit about the wind turbine it self.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1 WIND TURBINES

Wind turbines have a long history spanning centuries and enough differing designs to fill an multi print encyclopaedia. This chapter will only shortly touch on wind turbines leaving their vast history for others to write about. Wind turbine blades (WTB) are part of a larger system of a wind turbine and it is good to have a better understanding of how they fit in. This chapter will thus give a small overview of wind turbines but we will quickly go to wind turbine blades, the main focus of this thesis.

1.1 WIND TURBINE HISTORY

Wind turbines have been a relatively recent addition to our landscape but they have a long history of doing work for us. The historical counterparts of wind turbines, windmills, have existed for centuries doing work like grinding flour or pumping water. The Dutch windmills have existed since around the 1200s (Cheng, 2020), but the history of wind mills being used for electricity generation started just shy of 700 years later. The first electric generating wind turbine was designed by James Blyth in the year 1887 (Gipe & Möllerström, 2022). The design of this wind turbine is quite different than what we are accustomed to today. The modern wind turbines have their foundation around 1970s when an oil embargo triggered a new found interest in the alternative energy production techniques (Gipe & Möllerström, 2023). Resulting in the first offshore wind farm being built in 1991 (Environmental and Energy Study Institute (EESI), 2010).

1.1 WIND TURBINE TYPES

There are many types of wind turbines but the main differentiator is the axis direction, which can be vertical (VAWT) or horizontal (HAWT). Both designs have their advantages and disadvantages, but HAWTs are the most prevalent today (Eriksson et al., 2006). There are many different types of HAWTs (just like with VAWTs) but the main focus of this thesis are the blades of a three bladed HAWT. This type of wind turbine can be found both on land and at sea, called onshore and offshore respectively. The three bladed HAWT consist out of three parts: the tower, the nacelle and the rotor. (Electrical Academia, n.d.) These three parts can be seen in the picture on the next page, the tower supports the entire structure and gives the necessary height to the WT, the nacelle is located on top of the tower and houses all the electronic systems (generator, gearbox etc) and lastly the rotor which is affixed to the nacelle and translates the kinetic energy of the wind into mechanical energy, rotation. This translation of energy is accomplished using the three blades.

This small overview was only the surface level of information that can be found about wind turbines, but now this thesis will go to the main focus wind turbine blades. Starting with part one: The end of life of wind turbine blades.

Picture 1. Wind turbine north of Essen Germany. Photo by Sammie van der Vinne

PART 1

THE END OF LIFE OF WIND TURBINE BLADES

Picture by Benjamin Rasmussen (2020) for Bloomberg Green

The first part will investigate the end of life challenges surrounding wind turbine blades. Trying to answer the first research question: *What are current and possible future end of life solutions for wind turbine blades?* Trying *to* create a better understanding of problem size, problem intricacies, current solutions and possible future solutions. The main reason for asking these questions is to figure out how structural reuse fits into the problem space as a solution, and how any cutting strategy can be designed tailored to solve this problem.

Part one will start by analysing the problem size and then goes on to explaining a waste hierarchy which will be used as a lens, structuring information of current and future end of life solutions.

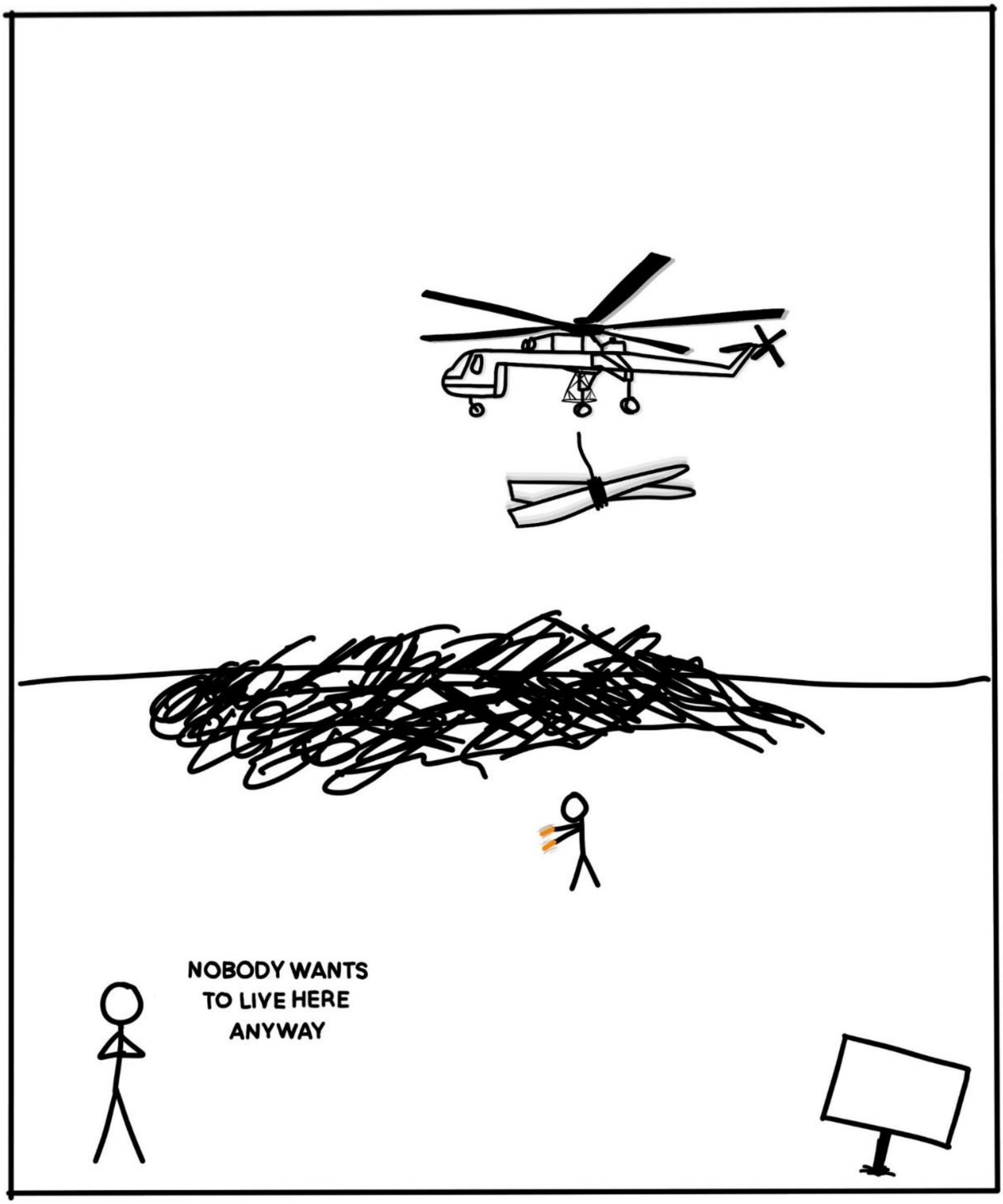
2 THE END OF LIFE OF WIND TURIBNE BLADES

Wind turbines can almost fully be recycled, to about 94% (Schleisner, 1999), but the remaining 6% is a challenge. One challenge is the end of life of the composite blades, one such blade can be seen in picture 2. The blades are often made from a GFRP and balsa sandwich (elaborated upon in chapter 6), which is hard to recycle (elaborated upon in chapter 3). The blades are, at the moment, undesirable, but are they here to stay?

Yes these blades are here to stay, multiple life cycle analyses (LCA's) have shown that wind turbines are a sustainable source of electricity. Wind turbines, depending on the model analysed, can generate the energy cost of construction within 3.1 to 7.8 months (Schleisner, 1999), (Vestas, 2006), (Vestas, 2022) and (Guezuraga et al., 2012). Thus the blades are a necessary evil which need to be dealt with.

So what can be done when the service life of blades has ended and we have to deal with the fact that there isn't enough space to keep dumping blades. The goal of this chapter is to better understand if the challenges surrounding the end of life of WTBs. This will be achieved by first an investigating literature about WTB waste and then present current and possible future end of life strategies.

Picture 2. Wind turbine blade being transported by Collet & Sons UK . Image credit: theconstructionindex.co.uk, 2016.


NOBODY WANTS
TO LIVE HERE
ANYWAY

2.1 A DRIFTING PROBLEM SIZE

The end of life of WTBs is not the only source of waste in the life time of a wind turbine. WTBs also generate waste during the manufacturing stage, operation, maintenance and while upgrading. This can add between 16% to 45% of total blade mass to the end of life waste of a WTB (Liu & Barlow, 2017). It shows that there is a bigger problem than just WTBs and one that will grow with the increasing use of wind turbines. This could be an interesting research avenue, but it is outside the scope of this thesis. For now the focus is on the end of life stage of WTBs and it will become and increasing problem.

WTB waste is becoming a big problem. The European Commission is trying to boost the European wind power industry to be able to achieve their renewable targets (European Commission, 2023). Liu & Barlow (2017) project that in 2050 the world will have to deal with an annual waste generation of 2.000.000 tons. Europe will generate about 25% of this total, around 500.000 tons. The largest amount of waste will be generated in China, around 40%. Thus when looking at the bigger picture of WTB waste management solutions the differing cultures should also be taken into account. But the design the context of this thesis will be Europe.

Lichtenegger et al. (2020) have also generated a WT blade waste forecast, but focused on Europe until 2050. Their forecast shows an increase of waste until 2045 where it will plateau at 325.000 ton per year. This plateauing of the forecast is attributed to the saturation levels of wind turbines in Europe. They also analysed how regional levels are effected which shows that there will be moving waste hot spots throughout Europe and that certain ports will become important hubs for WT blade management. These two facts make the cross border collaboration of WTB management an important ambition. The same effect of moving waste hotspots is seen on a smaller scale in the research of Delaney et al. (2021). They did a case study on a geospatial approach for repurposing wind turbine blades in the context of Ireland. Their analysis shows that there needs to be a strategy that can take into account the movement WT waste hot spots across the country. If only one place is used as a repurposing site then it will lead to large transport distances and logistical difficulties.

One element all waste forecasts have In common is that it will become an increasingly big problem that will necessitate collaboration between all parties involved. But it cannot be forgotten that it is already a problem that will need solving so what are we currently doing?

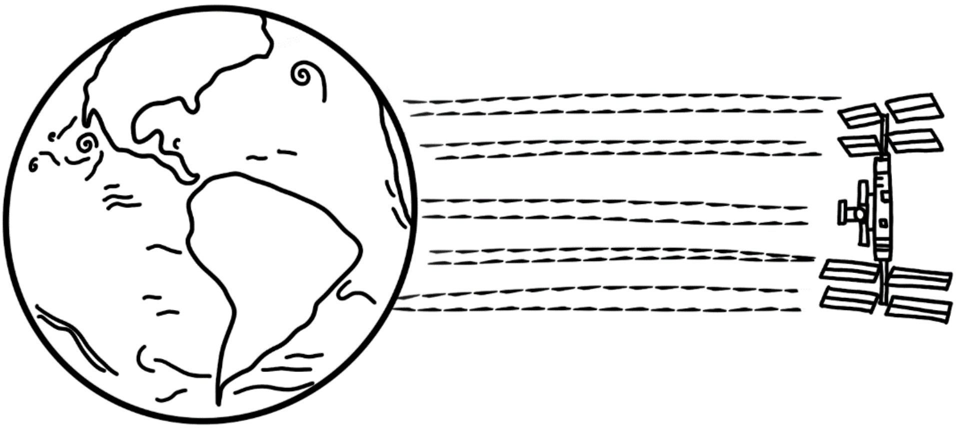


Figure 1. 2.000.000 tons would equate to around 36.367 GE Haliade-X blades at 55 tons (de Vries, 2019), one of the longest blades ever manufactured (Kellner, 2019). With a length of 107m, if laid end to end it can go 5 round trips from the earth to the ISS and back. (When using a smaller 38m blade with an weight of 2,36 tons (Malshan, 2022) this number goes up to about 20 round trips). [2]

[1] Figure is not drawn to scale, the international space station orbits about 422 km from the earths surface (heavens-above.com, n.d.).

3 WASTING WIND TURBINE BLADES?

This chapter will look at the current and possible future waste management techniques. A good starting point trying to understand the waste challenge of WTBs is to understand the waste hierarchy. Waste hierarchies rank, as the name suggest, ways to manage and get rid of waste. A waste hierarchy can be used as a lens to look at and group end of life strategies, but there are many different adaptations of waste hierarchies. The United States Environmental Protection Agency (EPA, 2023), the United Nations environment programme (Wilson et al., 2015), and the European Union (European Commission, n.d.) have one. Next to different versions there also exist a plethora of interpretations that are used in literature. For this thesis the European Union's Waste Framework Directive (Directive 2008/98/EC.) is chosen as the leading hierarchy and definition. The hierarchy is depicted on the next page and goes from most preferred at the top to least preferred at the bottom.

The directive states in article four that member states need to encourage industries to take actions that have the best environmental outcomes, but disposal (Paulsen & Enevoldsen, 2021) and recovery (Jensen & Skelton, 2018) techniques are still the most common ways to manage WT blade waste. The waste management of wind turbine blades still has some room for improvement. The coming chapters will go into the different waste management techniques and how they are applied on WTBs.

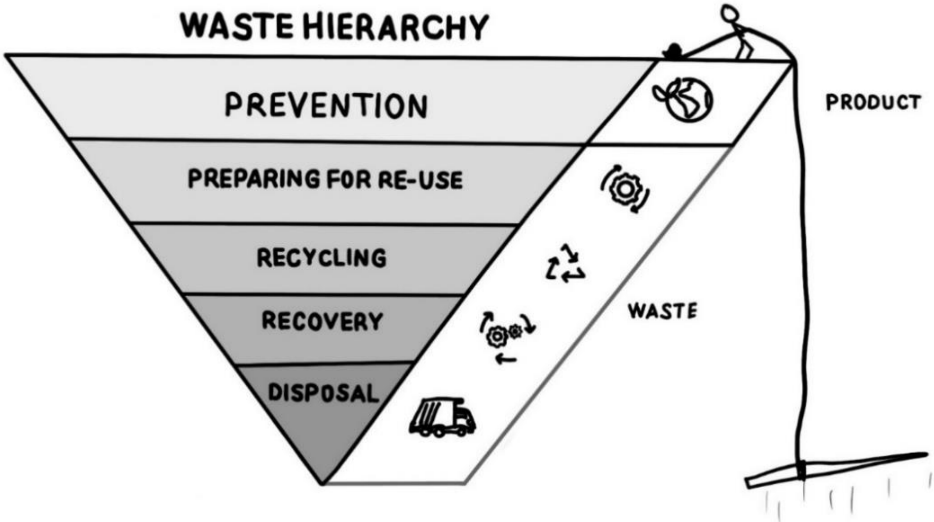


Figure 2. Visual recreated from European Commission, n.d.

The directive gives the following (paraphrased) definitions for the levels:

> **Prevention**: Measures that reduce the quantity of waste.
>
> **Preparing for re-use**: Operations so products or components that become waste can be re-used. Re-use: any operation where components or products are used for the same purpose.
>
> **Recycling**: Reprocessing waste materials into new products materials or substances.
>
> **Recovery**: Using waste in place of other materials which would otherwise be needed to be used. For example incineration and composting (Annex 2 of the directive).
>
> **Disposal**: Any operation that is not recovery. For example landfilling and landfilling adjacent operations (Annex 1 of the directive).

3.1 DISPOSAL – AN EARLY RETIREMENT STRATEGY

The lowest strategy on the waste hierarchy is disposal, it is the least preferred strategy because the materials are, to a certain extent, retired to their disposal location not to be used for any useful purposes. There are many ways to dispose of waste: land treatment, deep injection, surface impoundment, releasing into a body of water, incineration on land, (Directive 2008/98/EC.) but the most common one is land filling.

3.1.1 LANDFILLING

Land filling is the act of disposing of waste by dumping it on land, it is quite a commonly used around the world. The world bank group (Kaza et al., 2018) notes that about 70% of all global waste gets land filled or dumped. This number is around 16% in Europe (on the website of the European Environment Agency 2022). Landfilling is also used to dump decommissioned WTBs, but it has the distinct drawback that stems from the materials used in wind turbine blades. Once dumped it can be expected that the blades will be there for ever. Below we can see a picture by Benjamin Rasmussen of WTBs being landfilled in Wyoming.

Landfilling of WTBs is still a current practice in the United states of America (Cooperman et al., 2021), but it is starting to be less common in Europe. The WindEuope organisation, the European industry organisation for wind energy, even advocates for an Europe-wide landfill ban for composite WTBs. Which some countries have already done (Austria, Finland, Germany, and the Netherlands) (WindEruope, 2021). Certain companies also set their own targets for landfill bans, for example Vattenfall has stated to stop landfilling by 2030 and to fully recycle their WT blades (Vattenfall, 2021).

Picture 3. Wind turbine blades being covered by dirt in a landfill. Benjamin Rasmussen (2020) for Bloomberg Green

3.2 RECOVERY – RETRIVING THE SPEND ENERGY

Recovery strategies use waste in place of other materials which would otherwise be needed, this way the energy within the waste can be recovered. There are multiple recovery strategies but the main utilized for WTB waste is incineration (Jensen & Skelton, 2018). Another strategy is co-processing, in this process the waste is used as both fuel and mineral source.

3.2.1 INCINERATION

Incineration is a process where waste is burned in a furnace, this generates: ash, flue gas and heat. This is done in a incineration plant and the heat can be used for electricity production (Wikipedia, 2024). Two drawbacks of incinerating WTB waste is the amount of ash it leaves behind, about 60% of the original weight (Jensen & Skelton, 2018). Incinerating WTB waste also creates problems for the flue gas cleaning system (Beauson & Brønsted, 2016). Thus although incineration is a solution it isn't always preferred.

3.2.2 CO-PROCESSING

Co-processing uses the WTB waste both as energy and as a mineral source. This is often done in a cement kiln (see picture below) The shredded waste is mixed with other fuels and is ignited to heat the cement kiln. When the mixture is heated past 1450 degrees Celsius then the minerals of the glass fibre change into alumina, silica and calcium oxide (components of Portland cement), (Nagle et al., 2020). One drawback of using WTB waste is the baron that exist in glass fibres. To much boron can slow down the drying process of cement. But this can be mitigated by using a mixture with a maximum of 10% composite waste (Pickering, 2005). Thus Co-processing is a usable management technique but it has its limitations.

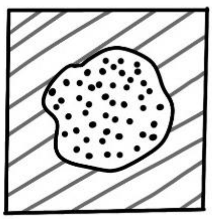
Picture 4 Incineration plant of Roskilde Denmark. Picture by Hielpler (2020). It must be noted that incineration plants often don't look this nice.

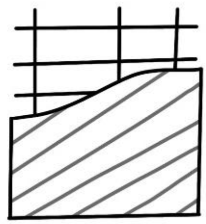
Picture 5 Rotary kiln which is used for cement production. Picture from heavy-plant..com (n.d.) The kiln is only one step of the entire cement production process.

3.3 RECYCLING – RETRIEVING THE USED MATERIALS

Recycling strategies, at first sight, seem like better solution than recovery and disposal, but there are some challenges inherent to the materials and recycling strategies that could explain their underutilisation. These challenges will be elaborated upon later, first the existing recycling strategies will be explained.

Recycling strategies can be clustered in three categories, mechanical, thermal and chemical (Palmer, 2009) and can yield bulk materials, fibres, powders and polymers (Zhang et al., 2023). The yielded materials are then used for secondary applications. There exist a plethora of uses but they can mostly be divided into three groups: fillers, reinforcements and mineral utilisation. Some examples are displayed in table 1 below.





Filler	**Reinforcement**	**Mineral utilisation**
In wood particle board. (Pickering, 2005).	In asphalt. (Pickering, 2005).	Production of concrete (Pickering, 2005), (Baturkin et al., 2021).
Aggregates in concrete. (Baturkin et al., 2021).	In composites. (Chen et. al., 2019). (Mamanpush et al, 2018). (Caramelo et al, 2024)	Production of geopolymers. (Zheng et al., 2023).
	In concrete. (Chen et. al., 2019), (Baturkin et al., 2021), (Yazdankbakhsh et al., 2018).	
	In wood particle board (Jensen & Skelton, 2018).	
	Additive in paint for UV stability. (Jensen & Skelton, 2018).	
	In mortar. (Rodin et al., 2018).	

Table 1, Secondary applications for recycled wind turbine blades, non-exhaustive list.

3.3.1 THE FIRST STEP OF RECYCLING

Before the recycling of WTBs can commence the blades first need to be reduced in size to ease logistical challenges of moving large WT blades. Multiple techniques exist: concrete cutter, diamond saw, grinding belt and water jet cutting (Ten Busschen et al., 2023). Next to size reduction for logistical reasons it is also necessary to reduce the size of the segments to smaller pieces for almost all recycling strategies. Each technique has its advantages and disadvantages, this can be the amount of dust created, design freedom and cutting damage. It is good understand these because one of these tools will be used to process the wind turbine blades.

Picture 6. Grinding belt (Ten Busschen et al, 2023). Image credit: Odolphi Technical Support

Picture 7. Echidna rock saw (echidna.com.au, n.d.). Image credit: Echidna.com.au.

Picture 8. Water jet cutting (Nehls, 2022). Image credit: TNO.

Picture 9. Jaw crusher (lifebrio.eu, 2015). Image credit: lifebrio.eu

3.3.2 MECHANICAL RECYCLING

The main goal of mechanical recycling is to reduce the size of the blade to manageable pieces that can be used in secondary applications or processes. This can be done with a large array of sizes, for example 20mm cubes (Baturkin et al., 2021) or to a size of a couple of millimetres (Beauson et al., 2016). Multiple techniques can be chosen, depending on the size and homogeneity needed. These are: shredding, crushing (Jensen & Skelton, 2018), grinding and milling (Paulsen & Enevoldsen, 2021). There are three main steps to mechanical recycling: the first step is to cut the blades into manageable chunks, these chunks then get processed in step two using the aforementioned techniques (multiple cycles or tools might be needed depending on required material size) and the final step is sieving to filter out the right size for secondary applications (Rahimizadeh, et al., 2019). Good to note is that most recycling processes can only handle smaller pieces and thus utilise mechanical recycling techniques for a size reduction step (Paulsen & Enevoldsen, 2021) .

3.3.3 THERMAL RECYCLING

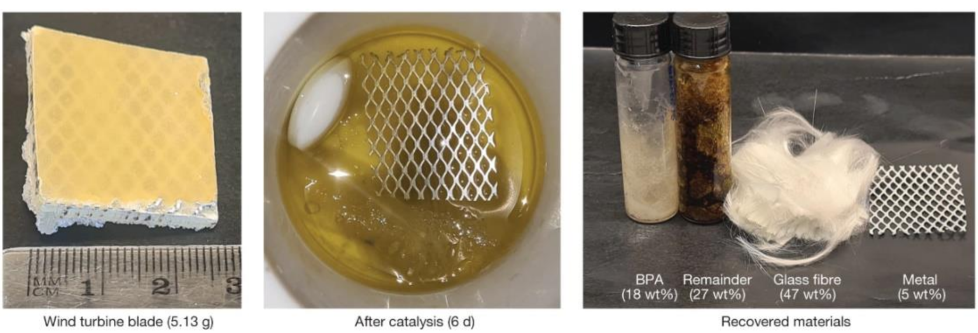
The goal of thermal recycling is to degrade the chemical bonds within the polymer matrix to free the fibres using heat. The fibres can be reclaimed and the degraded polymer can be used as an energy source (Ramirez-Tejada et al., 2016). The temperature usually ranges from 300 to 1000 but can depend on the process used and material that is being recycled (Paulsen & Enevoldsen, 2021). Multiple techniques exist to accomplish this: pyrolysis, microwave pyrolysis, fluidized bed combustion (Paulsen & Enevoldsen, 2021), (Asmatulu et al., 2013), (Ramirez-Tejada et al., 2016), (Pickering, 2006). These processes differ in heat, environment and heating method. One problem with the high temperatures is that glass fibres will lose about 50% of its tensile properties at 450 degrees (Pickering, 2000).

3.3.4 CHECMIAL RECYLING

The goal of chemical recycling is to remove the polymer matrix from the fibres using chemicals. This process creates clean fibres, clean filers and depolymerised matrix. This process also goes by the name of solvolysis and depending on the solvent used can be named hydrolysis (using water), glycolysis (using glycols, organic compounds from the alcohol family (Britannica, n.d.)) and acid digestion (using acid), (Yang et al., 2012). There are two types of solvolysis processes, high temperature pressure (HTP) and low temperature pressure (LTP). HTP is usually above 200 degrees Celsius and uses water or alcohol as solvents. LTP is usually below 200 degrees Celsius and uses aggressive solvents to achieve the same results as HTP with a lower temperature and pressure. The advantage of LTP is that the lower temperature doesn't damage the fibres as much as the high temperatures of HTP (Paulsen & Enevoldsen, 2021).

Picture 10. Portable wind turbine blade recycling solution (left) and shredded wind turbine blade (right). Image credit: ssiworld.com (2023).

Picture 11. Thermal decomposed wind turbine blade (pyrolysis), left: before, right: after. Image credit: refiber.com (n.d.).



Picture 12. Breaking bods with in the matrix to retrieve materials for recycling. (Ahrens et al, 2023).

3.3.5 RECYCLING CHALLENGES

Recycling strategies sound like better solutions than disposal and incineration, but these two are still the most common solutions. Recycling strategies have some challenges that could explain their underutilisation and why they are sometimes a difficult proposition to make. These challenges are the design of the blades, the technical readiness/ availability of recycling strategies, the obtained material quality, yield rate and finally operational difficulties.

COMPOSITE BLADES

The first challenges lies within the innate difficulty of recycling a large composite structure. Cherrington et al., (2012) notes several factors. The first factor are the logistical problems during decommission that stem from the large size of the blades, there are currently blade being manufactured north of a hundred meters long (Kellner, 2019). The second factor is the material composition of blades can be vastly different (fibres, matrix, core, additives, coatings). Most blades use thermosets (creating difficult to break crosslinks). The final factor is the harsh life that blades have to endure which can result in their quality being reduced. Jensen & Skelton (2018) also noted that adding composite material to virgin material can have implications for the end of life recycling of the new created materials and that blades can have unknown materials that can influence processes later on.

READINESS AND AVAILABILITY

The second challenge stems from the technical readiness and availability of recycling strategies. Paulsen & Enevoldsen (2021) have analysed the technology readiness levels (TRL) of certain recycling techniques[1]. Their conclusion is that only mechanical, incineration and landfilling strategies are in the deployment phase. Co-processing is a close second with a score of 8-9 and Pyrolysis with a score of 7. The remaining strategies are all still in the development phase: solvolysis (5-6), high voltage pulse fragmentation (5), fluidized bed (4-5) and microwave pyrolysis (4). The low TRL scores also indicate a low availability of the certain recycling techniques. The European Composite Industry Association (EuCIA, 2023) publishes a regular updated but non-exhaustive database of recycling solutions. This database contains 39 companies of which 20 gave their process. Of these 20, 14 use mechanical recycling as one of their processes eight use thermal recycling as one of their processes and four use chemical recycling as one of their processes. Thus there aren't enough recyclers to handle the waste stream and most strategies are not yet deployed on a large scale

[1] The TRL score is ranked from 1 to 9 with four phases: Discovery phase (1, 2 & 3), Development phase (4, 5 & 6), demonstration phase (7 & 8) and Deployment phase (9) (Rijksdienst voor Ondernemend Nederland, RVO, 2023).

YIELD AND QUALITY

The third challenge is the obtained material yield and quality. As Cherrington et al., (2012) noted an drawback of recycling WT blades is the harsh life that blades have to endure (which will be elaborated on in chapter 9), but recycling it self also reduces the material properties. Glass fibres looses about 50% of its tensile strength when heated to 450 degrees (Pickering et al., 2000). Many recycling processes use temperatures around or above 450 degrees and can thus decrease the material properties of the fibres. Liu et al. (2018) reviewed multiple sources and summarized the retained tensile strength of recycled fibres in comparison to virgin fibre. For glass fibre the range is 52% to 88% and for carbon fibre the range is 50% to 95%. Although they have quite similar ranges, carbon overall retains better material properties. Liu et al. (2018) also reviewed the yield rate of several strategies and its range lies between 42% and 95%, with an average of 67%. Thus you don't get all your fibres back, they aren't at the strength they were originally and because most strategies recycle smaller pieces you also lose the advantage of long fibres.

OPERATIONAL DIFICULTIES

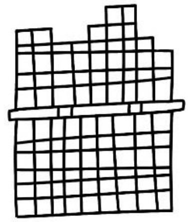
The final challenge is the cost and difficulties of operating most recycling techniques. Jensen and Skelton (2018), part of the GENVIND consortium, noted some drawbacks and difficulties of mechanical recycling. Getting a homogenous mass is difficult and requires a lot of processing steps, increasing the cost. They also note that many recycling techniques are demanding in terms of time and energy. For example chemical recycling requires hazardous chemicals and is rather costly (Jensen, 2018).

3.4 REUSE STRATEGIES – EXTENDING THE USAGE

The EU directive states that re-using is the act of using the component or part for the original purpose. This can be a difficult task depending on the state of the entire wind turbine and its individual components, the supplied design information and any possible run time information (Lauritsen et al., 2016). Strategies exist to extend their life time and re-use the blades but they will eventually get decommissioned. The next step on the waste directives ladder is recycling, but the energy put into the manufacturing of the parts is lost when the materials are recycled. The fact is, there is a missing step on the directives ladder. Re-use within the sustainability research looks outside this definition and looks at re-using the wind turbine blades for other purposes. This way the energy that is used in the manufacturing of the materials and product is not lost prematurely. Reuse is thus often seen as extending the useful life time of a material and not as a way of managing waste. The material still becomes waste but now when its life is spent and it has been used to the fullest extend.

3.4.1 SCHOOLS OF THOUGHT

Multiple schools of thought can be found when looking at research using this revised meaning of reuse strategies. These are: Entire blade, custom cutting and generic cutting. The distinction between the three can be best explained by an analogy, a tree. A tree can be used for a myriad of uses and by cutting or processing this list only increases exponentially. The first school of thought is the simplest way to utilize a tree is to use its entire structure, for example as a base of a treehouse or as a way to generate shade. The three doesn't have to be significantly altered and can be used almost as is. The entire blade camp has the same idea, why alter an already existing structure that already is useful for us. The second school of thought can be explained as cutting down the tree and milling it to use as a beam for your log house. The three gets cut and milled to the specific specifications for your application and cannot be used for anything else any more. The cutting for single application camp has the same goal, find a way to cut the blade strategically so it can be used for a specific application. The third, and last, school of thought is to cut down and mill the tree into standardized beams and planks, like you can buy in the hardware store. You are not sure what application will be able to utilize the beams but this way they are easy to use and the process is easier to scale. The cutting for multiple applications camp has the same goal, processing the blades into standardized pieces so they can easily be used for multiple applications. Table 2 on the next page gives some examples of reuse applications grouped into the three schools of thought.



ENTIRE BLADE	**CUSTOM CUTTING**	**GENERIC CUTTING**
Bridge. (Andre et al, 2020)* (anmet.com, n.d. b) (bladebridge.ie, 2022)	Roofs and panels for affordable housing. (Bank et al, 2018).*	Beams. (Joustra et al, 2021 a)*
Lookout tower. (blade-made.com, 2022b) (anmet.com, n.d. a)	(Urban) furniture. (Joustra et al, 2021 b)* (anmet.com, n.d. c) (blade-made.com, 2018) (Kirilova & Narua, n.d.)	Panels. (Bank et al, 2018)* (Joustra et al, 2021 a)*
Transmission pole. (Alshannaq et al, 2021)*	Playground. (blade-made.com, 2008)	
Architectural applications. (Goodman, 2010)*	Shelter. (Katsikopoulou, 2021) (blade-made.com, n.d.)	
Art installations. (arlnow.com, 2017) (blade-made.com, 2019)	Planters. (blade-made.com, 2022a)	
Solar structure. (turn2sun.com, 2023)	Partitions / walls. (Nagle et al, 2022)*	
Pontoon / floater. (dutchdesingfoundation.com, 2024)	Architectural applications. (Dickson, 2024)	

Table 2, Overview of reuse applications from literature and online sources, a non-exhaustive list. Many more examples can be found in the Re-Wind Desing catalogue at re-wind.info*

ENTIRE BLADE

The goal is to find applications that can utilize the entire or as much of the original structure as to not lose the effort and energy that has been put into the creation of the original part. Multiple examples can be found as was shown in table 2. The biggest disadvantage of this strategy is that larger blades are harder to utilize and transport, and in the future the decommissioned blades are only getting bigger. This also why most of the applications that can be found that utilize the entire blade are using smaller blades. Its biggest advantage is the lack of processing (depending on the application) in comparison to the other strategies.

Picture 13. WTB used as structure to hold solar panels created by turn2sun.com (2023). Image credit: Turn2Sun Renewables.

Picture 14. WTB used as structure for a bridge created by bladebridge.ie (2022). Image credit: BladeBridge Repurposing Solutions.

CUSTOM CUTTING

The goal of custom cutting is to find applications for which WT blade material could be a good substitute. The application and cutting strategy are often designed alongside each other to find a good fit for the material and final design. The disadvantage is that the cutting strategy is often only usable for the specific application, if a shelter is designed the cutting strategy can create a shelter and not anything else making it harder to scale. But this way of designing both the cutting strategy and application alongside of each other gives a designer more control and thus is its advantage.

Picture 16. Table and bench set designed by GP-Reneweables group (n.d.). Image credit: GP Renewables.

Picture 15. Bike garage in Aalborg Denmark, katsikopoulou (2021). Image credit: Siemens Gamesa.

GENERIC CUTTING

The goal of generic cutting is to find a cutting strategy that creates standardized pieces in the most optimal way. The strategy aims at creating panels, beams, planks or any other standardized piece that can be envisioned. Its advantage is that is easier to scale up but its biggest disadvantage is the uncertainty of the usefulness of the created parts. Just like wood from the hard ware store they don't always have the size or shape that is needed, it can thus be uncertain how much the created parts can be used. It is thus good to design applications at the same time as designing the cutting strategy. This can ease the finding of a cutting strategy that will be useful for multiple applications.

This school of thought doesn't have that many examples as can be seen in table 2. Only one true generic cutting strategy was found, the structural reuse of wind turbine blades trough segmentation by Joustra et al (2021). But Bank et al 2018, also introduces some applications for panels withing the context of affordable housing which could have more applications outside of that scope.

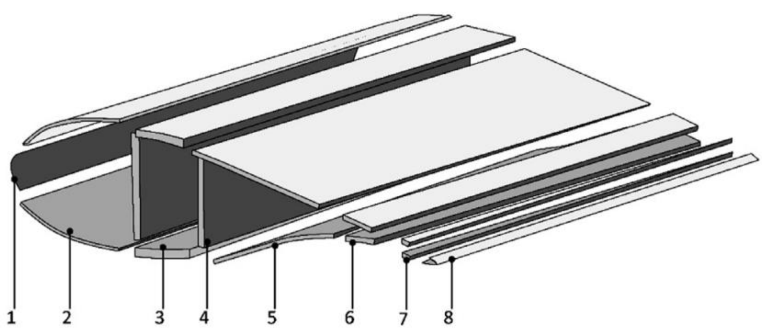


Figure 4. Panels and beams from research by Joustra et al (2021 a).

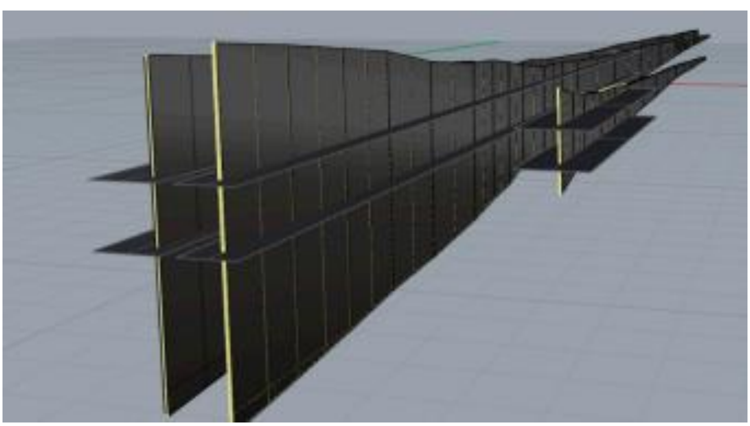


Figure 3. Door and window covers by Bank et al, 2018)

3.5 PREVENTION

The last step on the waste hierarchy is prevention, If you can prevent the parts for becoming waste in the first place then you won't have a problem with waste management. The lifetime of WTBs is mostly extended through monitoring and subsequent repairs.

3.5.1 REPAIRING WTBs

WTBs can be repaired in multiple ways depending on the type and severity of the damage. The ways wind turbines get damage will be explained in chapter 9, but for now it is good to understand that repairable damage can be divided into two groups superficial damage (mostly erosion) and structural damage.

SUPERFICIAL DAMAGE

Superficial damage, damage where the gelcoat or paint layers are affected but not the structure. This type of damage is often repaired using thick protective shields or tapes (see picture 17 below), but can also be repaired using coatings (Mishnaevsky Jr. et al 2021). Small surface and delamination cracks can also fall under superficial damage, the structural integrity is not in danger and these types of damages can be repaired using resin injections (Mishnaevsky Jr., 2019). It is good to search for these types of repairs on WTBs because they could indicate moisture intrusion which can weaken the blade (will be explained more in chapter 9).

Picture 17. Leading edge protection tape being applied. Image credit: Polytech.com (n.d.).

STRUCTURAL DAMAGE

Structural damage is damage where the sandwich structure or one of its parts has failed, for example large delamination cracks, layer debonding, fibre failure, etc. There are two repair techniques that can be used: bolted and bonded techniques (Mishnaevsky Jr., 2019). Bolted repairs used bolted fasteners to repair the broken pieces, this technique has it downsides and was probably last used around 1990 (Dorworth, 2016). It is almost 35 years since its last usage and there is only a small change designers will come across it during reuse. But if it happens it is better to stay clear of them because of their inferior specifications (Dorworth, 2016). Bonded repairs have replaced their bolted predecessors and thus it will be something that designers will have to contend with. There are multiple ways to repair using bonded techniques: external or internal and soft or hard. External patches are also called doublers and are affixed outside the blade and will create a protrusion. Internal patches are also called scarf patches, these work by removing damaged material in a cone shape and then fill the hole with new materials (Katnam et al, 2014). Soft patches are made and infused at the blade and hard patches are manufactured beforehand and bonded with the blade (Mishnaevsky Jr., 2019). Katnam et al (2014) states that bonded composite joints often fail in service even though they can be engineered stronger than the original part. There are many reasons why these repairs would fail but the lesson for designers is depending on the reuse application it might be better to cut around repairs and keep them intact or not use them for large structural loads.

Picture 18. Blade being repaired by ropepartner.com (n.d.). Photo by: J. Castagnetto.

4 CONCLUSION PART 1

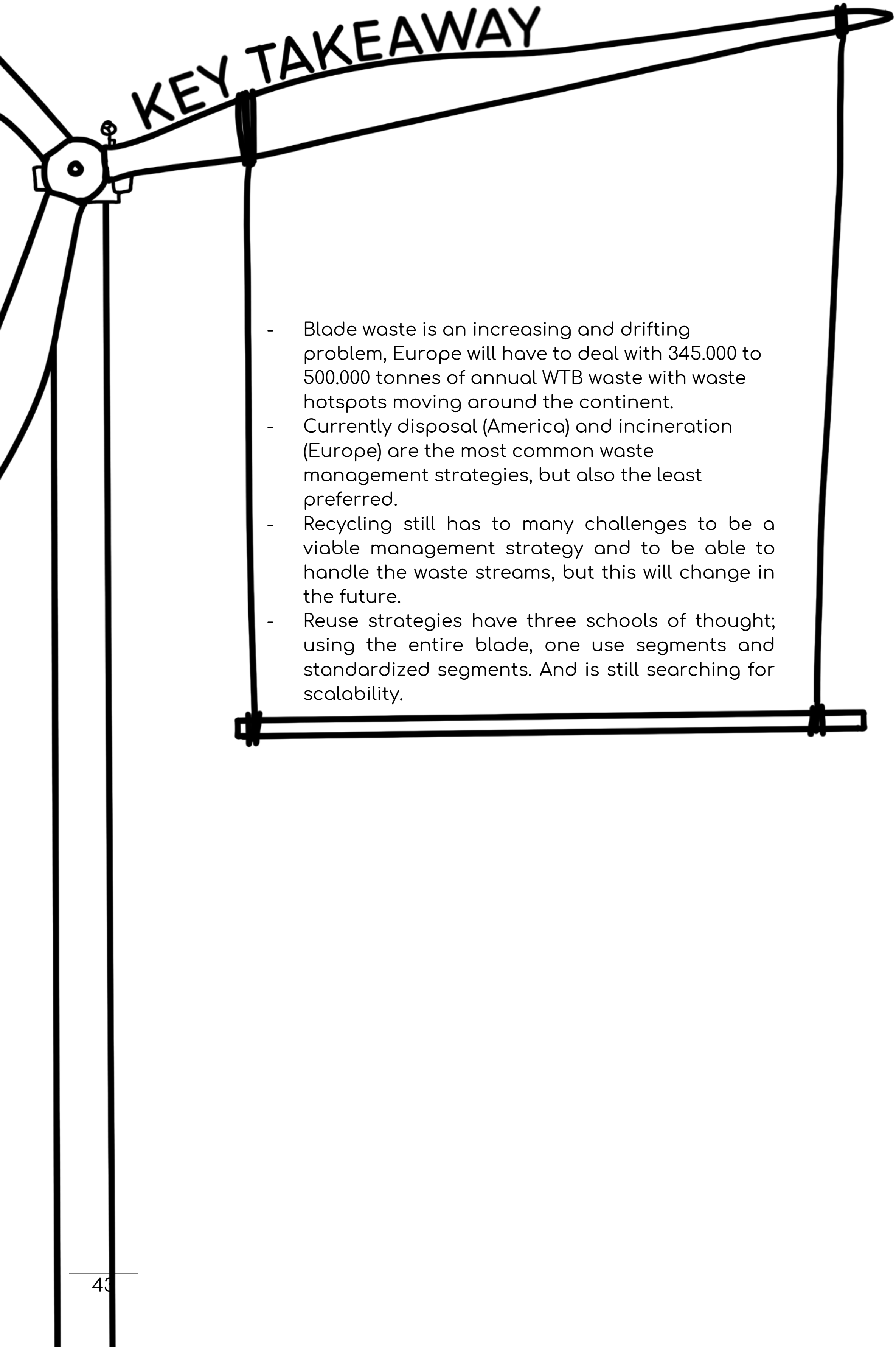
The goal of part one was to answer the research question: *What are current and possible future end of life solutions for wind turbine blades?* Trying to figure out how the problem space looks.

The first step was figuring out how big the problem is. It was found that with the current rise of renewable energy, Europe will look at 500.000 tonnes of blade waste in 2050 (Liu & Barlow, 2017). And by looking at waste predictions in combination with locations it becomes clear that this increasing problem is a drifting problem. It can't be dealt with by single organisation and calls for larger, border crossing, collaborations between designers, manufactures, operators, service providers, recyclers and the general public.

Understanding the problem size, the next step is to understand the problem it self. This was done by looking at the WTB waste problem through the lens of the European waste hierarchy (Directive 2008/98/EC). WTBs are currently mostly managed by landfilling (America) and incineration (Europe), these techniques are undesirable and are also at the bottom of the waste hierarchy. The next best technique is recycling but recycling WTBs still has many challenges: readiness, availability, yield, quality, operational difficulties and cost. The optimist will note that recycling will improve in the future but until then other solutions have to be found.

One such solution is reusing WTBs for other purposes than they are initially intended for. Reuse could bridge the gap until recycling is better suited and extends the duration that the materials are in use before they are degraded by recycling. Reuse techniques can be grouped into three schools of thought: reusing the entire blade, custom cutting (large specialised segments) and generic cutting (standardized segments). They all have their merits but the generic cutting has the most scalability and is currently the least explored strategy. It thus has the largest room for opportunities and will be the focus of the cutting strategy and cutting pattern explained in part three and four of this thesis.

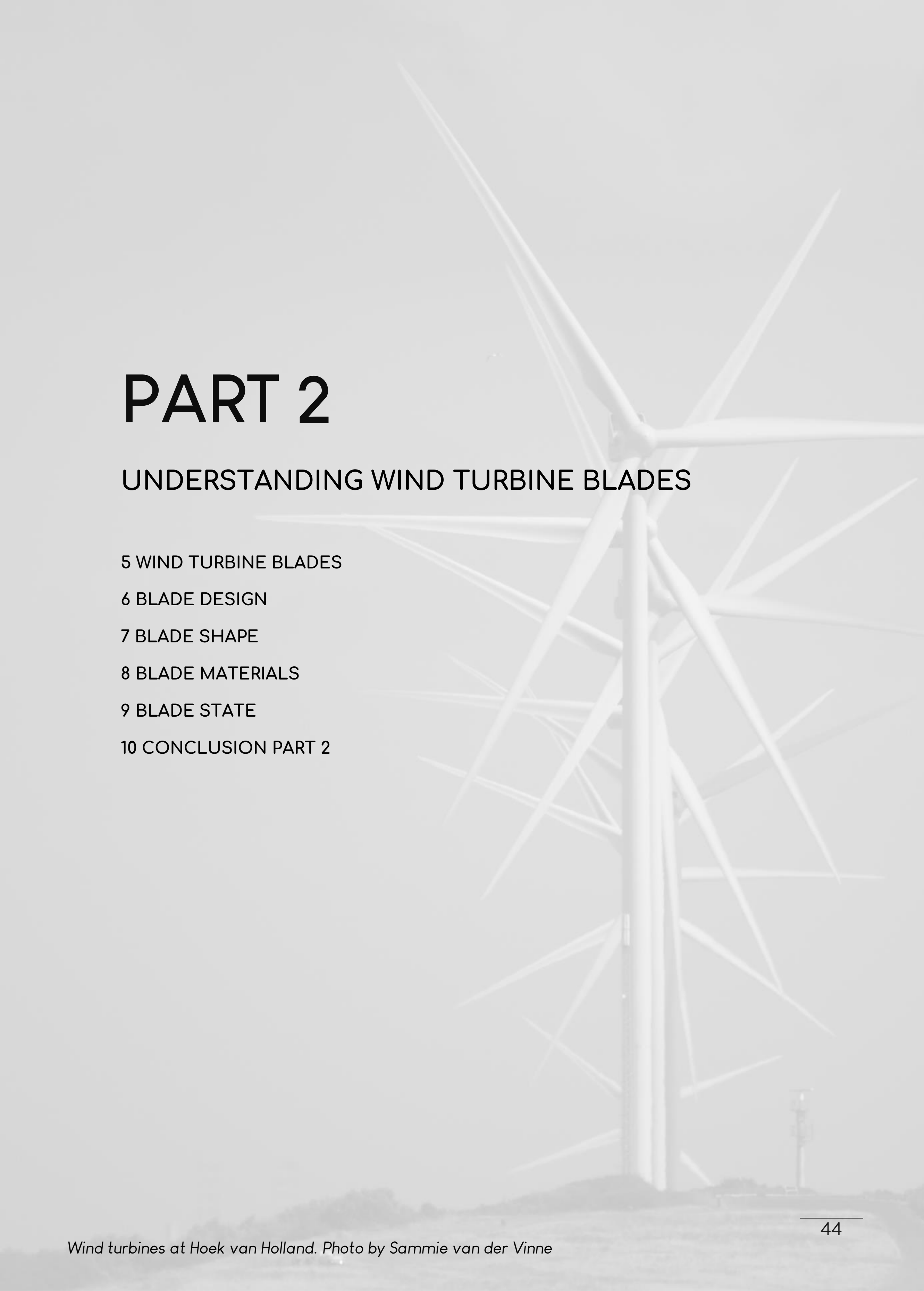
KEY TAKEAWAY



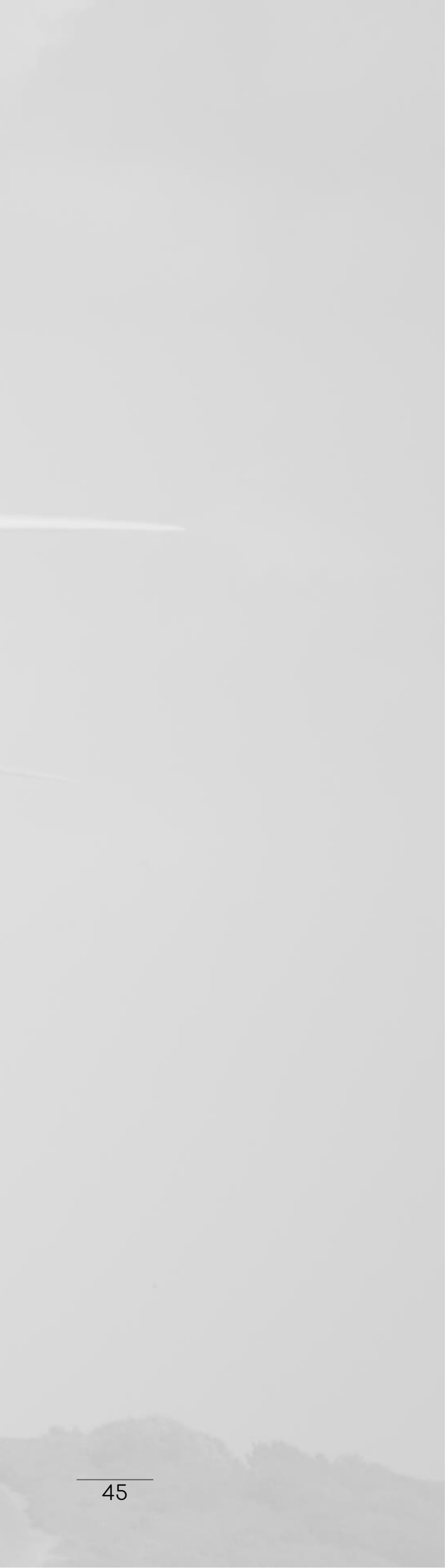
- Blade waste is an increasing and drifting problem, Europe will have to deal with 345.000 to 500.000 tonnes of annual WTB waste with waste hotspots moving around the continent.
- Currently disposal (America) and incineration (Europe) are the most common waste management strategies, but also the least preferred.
- Recycling still has to many challenges to be a viable management strategy and to be able to handle the waste streams, but this will change in the future.
- Reuse strategies have three schools of thought; using the entire blade, one use segments and standardized segments. And is still searching for scalability.

PART 2

UNDERSTANDING WIND TURBINE BLADES



Wind turbines at Hoek van Holland. Photo by Sammie van der Vinne

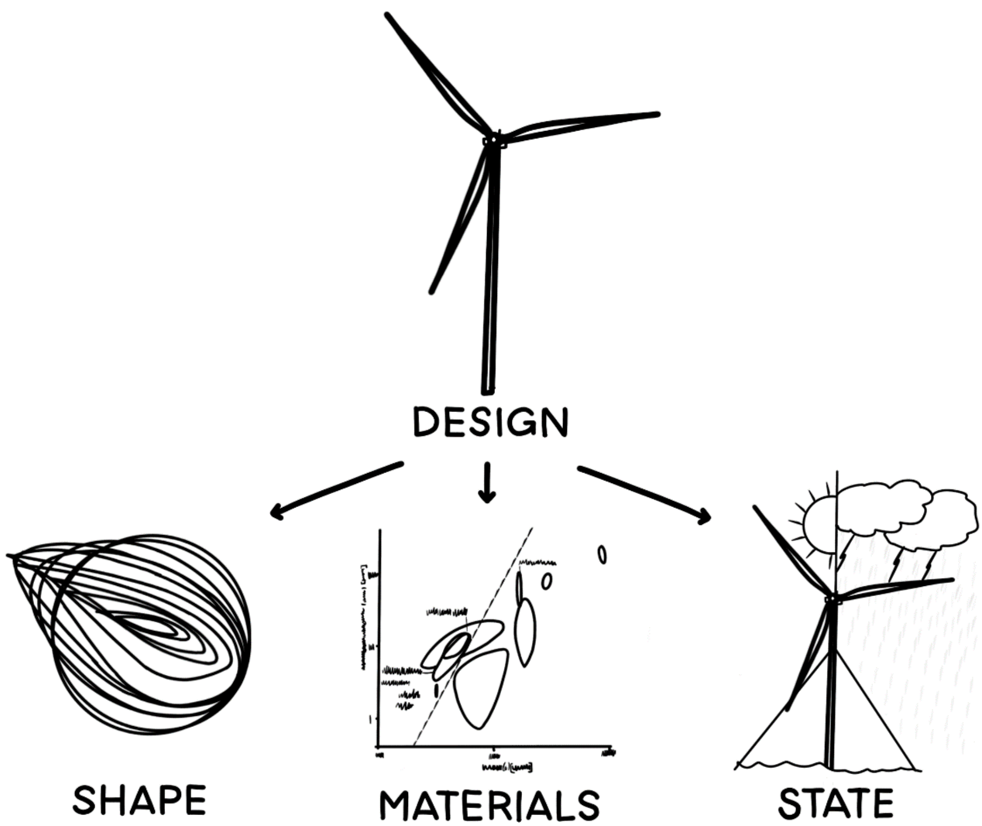


The last part investigated the EOL problems surrounding wind turbine blades and painted the picture of how this thesis fits in the current EOL landscape. But it is also important to understand wind turbine blades. This part will try to answer research question 2: *What is the composition and build-up of wind turbine blades?* Trying to better understand the material that will be used by investigating the design, the shape, the materials and state of wind turbine blades. This information can then be used to create design requirements for possible applications and cutting strategies.

5 WIND TURBINE BLADES

Wind turbine blades have an as limitless history as the wind turbine itself. They were made from wood with a canvas sail in the early history, to metal blades (Decker, 2009) and modern blades are made from complex composites of fibres, polymers, woods and foams. Blades have complex shapes and can have lengths in excess of 100 meters. Blades are a complex combination of complex parts. These coming chapters will investigate the modern WT blade and try to understand the design philosophies behind it.

The first of chapter (chapter 6) will give a small overview of the design of a general blade, as to better understand the context of all the parts that will be talked about in later chapters. The following three chapters will go into the aspects that make it difficult to design structural reus applications with WTBs. These are: the shape of blades (chapter 7), the material composition used in blades (chapter 8) and the blade state (life time damage / living circumstances of the blades) (chapter 9).



Wind turbines at Hoek van Holland. Photo by Sammie van der Vinne

6 BLADE DESIGN

The goal of a blade is to translate the energy of the wind as efficiently as possible into rotational energy for electricity generation. Engineers use many tools in there tool box to be able to achieve the most optimal design. It is good to understand how a blade is designed to be able to better understand how it can be reused. This chapter will discuss a couple of aspects of WWTBs: size and weight, internal structure, sandwich structure and manufacturing techniques.

6.1 SIZE AND WEIGHT

Wind turbines aren't small feats of engineering, through their history they have become larger and larger. It is good to understand that handling them during the processing for structural reuse also won't be easy. Blades can weigh 55 tons and have lengths in excess of a 100 meters. It is interesting to note that the smaller blades were heavier in comparison to the larger blades. Research by Faulstich et al (2008) also shows that blades of larger turbines have a higher annual failure frequency. This could mean that newer and larger blades are over al weaker and more damage prone than older smaller blades. This is due to the fact that while the blades have grown in size, the engineering knowledge has also grown. Older blades were over engineered for their use leaving them with more residual strength after decommissioning. While more modern blades have been optimised to the leading edge of what is possible. This was also acknowledged by Thomas Hjort (director innovation offshore wind at Vattenfall) during a public presentation in collaboration with the Dutch Design foundation and What if labs.

Taking into account the life time of 25 to 30 years we can expect that WT blades of around 50 meters (north of 10 tons) will be decommissioned in the coming years.

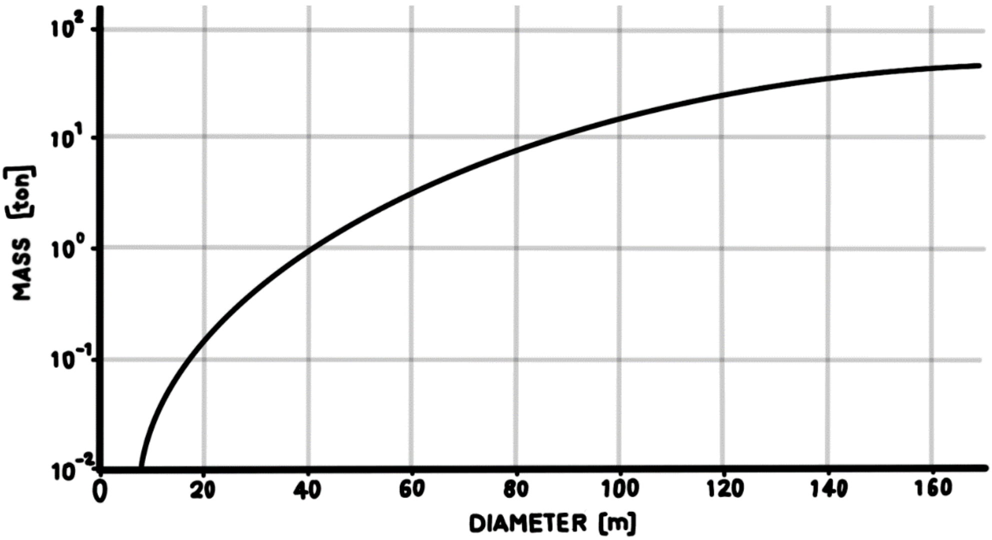


Figure 6. Development of Blade mass against rotor diameter. Simplified from Krimmer (2014).

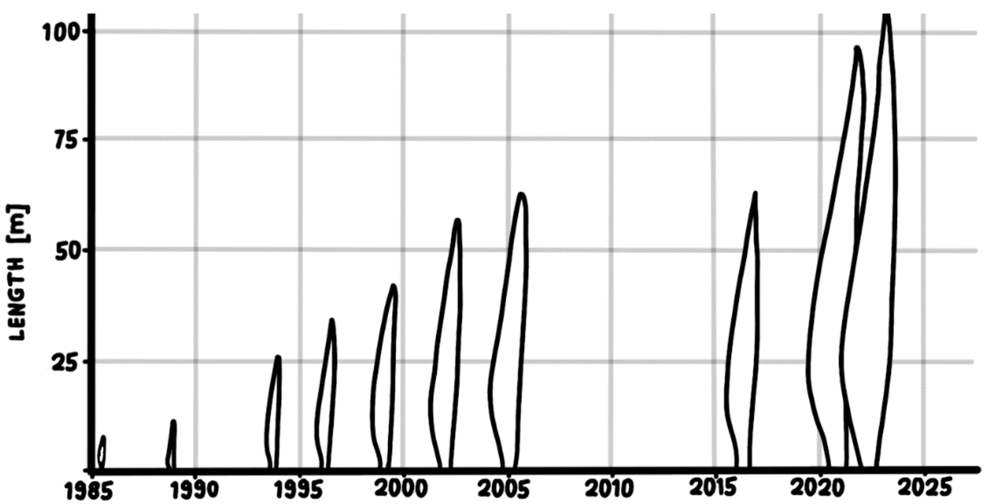


Figure 5. Blade length throughout time. Based on Rosemeier & Krimmer (2023).

6.2 HOLLOW BLADES ARE A SOLID CHOICE

The energy that a wind turbine generates is proportional to the amount of air that pass through the rotor. Thus a larger blade has the potential to generate more electricity. Modern blades can have lengths up to and exceeding a 100 meters, and thus a solid blade will be to heavy. Blades are designed hollow and the two "surfaces" are often glued together (manufacturing techniques will be explained later in this chapter). But only glueing the two surfaces together is not strong enough, they also need reinforcements to counteract the shear forces of the wind. This used to be accomplished using a central box beam running through the blade but recent blades use a shear web with spar cap design. The shear webs are separate beams that are glued lengthwise trough the blade. It is not unheard of to have three shear webs in longer blades. A schematic overview can be seen below and to real life examples can be seen on the next page.

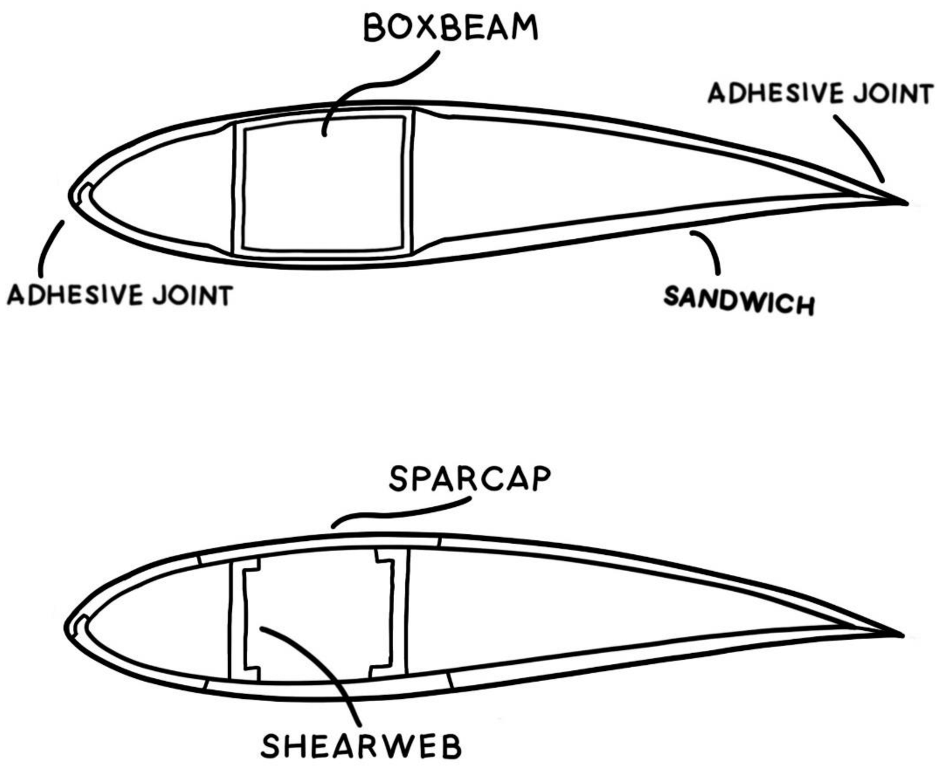


Figure 7. Simple representation of WT blade structure, the top figure shows the older box beam design and the bottom figure shows a modern shear web and sparcap design, it is not unheard of to have three shear webs for longer blades. Inspired by Thomsen (2009) & Mishnaevsky et al (2017).

Picture 19. Cross section of a wind turbine blade with a box beam design (Planddaily.com, 2024). Photo by Dariusz Piekut.

Picture 20. Cross section of a wind turbine blade with a shearweb design (Juntikka et al, 2018)

6.3 SANDWICH STRUCTURE

Blades use a sandwich structure for a couple reasons: a way to design against fatigue, the sandwich is stronger in compression reducing problems with buckling and it reduces weight (Thomsen, 2009). In this sandwich the pieces of bread are replaced with fibre reinforced polymers and the filling in between is the core material. The fibres can easily form to the curved shaped but the core material cant be bent and is thus shaped trough kerf bending (picture 22) (Sloan, 2020).

Fibres are the main load baring parts of composite materials (Erden & Ho, 2017) and the strength of a fibre mat is dependent on the direction of the fibres. Fibres are the strongest in tension / lengthwise direction, this creates an anisotropic behaviour within the blade. Thus knowing how the fibres are orientated in a blade can steer the cutting direction of possible segments. The way fibres are orientated is called the layup an example is given in figure 8.

Another important distinction of the fibres is the location of ply drops. Blades need to be stronger at their root section and to accomplish this the fibre layers have a differing thickness trough out the blade (just like the core material, see picture 21). But this results in ply drops, the locations where a fibre mat ends. These ply drops can increase stress concentrations and the chance of delamination (He et al, 2000).

All in all it is good to understand how the fibre layers are laid down in the blades. And an indication of the varying thickness will also be helpful for designers. These two together can indicate the strength distribution throughout the blade.

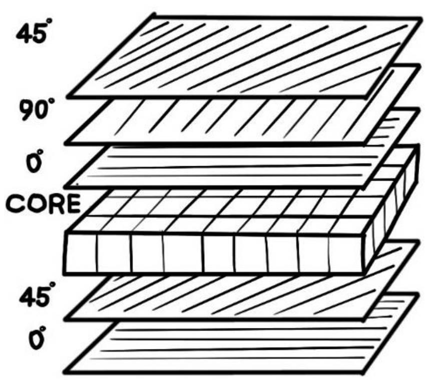


Figure 8. Layup diagram for a sandwich structure.

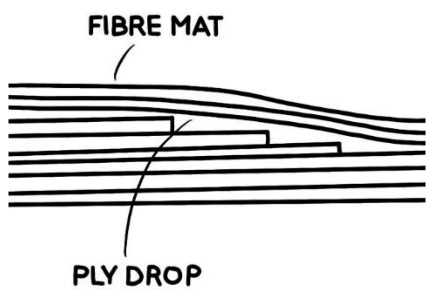
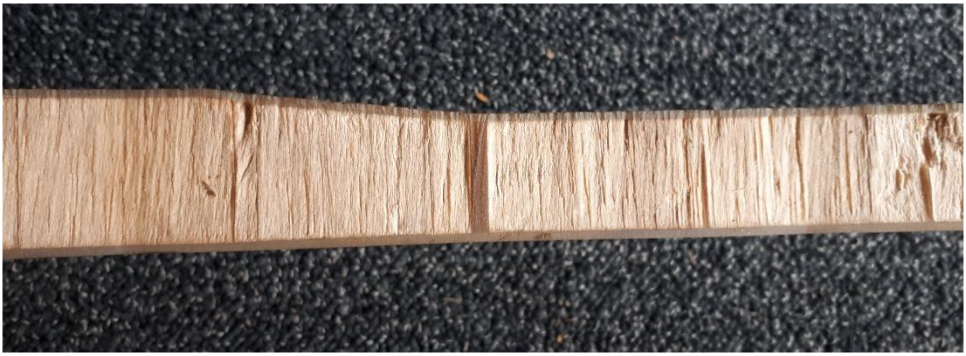


Figure 9. Plydrop in fibre reinforced polymers.



Picture 21, Thickness change of core material.

Picture 22. Side view of core with kerfs.

6.4 MANUFACTURRING TECHINQUES

The materials used for creating blades need to give a lot of design freedom. Fibre reinforced polymers give the needed design freedom (Erden & Ho, 2017) and in combination with core structures a good weight, stiffens and strength ratio can be found. Multiple manufacturing techniques exist for fibre reinforced polymers: wet hand-lay-up, filament winding, prepreg, resin infusion (Brøndsted et al, 2005), resin transfer moulding, compression moulding, pultrusion and automated layup (Rogers, 2021). There are even more sub categories and specialized techniques. It is important to understand the used manufacturing technique because each technique has their own drawback. For example prepreg has the tendency to create air bubbles due to of gassing increasing the change of delamination (Griffen & Ashwill, 2003). Small delamination sites aren't a big problem for the entire structure of a blade but by segmenting the blade these delamination sites can grow due to cutting forces and weaken the segments.

There are many manufactures that make blades but LM wind Power has a great video explain their manufacturing technique, the reader is recommended to watch this video but in short: they use two big mould halves in which each blade half is manufactured using resin infusion, the mould halves are then laid on top of each other and bonded to create the blade. The steps are shown below (LM Wind Power, 2022). Understanding where these adhesive joints are is necessary because they are often weaker and have an increased change of delamination.

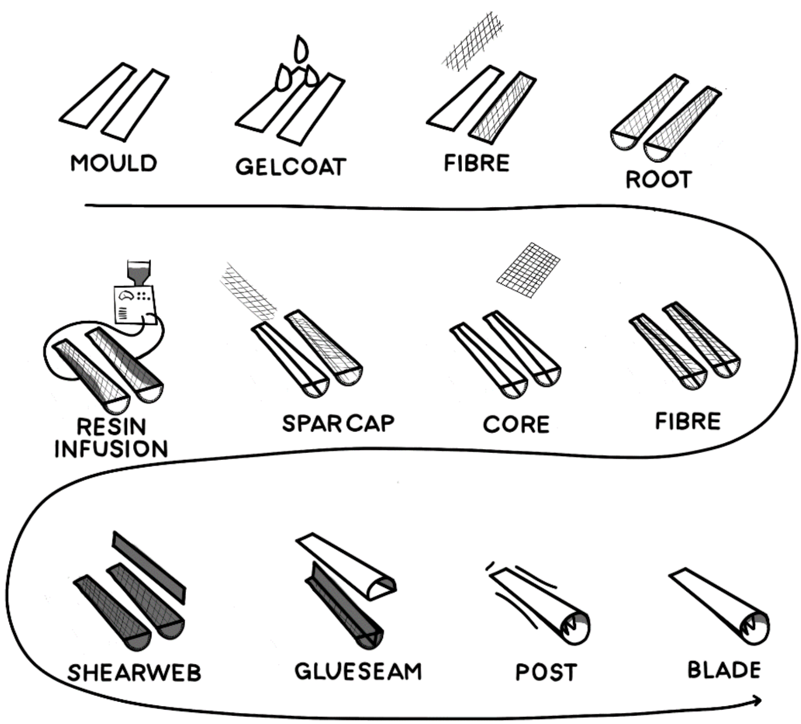


Figure 10, Manufacturing steps of a wind turbine blade.

Picture 23. 97m blade by Siemens Gamesa (Veers et al, 2023). Image credit: Siemens Gamesa Renewable Energy.

7 BLADE SHAPE

WTBs have extremely complex shapes and their shape will be a constraining factor for any cutting strategy and or applications that will be designed later on. It is thus imperative to understand what shapes can be expected. There are three aspects that make their shapes complex: (changing) aerofoils, twist and pre-bent.

Picture 24. The GE/LM Wind Power LM 107.0P wind turbine blade with the three aspects visible (ge.com, 2019). Image credit: GE Renewable Energy

7.1 AEROFOILS

Aerofoils are the primary type of shape used in WTBs. The simplest form is a plank, which can already have an efficiency of 75 to 80% (Brøndsted et al, 2005). But a simple plank isn't efficient enough and thus engineers have dedicated their lives to designing better shapes for more efficient lift generation, figure 11 shows the general working principle of a blade.

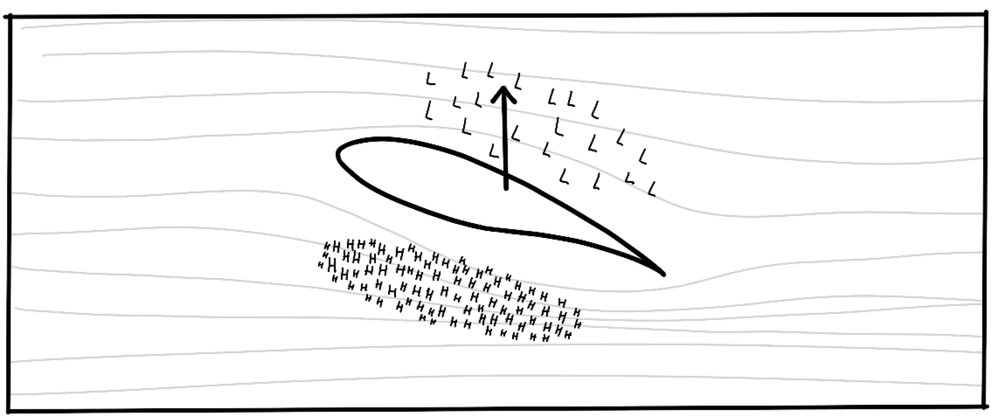


Figure 11. Simplified workings of a wind turbine blade. With a high and low pressure zone, where the high pressure zone generates a force directed into the low pressure zone.

There are multiple systems for describing the geometry of aerofoils, one such is the NACA aerofoil system (NASA.gov, 2017). These systems use a numerical system to describe the geometry and profile of an aerofoil. Describing the chord, chamber, length and midline. A WTB will utilise different aerofoils throughout its length. It is good to understand the general shapes that are used so it can be kept in mind while designing applications.

We can use the Sandia SNL100-00 all-glass baseline blade (Griffith & Ashwill, 2011) as a small case study. The blade is divided into 34 stations with 26 different aerofoils. The blade starts with a cylinder of 5,7 meters and starts to transition into ellipses which than transform into the first aerofoil at 19,5 meters. This is also the location with the largest chord (sort of the diameter or length of aerofoils) of 7.6 meters. After the first aerofoil different aerofoils are used and the chord decreases in size.

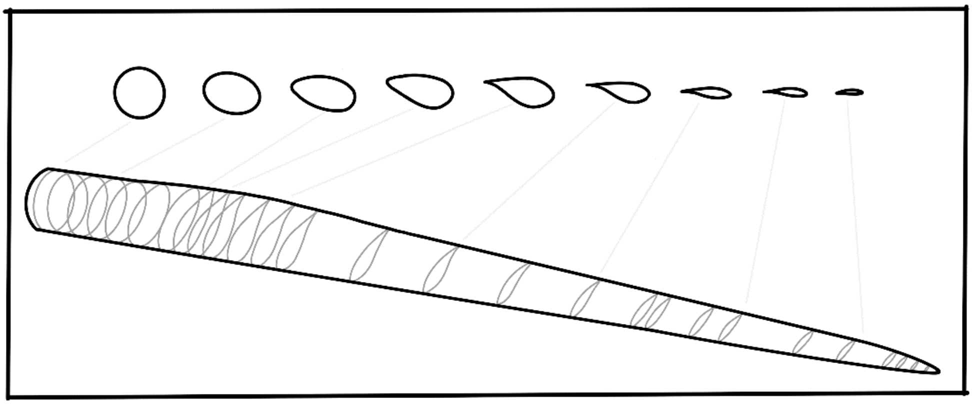


Figure 12. Shape profile of the SNL 100-00 all-glass baseline blade.

7.2 TWIST

Another aspect that creates the difficult shape of WTBs is the twist. WT blades need to be as efficient as possible and one way this is done is by changing the attack angle of the aerofoils trough out the length of the blade (Capellaro & Cheng, 2014). If we again look at the Sandia SNL100-00 blade we can see that its twist goes from 13,308 degrees at the root to 0 degrees at the tip (Griffith & Ashwill, 2011). This doesn't sound as much but it is enough to create an extra degree of difficulty. For example if you want to create long beams from certain parts you will have to take into account that the ends of a beam don't lie in the same plane.

7.3 PRE-BENDING

WTBs might look like they are extremely rigid but the contrary is true. The forces with which the wind pushes on the blades can be significant enough to push the blades into the tower. There are multiple techniques to negate this issue: tilted nacelle, pre-coning and pre-bending (spinningwing.com, n.d.). Pre-bending affects the shape of the blade and could also increase the processing difficulty, it is thus important to understand. A pre-bended blade will have a tip that has a large distance to the tower so it can counteract bending forces of the wind. Figure 13 show the difference between a non pre-bend blade an a pre-bend blade. The pre-bend is often about 3 to 4 meters at the tip of the blade (Bortolotti et al, 2021).

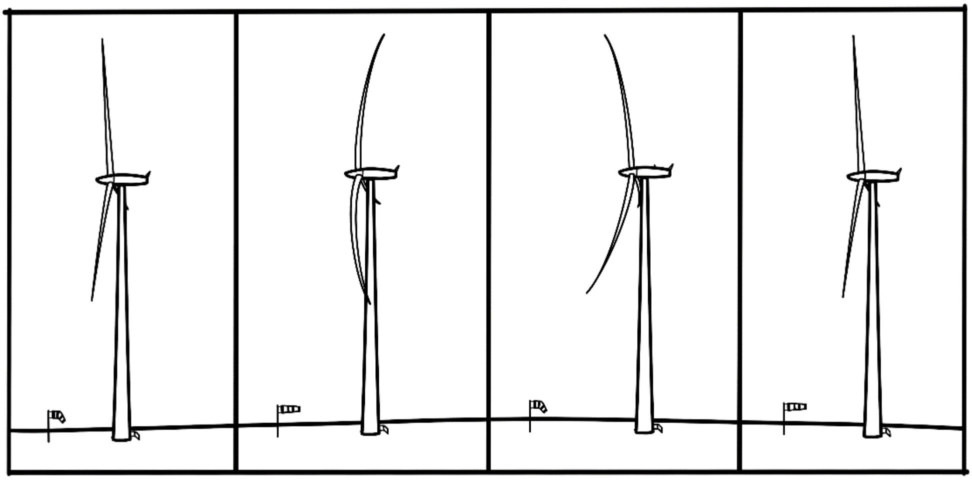


Figure 13. The effect of the wind on a blade without (left) and with a pre-bend (right).

7.4 SHAPE MAP

Beter understanding the shape we can now start to generate a possible shape map. Generalising WTBs to simple shape indications still looses a lot of nuance, every blade is different and thus a specific shape map quickly becomes irrelevant. Thus the proposed shape map only uses three levels. The slightly curved parts are almost flat and can be used as a flat panel. The moderate curved area's can be used as a panel when curvature isn't a problem or the application can utilise them. But fitting panels edge to edge becomes difficult. And the extreme curved parts are most likely great for beams, panels become curved to such an extent that they don't fit next to eachters or with extreme gaps. This of course can be useful in an application but this is a question for part four of this thesis.

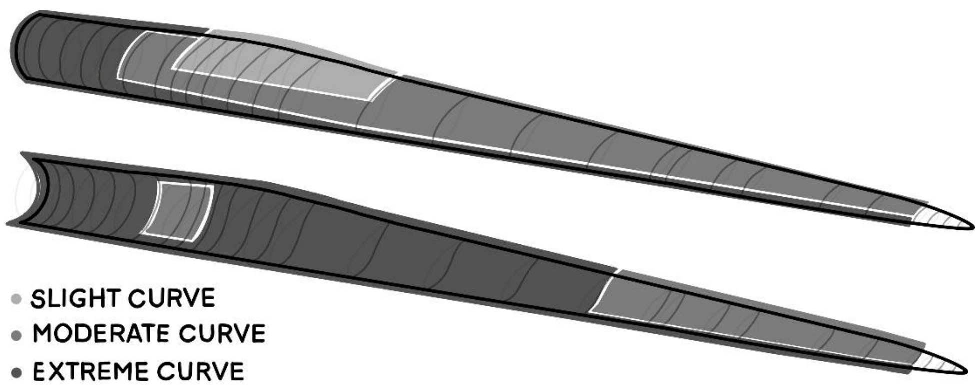


Figure 14. Curvature of a WTB translated to a use case map.

8 BLADE MATERIALS

Blades can be made from many different materials in early history they were made from canvas and now they are complex composites with a plethora of different materials that are used. It is also an ever changing design landscape with a lot of development in the last decade (Chen & Eder, 2020).

There are five groups of materials used in a blade of which four are main groups and one is and additional group. The four main groups are: Fibres, Matrix, the Core and Coatings. The fifth additional group encompasses materials that can be added for additional functionality for example lighting protection. These five groups will be explored in this chapter, with the main goal to figure out the strengths and weaknesses of the possible materials.

The chapter has divided the five material groups to ease the explanation of them but by doing this it becomes less apparent that these materials all work in unison to create the final product. This was shown in chapter 6 but it is important to reiterate it.

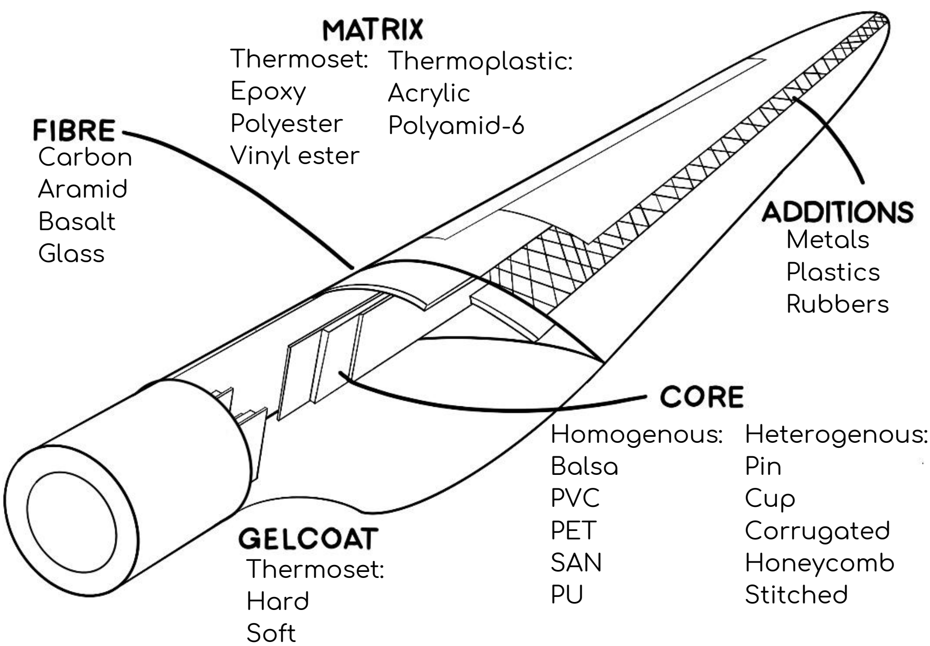


Figure 15. Buildup of a generic wind turbine blade. Recreated from gurit.com. With the five material groups.

8.1 MATRIX

The matrix has several roles in the FRPs; contain the fibres, transfer stress, protect against environmental factors (e.g. moisture) and protect against mechanical factors (e.g. abrasion) (Mallick, 2007, p. 60). The matrix is made of a polymer which is categorized in one of two groups, thermosets and thermoplastics. The main difference is that thermosets create cross-links between the polymer chains creating a difficult to break bond and thermoplastic do no such thing. This makes it possible to re-heat and form thermoplastic while thermosets are more resistant to heat. Thermosets are the most used with about an 80% market utilisation for FRPs, polyester, epoxy and vinyl ester are the used thermosets (NREL.gov, 2019). Thermosets are cured at a lower temperature and have a lower viscosity (Mishnaevsky et al, 2017).

Thermoplastics are less used but their formability while applying heat makes them better recyclable. The same material property is also a disadvantage because a high processing temperature is needed which takes more energy (a higher viscosity also takes a role in the higher energy demand) (Mishnaevsky et al, 2017). The higher temperature during the solidification introduces thermal contraction when cooling which will introduce stresses (Brøndsted et al, 2005). Their higher viscosity can also introduce unwanted fibre shift during infusion. Thermoplastics that can be used are acrylic (Murray et al, 2019) or polyamide-6 (Rijswijk et al, 2005). Thermoplastic have a better fracture toughens than thermosets but have worse fatigue behaviour (Mishnaevsky et al, 2017).

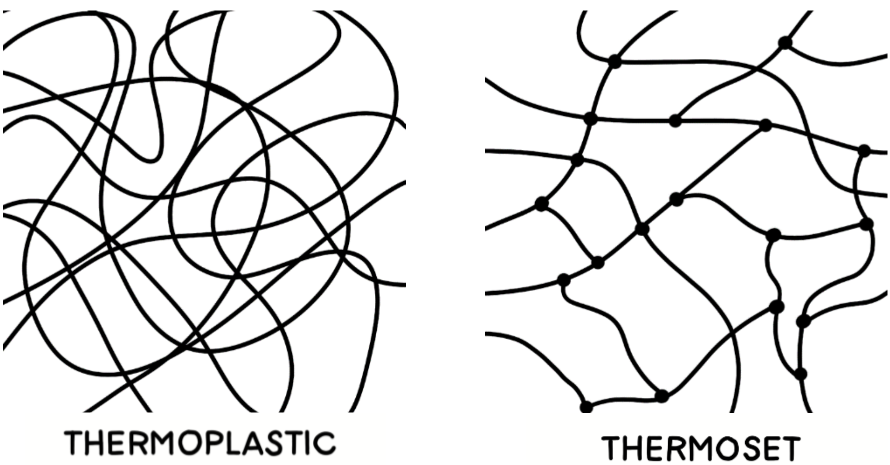


Figure 16. Schematic representation of a thermoplastic and thermoset.

8.2 FIBERS

Fibres are the main load baring parts of composites (Erden & Ho, 2017), E-glass is the most used in WTBs (Brøndsted et al, 2005), but other fibres do exist: carbon, aramid and basalt (Mishnaevsky et al, 2017). There are also less utilised materials like boron, natural and self-reinforcing (Middelton, 2016).[1]

Understanding these materials can help steer the cutting strategy or design of applications. Usually one material is chosen for the fibres but certain WTBs have used multiple materials. For example a glass fibre shell with a carbon fibre box beam or spar cap (Mishnaevsky et al, 2017). This way the strengths of both materials can be combined for a better product.

Picture 25. Top left to bottom right: Carbon fibre (jinggongrobot.com, n.d.), Aramide fibre (swift-fibre.com, n.d.), glass fibre (indiamart.com, n.d.), Basalt fibre (nauticexpo.com, n.d.).

[1] These fibres aren't being used in the production of WTBs, but this could change in the future. Bora et al (2023) shows a bamboo epoxy WTB and concludes it is a viable alternative to glass fibres. The future landscape can thus change and designers should be aware of the future possibilities.

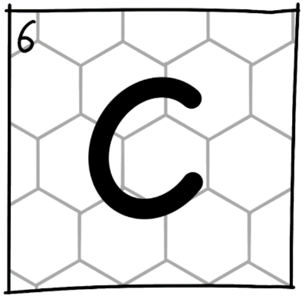
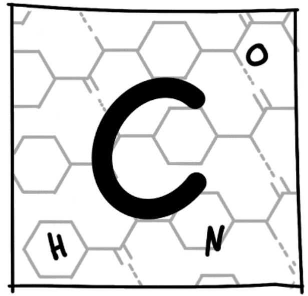
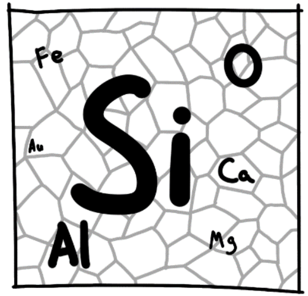
Material				
	Carbon (Pan)	**Aramid**	**Glass**	**Basalt**
Types	HS, IM, HM, UHM	Kevlar, Nomex, Twaron	E, S2, D, C, AR, AE, A, M, etc.	Natural rock
Tensile strength [MPa]	3500-6000	2900-3450	E: 3100-3800 S2: 4020-4650	3000-4840
Elastic modulus [GPa]	230-600	70-140	E: 72.5-75.5 S2: 83-97	93-110
Strengths	Extremely strong . Extremely stiff.	Energy dissipation. Damage tolerant.	Lightweight. Resistance to heat. High strength.	High strength. Good wear resistance.
Weaknesses	w damage tolerance. Low tolerance to manufacturing defects. Can be quite brittle.	Low compressive strength. Easily damaged by moisture and UV	Moderate stiffness.	Natural material with variable properties.
Design considerations	Is more often used in the box beam and spar cap resulting in beam like segments	Fibre should be protected from the environment.	Most used material.	Almost interchangeable with glass fibres.

Table 3. Fibre material and their properties. Based on: Jamshaid & Mishra (2015), Erteking (2017), Haberkern (2006), Kiron (2022), McConnel (2008), Middelton (2016), Mishnaevsky et al (2017), Seluck et al (2023), Xometry (2023).

8.3 CORE

The core in the blade sandwich has multiple purposes: it is used to design against fatigue, the sandwich is stronger in compression reducing problems with buckling and it reduces weight (Thomsen, 2009). Two types of cores can be found: homogenous support (e.g. natural materials or foams) which is mostly used and heterogenous support (e.g. structures like honeycombs).

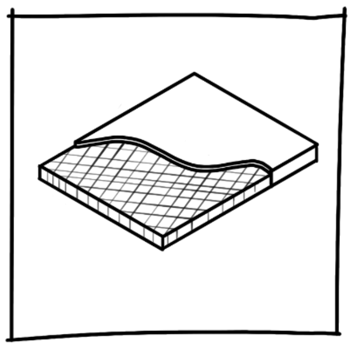
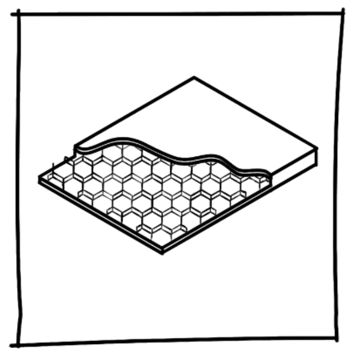
Structure		
	Homogeneous	**Heterogeneous**
Types / Materials	Wood: Balsa Foam: PVC, PET, SAN, PU	Pin, cup, corrugated, honeycomb, stitched
Strengths	Support on entire interface surface between core and fibre shell. Foam: Resistance to environmental factors.	Light weight.
Weaknesses	Heavy weight. Balsa: varying density and resin uptake Foam: lesser mechanical properties.	High shear loads on the interface between core and fibre mats
Design considerations	Wood is a natural material that degrades due to environmental factors. Foams have weak holding power for connection strategies.	Partially hollow structure could increase segments connection difficulties. Surface can dimple under load.

Table 4 Core material and structure usage. Based on: Feng et al (2020), Rosemeier et al (2018), Sloan (2020), Thomsen (2009), Yan et al (2019).

8.4 GELCOATS AND PAINTS

Gelcoats and paints have a big part in the longevity of WTBs, their main job is to protect the blade against environmental damage. The composite laminate will inevitably have manufacturing defects like pinholes which can introduce foreign objects of substances which could damage the blade. Next to this WTBs also have to deal will environmental damage for example: UV radiation, small airborne particles, rain, insects, bird faeces, etc. Gelcoats and paints protect the WT blade against these (Storm, 2013). Two types of surfaces can be used, soft or hard surfaces (Storm, 2013), which could be interesting for reuse, soft surface might need to be resurfaced to be able to be suitable for the different use case. It is also important to note that when WTBs are cut for reuse applications it is thus necessary to reseal the edges to protect against the environment.

There are many materials that can be chosen for the gelcoats of paints this of course depends on environmental factors and material composition (does it adhere) of the blade, but they are always thermosets (Storm, 2013). These materials of course will also degrade over time due to the environment thus depending on the reuse application it could be needed to add extra surface protection. The surface coating or paint can be inspected by measuring the colour and gloss change, but this doesn't show the entire picture and other techniques are needed for a more detailed answer (Storm, 2013). Checking the surface by eye should be enough for reuse applications as they might not be as demanding as the original use case.

Picture 26. Coating being applied to the blade mold of the Haliade-X blade . Image credit: GE Renewable Energy.

8.5 ADDITIONS

WTBs can also have additional materials added to and in the blades. This is often done to protect or monitor the blade. One such protection addition is to minimize lightning damage, metal meshes or conductors are used to re direct the lighting strike (Yan et al, 2019). Another protection addition that can be found is to de-ice the blades. Heater fans can be placed in the root that blow hot air or resistive foils / wires are added to the blade to heat it up and melt the ice or snow (Katsaprakakis et al, 2021). Sensors are sometimes added to monitor the structural health of the blade (Ciang et al. 2008), there are many ways to do this but they are ultimately just some added wires. It is good to understand that during the processing of the WT blades you will thus also have other materials like metals that could introduce processing difficulties or need extra attention to protect against corrosion or rust.

Picture 27. Exterior lighting diverters on a wind turbine blade (Hall, 2021).
Image credit: Weather Guard Lightning Tech.

Picture 28. Sensors and cabling in a test blade (Dlr.de, 2022). This amount of equipment is abnormal for normal production blades but it show cases what can be expected.
Image credit: Enercon.

9 BLADE STATE

Wind turbines have a designed life time of about 20 to 25 years (Lauritsen et al., 2016), meaning that a blade that will be repurposed or reused has had years to degrade in strength or get damaged. It is important to understand what the state of a blade is when it is received for segmentation. This is because a weaker blade might not be usable for structural purposes and an aesthetic use might be the way to go. The following paragraphs will investigate the states that blades can be in and create a possible damage map to aid in the inspection of WTBs for reuse. But first it is good to understand how often blades are damaged and thus if it is even necessary to take blade state into account.

9.1 BLADE FAILURE FREQUENCY

Blades will accumulate damage trough out their usage but how often does it lead to failure or significant damage. It is good to understand the frequency of blade failure so it can be understood if possible damage should be taken into consideration during the cutting of the blades.

Understanding WTB failure frequency can be rather difficult. Of course a lot of research has been done into the failure frequency of wind turbines, but there are a lot of different blades, wind turbines, control schemes, techniques, power ratings and environments. These all influence the failure frequency in their own way, it is thus often difficult to give one definitive answer. There will also be contradicting information about blade failure frequency, making it all that more difficult. Research by Pérez et al (2013) goes into the failure frequency of wind turbines where they experience this difficulty. An example they give is that one study suggest that blades fail three times every four years while an other study suggest one failure every 5 years. For reuse strategies it is good to know that even at the lowest frequency of once every five years could mean that every blade that has operated for about 25 years will have 5 damage incidents. It can thus be expected that every blade will have some type of damage which should be looked at and decided on its effect for the cutting strategy (cut around it, aesthetic usage, etc).

9.2 WHY DO BLADES FAIL

There are a multitude of reasons that can be found when reading the literature about why WTBs get damaged and fail during their life time. Manufacturing defects, transportation damage, assembly damage, installation damage, lighting strikes, environmental wear, rain, contaminants erosion, fatigue, moisture intrusion, object impact, failure of control system, blade overspeed and bad blade design (Mishnaevsky, 2019) & (Chen & Eder, 2020). Even more reasons for blade failure can be found than was added to this list, but they often have the same meaning with small semantic differences. Al these reasons can be clustered into three groups: fatigue, natural influences (outside of wind) and huma error.

9.2.1 FATIGUE

The job description of wind turbines can be described as constant turning. Wind turbines do stop occasionally (Giallanza et al., 2016) but a parked wind turbine will still experience wind loads (Tang et al., 2019). This all to say that wind turbines have to endure a lot during their lifetime.

The main loads that a WT blade experiences are edgewise (cutting through the wind) and flap wise (pushing blade into the tower) bending (Manwell et al., 2009). Blades experience about 10^8 to 10^9 cycles of these loads with an annual 4000 hour operation (Rashedi et al., 2012), (Ma et al., 2018). Next to these important loads there are also other loads: gravity and centrifugal forces acting on the blade (Brøndsted et al., 2005). All these loads together create fatigue damage. Fatigue damage will most likely originate at the root of the blade, where the blade joins with the turbine hub. (Katsaprakakis et al., 2021). Gamesa also presented the same conclusion at EWEA 2015, explaining that their 17 and 18 year old blades mostly suffer from fatigue problems at the root connections and shell boding (unpublished presentation explained in Liu & Barlow, 2017). But this of course depends on the specific blade in question and every manufacture has their own formula for blade design. Thus the specifics might changes but it generally holds true.

Fatigue loads can have many consequences but these can be clustered in four groups: fibre failure, matrix failure, debonding failure and core failure. Lambert et al., 2011 shows the first two failure types in research about the role of voids in WT blades. Fibre failure is most predominate at high loads, and can be described as the literal fibres breaking. Matrix failures consist of matrix cracking (small cracks forming in the matrix in between the fibres, happens at low loads) and matrix delamination (larger parts of the matrix delaminate between fibre layers, happens at medium load). Debonding failure can happen between the two blade halves (Liu & Barlow, 2017) but also between the core and fibre layers (Chen & Eder, 2020). The final failure type is core failure, the core can get crushed, ruptured and shear crimped (Abbott, 2019).

There are many ways a blade can fail[1] due to fatigue and with a life time of 20+ years it would thus be prudent to inspect[2] blades before the are processed.

[1] There are many more specific ways to describe blade damage and readers are recommended to read Sørensen et al., 2004 for more information on specific damage types

[2] AL-Khudairi et al, 2017 has pictures of a full scale fatigue tested WTB showing how these damages might look.

9.2.2 NATURAL INFLUENCES OUTSIDE WIND

Next to fatigue damage caused by wind, nature also makes the life of WTBs difficult in other ways. These are: particulates (sand, rain, hail), moisture, thunder, temperature and land morphology. In a literature review by Chou et al (2013) 846 incident reports were analysed of which 80% can be attributed to weather related events .

PARTICUALTES

Particulates become problematic for WTBs because they can erode away the aerodynamic surfaces and reduce the efficiency of the blades. Rain and hail can have velocities higher than 100 m/s (Katsaprakakis et al, 2021). For example rain can have enough energy to leave pin holes, gouges, and can remove relatively large pieces of material (Groucott et al., 2021). Sand and other smaller particulates, although smaller than rain and hail can have similar consequences of blade erosion and increased surface roughness (Slot et al., 2015).

Picture 29. Leading edge erosion on an offshore wind turbine blade (stateofgreen.com, 2023). Photo credit: Polytech

Surface erosion only effects the aerodynamic performance of the WT blades but the created openings can create a water ingress point (Mishnaevsky, 2019) . Once water/ moisture is inside the blade it can have multiple consequences: reduction of glass transition temperature of the matrix resin, damage to the interface between matrix and fibres (Mishnaevsky et al, 2012), swelling and ice formation (Katsaprakakis et al, 2021). For example glass fibres and polyester or epoxy composite lose about 10% of its stiffness due to moisture absorption (Katsaprakakis et al, 2021).

LIGHTING

Lighting strikes are also a problem for WTBs. With a heights reaching about 260 meters they become perfect lighting rods. LM wind power (manufacture of wind turbine blades) states that on average every blade will be struck 128 times during a period of 20 years (lmwindpower.com, n.d.). But takes this with a grain of salt because Garolera et al, (2016) analysed lighting damage to WTBs and show a way less extreme number. Their analysis of 508 wind turbines during a period of 5 years showed that a wind turbine will experience about two to three damage resulting lighting strikes during a lifetime of 20 years. There analysis showed that the damage occurred mostly in the last meter of the blade (60%) but almost all the damage will be in the last 4 meters (90%).

Lighting damages can entail: tip detachment, shell detachment, localized delamination / debonding and delamination. It was shown that there is almost no difference between GF and CF blades. But the research of Yan et al. (2019) does show different effects of lighting on the core materials. PVC, PET and balsa were compared and it was shown that balsa wood was the weakest and although PET and PVC have the same electrical strength, PVC behaves worse. The type of lighting is also of influence, there are two types of lighting. One originates from the cloud and goes down the second originates from the ground and goes up. This second upward lighting has a longer discharge duration and thus damages the blade to a greater extent. It is also more prone to happen in areas with cold air mass thunderstorm (Yan et al, 2019).

Picture 30. Wind turbine blade being tested on lighting strikes. Photo credit: LM Wind Power.

Picture 31. Damage due to a lighting strike. Picture from betterplan.squarespace.com, (2009).

TEMPRATURE

Temperature can damage blades through two ways, it can influence fatigue performance and lower temperatures can result in ice forming. Tests by Mishnaevsky et al. (2012) showed that an increase of ambient temperature during cycle testing of a sample could decrease fatigue performance. A to low temperature can on the other hand instigate ice forming on the blades. There area three distinct types of ice formation that can occur depending on the temperature: rime ice (-20 to 0 C), glaze (-6 to 0 C) and wet snow (0 to 3 C). Ice can affect the balance of the blade increasing vibration, alter the aerodynamic shape reducing efficiency and dislodged ice can damage property or people (Baring-Gould et al, 2021). It is thus good to understand what temperature the blade has experienced both a to hot and to cold temperature can increase the fatigue damage, and ice can result in more moisture damage. This thus result in a weaker blade which should be taken into account when designing with WWTB segments.

Picture 32. Ice formation on a wind turbine in Sweden, ice is being removed through the use of warm wate (Schultz, 2023). Photo credit: Alpine Helicopter Inc.

LOCATION

Location also has a great influence on the failure of wind turbine blades because it will determine the environment that it will have to contend with. Which influences: wind speeds, temperature, precipitation / moisture, amount of UV light, airborne particles (close to sand, salt, etc) and type of lighting.

The location is also important in terms of land morphology, hilly regions for example can induce turbulent air increasing the fatigue load on a blade (Katsaprakakis et al, 2021).

The location of a wind turbine could be use full information during the reuse phase because it is an easy and simple data point that could possible predict the state of a wind turbine. Research by Tavner et al (2006) and Tavner et al (2012) looked at the correlation between weather data, location data and how they influence WT failures. The data used for the 2006 study was failure rates with the wind energy index and for the 2013 study failure data, wind speed, temperature and humidity was used. Both studies showed a clear relationship between the failure rate and temperature.

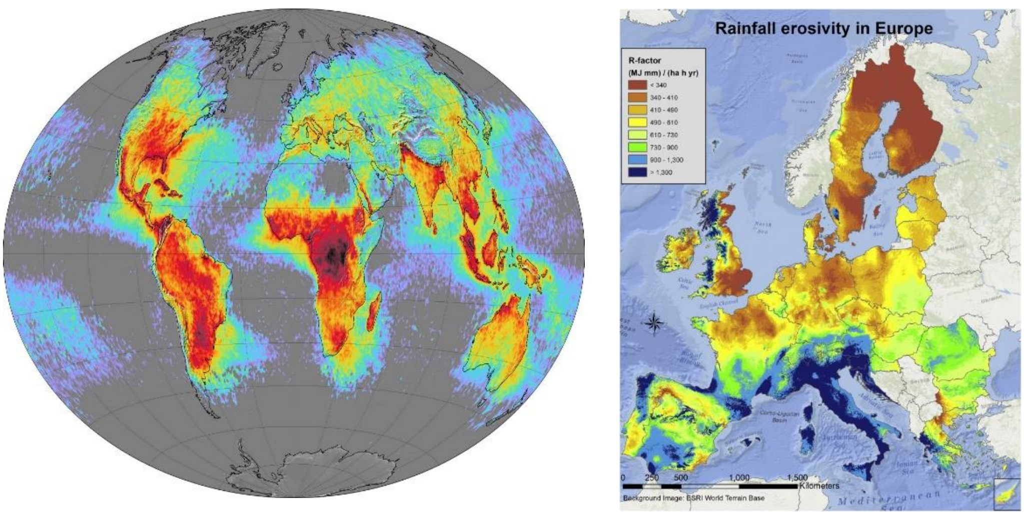


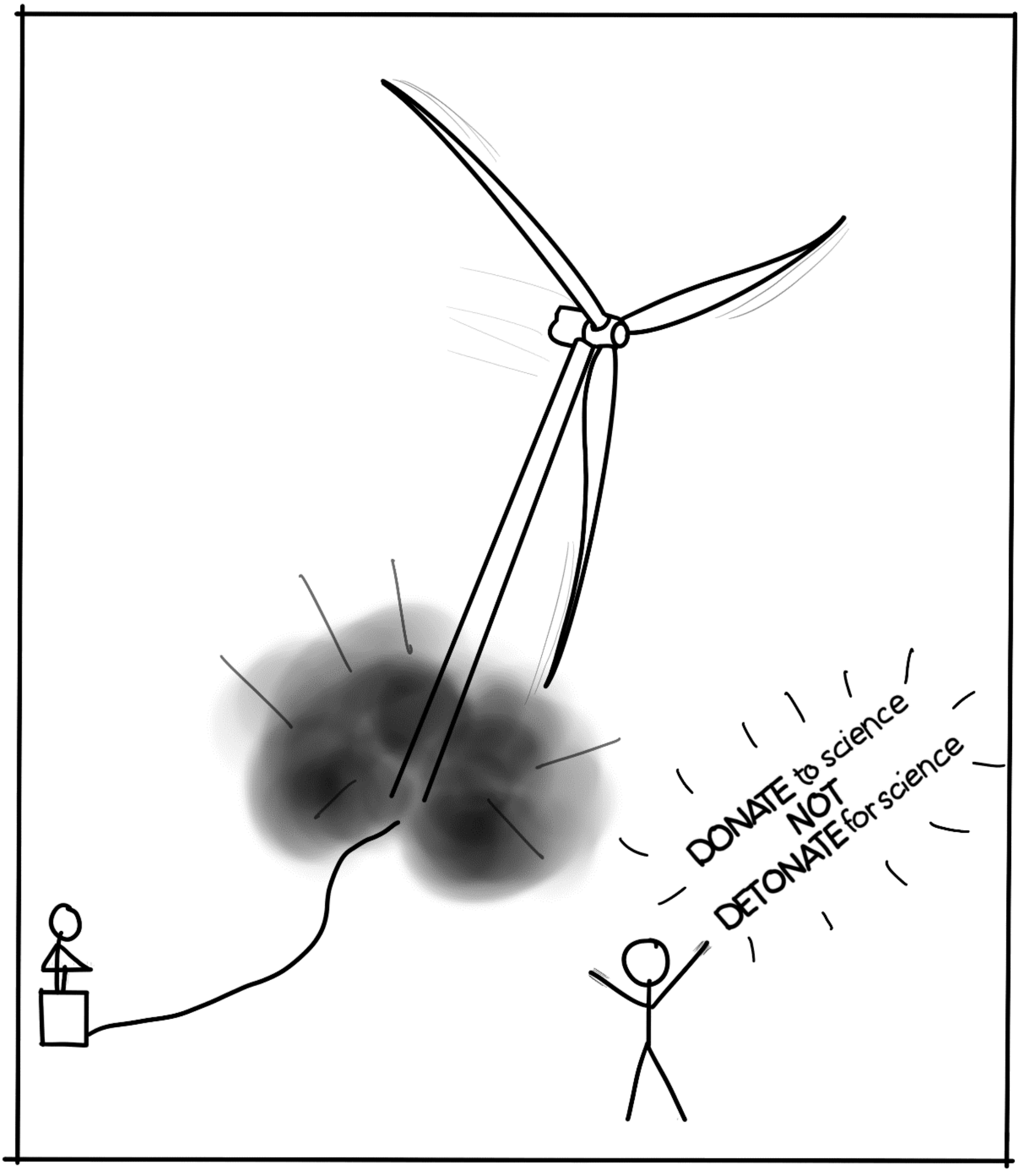
Figure 17. World lighting map left (King, n.d.) and rainfall erosivity in Europe right (Panagos et al, 2015). Showing how location data of WTs could be linked to weather data to indicate the severity of the state of a blade.

9.2.3 HUMAN ERROR

The last factor that can influence the state of wind turbines is human error. Human error can occur in every stage of the wind turbines service life; manufacturing, installation, operation and decommissioning. During manufacturing it is important to have the right fibre direction, a miss matched load to fibre direction can increase stress concentrations, weakening the blade (Mishnaevsky et al. 2012). Other factors in research by Mishnaevsky et al. (2012) showed that could weaken the blade are: fibre misalignment and fibre clustering. The last problem during manufacturing is the introduction of voids, Lambert et al (2012) researched the role of voids in the fatigue of wind turbine blades and showed a statistically significant relationship. Voids can be introduced by trapped air during manufacturing or by off gassing of volatile substances used during the manufacturing. Prepreg is most susceptible to air entrapment showing the importance of knowing the manufacturing techniques used.

The operational phase is also a great moment for human error to occur (Mishnaevsky, 2019), (Chen & Eder, 2020). Two interesting factors are the layout of a wind park, which can introduce unwanted turbulence (Cao et al, 2022) and the way a wind turbine is parked in extreme weather can increase the load (Tang et al., 2019). These problems can be mitigated by using software for example Qblade (n.d.) but the level of influence will be uncertain during the reuse phase.

Decommissioning of the blades is also really important for future reuse because blades can get damaged more if they are not handled with care. Blades are currently cut at the decommissioning site to be transported for recycling. Thus it isn’t necessary to handle the blade with care. This can entail that blades aren’t lowered or secured properly, as to not damage them or not handled with care while cutting. An extreme example of this is the act of using controlled demolition to decommission a wind turbine (TheLoizeauxGroupLLC, 2021). It is thus quite important that decommissioners are aware of the possibilities of reuse and the need for increased care while handling the blades.



Although wind turbines are usually decommissioned with care it is not unheard of to blast them into oblivion to make decommissioning easier.

9.3 DAMAGE MAP

Better understanding the damage that can be expected we can now start to generate a possible damage map. The shape map can be used the steer inspection efforts of WTB during the processing for reuse. Generalising WTBs to simple damage indications still looses a lot of nuance, every blade is different and has different environmental circumstances. Thus a too specific damage map can quickly become irrelevant. Thus the damage maps uses three levels, loosing some nuance but gaining some generality. These levels are slight change, moderate change and extreme change. The extreme change are cand be greatly damage to the point if becomes easier to remove it entirely.

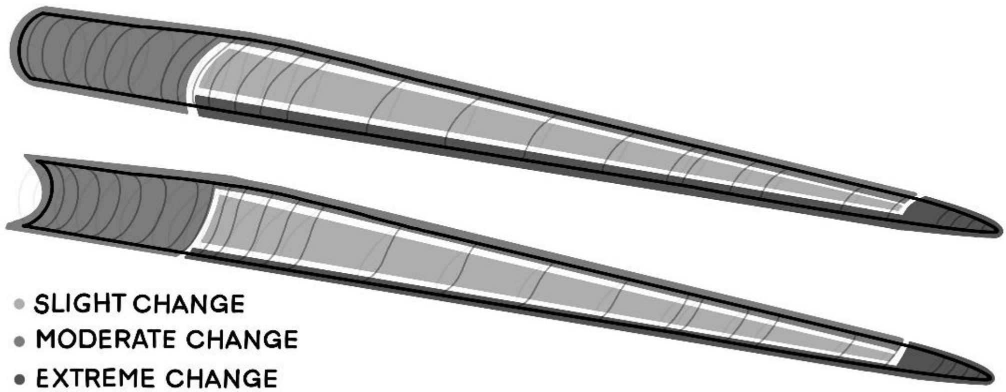


Figure 18. Damage map.

10 CONCLUSION PART 2

The goal of part two was to answer the research question: *How does the composition and build-up of wind turbine blades influence a possible application and cutting strategy?* Trying to figure out what aspects of a WTB would influence the application and cutting strategy. This question was answered by going trough four aspects of WTBs, the design, shape, materials and state.

By exploring the design of a WTB multiple factors were found that influences the reuse of WTBs. The increasing size and weight will increase the difficulties of processing strategies. The structure of a blade will influence the cutting strategy and cutting pattern depending on what type is used. And that because the sandwich structure changes throughout the blade it creates variable strength segments.

By exploring the shape of WTB it is possible to create a shape map based on the changing aerofoils, twist and pre-bend. The map has three indication levels showing what areas can be used for different application and how to best pattern the blade to optimise its usage.

By exploring the materials used in a WTB multiple factors were found that influence how segments can be best utilized. Depending on the materials used certain blades could have weaknesses or strengths, for example Aramid fibres that are extremely susceptible to moisture and UV or how certain core structure could dimple under certain use cases.

By exploring the possible states that blades can be in at the end of their service life it was found that there are hidden and exposed factors that will influence the state of the blade. The exposed factors like visible damage or weather conditions can be used to determine the state of the blade for further reuse purposes. But the hidden factors like material composition or service life have and similar big role. Making it important that manufactures and operators help by sharing information so that informed decisions can be made for structural reuse applications.

Many different influences were found within The four aspects but the severity at which they exert influence is hard to quantify, this would require more research and tests which is outside of the scope of this project. But the main point that needs to be remembered is that every blade that will be reused will be different. These difference can be large or small, but this will be uncertain until the blade is inspected.

KEY TAKEAWAY

- Blades have four factors that makes reusing them a difficult endeavour: design, shape, materials and state.
- Blade design is an ever changing landscape and thus reuse strategies should be able to dynamically adjust accordingly.
- Blades have the same purpose but can vary greatly making it necessary to inspect blades before they can be processed.

PART 3

CUTTING STRATEGIES

The last two parts investigated wind turbine blades with the goal to create a fundamental understanding which will be used as a basis for the following steps. Part 3 will use this foundation of information to answer research question 4: *How can wind turbine blades be strategically cut to ease structural reuse solutions?* The goal is to propose a cutting strategy that looks at the entire picture. This is done by looking at the factors of influence found in the preceding parts. And then exploring different cutting strategies.

This part is divided into 3 chapters the first part will elaborate on the factors that were found during the first research phase. The second chapter will explore different cutting strategies and the third chapter will end with a conclusion

11 FACTORS OF INFLUENCE

From the research done in the first two parts of this thesis multiple factors were found that can steer the proposed cutting strategy, cutting pattern or application. As stated before it is quite difficult to state the extend of the influence of these factors. Nevertheless it is good to have an understanding of what to think about when reusing WTBs. The following pages will elaborate on these factors and introduce possible design criteria derived from these factors of influence.

11.1 THE FACTORS OF INFLUENCE AND DESIGN CRITERIA

SYSTEMIC INFLUENCES

- **Increasing problem size.**
  The amount of waste is only rising and thus more and more blades will need to be processed.
  - A processing strategy should be scalable.
  - The designed segments should be useable for multiple applications (less need to change cutting pattern).
  - A processing strategy should be as efficient as possible in processing time.
  - A processing strategy should be as efficient as possible in material usage.
- **Dynamic availability.**
  Wind turbine parks are build at different times and are thus decommissioned at different times, the amount of waste can differ throughout the year.
  - A processing strategy should be able dynamically adjust to processing amounts.
- **Drifting availability.**
  Wind turbine parks are build at different locations and thus the distance to which blades have to be transported can increase to unworkable amounts.
  - A processing strategy should be able to deal with changing logistical routes depending on where the blades will be sourced from.
  - A processing strategy should be able to transport blades or itself as efficiently as possible to reduce emissions.
- **Information accessibility and transparency.**
  Manufacturers, operators, service companies, etc. are hesitant to share information.
  - Processing strategies should be able to work without any provided information form the industry.
  - Applications should allow for sufficient safety factors to combat unknown factors.

- **Communication transparency**
  Companies are starting to realise that WTBs can be a valuable material, but it is still not at a level that is needed for a good resus system.
    - A processing strategy should include communications towards the public.
    - A processing strategy should include communication towards the industry

WASTE GENERATION

- **Waste hierarchy.**
  The waste hierarchy is a big part of regulations and can be used to steer possible processing strategies.
    - A processing strategy should aim to be as high up on the waste hierarchy ladder as possible.
    - A processing strategy should generate as little processing waste possible.
    - A processing strategy should manage generated waste trough an as high as possible management technique on the hierarchy.
- **End of life.**
  Reuse isn't the end of the life cycle of WTBs and the waste will eventually be needed to be managed.
    - Applications should be designed to not hinder possible waste management later on.

BLADE DESIGN

- **Different and non generic blades.**
  There are many different blades on the market and in use, which can differ in shape, material, structure and state.
    - A processing strategy should be able to handle different types of blades.
    - A cutting pattern should be able to handle different types of blades.
    - Applications should be segment dynamic, a slightly different segment shouldn't break the application.
    - A cutting tool should be able to handle different kinds of blades.
    - A reuse strategy should check the strengths and weaknesses of the materials used in the blade.
- **Evolving blades**
  Blade development isn't standing still and blades are getting heavier, longer, new materials will be used and they are getting engineered closer to the edge of what is possible.
    - A processing strategy should take into account that blades will become larger and heavier in the future.
    - A cutting pattern should take into account that blades can differ in size.

    - A processing strategy should take into account the future development of blades, should be able to dynamically adjust if necessary.
    - A processing tool selection should take into account the possible new materials.
    - A processing strategy should take into account that new blades are engineered closer to the edge of wat is possible and thus have tighter strength tolerances.
- **(Variable) blade structure.**
  The structure of a blade changes throughout the length and width of a blade, the thickness of the fibre layer, thickness of the core, locations of the core materials, locations of internal structures.
    - A processing strategy should take into account the different internal structures of blades, box beams vs shear web(S).
    - A processing strategy should take into account the varying thickness while cutting.
    - A cutting strategy should be able to handle multiple material thicknesses
    - An applications should be able to handle different segment thicknesses.
    - The cutting pattern should take into account the varying internal structure of the blades.
    - The cutting pater should take into account ply and core drops.
- **Anisotropic behaviour and fibre orientation.**
  The fibre orientation and layup varies throughout the length and thickens of the blade, resulting in an anisotropic behaviour.
    - The cutting pattern should take into account the different fibre directions for optimal strength.
    - The applications should take into account that segments can have different strength properties.
    - Connection strategies should take into account the fibre direction and resulting hold force.
- **Manufacturing.**
  Blades can be manufactured using multiple techniques that all have their own consequences.
    - The processing strategy should be able to handle blades manufactured suing different techniques.
    - The cutting pattern should take into account that different manufacturing techniques have more imperfections distributed through the blade
    - The cutting pattern should take into account the increased weakness off glue seams.
    - The application should take into account that the kerfs of the core structure will absorb some of the matrix material.

- **Complicated and variable curves.**
  The aerodynamic use case of blade necessitates complicated double curved shapes trough aerofoils, twists and pre-bending.
    - The cutting pattern should take into account the variable curving shape of the blade.
    - The applications should utilise or not be influenced by the curved shape of the segments.
    - An application should be able to handle different shaped segments.
    - The processing strategy should take into account curving nature of the blades.
    - The cutting directions should stay as close to normal to the surface of the blade.
- **Diverse fibre usage.**
  Blades can be manufactured using different fibres that all have their own properties.
    - A processing strategy should check which fibre materials are used.
    - A processing tool should be able to cut trough all fibres used in WTBs.
    - A reuse strategy should check if the loads used in the application load the fibres in the most optimal way.
- **Diverse core usage.**
  Blades can be manufactured using different types of core material and structure.
    - A reuse strategy should check what type of core materials is used.
    - A reuse strategy should check the core structurer used in blades, homo- vs heterogeneous.
    - The types of loads should be compared to the type of core that is used, (heterogeneous cores are bad at shear and surface compression).
- **Blade additions.**
  Blades are often integrated with additions features, for example sensor kits or lighting protection.
    - Blades should be checked for any "foreign" additions that could hinder the processing (e.g. wires getting stuck in a cutting blade).
    - Blade segments should be checked for exposed materials and parts that could rust or corrode.
    - The cutting tool should be able to cut additional materials that can be added to the blade and not be removed.

- **Coatings.**
  Blades are coated to protect the structure / materials from the elements.
    - o Damage to coatings and bare edges should be resealed, depending on the requirements for the application.
    - o The type of coating should be checked and tested for the application. (soft vs hard, traction, etc).

BLADE STATE

- **Failure frequency.**
  A blade will have enough damage incidents in its life time to expect that every blade will have significant cutting pattern altering defects.
    - o A reuse strategy should check the state of a blade for damage and assess areas to be used for structural or non structural purposes.
    - o A processing strategy should check if the blade still has it original shape.
    - o Blade should be used with a generous safety factor.
- **Blade damage**
  Blades can get damaged in many ways.
    - o The leading edge of a blade should be checked for erosion damage and superficial repairs.
    - o The tip (last four meters) of the blade should be checked for lighting damage.
    - o The blade should be checked for structural repairs.
    - o The glue seams should be checked for delamination damage.
    - o Segments should be checked for delamination damage at the edges or withing the surface.
    - o The blade should be checked for fatigue damage at the root and glue seems.
- **Environmental factors.**
  The environmental factors are a good indicator of the state of the blade and can be used as a pre screening measure.
    - o The environment should be checked for increased fatigue loads and the safety factors should be adjusted accordingly.
    - o The environment should be checked for possibilities of increased damage and the blade should be checked accordingly.

PROCESSING

- **DOF of processing tool**

  How mobile the cutting tool is will greatly influence the patterns that you can make and how closely it can follow the shape of the blade.
  - The DOF a tool has should be appropriate for the cutting pattern.
  - The stiffness and resulting tolerance of a chosen tool should be checked and compared with the required tolerances for the application.
- **Damage by tool**

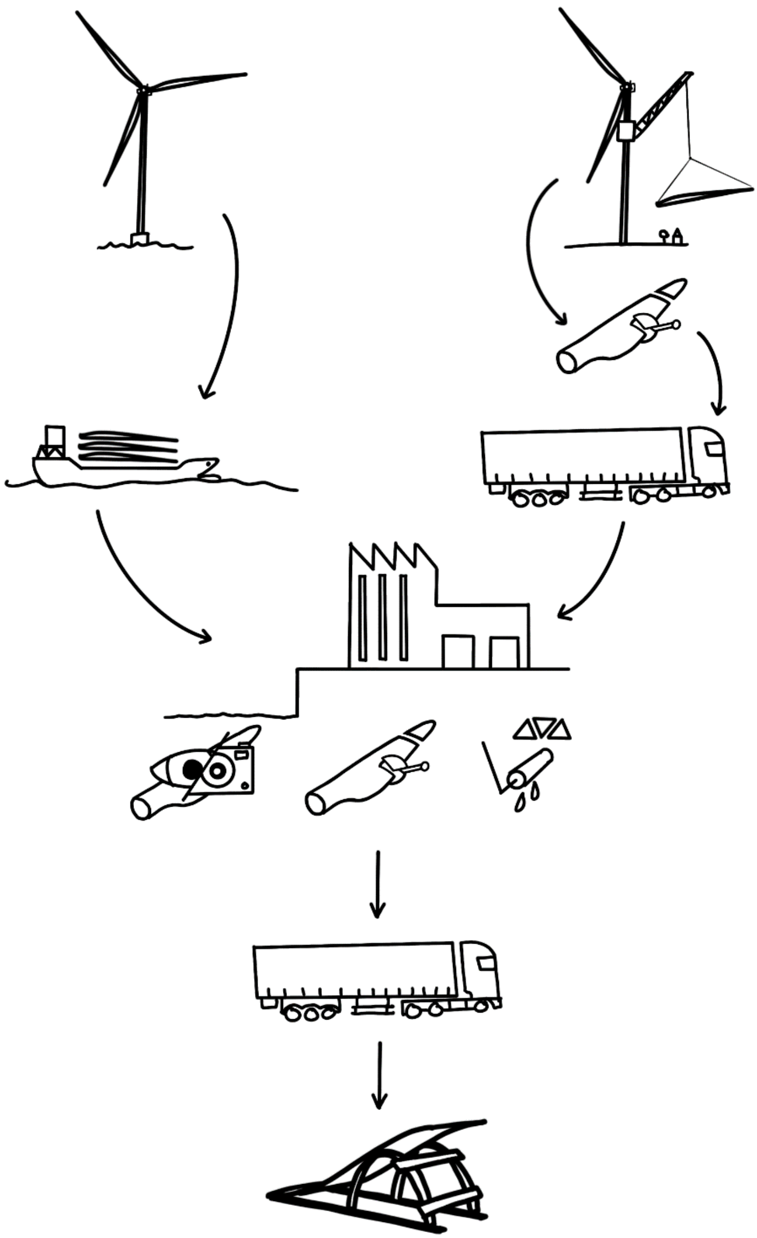
  Tools can have different effects on the cutting edge.
  - Post processing steps should assess the damage created by the processing tool and processes accordingly
  - Heat generation should be checked at the cutting edge and be reduced as much as possible.

- **Safety**

  Processing of composite materials can be dangerous.
  - A processing strategy should mitigate dust creation.
  - A processing strategy should included appropriate PPE.

12 PROCESSING STRATEGY

The factors of influence and resulting criteria can be used to create an initial proposal for a processing strategy to structurally reuse WT blades. The processing strategy will be presented by going through the two main processing groups: logistics and processing. This way the explanation won't be in chronological order but an overview of the steps can be found in the visual below.



12.1 LOGISTICS

The first big problem that has to be tackled is the logistical problems after the blades are decommissioned. There are two logistical problems that a reuse strategy has to contend with: transport and storage. The transport will be analysed because it has consequences for the cutting pattern but the storage will be only shortly mentioned because it is deemed that it is of little consequence for later design steps.

12.1.1 TRANSPORT

The first logistical difficulty greatly depends on the origin of the blade, is it from an offshore or onshore wind farm. For offshore it is quite easy to move the blades per boat to a nearby harbour (just like how they are currently transported to the wind farm). Offshore vs onshore is about a 40/60% split (Wikipedia, 2024 June 12) with offshore increasing fast. And thus a processing plant located around a harbour could safe any transportation over land (which is more difficult) for the offshore WTBs. But it becomes a different story for onshore wind farms.

A 50 meter blade weighs around 10 tons and the weight limit on European roads is around 40 to 50 ton per road train (truck with trailer) (Itf-oecd.org, 2022). If the shape is neglected this means that one truck can move four blades at a time. A rough estimate puts about 20 wind turbines per park for onshore wind farms in the Netherlands (Wikipedia, 2024 June 12). The resulting 60 blades would need 15 trucks to move them, but this number probably under estimates the amount because weight isn't the problem, the size is. It is really difficult to fit four blades in a truck plus trailer. And thus some preprocessing will be necessary to reduce the transportable size.

The best way to reduce the transportable size is to cut the blade apart and to remove all the undesirable and damaged parts. These undesirable parts cannot be used for reuse purposes and thus should be utilized in the next best option based on the waste hierarchy, recycling. Shredding is necessary for all the recycling techniques that are in use today and can be done by a comparable system showcased in chapter 2.3. The transportable wtb shredder can reduce the size of these parts and make the material easier to transport.

Cutting the blade to reduce size can be done with several levels of difficulty. The easiest is to cut the blade perpendicular to the length (done in strategic intervals based on the cutting pattern). The smaller pieces make it easier to pack the container in an efficient manner. But there is still empty space within the cross section of each blade. To reduce the size even more the glue seams can be cut of or broken. This way there are only panels left that can be fitted into a container. But this is a difficult task and could make the process more inefficient. These processing steps will be explained in more detail in the coming pages.

12.2 PROCESSING

The second step is the processing of the WTBs. Processing can be divided into three groups: preprocessing, processing and post processing.

12.2.1 PREPROCESSING

Preprocessing encompasses al the steps that need to be taken before the blade can be cut following the cutting pattern. In this is step it is important to figure out what type of blade has been received, as was concluded in part two. This entails the following tasks:

- Assessing the damage of the blade.
  - Check for damaged areas or areas where repairs have been made. This information should be used to alter the cutting pattern accordingly or create a strength indication which can be linked to possible applications.
  - This is blade specific task.
- Assessing the shape of the blade.
  - Multiple techniques can be used to assess the shape. The most thorough technique is to 3D scan the blade. A more manual approach can also be used but this will take considerably more time. 3D scanning will make it easy to automate the coming processing steps for example creating tool paths or fitting the cutting pattern on a blade. Manufactures might have shape data for a blade but these are usually not provided and the blades shape alters slightly due to use.
  - This is a blade model specific task.
- Asses materials used.
  - Knowing what materials are used in the blade could indicate what processing tools can be used. For example water jet cutting could introduce too much moisture for Aramid fibres. Manufactures have this information but might not be keen to share it, in that case the material will need to reversed engineered which can be a difficult task.
  - This is a blade model specific task.
- Check for any blade additions
  - The blade should be checked for blade additions that are loose within the blade. These could clog up cutting tools or interfere in unpredictable ways during processing.
  - Blade specific task.
- Pre cutting the blade.
  - The blade should be precut into more manageable pieces for the processing steps. A tool akin a bandsaw or wire cutter would be the best option for this step. Such a tool can be made large enough to cut a blade perpendicular to the length in one go.
  - This is a blade models specific task, but can be altered if a blade has significant damage.

12.2.2 PROCESSING

Processing encompasses al the steps and decisions that need to be taken to cut the blade into segments.

- Processing tool.
    - Multiple tools can be used but the decision depends on the materials and degrees of freedom that are needed. Using a straight forward cutting pattern with al lot of continues cuts makes it possible to use a simple diamond blade. When cut perpendicular to the length of a blade the diamond cutter can also stay at the right angle to the surface which is necessary to create good segments. But this isn’t possible for every cut and then a second tool can be used that has more degrees of freedom (for example water jets or milling tools on robotic arms), this way the cutting direction can stay perpendicular to the surface.
    - Blade model specific task.
- Blade fixation.
    - The awkward shape of a blade makes it difficult for the blade to remain flat and still on a cutting bed. It is thus important that the blade is fixated. Using holding clamps that clamp on the leading and trailing edge could be a good solution. These parts are often damaged and unsuitable for reuse and thus the cutting pattern does not cut trough them. This way the clamps can stay in place. By adding a extra degree of rotation it also becomes possible to rotate the segment to aid in the cutting.
    - This is a blade specific task.
- Safety.
    - Processing composite materials can be hazardous, the fibres and particulates can become airborne and easily irritate the skin or airways. It becomes necessary to process the blade away from people or with a lot of PPE. Waterjet cutting could remedy this by wetting the entire cutting area and reducing dust, but as discussed, water can damage certain materials. It is thus important that the processing is done an a controlled environment which can contain the dust.
    - Process specific task.

12.2.3 POST-PROCSSING

Post processing encompasses al the steps and decision that need to be taken to finalize the segments so they are ready for reuse applications.

- Assessing segment damage.
  - The cutting tool can damage the segments but there can also be preexisting damage that is exposed by segmenting the blade. This damage should be assessed and then checked if it could hinder the usage of the segment.
- Cutting tool specific steps.
  - Certain tools will have specific post processing steps depending on the material and tool used. For example when using water jet cutting with a balsa core it become important to firstly let the segments dry before any new steps are taken, sealing would trap the moisture inside which could negatively affect the performance of the segments.
- Application specific processing.
  - Depending on the application the segments need to be processed one step further to be able to be used. In part four multiple concepts will be discussed one of which is a boulder wall. Segments utilised in boulder wall would need extra holes drilled and chamfers added to the edges. This can vary greatly per application and should be taken into account that it is done in the right order.
- Reseal the segment edges.
  - The edges of a segment should be resealed to combat further environmental damages that could occur due to, for example, moisture. But it is also necessary as a safety precaution. The exposed edges could make it possible that pieces of fibres get dislodged or that users can be wounded. Current gelcoats can also have dangerous chemicals which is difficult to predict and by resealing it makes it possible to safeguard users (Medici et al 2020). Choosing the material to be used for resealing depends the application use case and gelcoat that is used on the blade.
- Strength and shape categories.
  - The last step is to categorize the segments based on shape and strength. For this the simple shape map could be used making it easier to gather the right segments for any application. The best way to non-destructively determine the strength is to use the thickness of the fibre layer and core. But because every blade is different every blade should be tested. This can be used to create a base line which can be extrapolated to the other segments from the blade.

13 CONCLUSION PART 3

The goal of part three was to answer the research question: *How can wind turbine blades be strategically cut to ease structural reuse solutions?* Trying to figure out what needs to be taken into account when reusing WTBs. This question was answered by first creating the factors of influences list with its resulting design criteria. This is then used to ideate a possible processing strategy. The processing strategy is far from being implementable, the main point to get across is to understand what steps should be taken when reusing a WTB.

Factors of influences where found around five categories: systemic influences (influences that work on a system level), waste generation, blade design, blade state and processing. These influences result in about 70 design criteria that steer the design of a cutting strategy, cutting pattern and application. The biggest influence is the changing design of WTBs. Every model can be different, any manufacture uses their own techniques and thus any strategy should be able dynamically adjust to the chagging circumstances.

Ideation on a processing strategy resulted in two problem areas: logistics and processing. The logistics around the reuse of WTBs is a difficult problem to tackle. The moving locations off decommissioning sites results in a potential for a lot of transportation and this can become environmentally expensive when you take into account the size and weight of WTBs. The second problem is the processing of the WTBs. These massive double curved structures make it difficult to just simple cut and process them. Lots of care needs to be given to the order of operations and the tool/ toolpath used.

KEY TAKEAWAY

- There are many factors that could influence the cutting strategy, cutting pattern and applications, which can change depending on the design of the WTB.
- The biggest problem with reusing WTBs is the dynamic nature of the design of WTBs. They can differ considerably and any reuse strategy should be able to adjust accordingly.
- A cutting strategy has two problem areas: the logistical problems and the processing problems.

PART 4

STRUCTURAL REUSE APPLICATIONS

14 APPLICATION EXPLORATION.

15 EXPLORING CUTTING PATTERNS.

16 APPLICATION CONCEPTS.

17 EMBODIED APPLICATIONS.

Eco-planetarium from team Seventh circus at Archidrom festival in Voronezh. (Mavrina, 2013)

Having analysed the design of a WTB and how it influences cutting strategies it is now time to use that information to design possible reuse applications and cutting patterns. This part will try to answer research question 4: *What applications can be identified to structurally reuse wind turbine blades?* And research question 5: *How can a structural application be designed/ made by repurposing wind turbine blades?*

These questions will be tackled by going trough ideation iterations and inspiration finding missions. The application and cutting pattern influence each other and are thus designed in parallel.

14 APPLICATION EXPLORATION

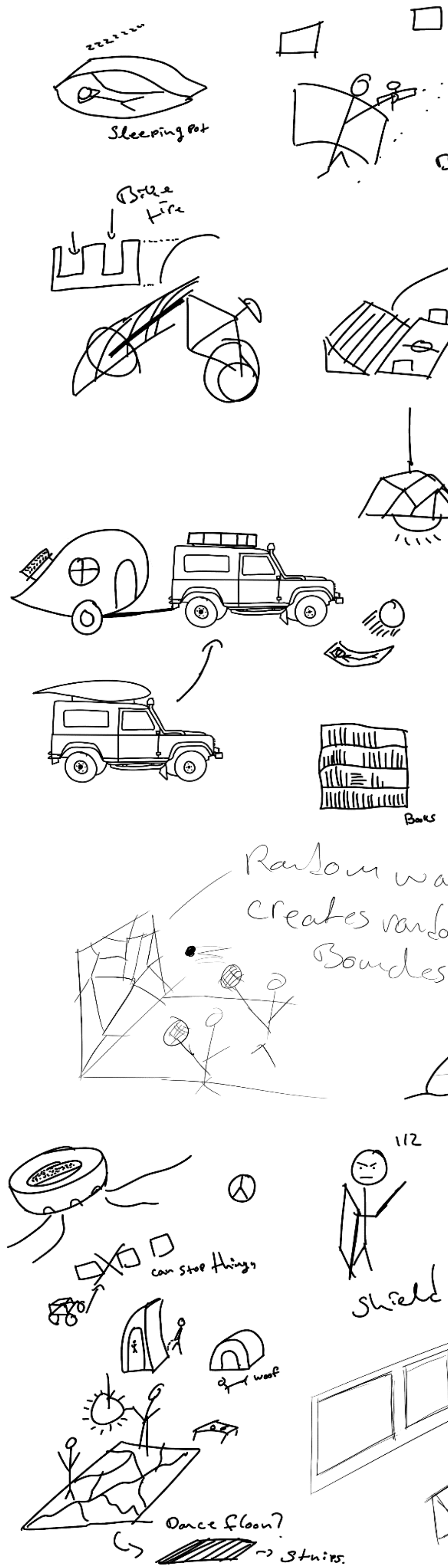
This chapter will be the first exploration for possible reuse applications where WTBs could be a interesting material choice. This will be done in three steps first an ideation dump, then a inspiration cycle and finally the identification of interesting areas. The first two steps will be as free as possible and all the previous information will be forgotten. The third step will couple possible applications to the information found in the previous three parts of this thesis.

14.1 IDEATION DUMP

The goal of the ideation dump was to get all the initial ideas that were roaming around out of way and to create a clean slate. It will also be used to kick start the inspiration steered application finding step. The ideation was confined to ideas that utilized processed / cut elements from WTB.

When comparing these possible applications to those found in chapter 3.4 some similarities can be seen. For example the usage for: (urban) furniture, shelters and partitions. But also some new areas have been found: construction, sport, market stalls and booths.

From this we can create some interesting areas to gather inspiration from: sports, shelters, (urban) furniture, construction and temporary structures.



BB / Paint
Live stock
Silo
trough
PLANK WEAVE
Ramp
Scoop
Megabench
fish
Vegetable
Temp roof in Disaster area
Stonewall
strong
Bouldering wall panels
Saftey Fence/
Sound Barrier at construction site
Windmills
protection
WTB Beams + Fabric
Twisty
Bridges
Skate park
Bike Ramps
Podium pads
Circus
geodesic dom
Hole for lightness
Small shelter
Bus/Duck out etc.
Acoustic Booth.

14.2 INSPRATION

The ideation dump is used to kickstart the inspiration finding mission. The goal is to look for current objects that could be made from WT blade elements in the realm of the areas of interests found in the ideation dump.

14.2.1 SPORTS

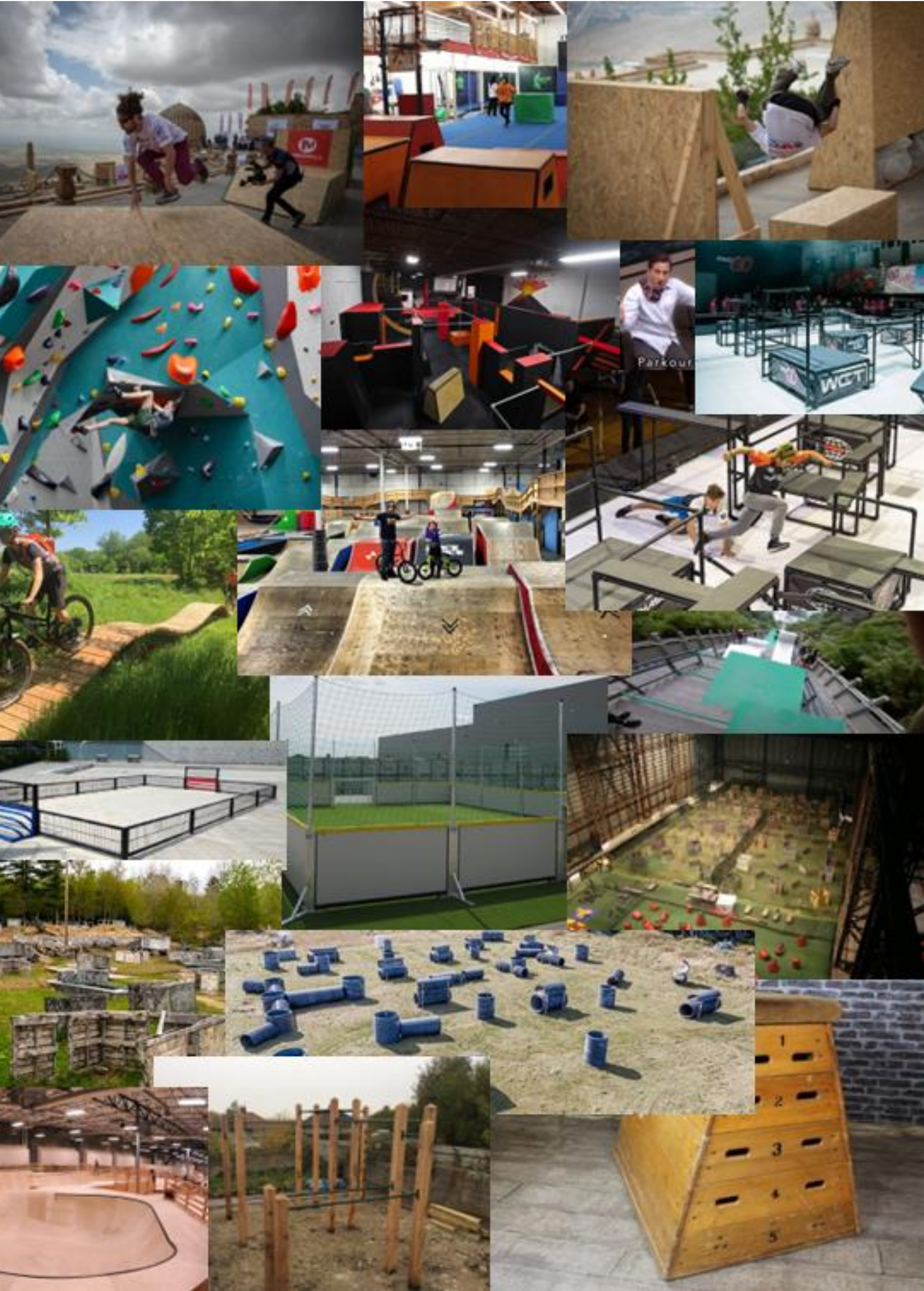
The first area that was looked at it sports. Sports could be interesting application area because of its use of wood, it also often uses panels to generate required shapes which has some resemblance of WTB segments.

Take aways:

- Usage of both panels and beams.
- Random curves could be an added game element.
- Force the WTB shape into the application vs force the application into the shape WTB. Or find harmony.
- Similar elements is better for scalability.
- Option for tailor made products vs reusable elements vs DIY projects.

Exploration points:

- Panel strength.
- Grip/ traction between segment and user.
- Safety requirements.


Parkour
WCT
1
2
3
4
5

14.2.2 SHELTERS

The second area looked at is shelters, small shelters could easily be made from panels cut from wind turbine blades although weather proofing might be difficult.

Take aways:

- Law of similarity for larger structures.
- Why only use WTB segments, why not a mixture of wood/metal and WTB segments.
- Reducing the size of segments makes it easier to create organic shapes.
- The randomness of panel shape from WTB segments could lend it self to DIY-esque projects.
- Triangular panels can be used as dragon scales, like in geodesic domes.

Exploration points:

- Weather proofing between panels.
- Connections system for panels.
- How do you efficiently make a larger structure out of smaller panels.


LEGACY FIELD

14.2.3 (URBAN) FURNITURE

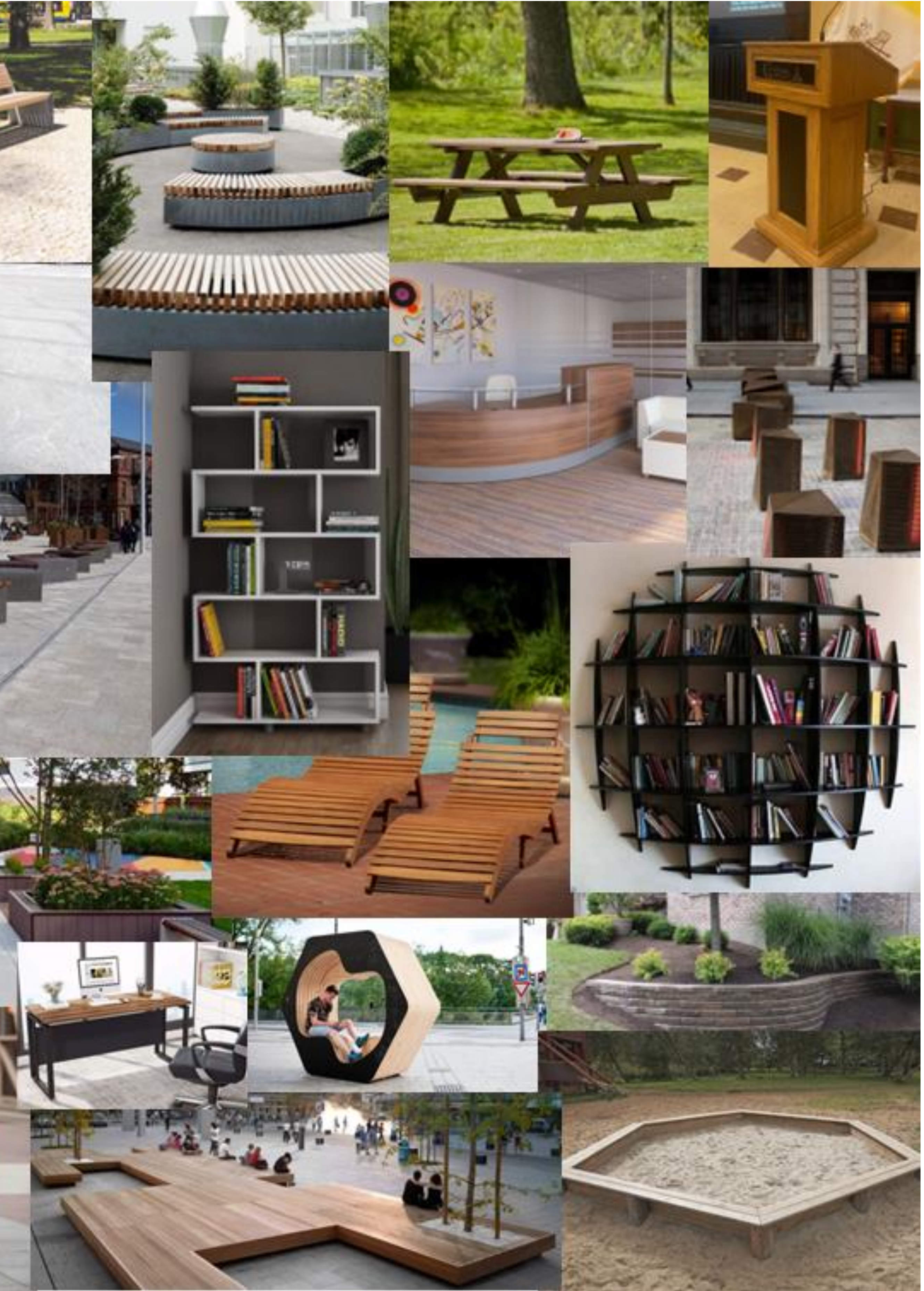
The third area looked at is furniture and urban furniture. Wood is often used for furniture and concreate as addition for urban furniture. WTB segments could be used as an replacement for wood and maybe even concrete elements.

Take aways:

- Difficult to use standardized elements, more in the area of "one of cutting".
- There are some applications that utilize the curve of the blade.
- Straight lines are possible but probably with many small elements.
- The WWTB segments have an outside surface of epoxy which might be easy to dry off when wet.

Exploration points:

- Furniture pieces that can utilize the increased structural properties of wtb segments in comparison to wood.
- Wood is often used for seating because of its low heat conductivity, would the thermoset surface of a WTB segment be desirable for sitting.
- Are the wtb segments easier to maintain than wood elements.



14.2.4 CONSTUCTION

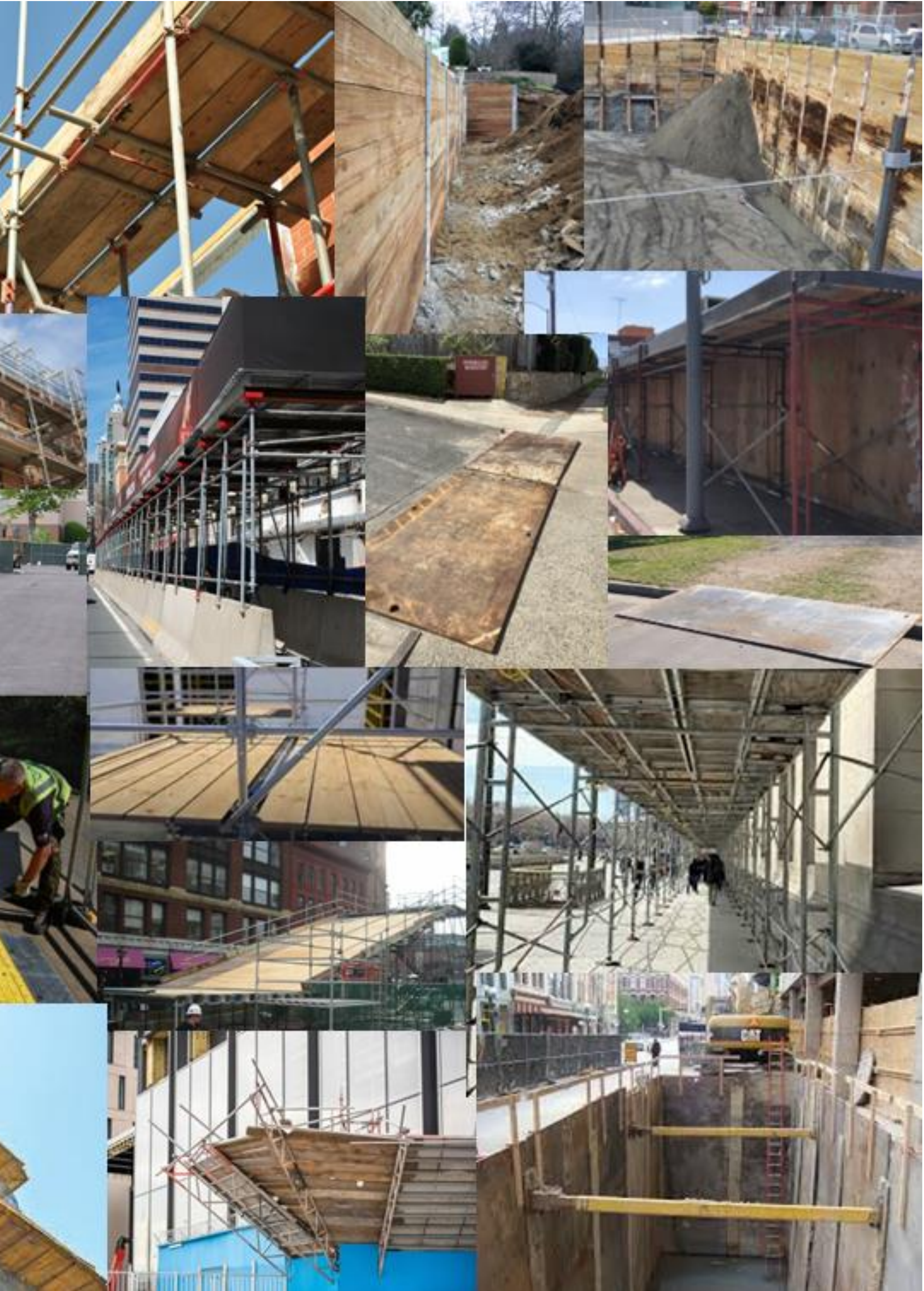
The fourth area looked at was construction. Construction uses a lot of board materials for temporary structures which could be an interesting use case WTB segments. And could WTB segments even replace some metal structures?

Take aways:

- The improved strength of wtb segments could bridge larger gaps and reduce the amount of metal needed.
- Could offer improved protection for pedestrians.
- The curbed shapes could be used to redirect falling objects.

Exploration points:

- Can WTB segments be designed to replace metal structures next to the wood panels?
- Would WTB segments fail in a desirable manner in comparison to metal structures?
- What is the maximum abuse that a wtb segment can take.



14.2.5 TEMPORARY STRUCTURES

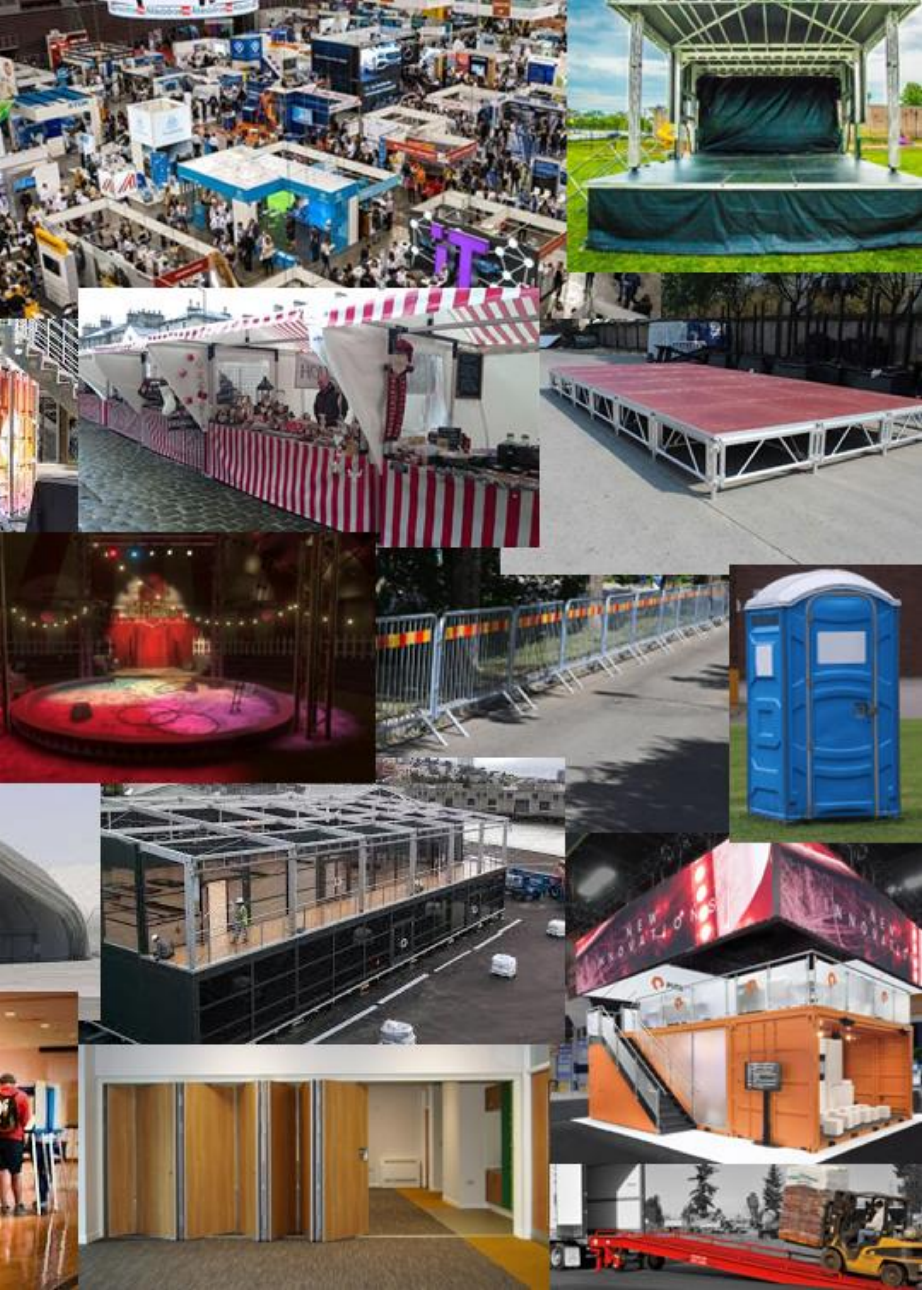
The fifth and final area looked at is temporary structures. One of the goals of this thesis is to find a segmentation pattern that can be reused for multiple applications, temporary structures could be an interesting way to utilize this.

Take aways:

- WTB segments could integrate the use of multiple materials from some applications.
- A need for efficient storage and transport ask for very flat panels.
- Not everything can be made from standardize panels, you might still need some beams or trusses.
- The length of the blade could have variable use cases, end could be light enough for voting booths.
- Most exhibition stalls have the same elements but want to look differently.

Exploration points:

- Could you make multi story structures from WTB elements, or is a combination of segments and metal structure needed.
- How to give the users the freedom to make their structure their own, with a limited set of segments.



14.3 AREAS OF INTEREST

The ideas gather in the previous steps can now be combined and clustered into a list of possible applications for which WT blades could be an alternative material source. These clusters can then be used to find areas of opportunity

14.3.1 IDEATION LIS

Sports: Bouldering wall / Skate park / Bike park / Bike ramp / Free running parkour / Parkour parkour / Tag course / Panna field / Skate board / Airsoft field / Paintball field / Visual acrobatics / Basketball back board / Squash back wall / Table tennis table.

Shelters: Tiny home / Tree house / Public toilet / Caravan / Dog house / Stables / Dug out / Carport / Bus shelter / Shade roof / Wind break / Animal shelter.

(urban) furniture: Bench / Picknick table / Desk / Lectern / Cabinets / Lounge chair / Flower bed / Anti terror architecture / Sandbox / Landscaping wall.

Construction: Shoring wall / Fence / Scaffolding platforms / Road plates / Debris screens / Canopies / Cable duct / Temporary cover.

Temporary structures: Stage elements / Market stall / Exhibition booth / Porta Potty / Ramps / Buildings.

Spaces: Sleep pods / Phone booth / Acoustic booth / voting booth / wall partitions.

Containers: Grain silo / Roof trunk / Industrial packaging / Pallet / Heat pump case / Aircon case.

14.3.2 AREAS OF OPPORTUNITY

Seven clusters have been found and the next step will be to reduce the size of this list. The goal is to find which area(s) create the most opportunities for applications. To aid in the evaluation a Harris profile [1] will be used. The criteria used for the profile will be (in descending order of importance):

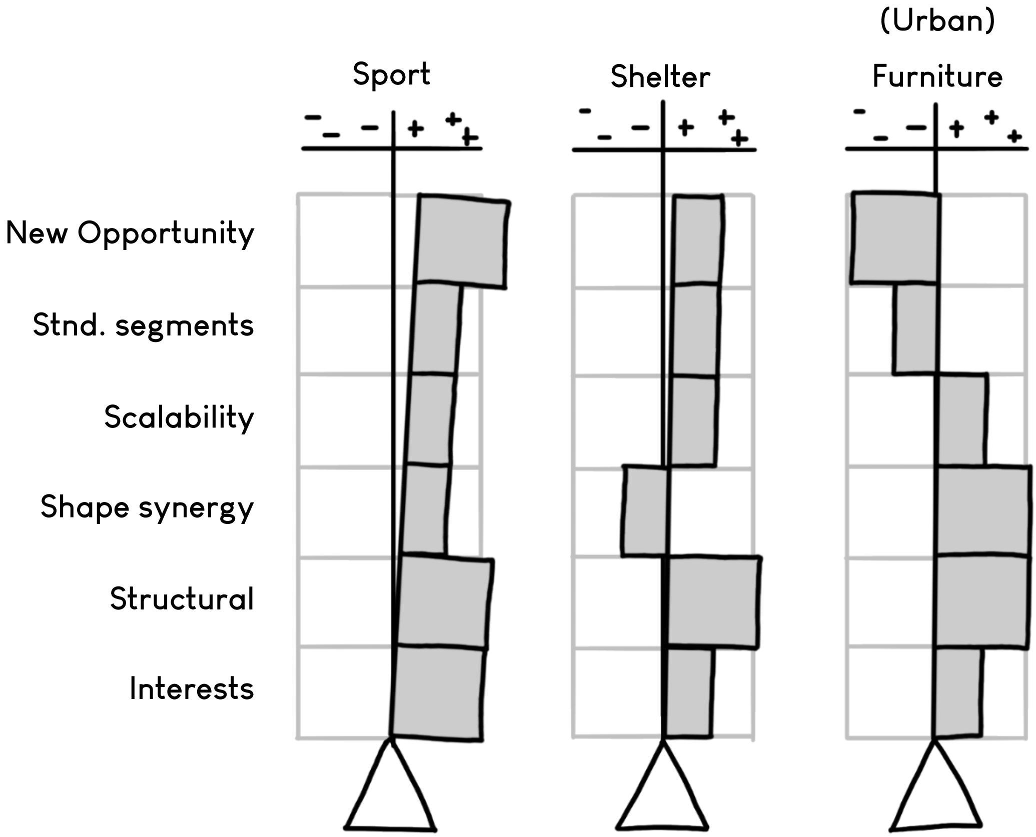
- New opportunities.
- Utilizing standardized segments.
- Scalability.
- Shape synergy.
- Structurally possible..

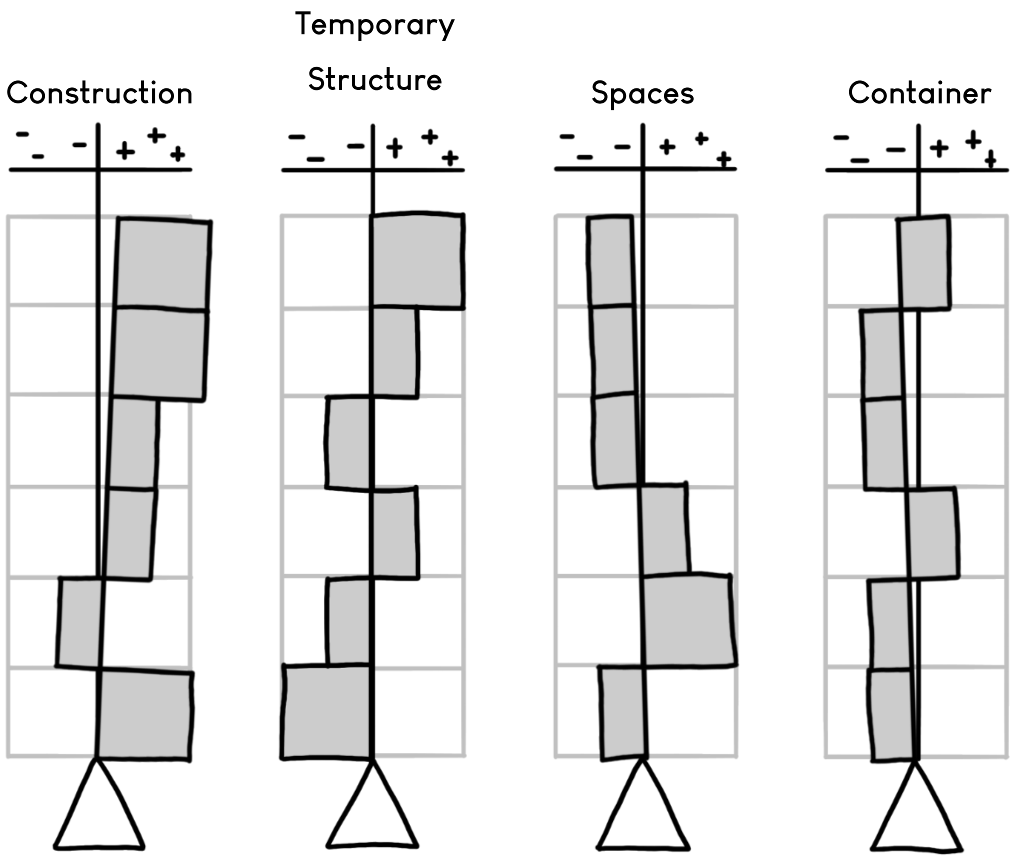
These criteria are simplifications of the criteria found in 11.1.

The Harris profiles can be found on the next page. The result: sports, shelters and construction are interesting areas. We can also make some overarching conclusions:

- **Sports**: many opportunities which can also utilize the shape of the blade.
- **Shelters**: there are existing shelters but none that utilize standardized segmentation.
- (**urban**) **furniture**: a lot has already been done, although they could better use the shape to their advantage.
- **Construction**: needs a lot of strong and durable materials, but are the panels strong enough.
- **Temporary structures:** interesting use case but a lot of transportation is involved which necessitates efficient weight/strength/shape/utility ratio's.
- **Spaces:** these panels have interesting properties that can be used but spaces might not use it to the fullest extent.
- **Containers:** really one off type structures that won't use standardized panels to the fullest extent.

[1] A Harris profile is a visual tool that compares the strengths and weaknesses between different concepts. By creating a visual tower that will fall to left (bad) or right (good) where the higher blocks make the tower more unstable and thus are of greater importance (van Boeijen et al. 2014. p. 139).


(Urban)
Sport
Shelter
Furniture
New Opportunity
Stnd. segments
Scalability
Shape synergy
Structural
Interests



Construction
Temporary Structure
Spaces
Container

15 EXPLORING CUTTING PATTERNS

In the inspiration collection of the applications there are some overarching segments of rectangular, triangular panels and trusses or beams. But the question in this chapter becomes if this is good way to segment the WTBs or if there are any other possibilities. This chapter will start whit an inspiration session and than goes into possible cutting patterns using low-fi prototypes to test those patterns.

15.1 STRUCTURAL AND INSPIRING GLASS

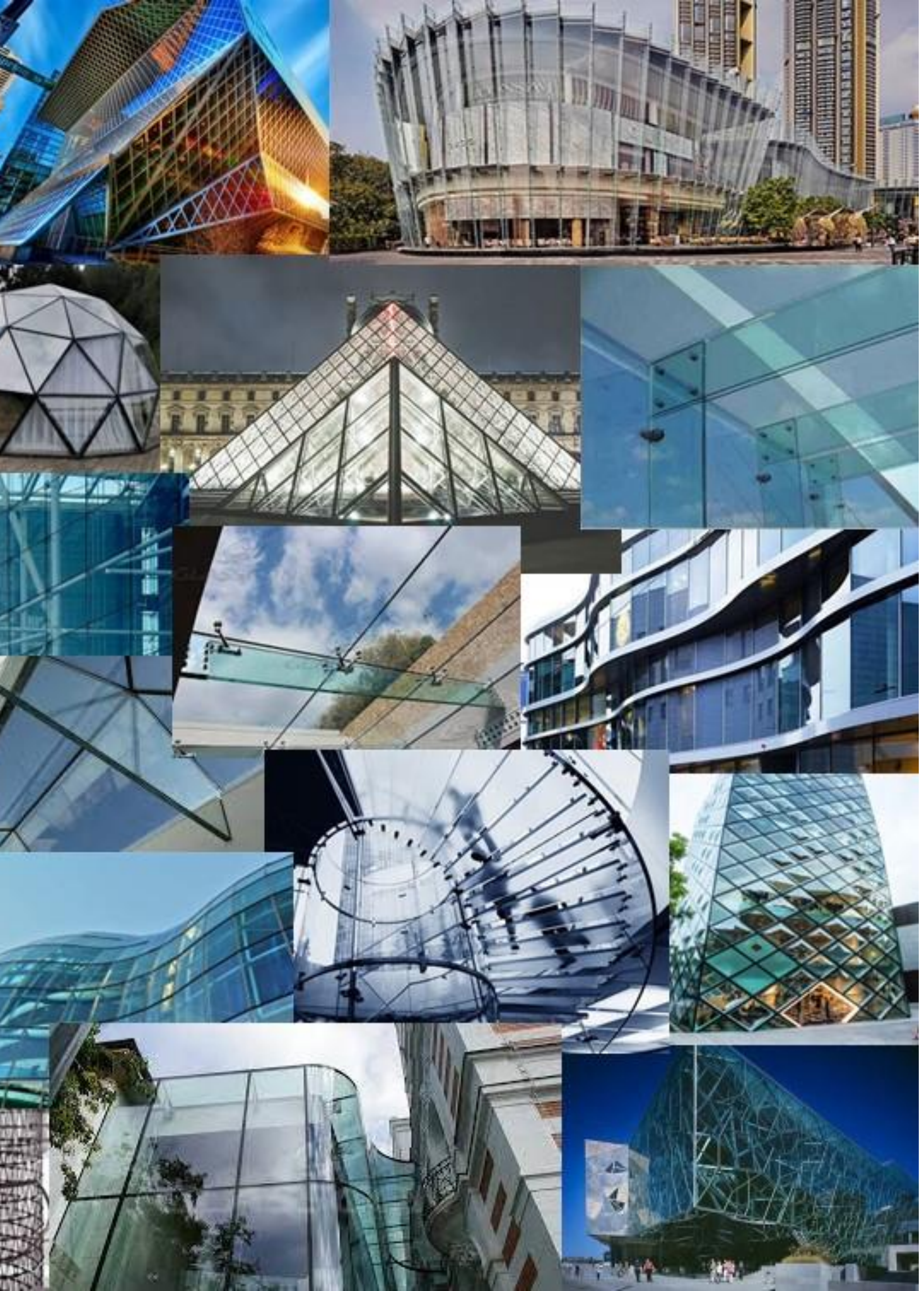
The goal of this thesis is to find structural reuse applications for segmented WTBs. The material will thus be taken out of its normal context and will be used in a new manner. Just as was done with the exploration of the applications a inspiration session was held to kick start the cutting pattern ideation. Structural glass was used for this because of its parallels to the segments of a WTB. Glass is taken out of its normal context of a more aesthetic use case to a structural use case.

Take aways:

- Simple trough bolt connections.
- Combination of materials: glass often with metal.
- Panels and beams can be made from the same materials.
- You can use both curved and flat panels.

Exploration points:

- Is the material strong enough to hold bolts in shear.
- Where would the best beams come from.
- Where would the best panels come from.



15.2 FIRST IDEATION

From the previous design tasks it was concluded that a combination of panels and beams could be used to build certain applications. Beams are relatively simple shapes and thus the focus was put on possible panel shapes.

The cutting patterns were tested by creating low-fi cardboard prototypes, creating different structures and volumes. The structures and volumes weren't necessarily linked to specific applications but more exploratory inside the different application areas. Only one specific application was used as an analogue for a random structure. The boulder wall test was used to see if the pattern could create random shapes / volumes and resolve itself into one structure. The random shapes is necessary because the goal of the cutting pattern is to work for multiple applications. Thus if the pattern can make something random than it is possible to assume it is not limited to one application and gives the freedom to create whatever you want.

The conclusion from all different iterations can be found in the table 5 on the next page and pictures of the iterations can be found one page further. But the final conclusion is that the equilateral triangle (60/60/60) has the greatest potential. It gives to most freedom to generate structures and volumes. But having only one shape doesn't create the best experience in generating structures. Other shapes are added to the cutting pattern designed around the base shape of the equilateral triangle. This also utilizes the entire blade to a greater extent because offcuts can now be used for other shapes. And this way flat parts of the blade can be used for larger segments reducing the amount of connections needed.

These findings are translated into multiple shapes and a cutting pattern fitted on a blade in the next chapter.

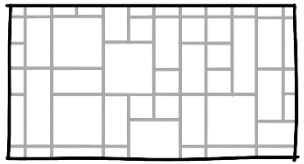
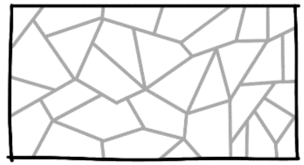
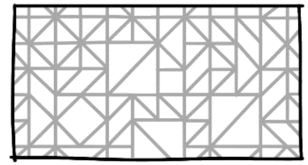
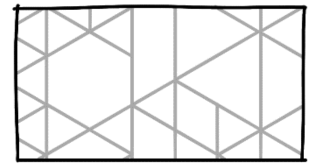
Iteration				
	Square	**Random**	**Triangle 90/45/45**	**Triangle 60/60/60**
Goal	Many shapes from the earlier inspirations where square so it is a good starting point.	Blades will be damaged randomly so maybe a random pattern would work	A shape that is not random but can create a square.	Different triangle shape, where all the edges are the same length or a multiple.
Strengths	Can create general structures.	Cuts around damage.	Can create general structures.	Easy to make random structures. The same length edges.
Weaknesses	Really hard to create random volumes. You can only create cubes.	Standard structures. Many useless pieces. Pieces needed to be re-cut.	Hard to create random structures. Stuck mostly to square shapes. Misses some larger pieces.	Harder to make generic cube like structures.
Conclusion	Square shapes will not work. Another shape should be found.	Will not work, but a shape with a standardized edge length could be interesting	Because of the different edge lengths it is hard to build something else than a square volume.	Hits the goal of making random structures and should be a great starting point for applications.

Table 5. Cutting pattern exploration conclusions.





15.3 CUTTING PATERN

From the cutting pattern ideation and tests it was found that an equilateral triangle with edges around 60 to 80 cm works as the best base element and depending on the shape of the blade different types of segments can be used.

15.3.1 SHAPES

There cutting pattern consists out of 6 shapes, all based on the base shape of an equilateral triangle. The shapes are:

- Right angled triangle (0,5x base shape)
- Equilateral triangle (base shape)
- Parallelogram (2x base shape)
- Trapezium (3x base shape
- Equilateral triangle (4x base shape)
- Hexagon (6x base shape)

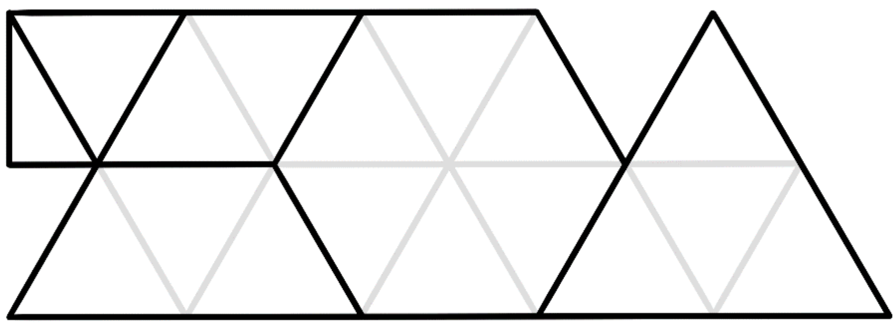


Figure 19. Shapes used the cutting pattern.

The smaller right angled triangle is used to create rectangular volumes and structures. The large segments are used to reduce the amount of connections needed. Based on the shape map from 7.4 there are certain parts of a blade that are flat enough that they can be used to cut larger segments without creating a segment that is too curved.

15.3.2 LAYOUT

The basic layout is mostly governed by the shape of the blade. The variable thickness and materials usage throughout the blade will only create a strength differential between the segments. Possible damage should be avoided and cut around, but because this hard to predict it isn't fully taken into account in this pattern (of course the tip and leading edge damage should always be avoided).

The shear webs are left out of the visualisation but these are mostly constructed from UD fibres and are thus best utilised as beams.

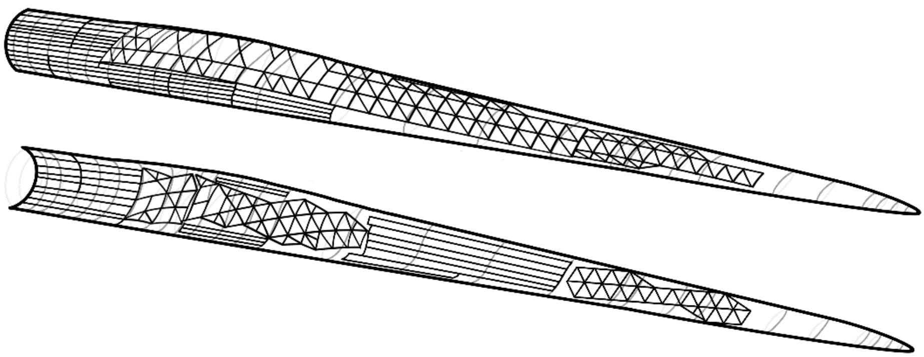


Figure 20. Simplified layout of cutting pattern on a wind turbine blade.

16 APLICATION CONCEPTS

Having ideated different cutting patterns and having tested them on the three applications areas the next step will be to decide on one area and generate multiple concepts.

16.1 AREA SELECTION

A Harris profile will be used again together with criteria from the insights of the cutting pattern ideation and simplified criteria from the list in 11.1. The new profile criteria can be found below. The Harris profile shows that sports is the best area. The sports area can really utilize the variable shape of a wind turbine blade, isn't to structural demanding, has both possibilities for indoor and outdoor environments and is the least influenced by the variable material usage.

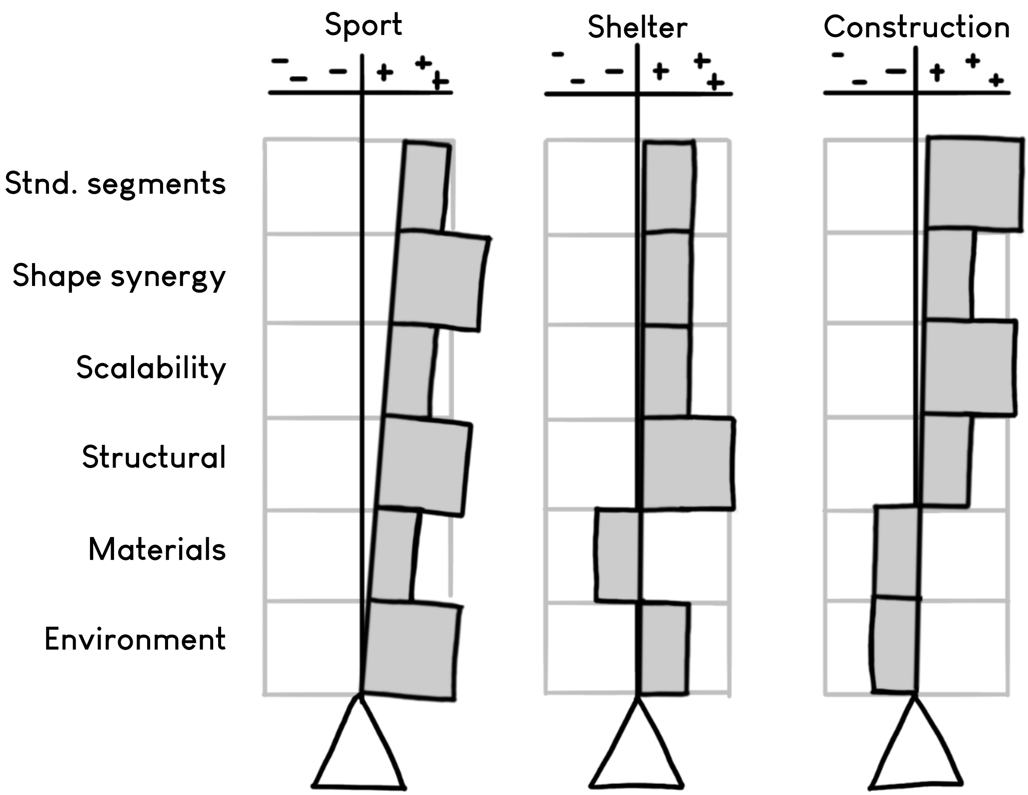


Figure 21. Harris profile to select application area.

16.2 SPORTS CONCEPTS

Having figured out what the most interesting application area it is now important to find possible applications. Chapter 14.3.1 shows a list of different sport applications. To aid in this a C-box[1] will be used, a C-box is two dimensional but I prefer the three dimensional variety. This variation can better encapsulate the criteria that an application should hold: utilizing standardized segments, utilizing blade shape and form freedom. The last property was found to be import during the exploration of the cutting patterns, by having a lot of form freedom within an application it is easier to utilize more of the blade.

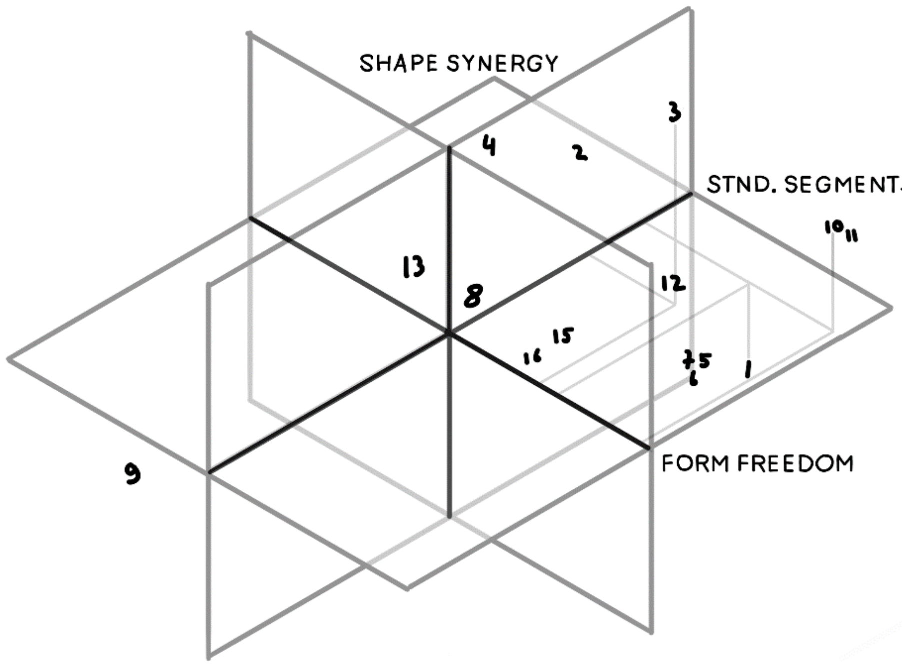


Figure 22. Three dimensional C-box, axis: Shape synergy, Stnd. segments and Form freedom. Numbers relate to their order in 10.3.1.

There are three applications that look interesting, these have an added location indication and they are: boulder wall, airsoft field and bike park. The boulder wall and airsoft field are interesting because they could utilize the same segments (good for scalability) and they both offer relative good form freedom. The bike park on thee other hand is a bit worse in that regard but has a lot of shape synergy which could increase the amount of usable panels from a blade.

[1] A C-box is a matrix that can be used to map many concepts based on (usually) two criteria. (van Boeijen et al. 2014. p. 143).

16.2.1 BOULDERING WALL

The bouldering wall can be made from flattest segments retrieved from a blade. When using the more curved segments it becomes difficult to align all the panels and it increases the amount of gaps there are. It should be possible but will ask for a more custom approach where using digital tools will become necessary. The standardized shapes are enough to create many different surfaces mimicking the randomness of rock walls.

The climbing surface is normally supported with a truss system that is located behind it. A combination of metal connectors and beams segments can be used for the same purpose.

Biggest strength: Standardization of panels and structural strength.

Biggest weakness: Gaps forming between panels.

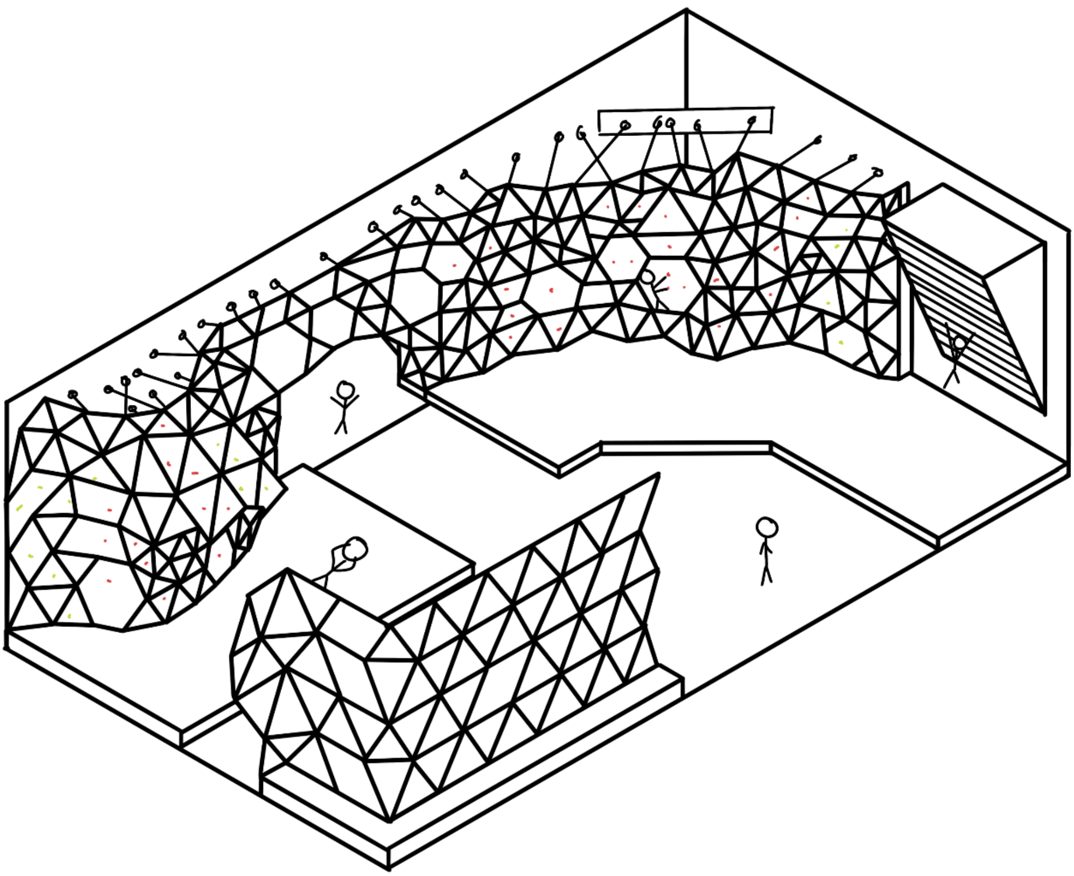


Figure 23. Bouldering wall concept made from triangular segments.

16.2.2 AIRSOFT OR PAINTBALL FIELD COVER

The playing field covers can be made from whatever panel you have access to from a blade. It is not necessary to be completely flat and the curved panels can even be utilized to create self supporting structures. The panels of stationary structures can be connected using screws and a connection brace. The connection material can be smaller blade pieces but it is easier to use simple sheet metal brackets. The panels of non stationary structures can be connected using a clamping mechanism this way the structures can easily be disassembled and reassembled. Users can then create their own cover and forts, adding a play or strategy element to the game.

Biggest strength: Any piece of the blade can be used for something.

Biggest weakness: Panels can become too heavy to use.

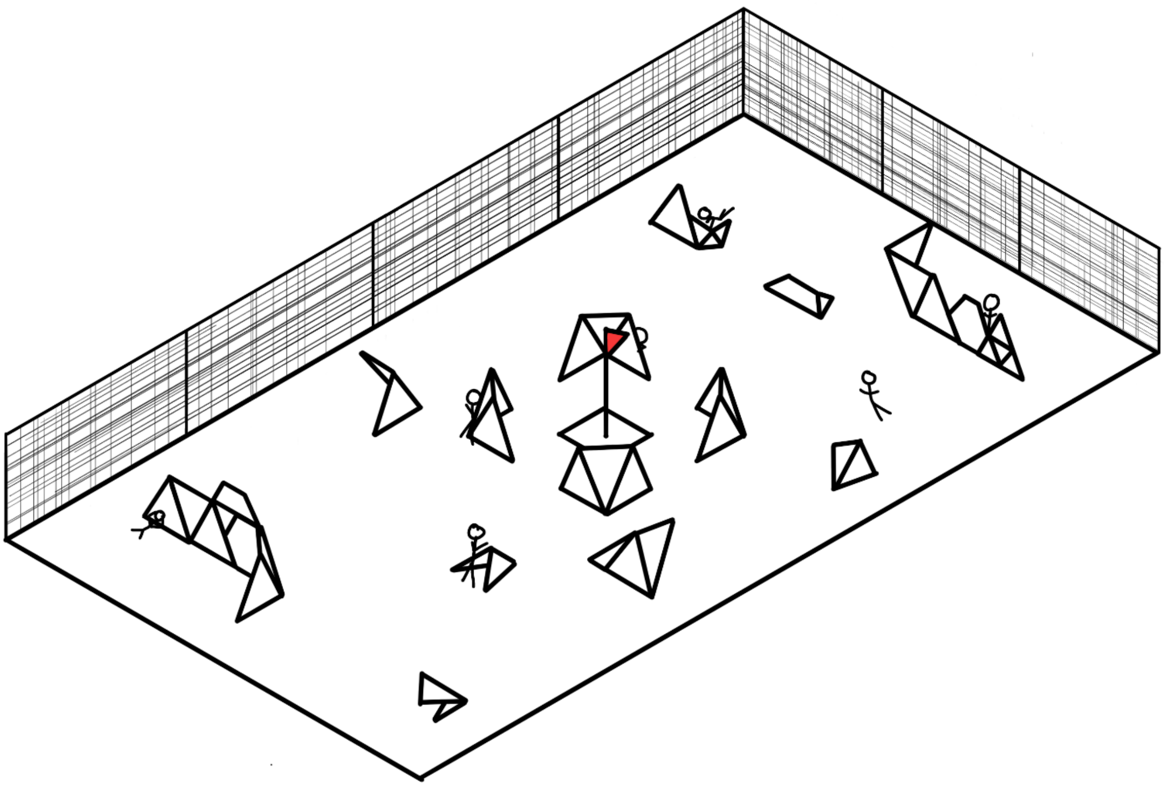


Figure 24. Airsoft and paintball play field made from triangular segments.

16.2.3 BIKEPARK

The bike park was originally made from the same panels as the previous concepts but they were connected back to each other as they were inside of the context of a blade. The decision was made to not cut the panels removing the reconnecting step. This way the already flowing shape of the blade is utilized to create jumps and other elements. The shape of the blade is thus matched to possible features but not everything can be made from large blade segments. Other features can be made using beams and planks cut from a blade. This mimics how they are normally build with wood.

Biggest strength: Utilizing the curvature and shape of a blade.

Biggest weakness: Loads of screw holes in an outdoor environment.

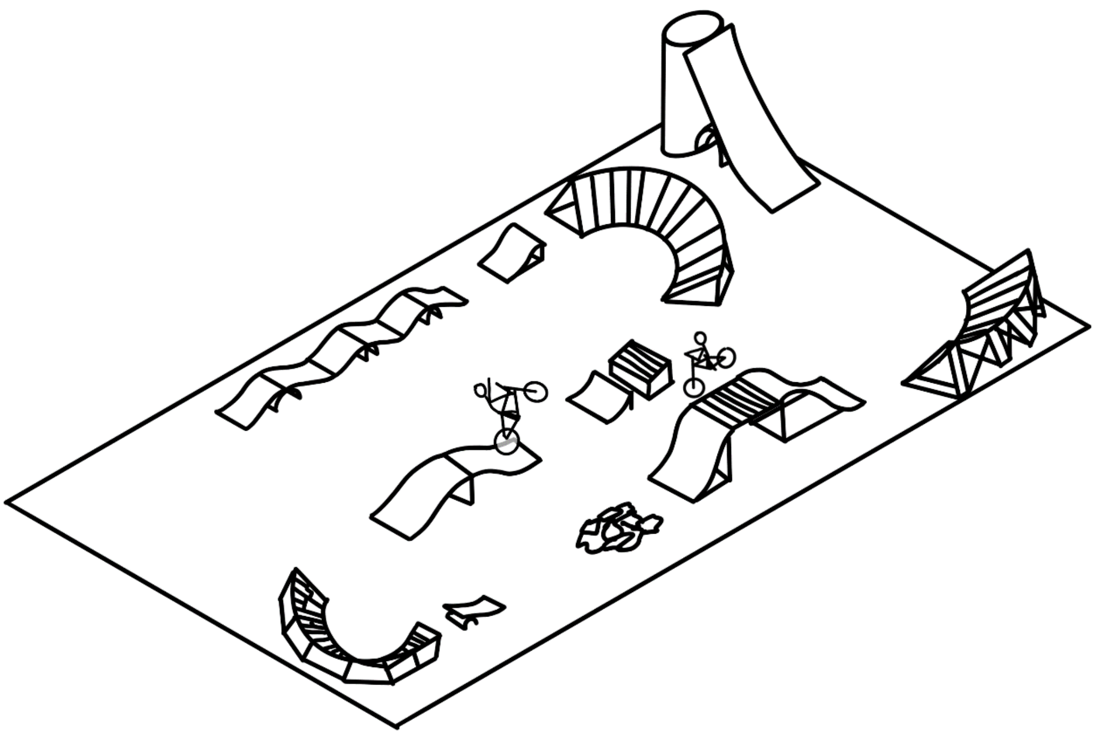


Figure 25. Bike park / bike jumps made from rectangular segments.

16.2 APPLICATION DECISION MISSION

Having three concepts it is now important to figure out one that will be used as a show case of the cutting strategy, pattern and applications. This will be done in two steps first the criteria found in 11.1 will be used to compare the different concepts. And the second step is to test the applications using blade segments.

16.2.1 DESIGN CRITERIA

Chapter 11.1 lists about 70 criteria, this is too on reflect on for the moment and thus the most important once are selected and used to check the designs.

Scalability

- Boulder wall: medium, boulders halls are extremely large and it uses simple repeatable segments, but needs a lot of post processing.
- Airsoft field cover: medium, fields aren't that extensive.
- Bike park: medium, only so many features can be build in a park.

Efficiency in material usage

- Boulder wall: bad, only the flattest panels can be used.
- Airsoft field cover: great, any panel or beam can be used.
- Bike park: great, in principle any panel or beam can be used.

End of life hindrance

- Boulder wall: bad, the added connectors for boulder holds make EOL recycling more difficult.
- Airsoft field cover: great, the segments can easily be disassembled.
- Bike park: medium, a lot of trough bolts are used so a lot of parts need to be disassembled.

Segment dynamic (shape, thickness and curvature)

- Boulder wall: medium, many shapes can be utilized, but only the flattest panels can be used.
- Airsoft field cover: great, the DIY-esque nature of this concepts makes it possible to utilize the panels however they fit best.
- Bike park: medium, the shape usefulness of the pattern is slightly reduced.

Connection strategy

- Boulder wall: Quite complex, the wall should be as flat as possible while also having extremely random angles between panels which makes a connection strategy rather cumbersome.
- Airsoft field cover: Extremely easy.
- Bike park: medium, easy but a lot of bolts need to be tightened.

Load to sandwich match.

- Boulder wall: great, not that much compression forces.
- Airsoft field cover: medium, forces are low and it doesn't utilise the full capabilities of WTB segments.
- Bike park: great: the large segments really utilize the strength of the composite structure.

16.2.2 REAL WORLD TESTS

Three tests were conducted to check if a blade segment could withstand the use cases of the three applications. These three tests were: a hanging load test (boulder wall), impact test (airsoft cover) and a full speed bike test (bike park).

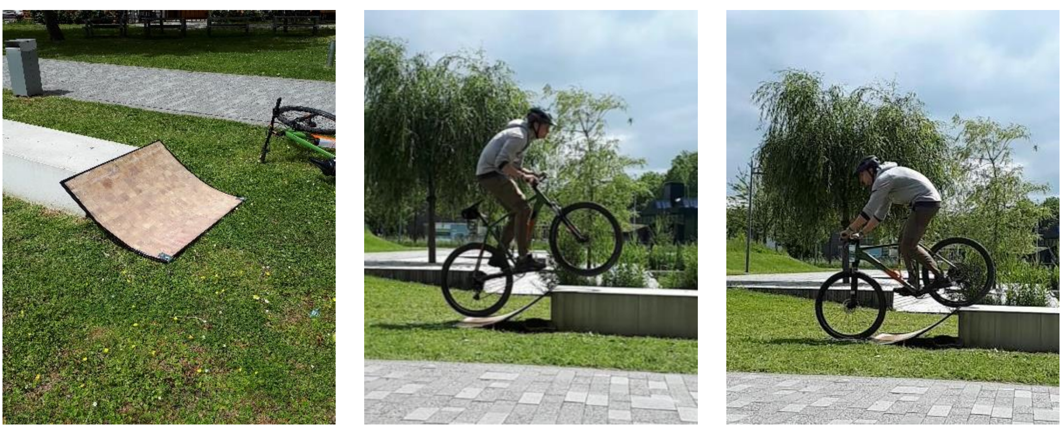
Hanging load test.
The hanging load test was based on the requirement of bouldering volumes to be able to hold 2.4 Kn (NEN 12572-3, 2017). This was simulated by using a similar bolt and washer which were loaded to about 2.7 Kn (Three adults at a combined weight of 275 kg). The panel did not show any change in shape or damage. It can thus be concluded that the panel is strong enough for bouldering applications.

Impact test.
The impact test was used to check if the panels would show any weird behaviour when impacted by BB's from an airsoft gun. Two airsoft guns (around 1 to 2 Joule) were tested at multiple distances but the panel did not show any resulting damage even at point blank range. It was then decided to increase the impact force by using an air rifle shooting at around 220 joules. This did damage the panels creating an area of delamination around 1cm in diameter with sometimes a sharp edge. But this did not create and dislodged splinters that would shoot away. The damage was also compared to multiple wood species where the BB's would indent and the air rifle would penetrate and go trough. It can thus be concluded that the panels are strong enough and don't have unwanted behaviour for airsoft or paintball fields. The panels even showed a fun play element of ricocheting BBs which can be used during games to shoot around corners.

Full speed bike test.
The full speed bike test was done using a curved segment of a WB. A piece of concrete was used to hold up the segment this way the segment could be tested until a possible failure without the support breaking. The test consisted of firstly going slow and trying out the segment in the four different orientations (bully up, belly down and both with switched riding directions). The test ended with a effort of going as fast as possible and trying to jump. The segment did not budge and felt extremely grippy on the tires. Air time was achieved but it wasn't a clean jump. A second test checked the traction of the segment while wet. The wet segment did not feel any different and still felt grippy. It can thus be concluded that a blade segment could be used as a bike jump.

Picture 33. Hanging load test, increasing load from left to right.

Picture 34. Impact test. Most right picture shows the damage created by the air rifle.



Picture 35. Biking test setup (left) and screen grabs of the full speed bike test.

16.3 APPLICATION PROPOSAL

During the comparison between the concepts in 16.2.1 it was found that each concept wouldn't fair nicely when used in and of it self. They fair great on certain aspects but fail miserably on others. This story changes when looked at from a perspective where al concepts are used together. This results in the concept proposal of an adventure park.

The ultimate goal is to be able to manage the current and future WTB waste in a sustainable manner and do this as efficiently as possible. This problem is probably best addressed by a strategy that can utilize as much as possible of a WTB. And a combination of the three concepts means that every segment will have a use case. An adventure park is a great show case for this line of thinking. There are many applications within an adventure park that could utilize segmented WTBs and also applications that utilize the other schools of though found in chapter 3.4. The segments can be used for boulder walls, airsoft covers, bike park elements, shelters picknick areas, etc and large blade segments could for example be used as towers for a rope climbing trail. Adventure parks need materials that are extremely strong and resistant to heavy use, wood is often used but WTBs could provide an longer lasting alternative. The figure to the right showcase the possibility of structural reused WTBs.

12.3.1 CUTTING PATTERN

With the proposed applications it is also possible to create a revised cutting pattern. Utilising a combination of the three found applications and shapes found in chapter 15. The flat segments can be used for the boulder walls, the moderately curved segments can be used for the airsoft fields and the extremely curved segments can be utilized by the bike park.

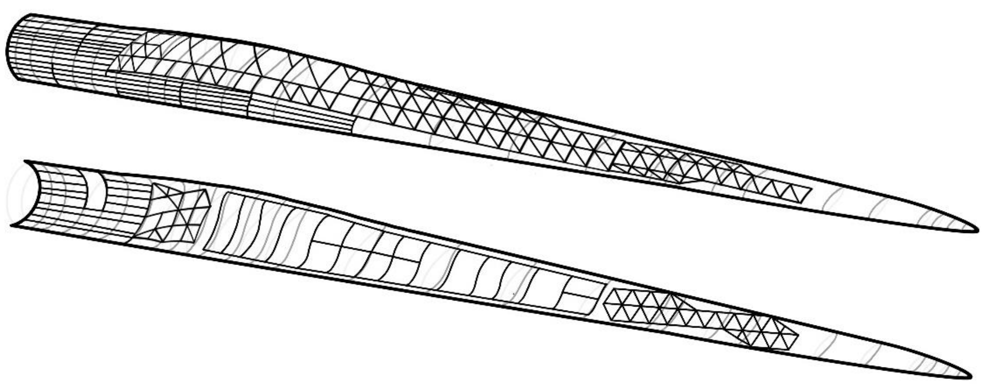


Figure 26. The revised cutting pattern.

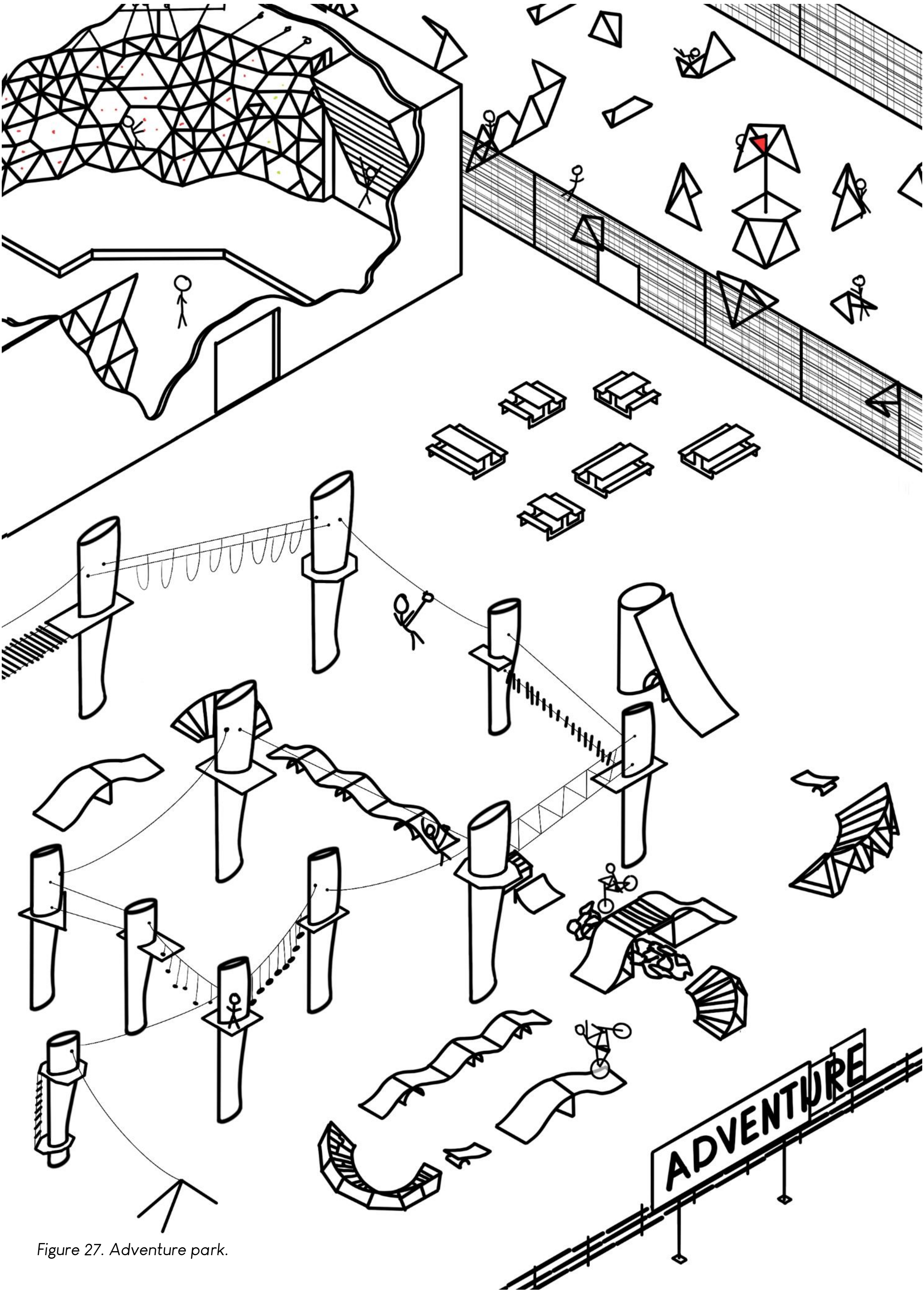


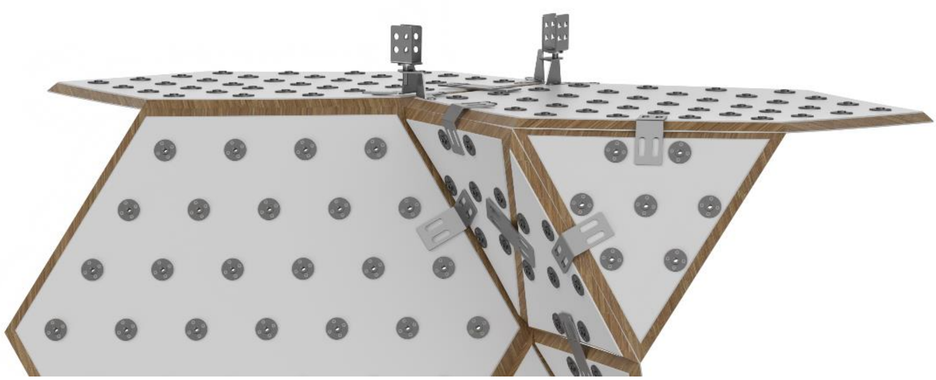
Figure 27. Adventure park.

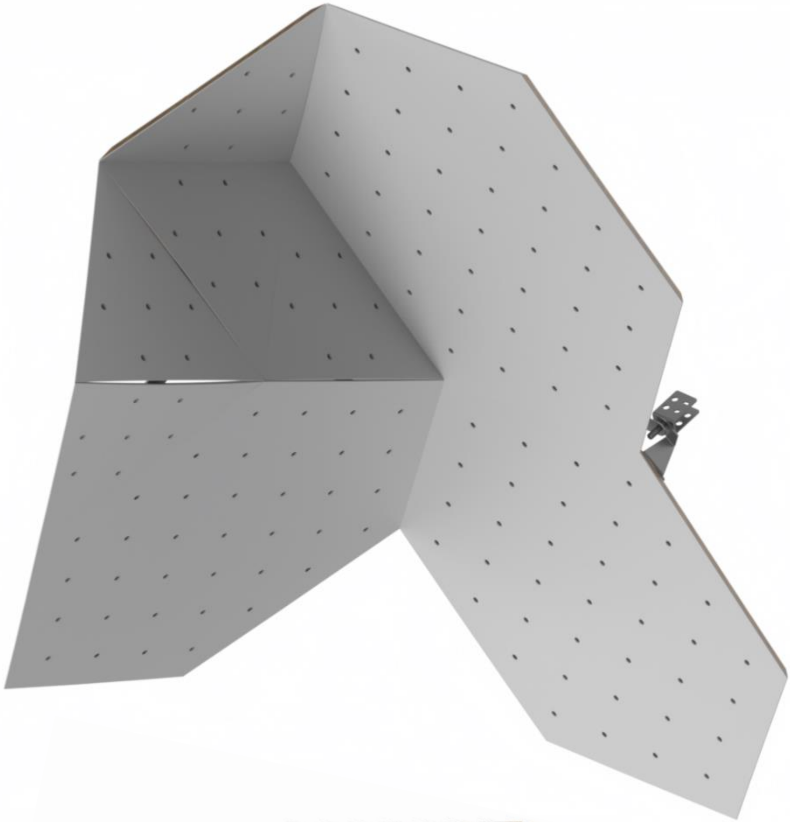
17 EMBODIED APPLICATIONS

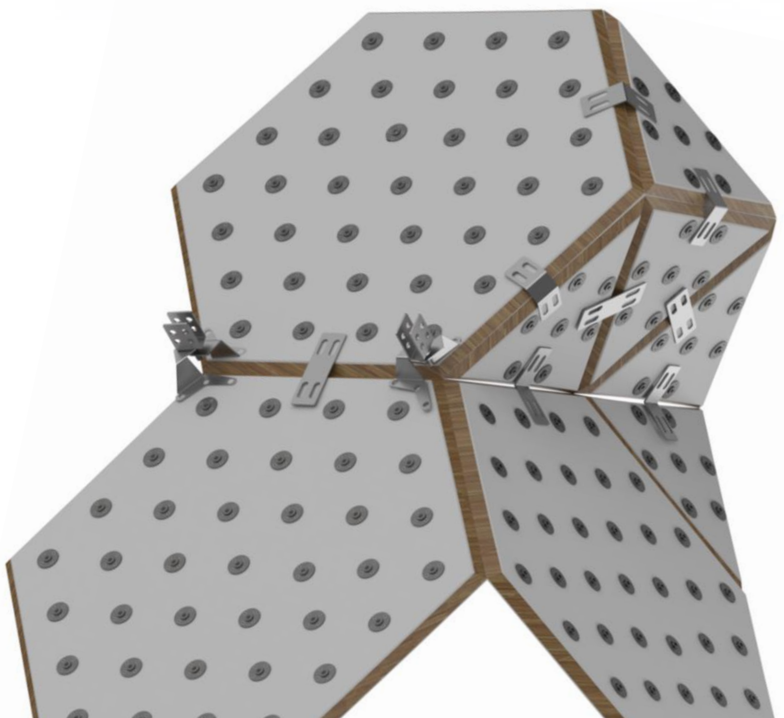
The last chapter ended with a concept for an adventure park that could utilise as much of a blade as possible, but this is still a concept. To better understand if the designs could work it is necessary to go trough an embodiment design phase. Doing this for the entire adventure park will be a fools errand and thus the three concepts will be embodied. After this embodiment it is also possible take another look at the three concepts and check how they fair in comparison to each other.

17.1 BOULDER WALL ELEMENTS

- Segments
  - Larger panels for large flat planes
  - Smaller panels to create more random shapes, and direction changes
- Connection strategy.
  - Structurally connected in the corners with distance adjustability, also used to connect wall to the back structure made from beams
  - Added supports between panels for increased strength
- Strengths
  - Usage of standardized segments.
- Weakness
  - Needs a lot of extra processing after normal processing of blade.
  - Can have gaps which is undesirable for a boulder wall.

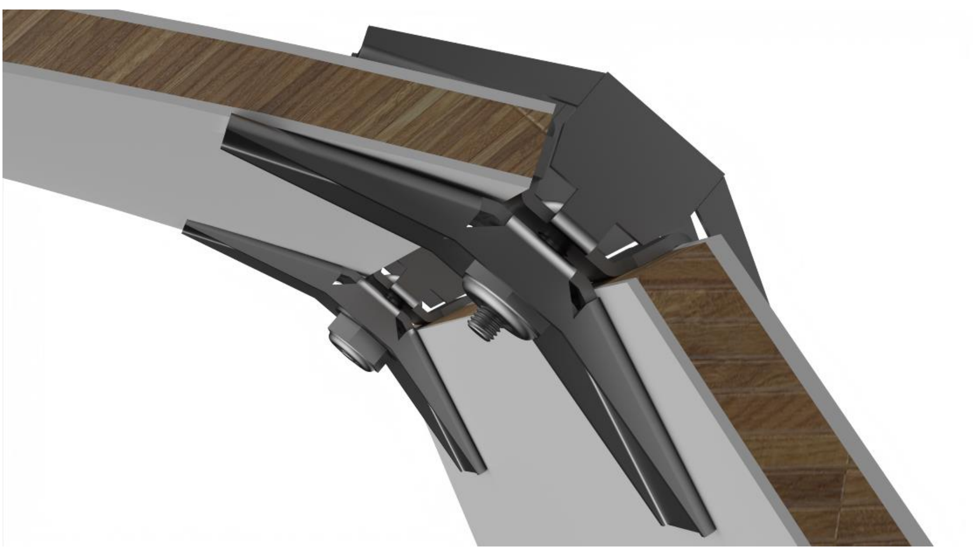


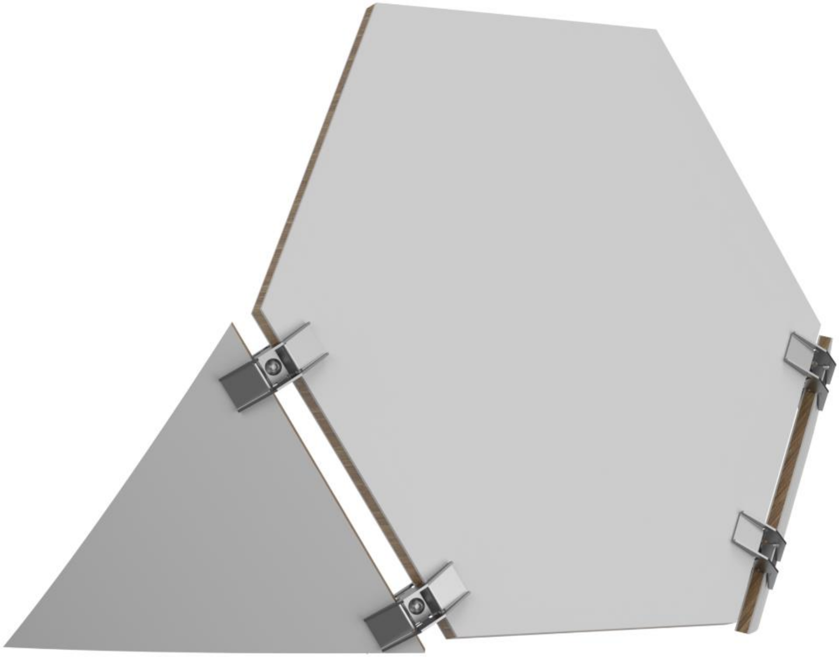


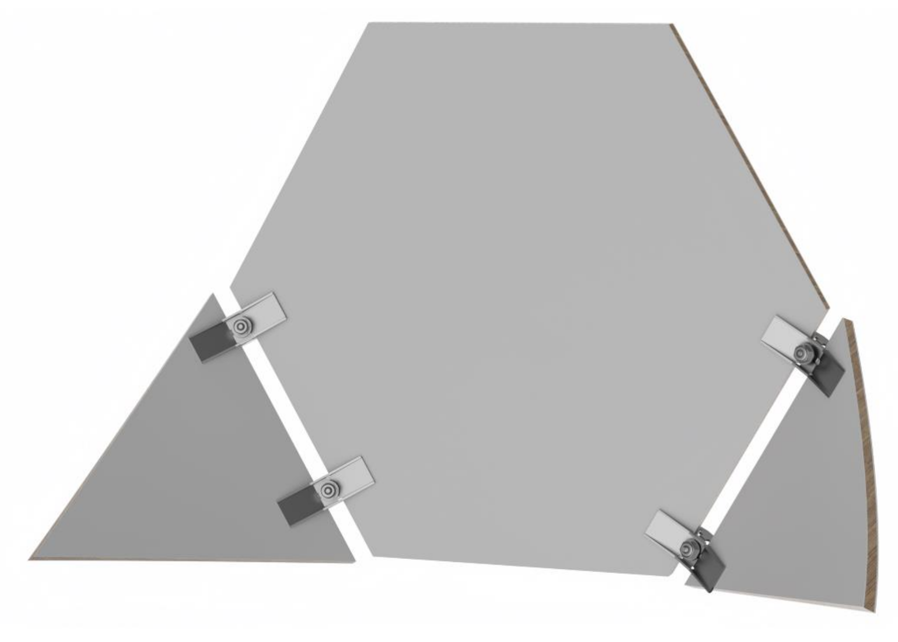


17.2 HIDE ELEMENENT

- Segments
  - The more curved panels that can't be used for boulder wall
  - Uses curves and angles to be self a self supporting structure.
- Connection strategy
  - Sheet metal parts that can slide between each other making it possible to connect different thickness segments.
  - Bolts to clamp down.
- Strength
  - Don't need much extra processing
  - Can utilise any segment.
- Weakness
  - Doesn't utilise the full capabilities of WTBs.

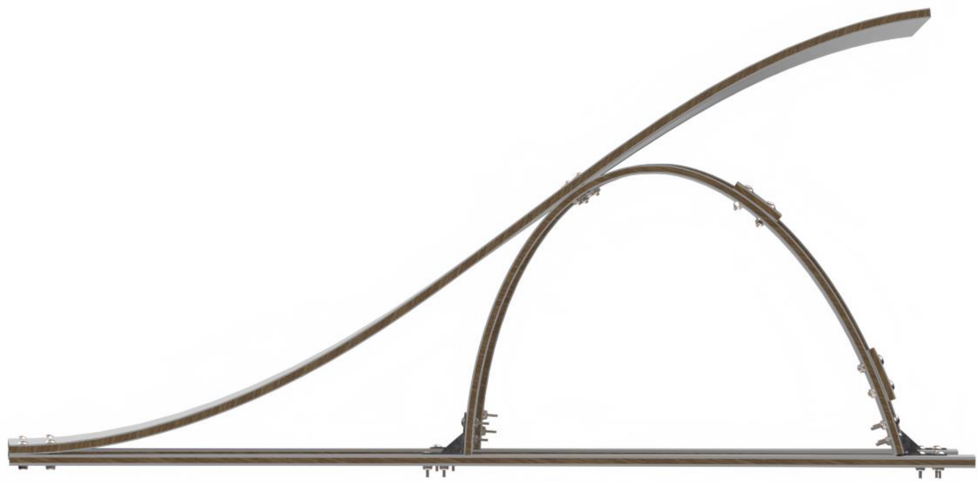


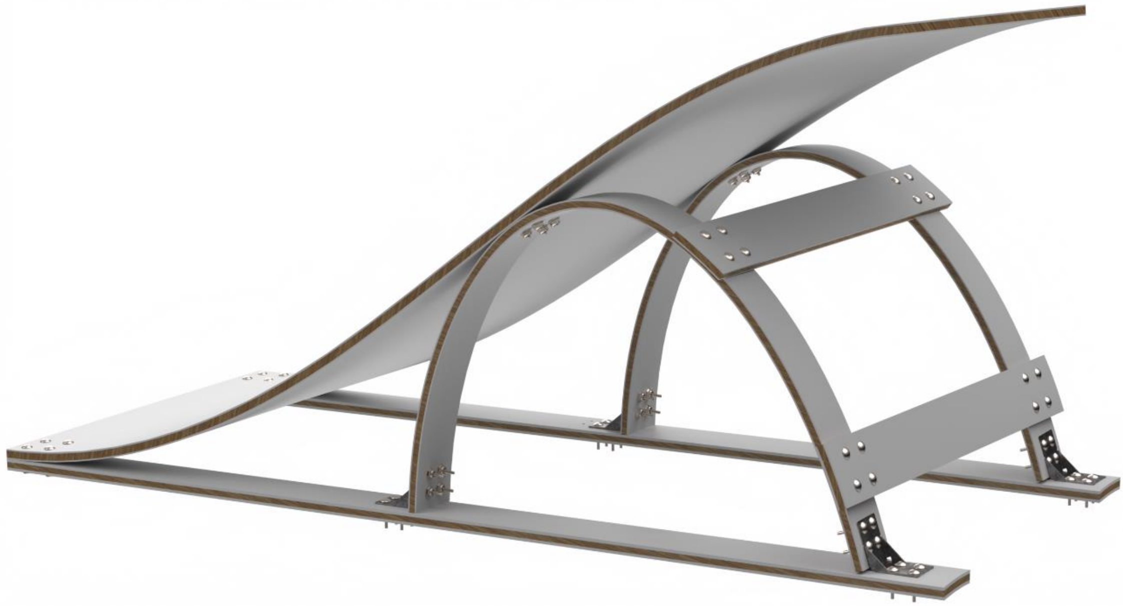




17.3 BIKE JUMP

- Segments
  - Uses rectangular segments from the most curbed parts.
  - Beams are used as support structure.
- Connection strategy
  - Simple trough bolts with rubber washes which are necessary to protect the holes against moisture.
- Strength
  - Utilize the existing shape from the wind turbine blade.
- Weakness
  - Loads of holes that where water could get into the segment.





17.3.1 EXTRA BIKE PARK FEATURES

During the embodiment phase it was found that the bike park is the best showcase of what is possible by segmenting WTBs for structural applications. The bike park utilises the shape of a blade, the loads generated by riding on the panels also match quite nicely to the strength of the composite sandwich and it doesn't need to much post processing. The connection strategy is also simple enough to be able to confidently create bike park features. On the other hand the boulder wall needs a lot of post processing, and the airsoft field covers don't utilise the capabilities that WTB segments have to offer. The decision was thus made to create more bike park features to better showcase what is possible. Three extra features have been designed: a flow trail, a table top and a simple jump.

Simple flow trail

The simple flow trail utilizes simple curved segments to create and rollercoaster like ride. These segments are connected to each other using metal brackets and supported by simple beams.

Picture 36. Simple flow trail.

Simple jump

The simple jump isn't fully embodied but showcases how the normal beam and plank segments could be utilized to create bike park features.

Picture 37. Simple jump.

Table top

The table top isn't fully embodied but showcases how the normal beam and plank segments could be utilized to create bike park features. It is supported by beams created from multiple planks stacked next to each other. It uses simple metal brackets and trough bolts to connect the individual segments. The table top is designed as an addition to for example the original jump. This creates a safer and more pleasant experience for riders.

Picture 38. Table top

Picture 39. The table top together with a jump.

PART 5

CONCLUSION

TRANSLATE

This thesis set out to better understand WTBs and how they can be structurally reused. The first two parts analysed the end of life solutions and the design of a WTB. The information found was then utilized in create a cutting strategy, cutting pattern and application proposal in part three and four. The fifth and last part will finalize this thesis and go trough the conclusion, limitations and recommendations.

18 CONCLUSION

This thesis set out to answer the following research goal:

Identify structural reuse applications for wind turbine blades and develop a cutting strategy that can be used to cut standardized elements from multiple wind turbine blade models. Then demonstrate the cutting strategy with a possible structure.

This was researched by going trough the end of life phase and design of a WTB. The knowledge gained was then used figure out how this thesis fits in the current end of life landscape and to generate factors of influence that would steer a possible cutting strategy, cutting pattern and application.

It was found that current end of life solutions are unable to process the amount of WTB waste that is projected for the coming years due to multiple challenges (availability, yield rate, quality and operation cost). Reuse is an option that could extend the material life time of WTBs and is currently mostly done by using entire blades or large segments. This thesis fits in this landscape by generating applications that utilise segmentations to structural reuse a WTB (a new and relatively unexplored philosophy created by Joustra et al, 2021).

Multiple influences were found that that would steer a possible cutting strategy, cutting pattern and application. These can be clustered in to five groups: system challenges, waste generation, blade design, blade state and processing tools. The factors of influence were then used to generate design criteria which were used to assess the possible cutting strategy, cutting pattern and applications. The most promising cutting pattern found was a combination of equilateral triangles, rectangles and beam segments. The segments can be used to create boulder walls, airsoft covers and bike park features. These three applications come together in a concept of an adventure park showcasing how multiple reuse philosophies can work in unison to handle WTB waste as effectively as possible by utilising as much of a blade as possible.

Wind turbine blades are extremely complex structures. But by strategically cutting their damaged areas away, segmenting them in smaller more manageable panels and utilising the composite materials structurally it becomes possible to extend the useful life time of wind turbine blades.

19 DISCUSSION

There are multiple limitations to this thesis stemming from the fact that the analysis has stayed broad and the generated designs have stayed conceptual.

19.1 LIMITATION OF THE FACTORS OF INFLUENCE

This thesis has analysed the reuse space of WTB in a broad manner, looking at the entire picture instead of focusing on certain aspects. This has resulted in more general conclusions instead of hard data showing what is possible with wind turbine blades. Its thus difficult to quantify how much certain factors of influence really influence the structural reuse of WTBs. . For example, it was found that structural repairs and superficial repairs reduce the strength of WTBs and subsequently also any created segment. But it is unknown by how much and if it is even significant enough that it should be taken into account.

19.2 LIMITATION OF THE CUTTING STRATEGY

The cutting strategy is used to showcase what needs to be though of when processing WTB. The strategy is in no shape or form a fully thought out strategy that could be utilized.

19.3 LIMITATION OF THE CUTTING PATTERN

A generalised blade shape based on actual blade has been used to generate the cutting pattern. But the cutting has never been fully fitted to a digital model of the blade and thus is still in a conceptual state.

19.4 LIMITATION OF THE APPLCIATIONS

This thesis proposes multiple applications with simple embodied models, but only a real world structure will show if these concepts could actually be made. This hasn't been achieved due to time constraints and difficulties obtaining WTB materials. And thus the applications have stayed conceptual. The embodied design also use simple segments cut from real blade data. Thus although it is a real segment only one or two segments are cut out from a blade. This might hide some interactions between the segments if they would have been different.

20 RECOMANDATIONS

There are multiple recommendations for future research if someone would continues in this avenue.

20.1 RECOMANDATIONS FOR THE FACTORS OF INFLUENCE

The factors of influence has stayed rather general, for future research it is thus important to analyse how much these factors really influence the cutting strategy, cutting pattern and applications.

20.2 RECOMANDATIONS FOR THE CUTTING PATTERN

The cutting pattern has stayed conceptual in this thesis sand it is recommended to use CAD/CAM software to fit possible cutting patterns onto a existing blades. This way the cutting pattern can finalised and proofed to be produceable.

20.3 RECOMANDATIONS FOR THE APPLCIATIONS

The applications have stayed conceptual it is thus recommended that when a application is chosen for future research it is in fact build in the real world. This way the application can really be tested and the possibilities that WTB contain can be showed.

Secondly, only simple single curved surfaces were used for the final application of a bike park. But by using different shaped segments it could be possible to create double curved shapes from WTBs. This would add another dimension to their possibilities and is thus recommended to be look into further.

Lastly the regulations and safety requirements of how these materials can be used should be analysed. Gelcoats could hold dangerous chemical that could harm users when blades are utilised outside their original context. It should also be checked how these materials fit in current regulations for specific applications. It is recommended that future research looks in to what is allowed to be done with these materials.

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APPENDICES

A. DESIGN BRIEF

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	van der Vinne
Initials	S
Given name	Sammie
Student number	

IDE master(s): IPD ✓ Dfl ☐ SPD ☐

2nd non-IDE master	
Individual programme *(date of approval)*	
Medisign	☐
HPM	☐

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Jelle Joustra	dept./section	SDE, DfS
mentor	Soroush Aghaeian	dept./section	SDE, DfS
2nd mentor			
client:			
city:		country:	

optional comments: I approached supervisors from the same section because they both have different backgrounds and skills that will help me during my graduation. Joustra has a design background and Aghaeian has a material science background.

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in by the Chair of the supervisory team

Sign for approval (Chair)

Name J. J. Joustra   Date 20-11-2023   Signature [redacted]

CHECK ON STUDY PROGRESS

To be filled in by SSC E&SA (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

X	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Name K. Veldman Date 5-12-2023 Signature [redacted]

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	V	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

V	ALLOWED to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name Monique von Morgen Date 13/12/2023 Signature [redacted]

DESIGN FOR our future

TUDelft

Personal Project Brief – IDE Master Graduation Project

Name student Sammie van der Vinne **Student number**

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

Project title The structural reuse of wind trubine blades

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

Introduction

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

Wind turbines have been a staple of our landscape for decades and with more effort being put into renewable energy we can speculate that this number will only rise. But what happens to them after their service life is ended. Around 94% of a wind turbine can be recycled (Schleisner, 1999) but there are difficulties with the remaining 6%. One problem is the recycling of the blades, they are made of a composite sandwich of GFRP with a light wood or foam in between. There are some options for recycling, but the most common route is incineration (Jensen & Skelton, 2018). An interesting alternative is to repurpose the old blades, an example of this is a playground made with old wind turbine blades designed by Blade Made or a picnic table made of old wind turbine blades (Joustra et al., 2021). These examples show an interesting opportunity to re-use old wind turbine blades but is it possible to combine the usage of smaller pieces of the table into a larger design like a playground?

Stake holders
- Wind turbine manufacturers: Prefers to design a blade as aerodynamic as possible, they won't want to change the blade shape but could be open to structural changes.
- Wind turbine recyclers: Prefers an easy and cost-effective recycling technique. Structural reuse can be an alternative, but it should be more efficient.
- Product/ system users: Prefers an easy to assemble structure than can be stored and transported without any hassle.
- Structure users: Prefers a safe and un intrusive experience.

Jensen, J. P., Skelton, K. (2018). Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. *Renewable and Sustainable Energy Reviews*, 97, 165-176. https://doi.org/10.1016/j.rser.2018.08.041
Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of high end composite products: A design case study on wind turbine blades. Resources, Conservation & Recycling, 167. https://doi.org/10.1016/j.resconrec.2020.105393
Schleisner, L. (1999). Life cycle assessment of a wind farm and related externalities. *Renewable Energy*, 20(3), 279-288.

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introduction (continued): space for images

image / figure 1 Table and playground made from old wind turbine blades.

image / figure 2 Wind trubine blades.

Problem Definition

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

Reusing old wind turbine blades is a difficult task because of the double curved aerodynamic shape that they are designed with and the plethora of different versions that are in use today. This often leads to the reuse of entire blades or the usage of large segments. A possible interesting direction is a system that strategically cuts smaller segments out of the blades that can be used in to build multiple structures. The goal of this project is to research if it is possible to design a cutting strategy suited for multiple models of wind turbine blades. Making it possible to build larger structures from smaller cuts of a wind turbine blade. These structures could then be taken apart and be built into something new. This could make it easier to reuse old wind turbine blades possible lowering the environmental load that is connected to the end of live of a wind turbine.

Research area's

- Current recycling and repurposing solutions for wind turbine blades.
- How to strategically cut wind turbine blades to be easily repurposed.
- The material properties and possibilities of old wind turbine blades.
- Identifying structural reuse applications for wind turbine blades.
- The design of a structure made by repurposing wind turbine blades.

Assignment

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

Identify structural reuse applications for wind turbine blades and develop a cutting strategy that can be used to cut reusable elements from multiple wind turbine blade models. Then demonstrate the cutting strategy with a possible structure.

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

The goal of this project will be to show a non- blade specific cutting strategy that can be used to make structures as a way to reuse old wind turbine blades. I want to achieve this using a Research trough Design methodology with critical journaling as a way to keep track of my work.

It will be difficult to make a full-scale structure thus I plan on making a digital model using SolidWorks or Rhino grasshopper with a small-scale representation as a proof of concept. I want to achieve this by first having a short analysis phase with a concept sprint, after which I have a second analysis phase with a larger concept phase. This way I can quickly identify knowledge gaps that I can research in the second analysis phase. The second concept phase will be used to create the final design and cutting strategy. Throughout which I want to use prototyping as a way to develop ideas, learn new information about the materials and shapes of wind turbine blades. The next step is to digitize the concept and cutting strategy after which I can start on a final showcase. The final part of the project will be creating the report and communication materials, although I plan to work on the report during the project, I have put some weeks in the end to be able to fully focus on them.

Project planning and key moments

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

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

Kick off meeting 16 nov 2023

Mid-term evaluation 29 jan 2024

Green light meeting 2 apr 2024

Graduation ceremony 30 apr 2024

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

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

Comments:

Motivation and personal ambitions

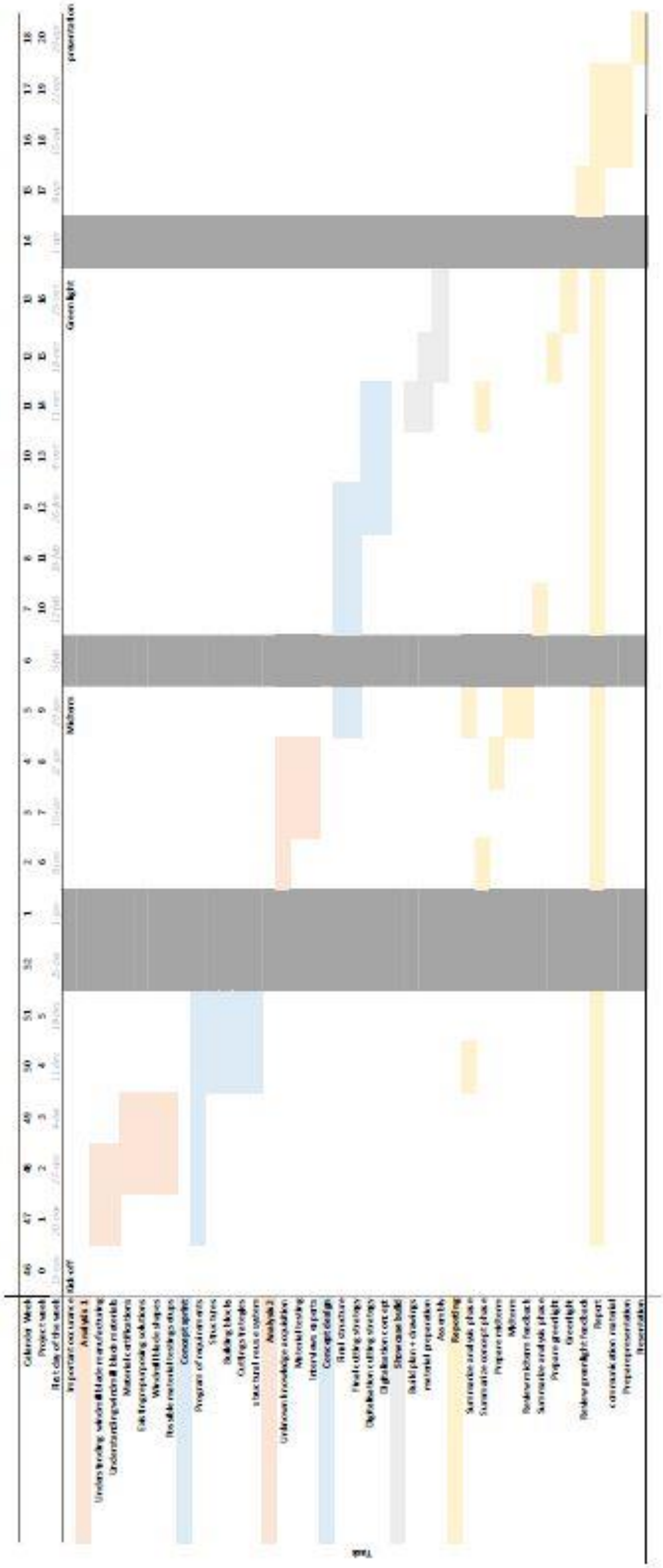
Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

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

My first inclination for my graduation was to find an AED like project, something where I could work on a physical product with some integrated electronics. But I realised that I have done a couple of projects that follow those general goals. I think I can show that I am able to design everyday products, taking into account ergonomics, technology, material properties, manufacturing methods etc. I still have a lot to learn but I think I would benefit more from learning something new during my graduation. I have always worked with small sized products, and I want to show that I can also work on a larger scale. My goal for my graduation project is to thus learn something new or work with something new, showing that I can adapt and design with something that is unfamiliar to me.
Next to learning these design goals I also want to improve how I write reports. Writing a report is usually the last thing I think about, and I want to change this habit. I plan to do this by taking a moment each week to work on my report and also use this as part of a more reflective design approach in comparison how I normally work.

Personal ambitions:

- Learn something new.
  - Work with new materials.
  - Work with new manufacturing methods.
- Show that I can design on a larger scale than hand sized products.
- Become better at writing reports.


Calendar Week
Project week
First day of the week
Important occurance
Kick-off
Midterm
Green light
presentation
Analysis 1
Understanding windmill blade manufacturing
Understanding windmill blade materials
Material certifications
Existing repurposing solutions
Windmill blade shapes
Possible material testing setups
Concept sprint
Program of requirements
Structures
Building blocks
Cutting strategies
structural reuse system
Analysis 2
Unknown knowledge acquisition
Material testing
Interviews experts
Concept design
Final structure
Final cutting strategy
Digitalisation cutting strategy
Digitalisation concept
Showcase build
Build plan + drawings
material preparation
Assembly
Reporting
Summarize analysis phase
Summarize concept phase
Prepare midterm
Midterm
Review midterm feedback
Summarize analysis phase
Prepare greenlight
Greenlight
Review greenlight feedback
Report
communication material
Prepare presentation
Presentation
Task

Everybody knows the joke about how designers and architects design the most complex products and buildings without any consideration on how the design can be made. Then it becomes the burden of the engineers to figure out how they can bring those designs to life. Well wind turbine blades are the revenge created by engineers. These complex structures are now being reinvestigated by designers for possible reuse strategies and their complex nature makes this a complicated task. This thesis goes into the problem space about why reuse is a current avenue that is being explored and why reusing wind turbine blades can be a difficult task. This thesis ends with a showcase of a possible processing strategy, cutting pattern and application.