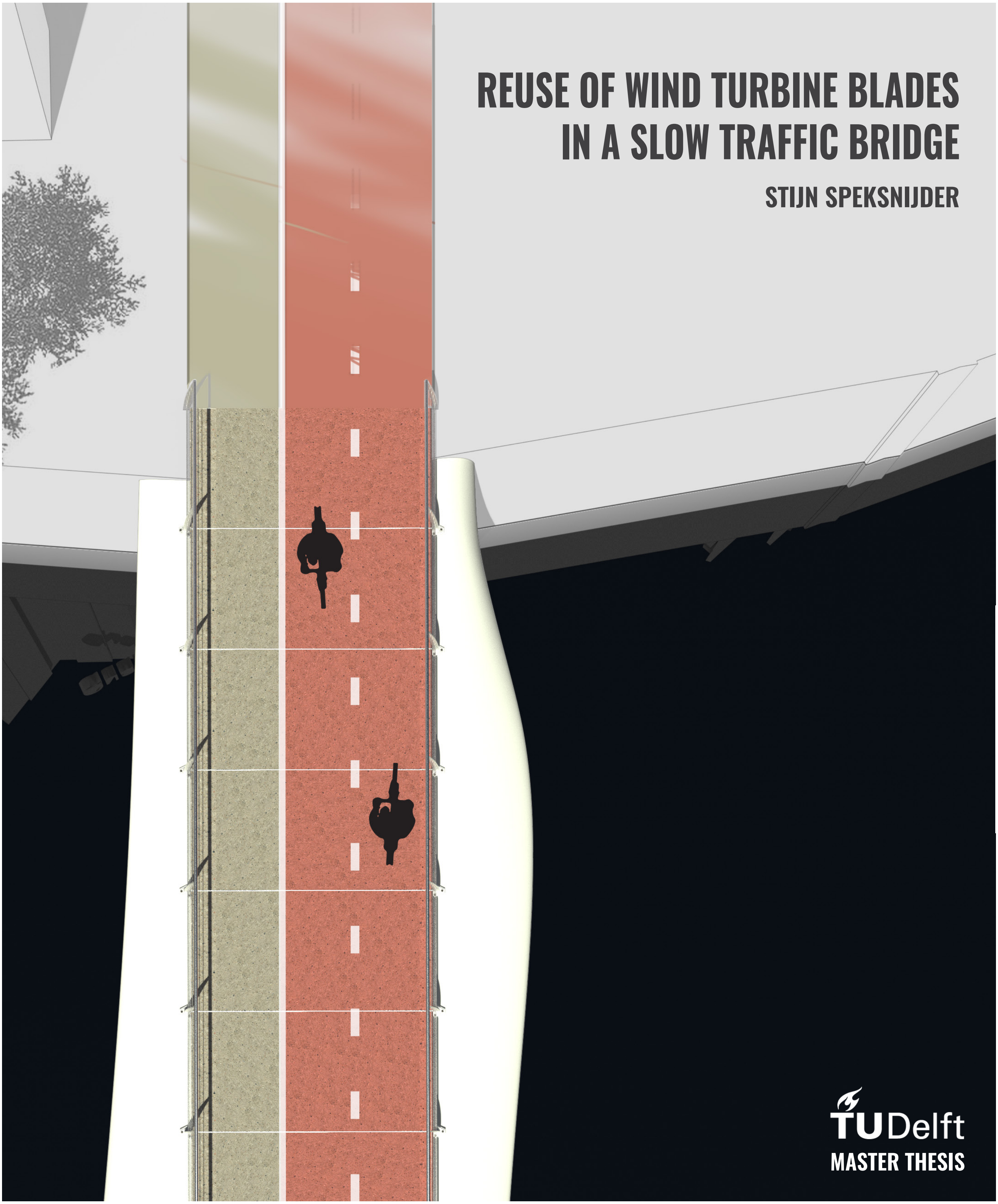
REUSE OF WIND TURBINE BLADES IN A SLOW TRAFFIC BRIDGE

STIJN SPEKSNIJDER



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MASTER THESIS

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MASTER THESIS

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EXECUTIVE SUMMARY

This master thesis presents a research & design project, aimed at finding a new use for decommissioned wind turbine blades. Wind energy is becoming a major source of renewable energy. As a result, a large stream of wind turbine materials arises. Most of these materials can be recycled very well, but the rotor blades pose a big problem after their lifespan of 20-25 years. These blades consist of complex composite materials that are doomed to end up in landfill or incineration plants, although the high performance material often still possesses excellent mechanical and chemical qualities. This confronts owners and manufacturers of wind turbines with high costs, as they paying ±€100 per tonne of waste to dispose of the blades. The blade waste problem is steadily growing. By 2050, between 21.4 and 69.4 million tonnes of cumulative wind turbine waste is expected.

On an industrial scale, no proper solutions to the wind turbine blade waste problem have yet been found. Most current solutions involve shredding of the blades, which generally results in loss of material qualities. Some solutions have been found that utilize the structural qualities of the blades. However, these new applications are often 'occasional solutions'; projects that are interesting but are difficult to upscale in an economically viable way.

In order for a new product application to be viable, it is important that the material qualities of the blades are utilized and that the resulting product offers an advantage over its competition. The solution must be applicable on a worldwide scale to offer a significant reduction of the blade waste problem. To solve this problem, a large amount of ideas was generated during different kinds of creative sessions. Based on the criteria found in the analysis, a slow traffic bridge was chosen as the most promising idea. This bridge was further developed into a concept.

The market potential was identified for the 'Bridge of Blades', and the product was designed to fit this purpose. The concept was developed regarding aesthetics, user interaction and structural performance. In the design, the previous life of the bridge is clearly visible. Two rotor blades cross the entire bridge and carry the bridge superstructure. Between the blades, a deck is placed, that provides a comfortable crossing for pedestrians, wheelchairs, bicycles and mopeds. The resulting design is playful, dynamic and tells the story of how high performance materials can be re-used in a commercially viable solution.

All components and connections were developed into detail with production and re-use of materials in mind. At the end of the lifespan of the bridge, all materials can be separated and find a new use in the circular economy. This way, the bridge offers a constructive solution to one problem, prevents new problems and acts as an example to fuel debate regarding material use in the technologies of the future.

The concept was evaluated, to predict how it could perform in its context. Approximations of the structural performance and a qualitative analysis of the environmental impact are presented.

The thesis is concluded with recommendations for further development and evaluation, that are required to make this concept reality. Finally, recommendations for blade designers are given, to make sure the problems that were faced in this project can be avoided in the future.

ACKNOWLEDGEMENTS

This project would not have been possible without the help of so many people. I would like to thank everybody who helped me during this project:

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All my friends and family that helped me survive.

CONTENT

In a hurry? Read only the green text boxes. These offer a summary of the text.

INTRODUCTION

The market of wind power has seen remarkable growth over the past years. Across the globe, governments, organisations and corporations are working together to support this development in renewable energy. With this multidisciplinary commitment to use renewable energy sources, the share of energy coming from wind is expected to grow enormously. In 2014, the European Wind Energy Association predicted wind power to reach a share of 14.9% of the global electricity production by 2020 (EWEA, 2014).

Wind turbines have an average life span of 20 years (Dolan & Heath, 2012; Beauson, 2014; Liu & Barlow, 2017), and so huge amounts of waste coming from wind turbines can be expected over the coming years. In 2050, more than 2 Mt (million tonnes) of blade waste is expected to be produced. By that time, between 21.4 Mt and 69.4 Mt of cumulative wind turbine waste is expected, with the most probable waste level being 43.4 Mt (Liu & Barlow, 2017).

Wind energy is becoming a major source of renewable energy and a large product stream. Most wind turbine components can be recycled very well, but the rotor blades consist of complex materials that are currently impossible to recycle. In this project, a solution is sought for this problem, which may benefit other markets too.

VISION
Like other materials, composite materials should be integrated in the circular economy.

MISSION
Commercially viable processing of used wind turbine blade materials into new products, while retaining their high-end characteristics.

These projections call for serious attention to wind turbine end-of-life (EoL) strategies. The most common materials used in wind turbine towers are steel, iron and copper, materials that are widely recycled (Andersen, 2015; Diepeveen, 2017).

The rotor blades, however, are made of composite materials. Wind turbine blades are complex designs that consist of many different materials and bonds. This allows for superior qualities, but results in waste material that is difficult to recycle. Some recycling methods exist, but none allow for commercially viable processing of the used materials into new products, while retaining their high-end characteristics.

This graduation project acts as an example of how designers can help to achieve a more closed loop for composite materials. A new (yet to define) product will be designed that uses discarded wind turbine rotor blade composite material. It is important not to consider the material as recycled material of poorer quality. Instead, the material's unique properties are identified and exploited to develop a new product. An additional goal is to develop a product that communicates the qualities of this material, making it obvious that it has had a previous life as a wind turbine blade. Integrating business, human interaction and technology considerations, an inclusive design can be achieved that is commercially viable. By doing so, the stream of wind turbine rotor blade composite waste going to landfill and incineration can be reduced.

In addition to wind turbines, composites are widely used in automotive, aviation and construction industries. Therefore, the product designed in this project has the potential to offer more than a reduction in wind turbine composite waste. It can serve as an example for other composite waste research and design projects. Future industrial product designs in any of these sectors can be adjusted to allow for better reuse of composite materials.

1.

METHOD

The project approach is presented. Two existing innovation methods were analysed and combined to develop a method specifically for this project. The resulting method could be used by designers in similar projects.

METHOD

The Delft Innovation Model (Buijs, 2012) is a methodology that is commonly used in a wide variety of design processes. It integrates the three Industrial Design Engineering pillars in a model for designers to use: business (company), technology (product) and human interaction (environment) (Figure 1). Although the model offers some good structure opportunities for this project, it assumes a client company and a target market is present. Because this project doesn't have either, the method can't be implemented blindly.

As explained in the introduction, the starting point for this project is a material. Elvin Karana has developed a methodology for design processes like these, called the Material Driven Design Method (Figure 2). The main focus of this method is to facilitate designers to design for material experiences (Karana et al., 2015). Although the method and this process share the structure of designing from a material (proposal) perspective, some aspects of the method are not directly implementable in this project. 'Tinkering' with the material, by bending, breaking, heating, burning etc. are important to the model. Some of these activities are not possible because of the size and material composition of the wind turbine blades. Only small parts of the blade could be tested this way, not allowing for structural reuse of the blade. Also, the materials can't be bent or melted due to their nature and burning them would release toxic gases.

Consequently, this project requires a different approach. Elements of the Delft Innovation Model and the Material Driven Design method were combined to develop a method specifically for this project.

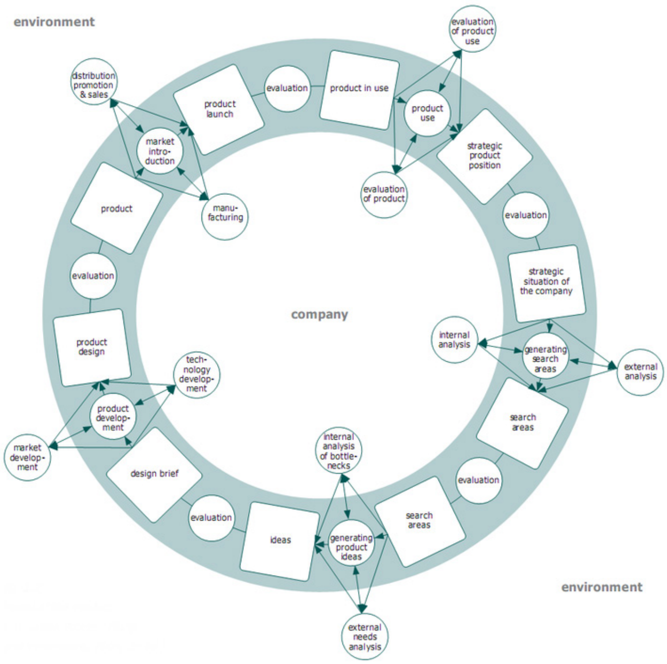


Figure 1: Delft Innovation Model (Buijs, 2012)

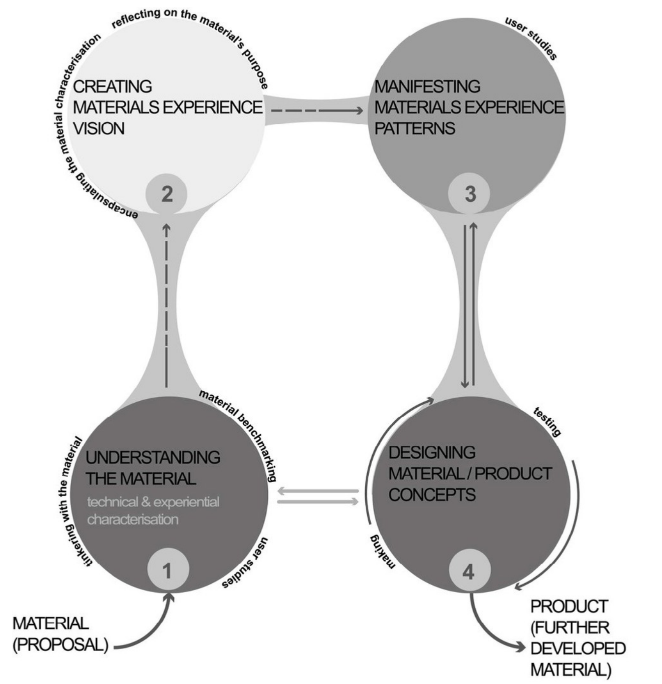


Figure 2: Material Driven Design method (Karana, 2015)

A combination of the Delft Innovation Model (Buijs, 2012) and the Material Driven Design Method (Karana, 2015) was made. The resulting method, that was used in this project, is explained on the next page.

METHOD

Figure 3 shows the method that was used in this project. Because the starting point for this project is an EoL product, this can be found at the center of the loop. Any product/company acts in a certain environment that should always be considered. Therefore, like in the delft Innovation Model, the environmental aspects are noted outside the loop.

The model consists of five steps/milestones, each followed by a stage of (product) development that leads to the next milestone. After the final milestone ‘product launch’, this method distinguishes itself by implementing a stage of ‘product in use’ analysis, that links back to the first milestone, ‘EoL product’. This gives designers the responsibility to consider the entire life cycle of their product in a closed loop. In order for a circular economy to work, it is important to consider the EoL of a product, even when EoL materials are used for that product.

It is important to note that in design processes, the steps are generally not executed as consecutively as presented in the models. More often than not, the designer will need to go back steps and combine stages to generate the best results.

The method works as follows:

1. END-OF-LIFE PRODUCT

A waste stream is identified that poses significant problems to the environment. This may also be materials that are currently recycled, but where the effectiveness of the material reuse can be improved.

This product (material) is analysed thoroughly on a wide range of aspects. Contextual analyses such as the existing EoL solutions and the shareholders influence are done. At the same time, the product properties are analysed. All findings are combined in a list of values & challenges.

2. VALUES & CHALLENGES

All discovered values, problems, opportunities and challenges are summarized in the second milestone. Taking into account people technology and business, the needs of the environment and the opportunities evoked by the product (material) form the basis for generating ideas to solve the design problem. A large amount of ideas is created through different kinds of creative sessions, such as brainwriting, reverse engineering, clustering, rapid prototyping etc.

3. PRODUCT IDEAS

A wide variety of ideas and opportunities is generated. It is important at this tage to identify the most promosing ideas/directions. The values & challenges are be used to rank and select the ideas. By doing this at different stages of the product development, ideas can be ranked on different detailing levels.

4. PRODUCT DESIGN

One concept is chosen or composed by combining different ideas. A detailed design is made, which is constantly tested against the values & challenges of the product. Throughout the process, the designer should be aware that it operates in a loop and the EoL of the resulting product must be considered.

5. PRODUCT LAUNCH

The final step marks the introduction of the new product to the market. If the method is applied well, possible maintenance, ownership and end-of-life issues have been accounted for.

This final stage will not be reached within this report, as it is outside the scope of this project. However, all elements of the loop are considered during the conceptual design.

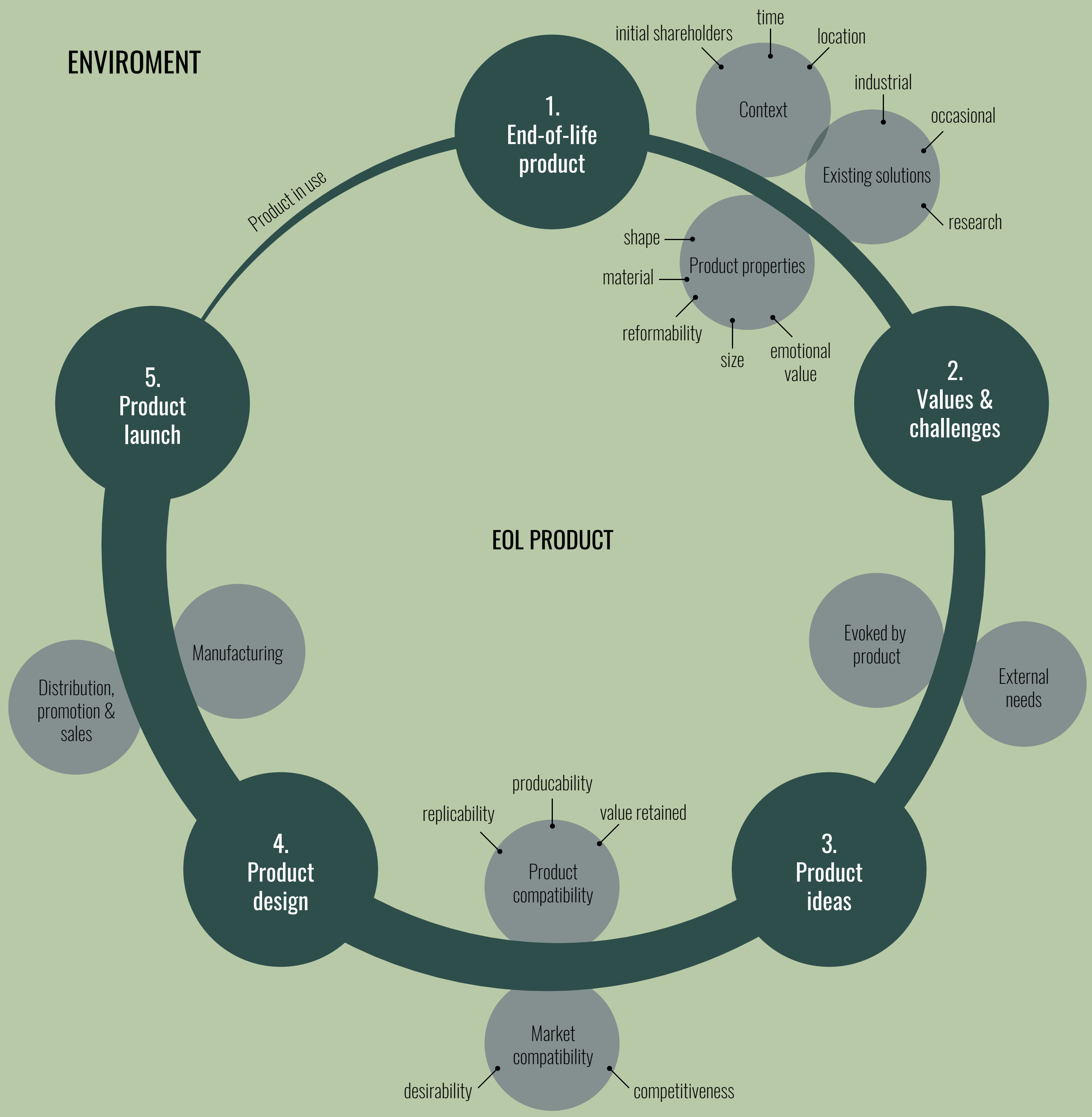


Figure 3: Method used in this project

2.

ANALYSIS

This chapter shows all the results that were found in the analysis. First, some basic knowledge of composites and wind turbine blades is shared to lay the foundation for the rest of the report. The different end-of-life strategies for blades are presented, comparing the current industrial processes with methods that are still in development.

All the important insights that are gained in the analysis come together in the criteria at the end of this chapter. These criteria are used for ideation and product development.

COMPOSITES INTRODUCTION

Because of their high stiffness, high specific strength and their ability to be tailored to very specific requirements, composites have become an important advanced material category. Composite materials are widely used in renewable energy, automotive, aviation and construction industries.

A composite is a material that is composed of two or more materials (phases). By combining these phases, composites offer advanced properties that single materials could not offer. Generally, a composite consists of a reinforcement material, called the 'dispersed phase' and a continuous material, called the 'matrix' (Callister, 2010). A well-known example of a composite with two phases is reinforced concrete (Figure 4)

Sandwich constructions are also considered to be a class of composite materials. In a sandwich panel, outer sheets are separated by a thick core (Figure 5).

Sometimes, more than two phases are combined and/or sandwich panels are added. A common example is a surfboard (Figure 6). Complex composite constructions such as these are widely used due to their excellent properties.

One major problem that composite materials face today is its poor recyclability. This thesis attempts to find a solution to this problem in the field of wind energy. Wind turbine rotor blades consist of complex composite materials, as will be discussed in the next chapter.

Composite materials offer advanced qualities and are widely used in high-end markets. Poor recyclability is inherent with the complex composite constructions.

Figure 4: In reinforced concrete, steel bars are the dispersed phase and a cement mix is the matrix.

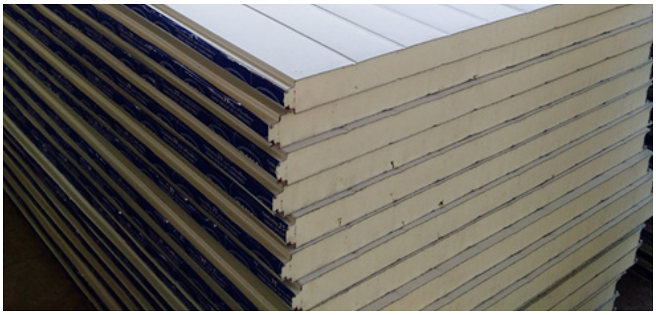


Figure 5: Sandwich panels with outer sheets of metal or wood and a foam core are often used in construction.

Figure 6: In a surfboard construction, a fibreglass (dispersed phase) and epoxy/polyester resin (matrix) composite shell is wrapped around an EPS/PU foam core (sandwich). Most surfboards also have a wooden 'stringer' glued into the foam construction for extra strength and stiffness.

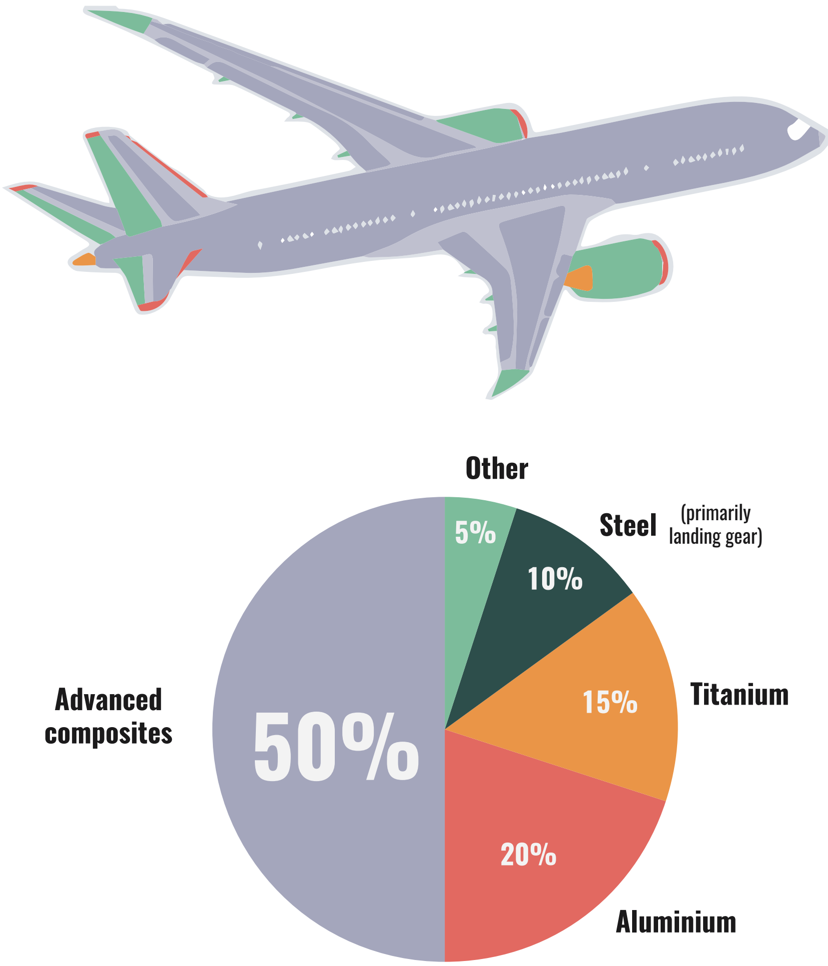


Figure 7: Material use in a boeing 787

ROTOR BLADES COMPOSITION

Most modern wind turbines are powered by three rotor blades. Technological development has caused for a strong increase in rotor blade size over the past years to increase efficiency. In 1990, 10 meters was a common size for a wind turbine blade. In 2016, LM Wind Power set the latest record with their 88.4 meter long blade (Breakbulk, 2016).

Blade designs have been altered simultaneously to facilitate this trend. Depending on size, manufacturer, build year, place and type (on- or offshore), rotor blades are different in shape, dimensioning and material composition.

Even within one blade, great differences can be found. In one Siemens rotor blade, the material thickness varies from 4 to 120 layers of fibreglass (How It's Made, n.d.). In the root of the blade, steel inserts are used to reinforce the connection with the hub.

It is safe to say that wind turbine blades are complex designs that consist of many different materials and bonds. The main challenge in this project will be to retain the superior qualities of composite materials, while being able to process the material into new products.

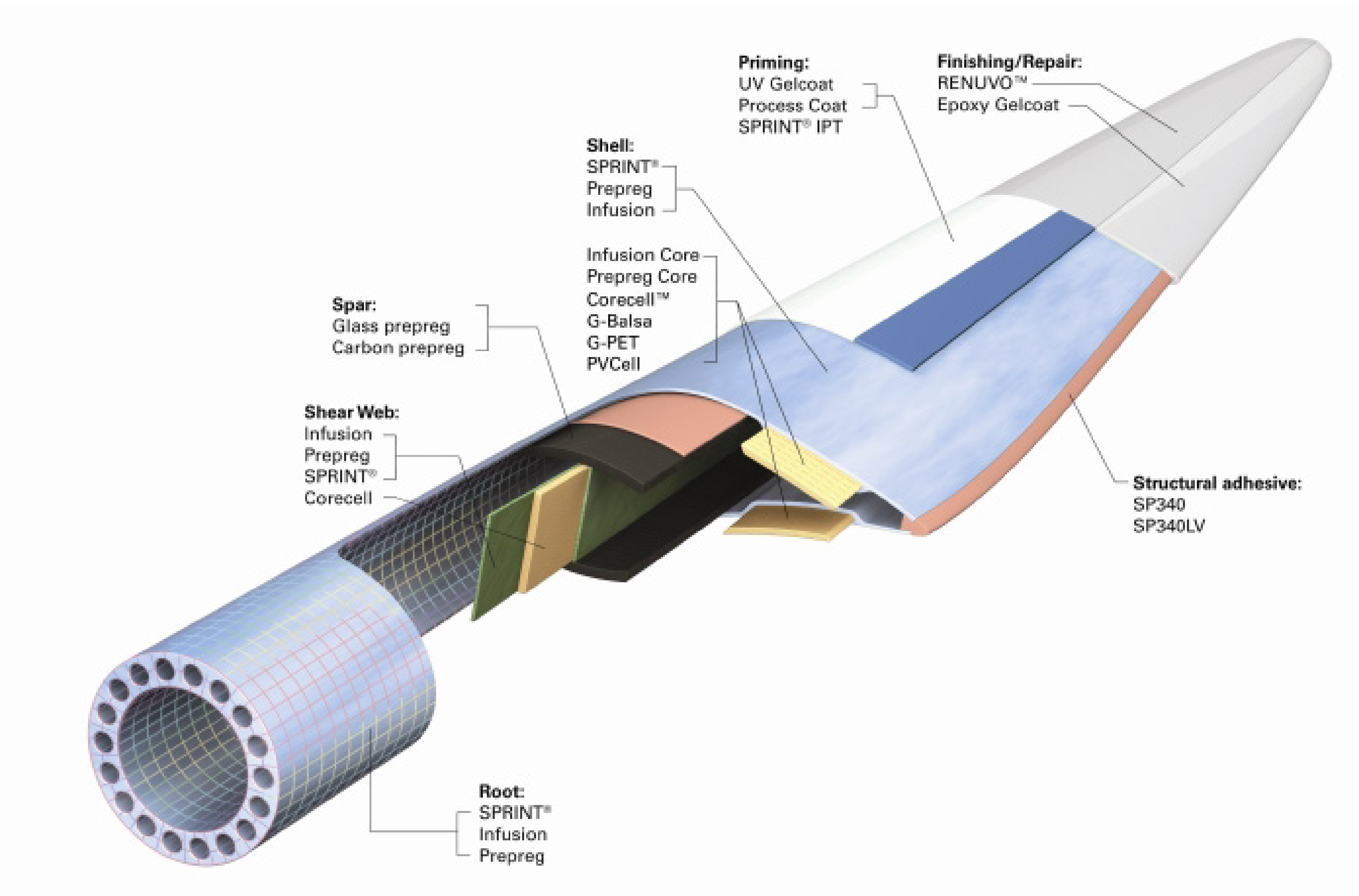


Figure 8: Complexity of a rotor blade

Despite the complexity and variety in rotor blades, some common characteristics can be identified. Unfortunately, wind turbine (blade) manufacturers are not very transparent in their communication about their blade designs. Only very general information about the material composition, measurements and shapes is publicly presented.

MATERIALS

Wind turbine blades are mainly composed of continuous glass fibre reinforced plastics (GFRP).

E-glass fibres are generally used as reinforcement material in the shell (Beauson et al., 2014a). This material is low in cost and offers high strength and stiffness. Especially in the offshore sector, where turbine size is not restricted as much as onshore, more increase in blade size can be expected the coming decades (Diepeveen, 2017). To facilitate this, carbon fibres are used to replace or complement glass fibres. At the moment, this is applied in few rotor blades.

Thermosetting polymers are used as matrix material; usually epoxy, polyester or vinylester resins (Beauson et al., 2014a). Thermosetting polymers are easy to manufacture and are very cost-effective. They are created with a chemical process and can't be melted or remoulded. This is the most important reason for the poor recyclability of wind turbine blades. Thermoplastic polymers are an alternative polymer class that can be remelted. Therefore, thermoplastic composites are recyclable. Unfortunately, thermoplastic polymers are currently too expensive to use as a matrix material in wind turbine blade composites.

Additionally, sandwich laminates with balsa wood or (PVC) foam are used. Gel coats, polyurethanes, foils and paints can be found on the blades' surfaces and edges (Brøndsted, 2005).

CONSTRUCTION

Two main types of blade construction can be identified (Figure 9). The shell structure is the same for almost all blades. The shell consists of a GFRP and balsa wood or PVC foam structure. One, two or three stiffeners are placed between the top and bottom of the shell (Teuwen, 2017), enabling the structure to bear extreme loads. Two stiffeners are most common. These stiffeners are constructed by glueing shear webs or a box spar into the shell.

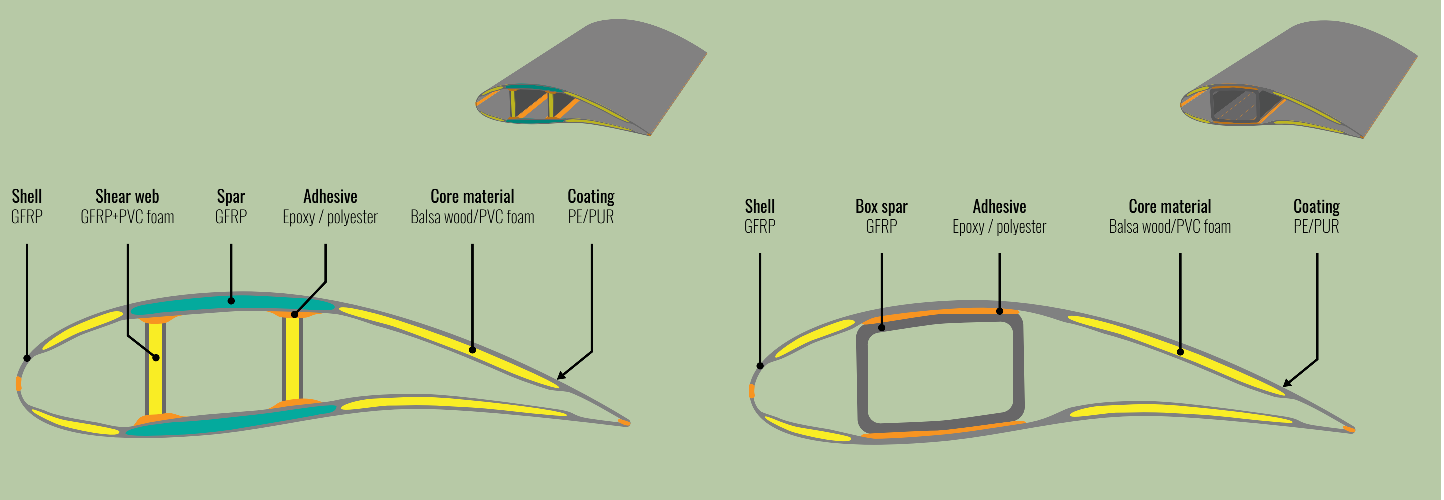


Figure 9: Two common types of blade composition

SCOPE

The wind energy sector is one of rapid innovation and wind turbine (blade) designs are ever changing. The materials, shapes and sizes of a rotor blade vary between different manufacturers, production dates and intended locations (on/offshore).

For this project, it is important to identify when the blade waste problem will be greatest, what the EoL blades will look like within this time period, and where they can be expected.

TIME

As can be seen in Figure 10, blade waste volumes are expected to grow steadily over the next decades.

As the first wind parks are decommissioned, manufacturers and owners are faced with the problem of blade waste. As a result, manufacturers are developing thermoplastic composite materials that can provide recyclable blades. Arkema Group (2017) has developed Elium, a thermoplastic resin with which a 9 meter scale model of a megawatt-sized rotor blade has been produced. Innovations like these can offer a recyclable alternative in the next 5-10 years on a commercial scale (Arkema Group, 2017; Teuwen, 2017). By 2030, wind turbine blades may very well consist of thermoplastic composites.

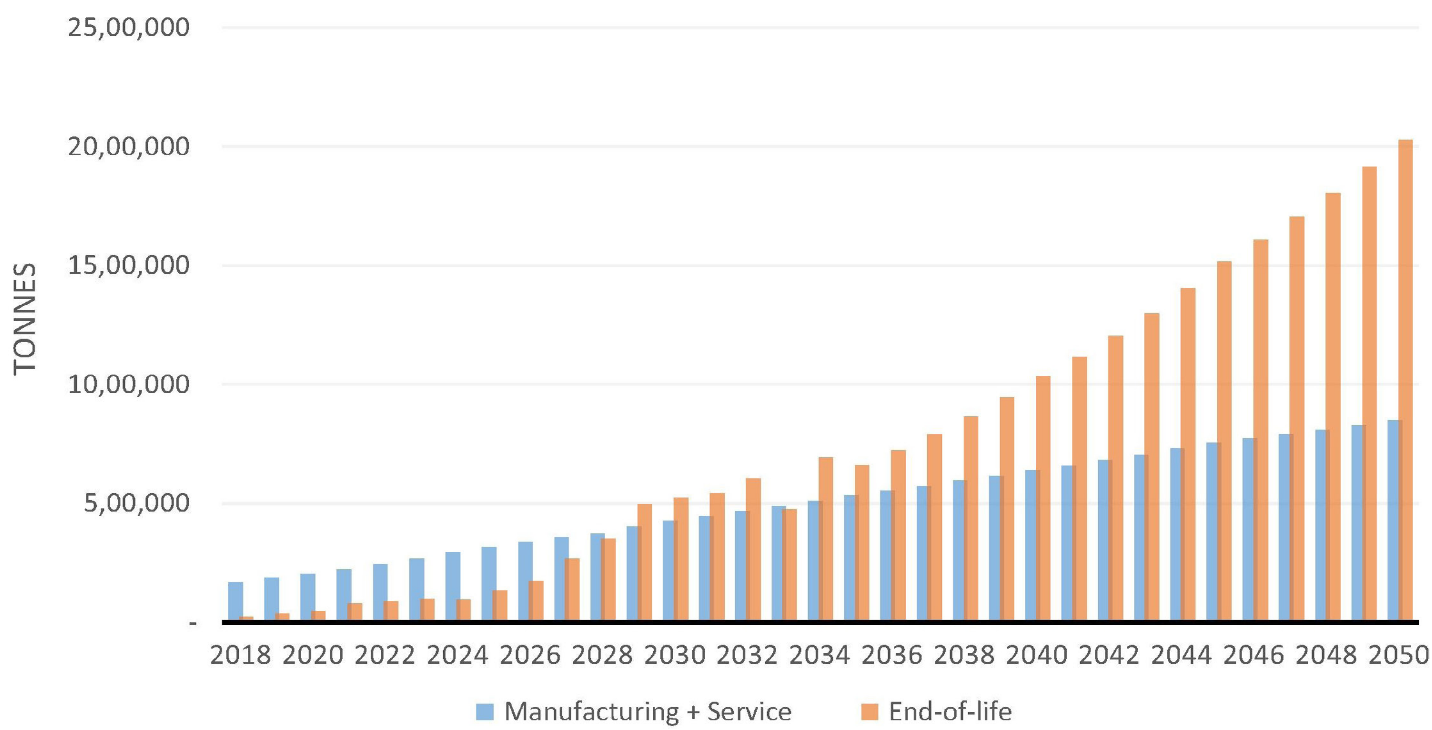


Figure 10: Annual blade waste projection (Liu & Barlow, 2017)

This means that by 2050, thermoplastic resins could be implemented in most wind turbine blade waste, offering easier recycling options.

Considering the waste projections and material innovations, the time scope for this project will be blade waste between approximately 2020 and 2050. Taking into account the average lifespan of 20 years, this means that these blades were designed and produced between 2000 and 2030.

HORIZON 1
Thermosetting composites are standard and blades are not recycled. Companies pay €100 per tonne to send decommissioned blades to landfill or incineration.

HORIZON 2
Direct structural composite recycling methods are used to reuse decommissioned blade material in new products. A cascading system allows for new business opportunities in multiple reuse phases.

HORIZON 3
Rotor blades can now be manufactured with thermoplastic composites or other seperable materials. Upcycling methods exist to separate the materials and retain their value using industrial processes.

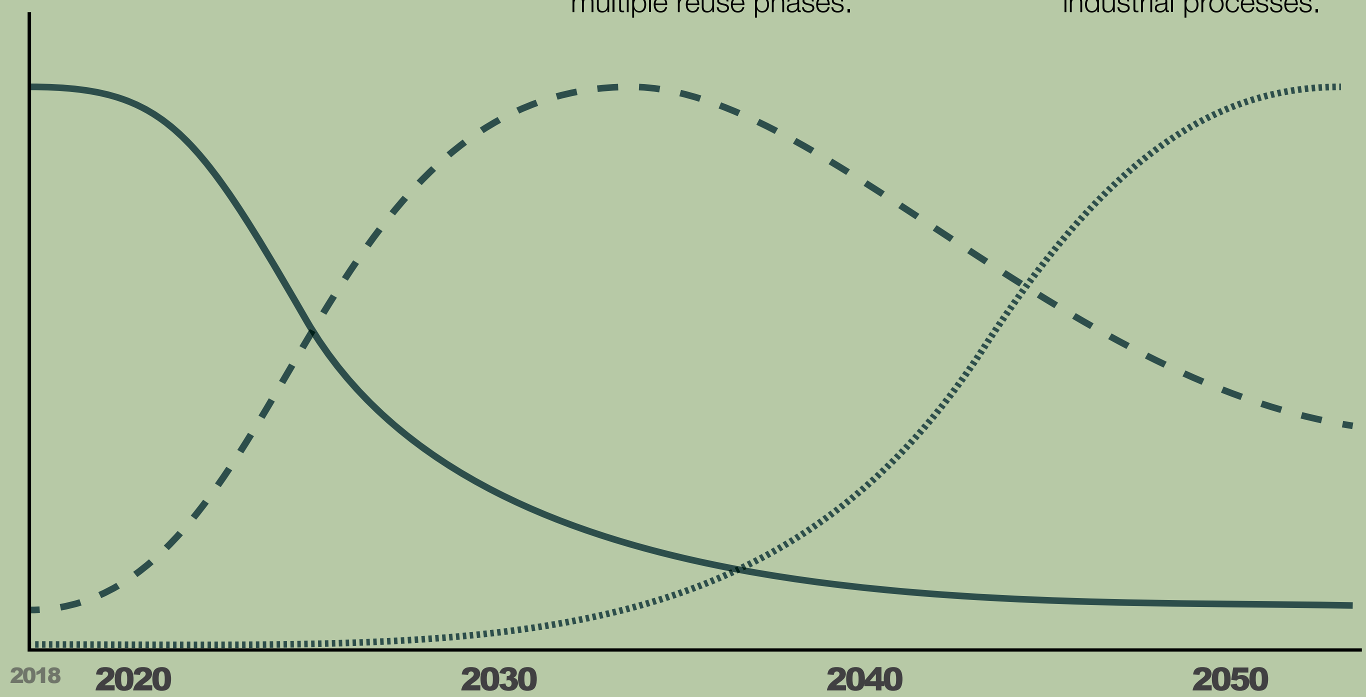


Figure 11: Material development projection using the three horizons model

SCOPE

LOCATION

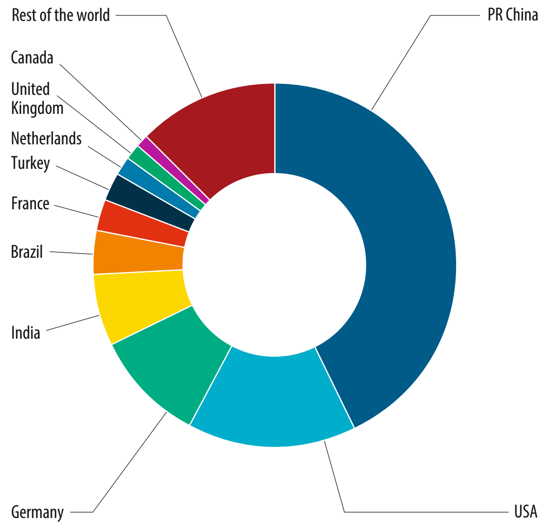
In their 2016 wind energy market report, the Global Wind Energy Council reviewed the global status of wind power, showing insight into the distribution of wind turbines across the world (GWEC, 2016). Together, China, the USA and Germany provide over 60% of the world's wind energy and a trend can be identified towards a higher share from Asia.

The report also shows an interesting division between onshore and offshore energy. The UK, Belgium, the Netherlands, Denmark and Germany are pioneers in the field of offshore wind energy, with 35%, 30%, 26%, 24% and 8% of wind energy generated offshore respectively. Surprisingly, the offshore wind energy share for all other countries is close to none. Consequently, the global share of wind energy coming from offshore turbines is only 3%.

As this technology develops, a larger offshore capacity is expected. According to EWEA (2015), by 2030, 30% of European wind energy is likely to be generated offshore (currently 7,8%). No global projections were found when writing this report.

The gathered data shows that most impact can be achieved when developing solutions for rotor blades found on onshore turbines in the context of China, India, the US and Germany.

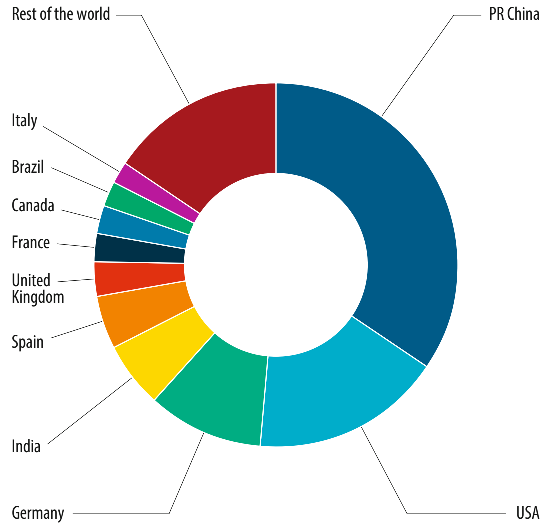
TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2016



Country	MW	% Share
PR China	23,370	42.8
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil*	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Rest of the world	6,727	12.3
Total TOP 10	**47,915**	**88**
World Total	**54,642**	**100**

Source: GWEC

TOP 10 CUMULATIVE CAPACITY DEC 2016



Country	MW	% Share
PR China	168,732	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil*	10,740	2.2
Italy	9,257	1.9
Rest of the world	75,576	15.5
Total TOP 10	**411,214**	**84**
World Total	**486,790**	**100**

Source: GWEC

Figure 12: Wind energy distribution (GWEC, 2016)

SIZE

According to a survey by Berkeley Lab (Wiser et al., 2016), the rotor diameter is expected to grow to approximately 135 meters for onshore turbines (Figure 13) and 190 meters for offshore turbines (Figure 14) by 2030.

Considering the production time scope (2000-2030), we can expect blades in the 10-90 meter range. When looking at onshore parks only, where turbine size is restricted more, a maximum blade size of approximately 60 meters is more likely.

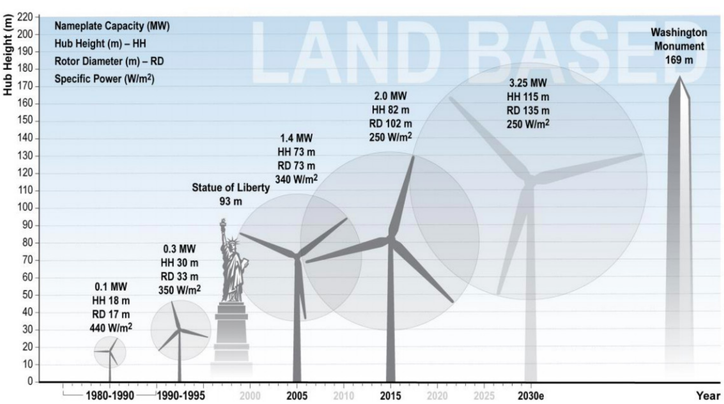


Figure 13: Onshore turbine size projection (Wiser et al., 2016)

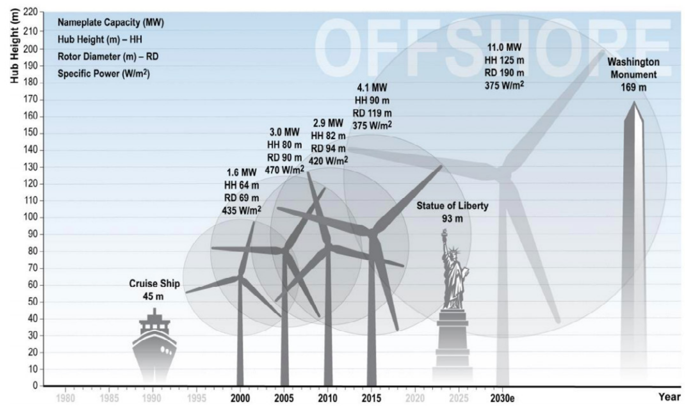


Figure 14: Offshore turbine size projection (Wiser et al., 2016)

INDUSTRIAL END-OF-LIFE STRATEGIES

Like mentioned before, one of the key characteristics of composites is the ability to alter the material to fit specific needs/products. As good as this may be from a product development perspective, it poses problems at the end-of-life (EoL) of a composite product. Re-certification of composite products with quality tests are unlikely to be cost effective (Halliwell, 2006). Beauson et al. (2014b) go so far as to say that “there are currently no viable recycling solutions for EoL WT blade material”, mostly due to their heterogeneous nature.

At the EoL, almost all rotor blades are either incinerated or landfilled (Beauson et al., 2014a). This confronts owners and manufacturers of wind turbines with high costs, since they pay ±€100 per tonne of waste to dispose the blades. As the amount of blade waste is growing, some researchers and companies are seeing a market opportunity. Although not yet (commercially) viable, options to refurbish or recycle blades are under investigation and so the following industrial scale solutions can be identified:

RE-USE / REFURBISH

Re-using structures could offer most economic value but is hard to apply. Wind turbines are generally designed for a lifetime of 20 years. Although the turbine blades are often still in good condition after 20 years (Sayer et al, 2009), it is more profitable to implement new blade technology when erecting a new wind turbine (Diepeveen, 2017).

This is mostly due to trends towards larger blades. Older blades can’t compete with the developments in blade size and technology. If this up-scaling reaches its limits, re-using entire blades may become more common in the future (Peeters et al., 2017). However, it is difficult to predict technological developments in blade design (segmented blades have recently gained new interest). Therefore, it is hard to say if blades will be commonly reused in the future.

Some blades are reused in developing countries where low investment costs are important. Some occasional solutions for re-using blades exist in other markets (see next chapter), but none are are suitable for up-scaling.

LANDFILL

Landfill is currently the cheapest waste management option for WT blades and therefore most commonly applied. With new legislations, this may change and other EoL solutions may become more financially interesting.

INCINERATION

Many facilities are already in use to incinerate composite materials. By burning the materials in a controlled environment, some energy can be recovered as electricity and heat. This is difficult, as glass fibres are not combustible and hinder the incineration (Duflou et al. 2012). Since rotor blade composites can contain as much as 70% glass fiber in weight (Beauson et al., 2016), this process is not very well suited for EoL rotor blades.

Moreover, no large parts can be incinerated and its high ash content (±50%) needs to be landfilled afterwards (EWEA, 2012).

RECYCLING

Mechanical grinding is applied as a recycling solution. Shredders are used to grind the materials down to pieces of a few centimetres or less, separating the fibres from the resins in the process (Beauson et al, 2016). The short fibres that are recovered are generally damaged.

Multiple companies have tried to commercially apply this recycling technique. Unfortunately, none of them exist today. Examples are Phoenix Fibreglass Inc. in Canada (1990-1996), ERCOM GmbH in Germany (1990-2004). More recently, Zajons and Holcim in Germany have used mechanically ground fibres as a filler material in cement production. Zajons terminated in 2014.

Using shredded fibres as reinforcement material in new composite materials has also been investigated globally. However, research has shown that the shredded fibres can't offer quality improvement (Beauson et al., 2016).

The problem with mechanical grinding of FRP's is that their initial material qualities are demolished with the shredding of the fibres. Since the thermosetting resins can't be melted, both injection moulding and proper material separation are impossible. The result is shredded fibres and resin that are inseparable. The value of the material is thereby reduced to that of other filler materials such as sand, glass or calcium. A solution could be to resize and realign fibres. However, this is costly and has not been experimented with yet (Beauson et al., 2014b).

Figure 15: Zajons cement clinkers

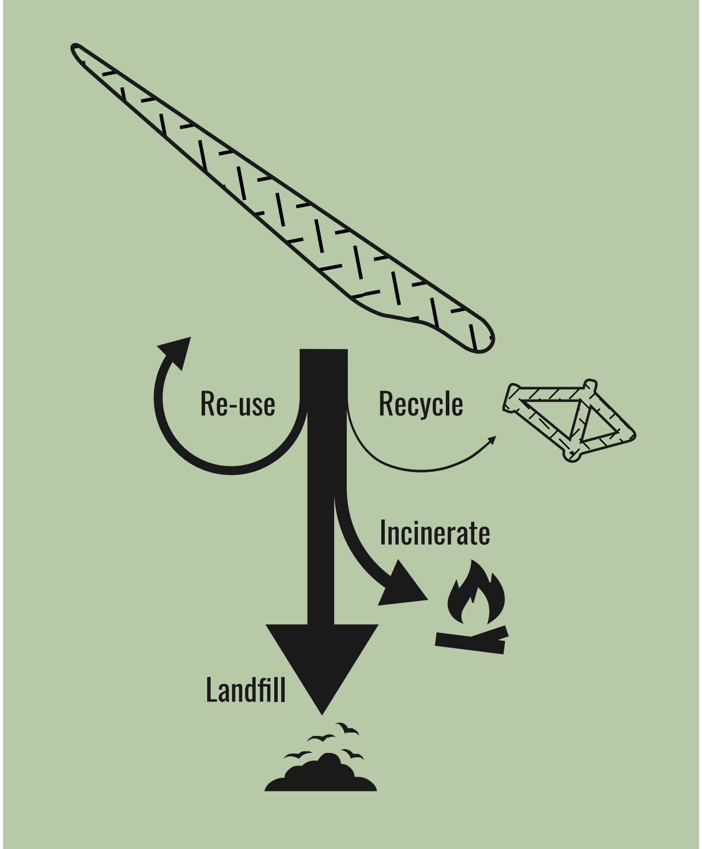


Figure 16: Current industrial end-of-life strategies

OCCASIONAL END-OF-LIFE SOLUTIONS

Recently, developing EoL strategies for rotor blades has gained interest and solutions are sought in many different ways. Institutions such as the GenVind Innovation Consortium are developing technologies to recycle composite materials (GenVind, 2014). The European Union considers this challenge important enough to invest €10 million in Ecobulk, a project aimed at 'closing the loop of composite products' (EU Publications Office, 2017).

Solutions found by different parties include ways to contain the material qualities, but are difficult to implement on an industrial scale. These occasional solutions (Beauson, 2016) can be divided in the categories as shown in Figure 13.

The existence of these occasional solutions to the blade waste problem shows the incentive to find new uses is certainly alive. These designs are highly valuable, because they show the world solutions to a problem that is still relatively unknown. However, the problem with all of these designs is that they cannot be sold commercially on a large scale because they are outperformed by competitor products on performance and/or cost.

SuperUse Studios in Rotterdam (formerly 2012Architecten) is an architecture/design company that has an interesting approach to sustainable design. They have used wind turbine blades in many of their projects, for both entire blades and major blade parts, under the name 'Blade Made'.

ENTIRE BLADE

Entire blades can be used without any other adjustments than a paint job. SuperUse studios applied this technique to create public benches In REwind @ Willemsplein (Figure 18) and a signpost (Figure 20).

MAJOR BLADE PARTS

In a slightly more altered form, SuperUse Studios have used large blade parts in their Wikado Playground (Figure 19). More recently, they have constructed a bus shelter (Figure 21).

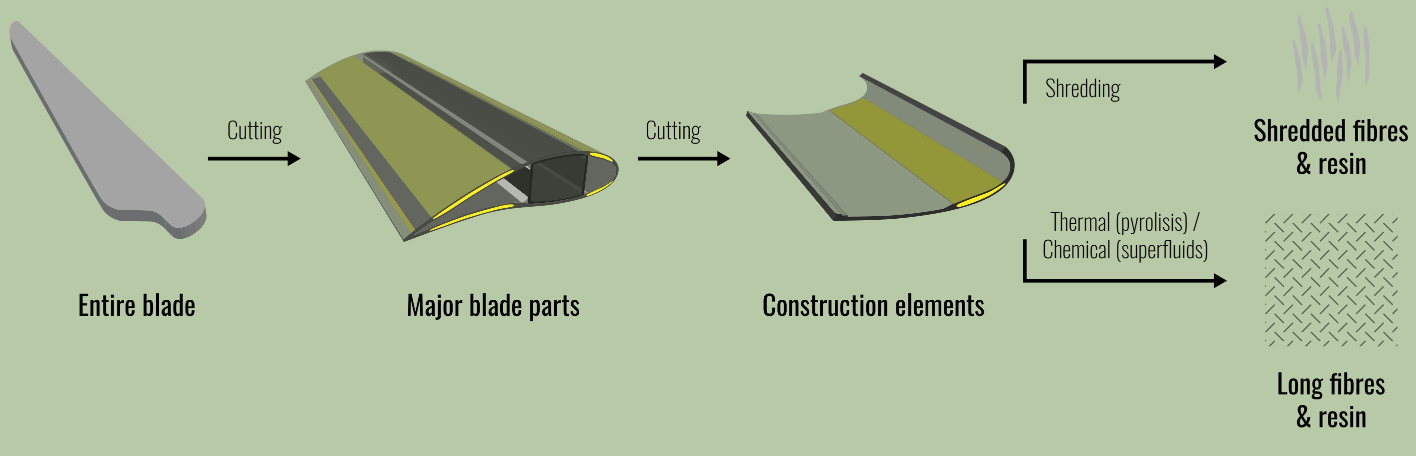


Figure 17: EoL solutions categories (Beauson, 2016))

Figure 18: (left) REwind @ Willemsplein (SuperUse Studios)

Figure 19: (top) Wikado playground (SuperUse Studios)

Figure 20: (right) Kringloop Zuid (SuperUse Studios)

Figure 21: (bottom right) REwind Almere (SuperUse Studios)

OCCASIONAL END-OF-LIFE SOLUTIONS

CONSTRUCTION ELEMENTS

In an attempt to find new applications for discarded thermosetting composites with as little processing (costs) as possible, Albert ten Busschen lead the KIEM-VANG project at Windesheim University. Wind turbine blades were deconstructed using saws to investigate possible structural profiles (Figure 24).

A prototype for a bench was made as part of the same project, which is now in use at the Windesheim University (Figure 22). The KIEM-VANG's focus was nog solely on wind turbine blades and so a different product is also interesting to note. Using thermosetting composites taken from boat hulls, ten Busschen designed retaining walls for Dutch canals, using strips of material as reinforcing elements in a vacuum-assisted infusion process (Figure 26).

Under the GenVind project, Lars Wigh has designed a concept design of a 'chill & work station', using construction elements (Figure 23). No further information can be found about this research project.

Figure 22: Bench prototype (ten Busschen et al., 2016)

Figure 23: Chill & Work station concept (Lars Wigh, n.d.)

Figure 24: Construction elements cut from a rotor blade (ten Busschen et al., 2016)

END-OF-LIFE SOLUTIONS IN RESEARCH PHASE

SHREDDED FIBRES & RESIN

Like mentioned in the previous chapter, shredded fibres & resin have been investigated to use in new materials. Most incentives and tests have proven that shredded fibres do not offer enough value.

Conenor, a Finnish company that is also a part of the EU's Ecobulk initiative, is bringing new life to this market. Researchers at the company are performing experiments, in which they extrude composite materials filled with shredded FRP-waste. They are doing large-scale tests to see if profiles can be produced and sold on a commercial scale.

LONG FIBRES & RESIN

If fibres and resin could be separated without mechanically grinding the material, the original value would be restored. Several solutions to do so are currently in a research stage.

Pyrolisis is a thermal recycling technique where the materials are heated to 450-700 °C, causing the matrix to convert (burn) into gas, leaving the glass fibres intact (Andersen, 2015). It recovers fibre structure to a great extent but is still too expensive to compete with virgin fibreglass. A Danish company ReFiber used the technology to produce glass fibre insulation material from wind turbine composites. The company terminated in 2007.

Chemical recycling is also being investigated, most often using supercritical fluids. The method uses a combination of heat and chemicals to separate the fibres and the resin.

Although these methods may prove valuable in the future, currently the degradation in properties of the recovered material and the cost of applying the technologies make them impossible to implement.

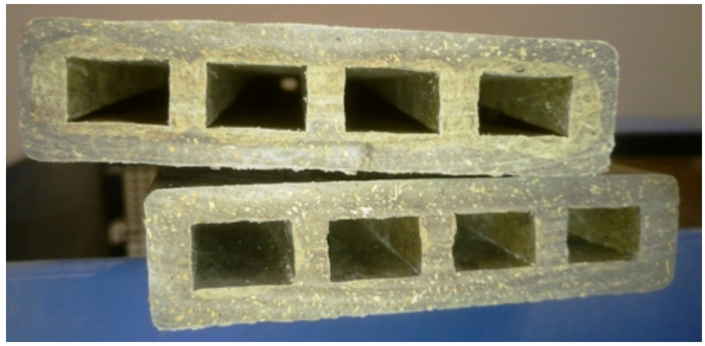


Figure 25: (bottom) Hollow decking boards (Conenor, n.d.)

Figure 26: Canal retaining wall (ten Busschen et al., 2016)

Companies have not yet given up their quest for commercially viable processing of end-of-life thermosetting composites. Solutions such as Conenor's decking boards and ten Busschen's retaining walls are developed to be applied on a large scale. It can be argued, however, that these solutions may not do the original material qualities justice.

CRITERIA

Based on the presented research, a list of criteria was made. The criteria are based on the three pillars of Industrial Design Engineering: Technology, business and people (Figure 27).

From a technology perspective, it is important that the values of the material are preserved as much as possible. The excellent mechanical, corrosion and aerodynamics properties should be exploited. At the same time, any new design should be adaptable to use the different shapes & sizes in a scalable product.

The new design will not be accepted if it does not offer an economical advantage. Therefore, it should be applicable on a large scale and transport and manufacturing costs should be reduced. The degree in which the product is environmentally friendly is also an important factor to create sustainable competitive advantage. If done well, subsidies could be an opportunity to make a design more economically viable.

From a human interaction perspective, it is important for this design to communicate the previous life of the product and the innovative qualities it possesses. However, a product of this size does not fit in every environment and the threat of visual pollution is important to identify and prevent.

These criteria are used to develop and evaluate ideas in the next phases of the project.

Figure 27: Evaluation criteria

3.

IDEATION

Due to the nature of this project, it is important to show the variety of solutions that can be found for a design problem. Ideas were generated in many different ways, selected and further developed.

Four promising ideas are presented and compared, based on the criteria that were generated in the previous chapter. One idea is chosen to be further developed into a concept.

CLUSTERS

Based on the results from the analysis, many different brainstorm sessions were held. Ideas were generated on paper, taking the product qualities and environmental needs as a starting point. The seemingly random ideas were of a very wide variety.

Multiple creative sessions with students and non-students were held. From a large amount of ideas, clusters were made. These clusters could be used to generate more ideas. The four most promising clusters are presented on the following pages.

Additionally, a 3D print was made of a turbine blade. This print was used as a three dimensional approach to the ideation. Sections were cut like they could be cut from an actual blade. In creative sessions, students could play with the materials and share their ideas.

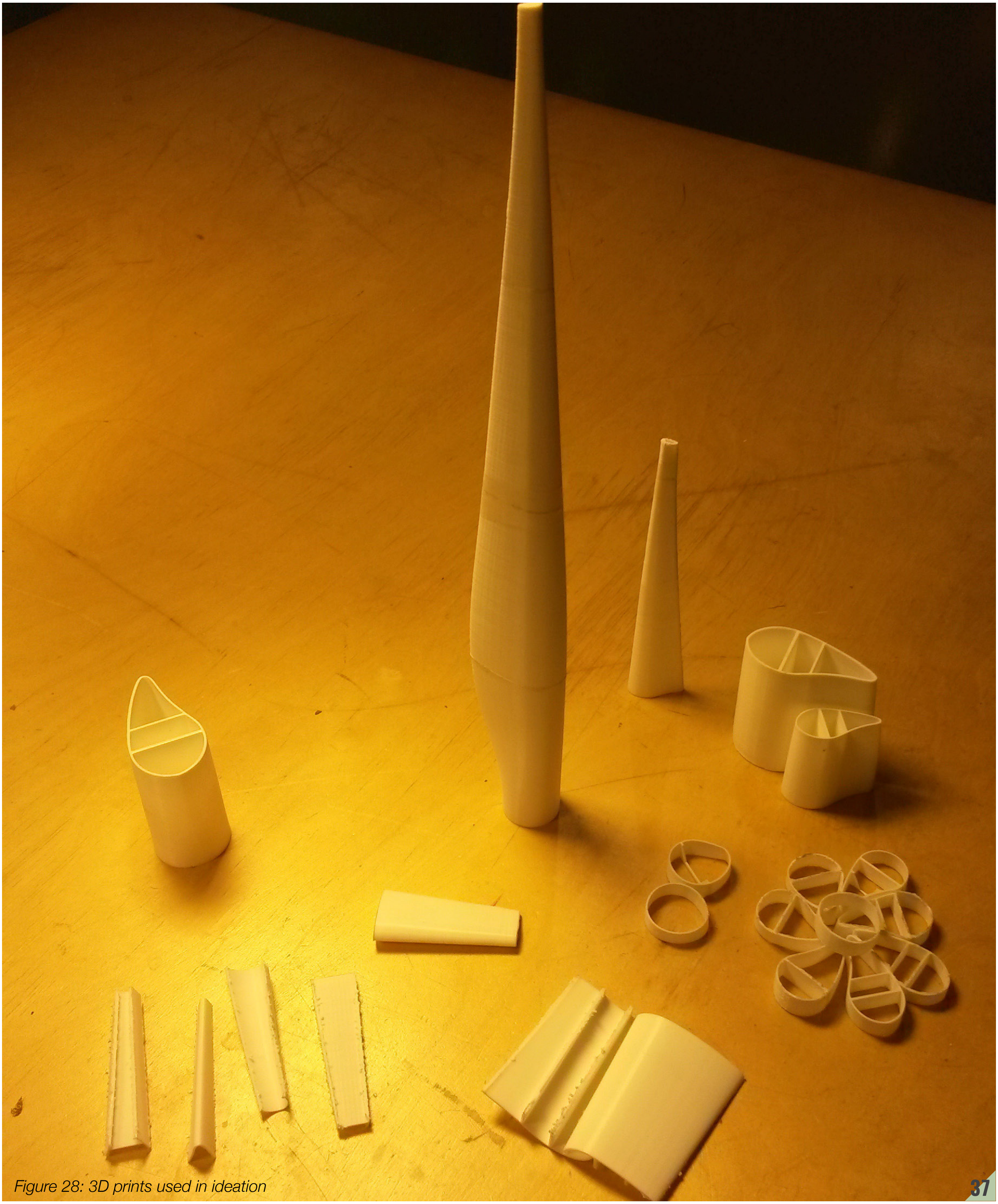
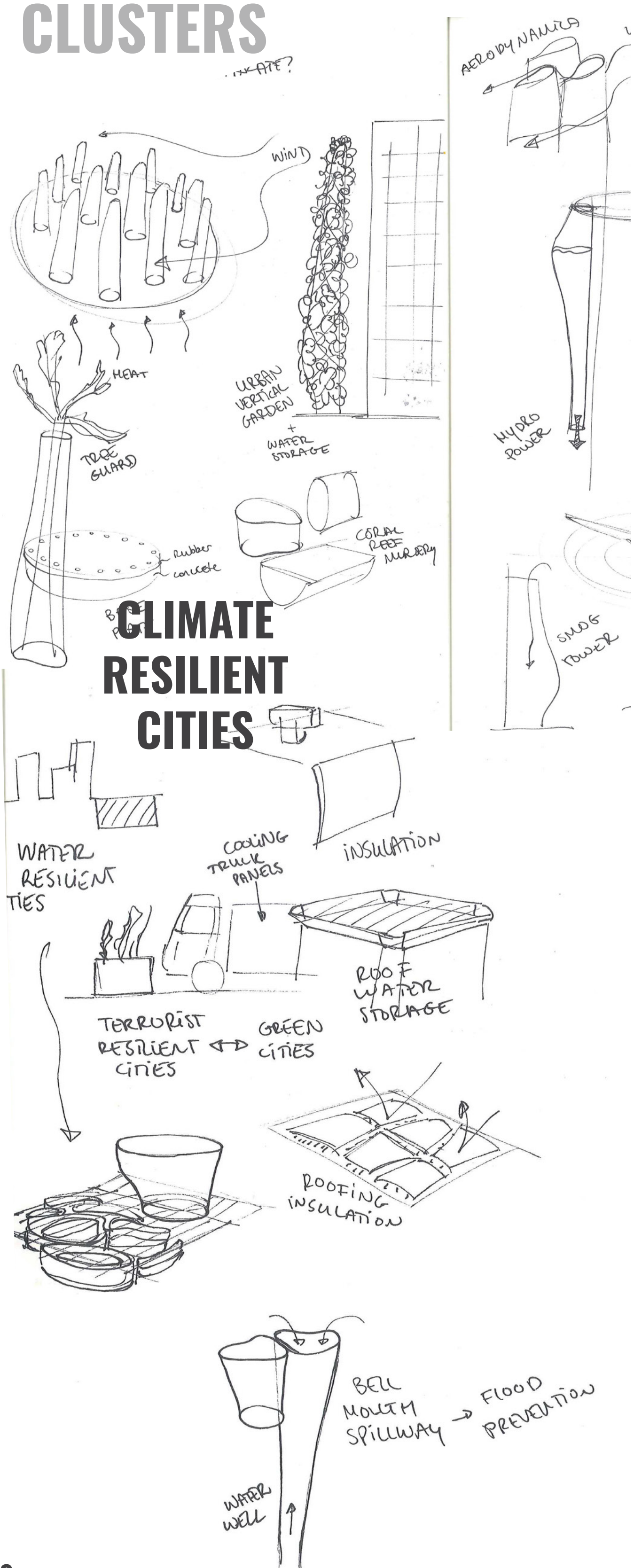


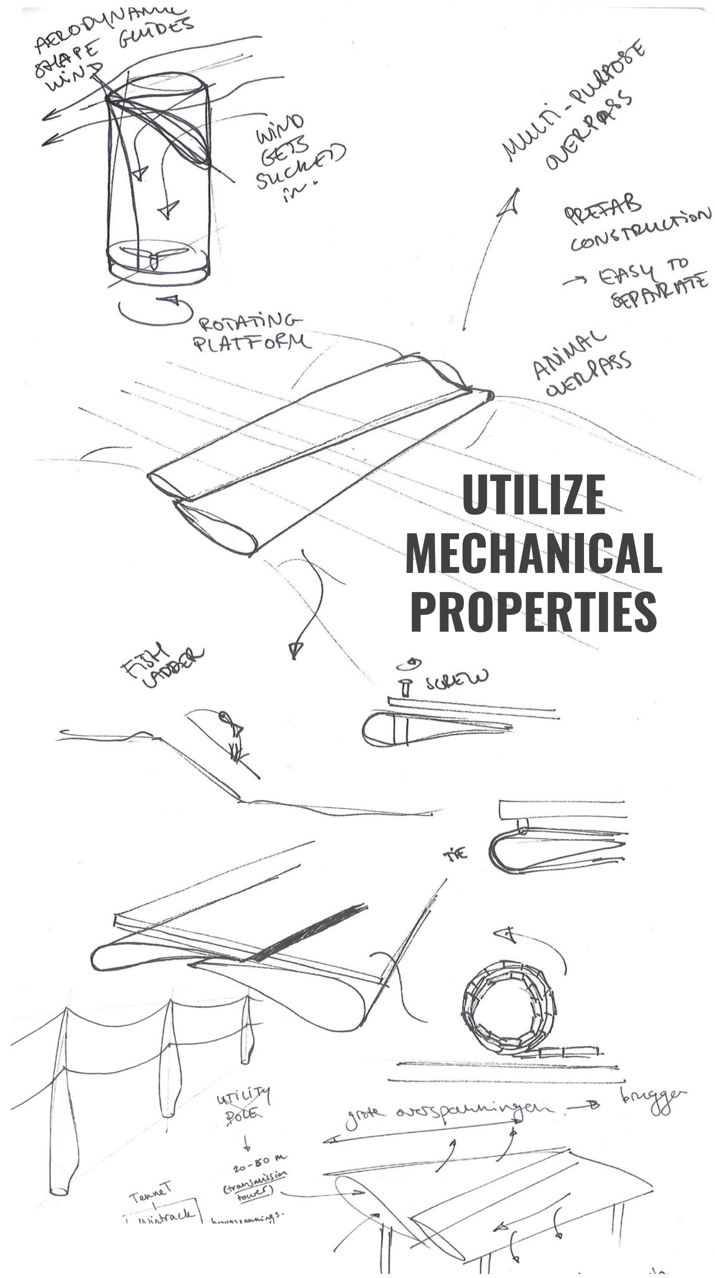
Figure 28: 3D prints used in ideation

CLUSTERS

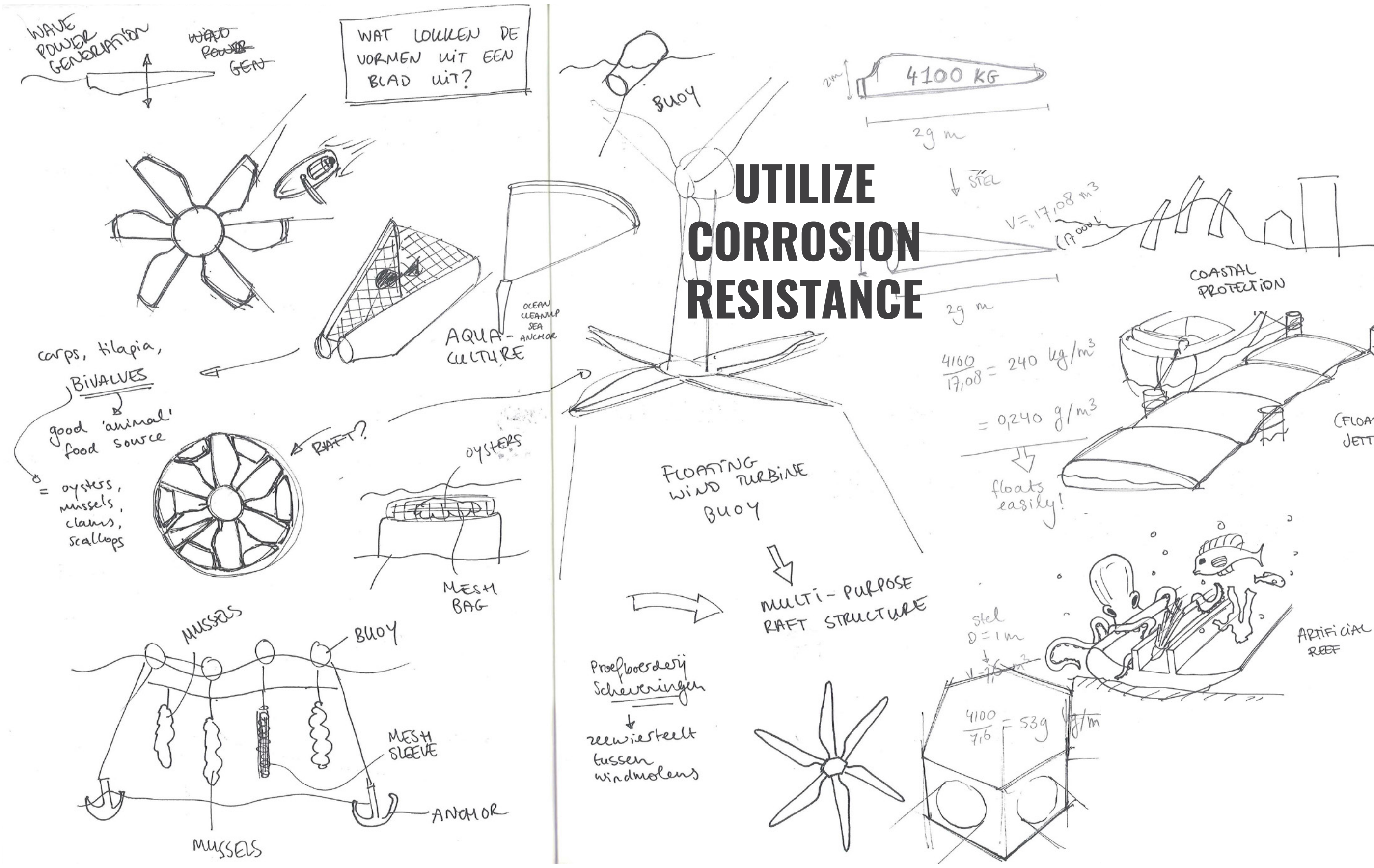
CLIMATE RESILIENT CITIES



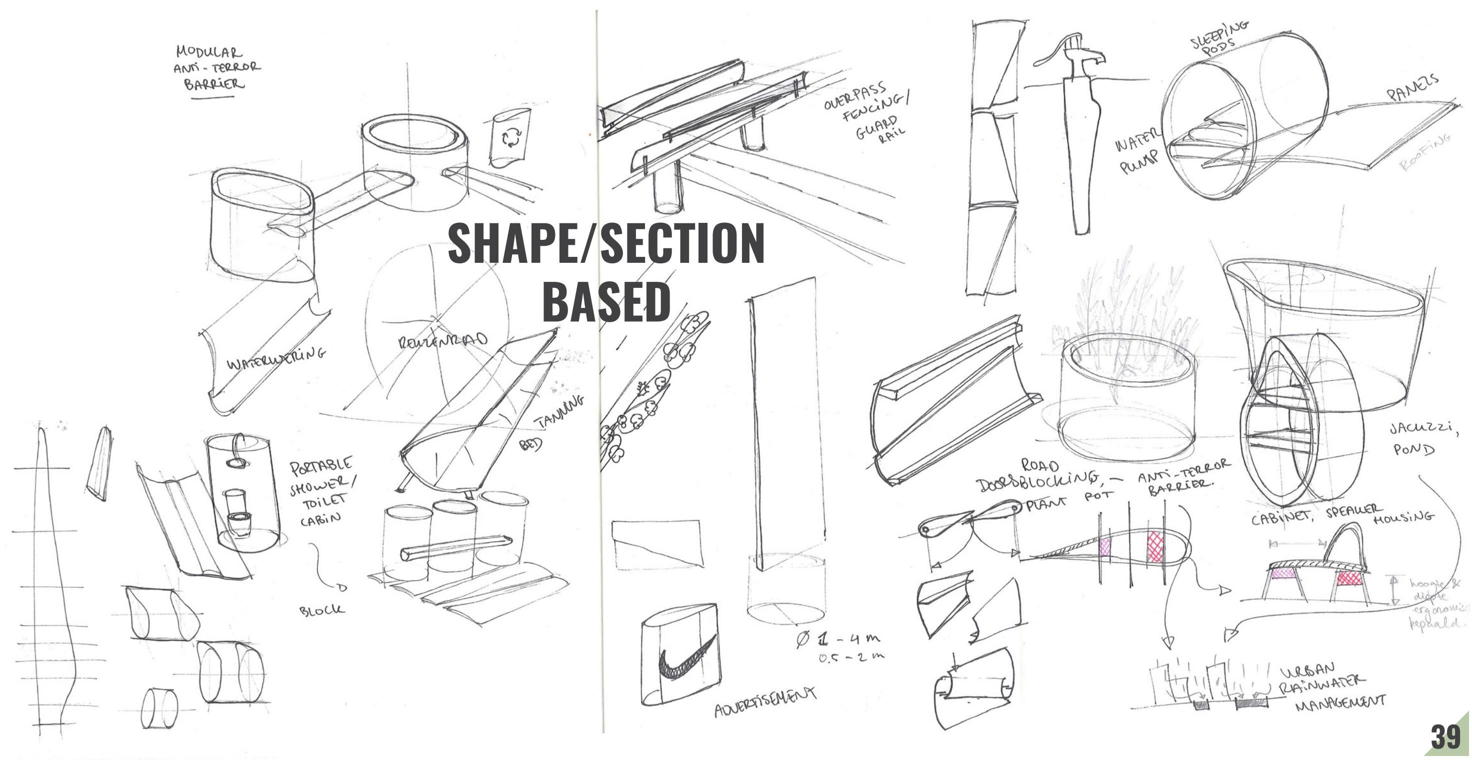
UTILIZE MECHANICAL PROPERTIES



UTILIZE CORROSION RESISTANCE



SHAPE/SECTION BASED



IDEAS

Many ideas were valid and so a rational comparison and selection had to be made. Because the goal of this project is to develop an economically scalable product, a large amount of ideas was based on sections of the product. When looking at the circular economy model by the Ellen Macarthur Foundation, a cascading trend can be identified in both the natural and technical cycle. Applying this theory to the wind turbine blade (Figure 29), we can see that the products become smaller at every step, ultimately being shredded for recycling. In the first step, the qualities of a wind turbine blade are utilized best by keeping the new product as large as possible.

Wind turbine blades are designed to withstand extreme shear loads over the entire length of the blade and resulting bending stresses. When using a section from a blade, this will be relatively heavy. Moreover, the material is difficult to machine and so processing costs can be quite high.

Something that should be taken into account is that the blades have exceptional mechanical properties, but that these are usually unknown. Using strips of the blades in load bearing structures is tricky because the material is not spread uniformly. The product can be used as a load bearing structure, but only when size reduction is not very important, so the structure can be over-dimensioned for safety purposes.

Based on these insights, the smaller product ideas were identified as interesting for future solutions, but in this project the focus will be on large solutions that use (almost) the entire blade.

From these ideas, a selection of the four most promising ideas was made. In order to find the most promising solutions, the criteria generated in the analysis were used (Figure 30). The ideas are presented on the following pages.

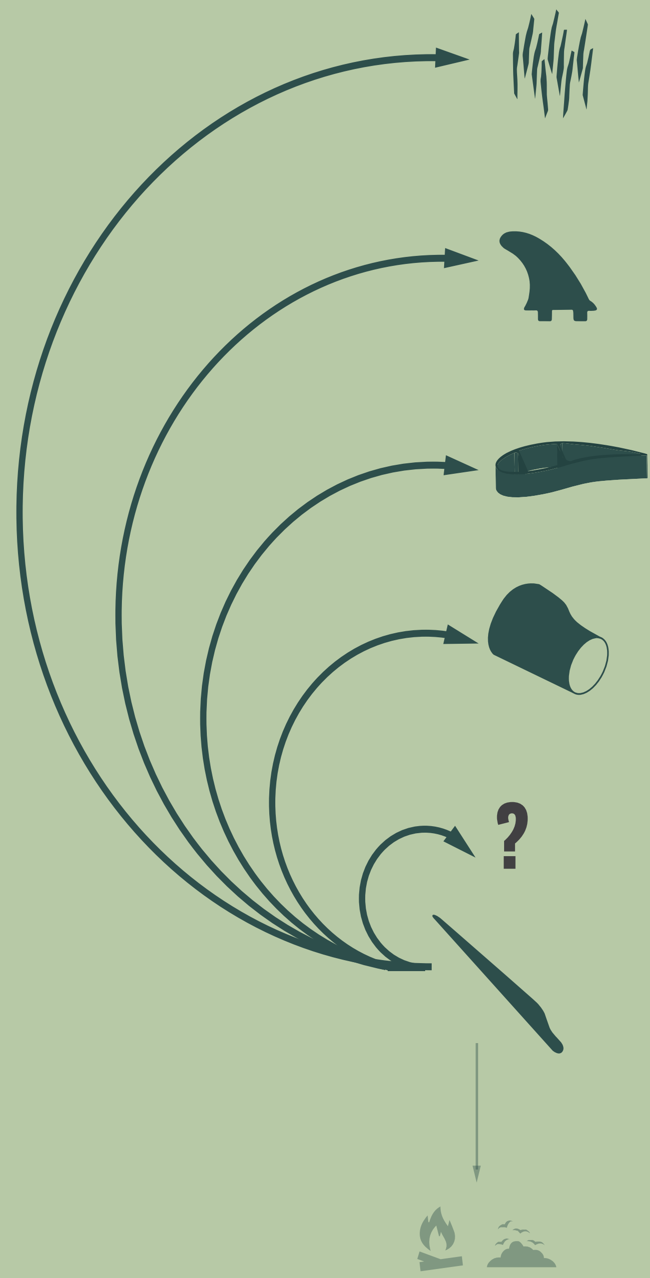


Figure 29: Circular Economy (Adapted from the CE model by the Ellen MacArthur Foundation)

SOLUTION SCOPE

As the previous chapters have shown, many EoL solutions are facing problems with the chemical composition of thermosetting polymers and utilising material values to create a product that is performance competitive and profitable.

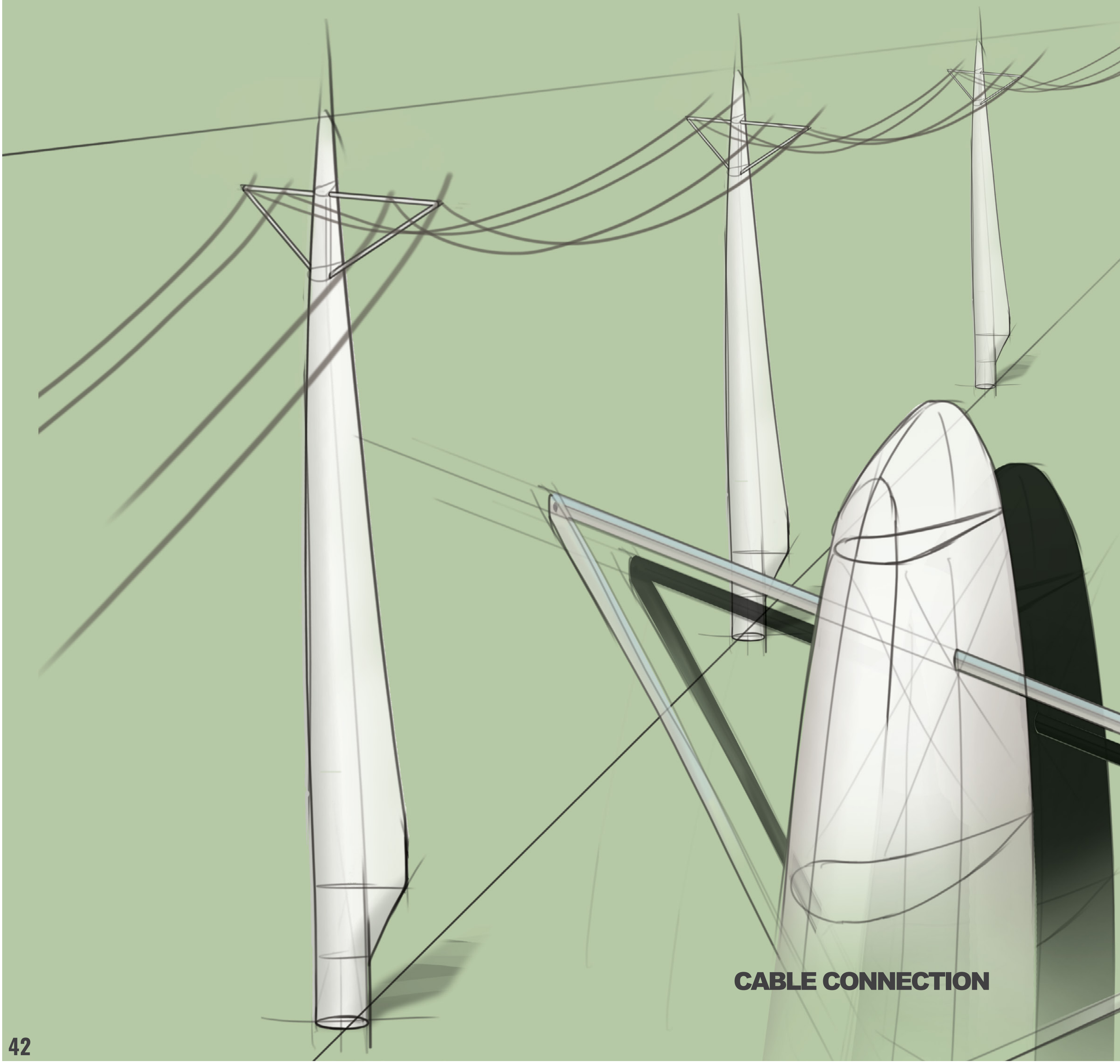
When reusing thermosetting composite materials, the material's value is best retained by using the entire structure or large parts of the structure. This requires other solutions than those of existing recycling methods (thermal, chemical and mechanical), By performing machining operations and minor modifications, new products can be designed. This method of reusing composite materials has been proposed by Asmatulu et al. (2014) under the name 'direct structural composite recycling'.

This method also allows for multiple life cycles of the same material, in a cascading system, thus becoming part of the circular economy.

The four presented ideas can all be considered 'direct structural composite recycling', with large product sizes, in order to keep the circular economy loop as small as possible.

Figure 30: Evaluation criteria

IDEAS



CABLE CONNECTION

1. TRANSMISSION TOWER

As renewable energy sources are increasingly used across the world, a location shift can be identified in where energy is sourced. This means that new power grids will be employed and so transmissions towers will be built.

This idea utilizes the root section of the blade, which can very easily be assembled to a foundation, creating a streamlined prefab tower. A cable connection system can be designed to attach to the top.

The result is a transmission tower that communicates the previous life of the blade to anyone who drives past it. At the same time, it offers a sleek design that offers similar aesthetic qualities as a Tennet Wintrack transmission tower (Figure 31).

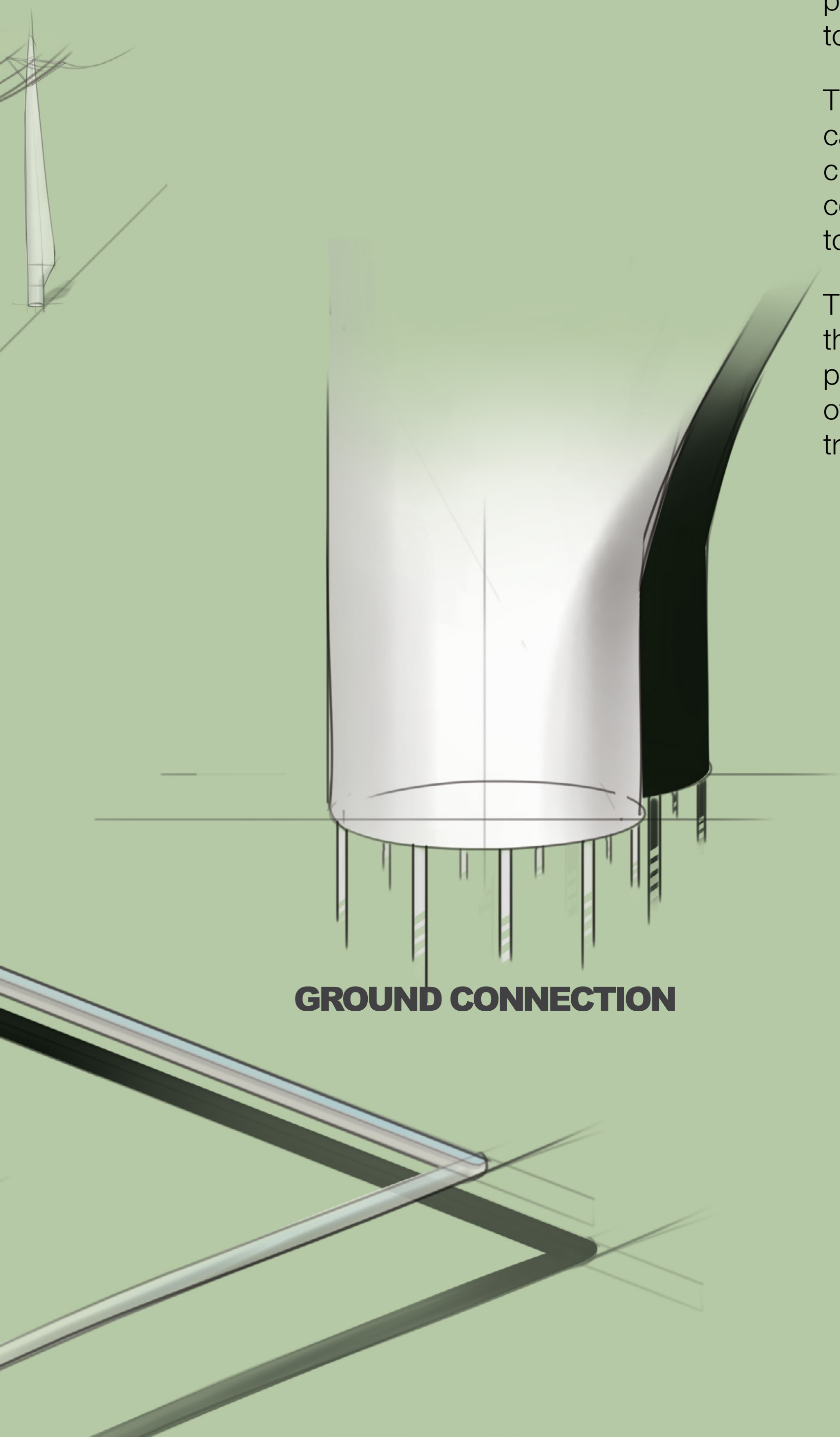
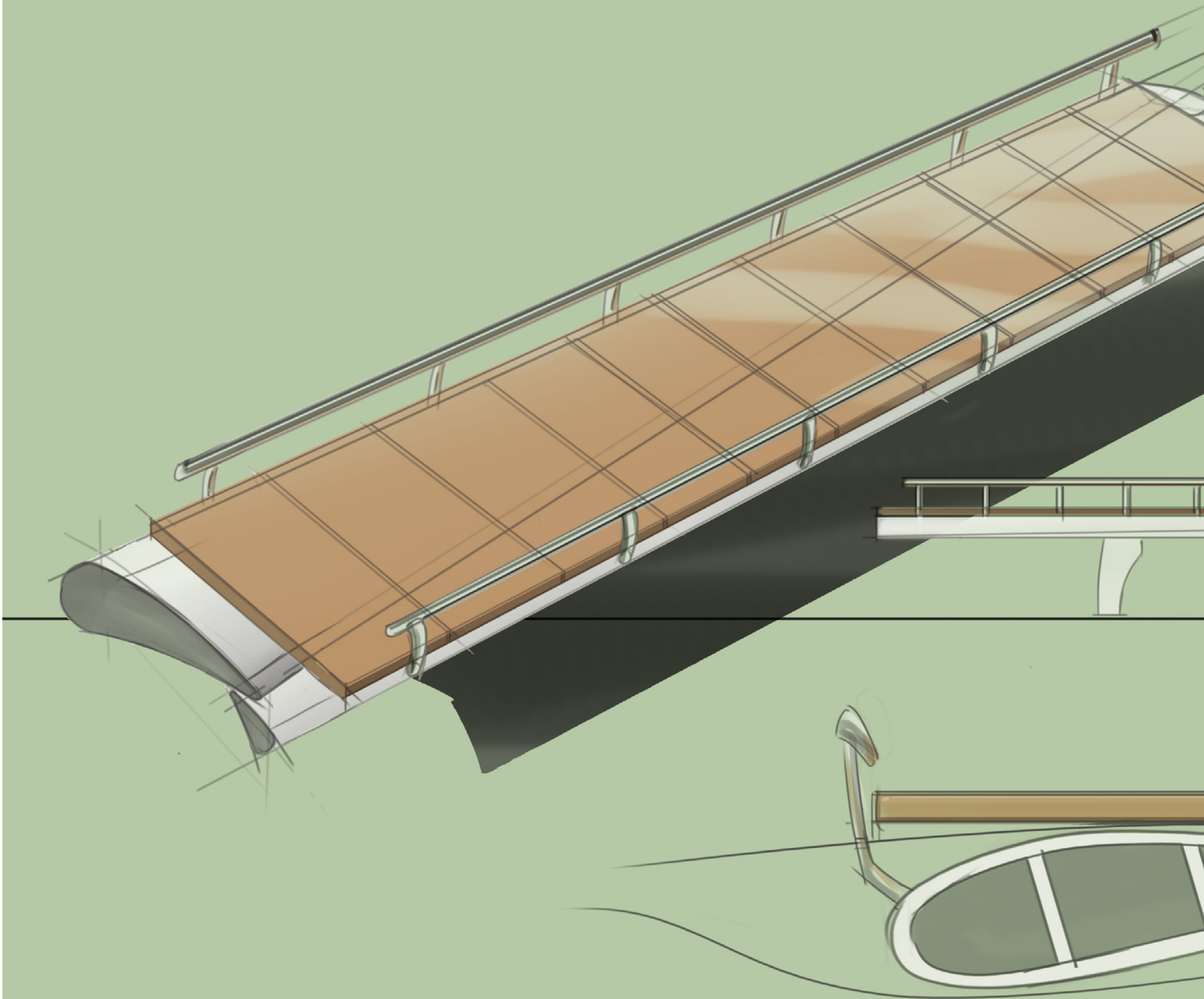


Figure 31: Wintrack transmission tower

IDEAS



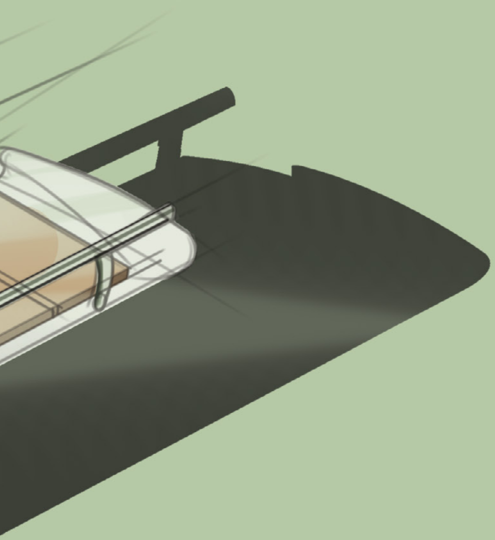
2. SLOW TRAFFIC BRIDGE

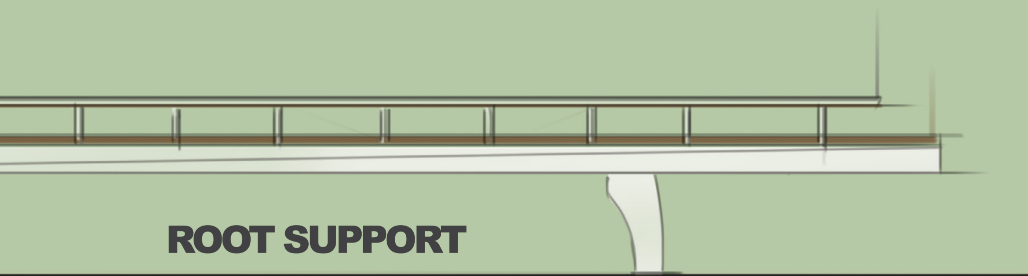
The most important performance quality of a wind turbine blade is its ability to withstand extreme shear loads over the entire length of the blade and the resulting bending stresses. Products that can use these qualities are span structures. In this case, pedestrian bridges.

The aerodynamic shape of the blade removes the threat of strong winds. Because the blade is supported on both sides of the span structure, deflections are minimised.

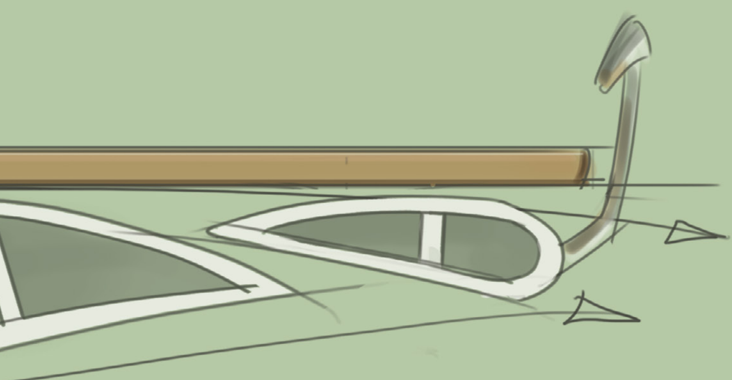
The blade roots can be used as support structures if needed. The only other materials that would need to be added are assembly parts, decking and handrails.

The product is visible to anyone passing under or over the bridge and user interaction exists in the form of people passing the bridge.



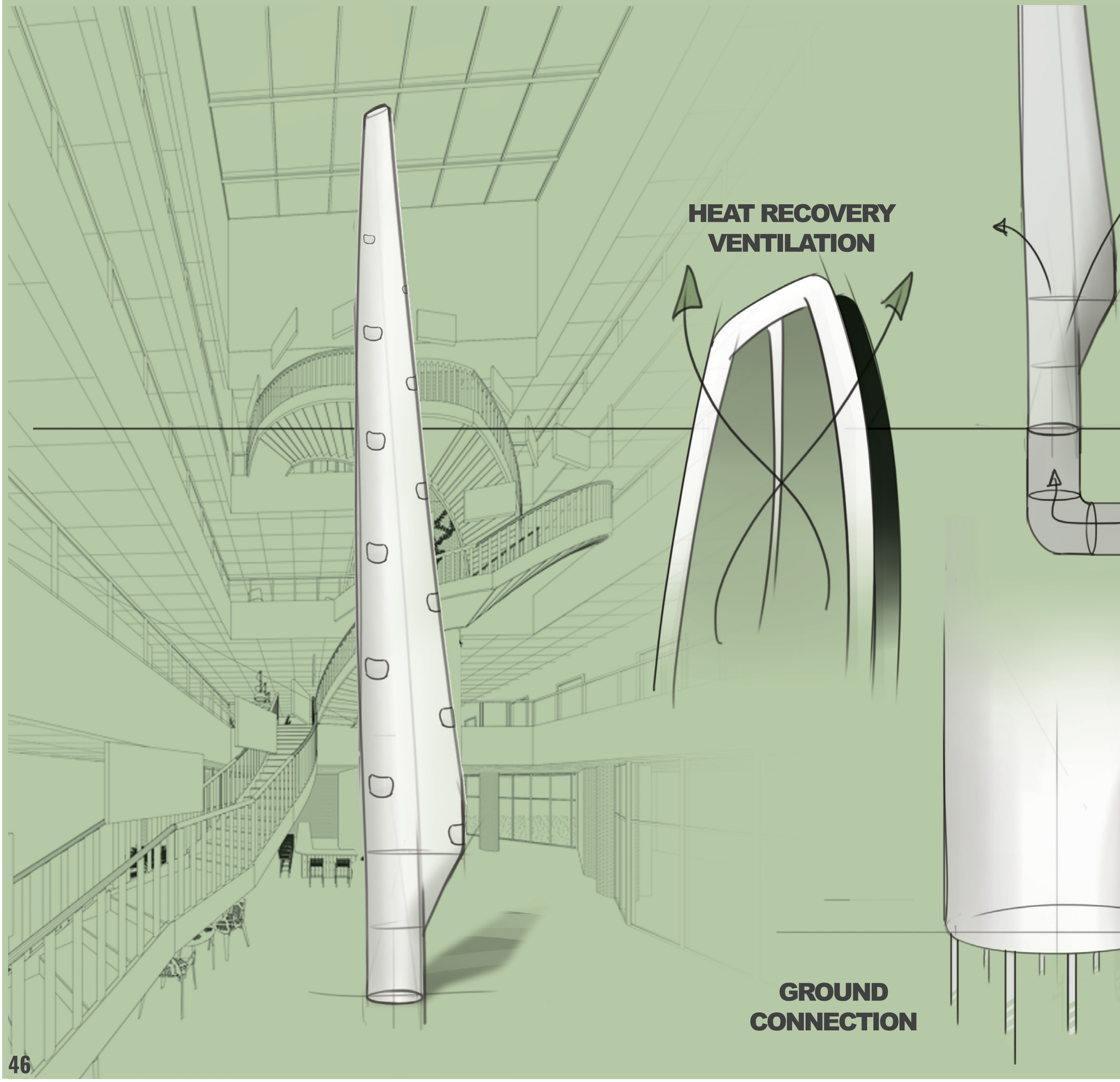


ROOT SUPPORT



AERODYNAMICS

IDEAS



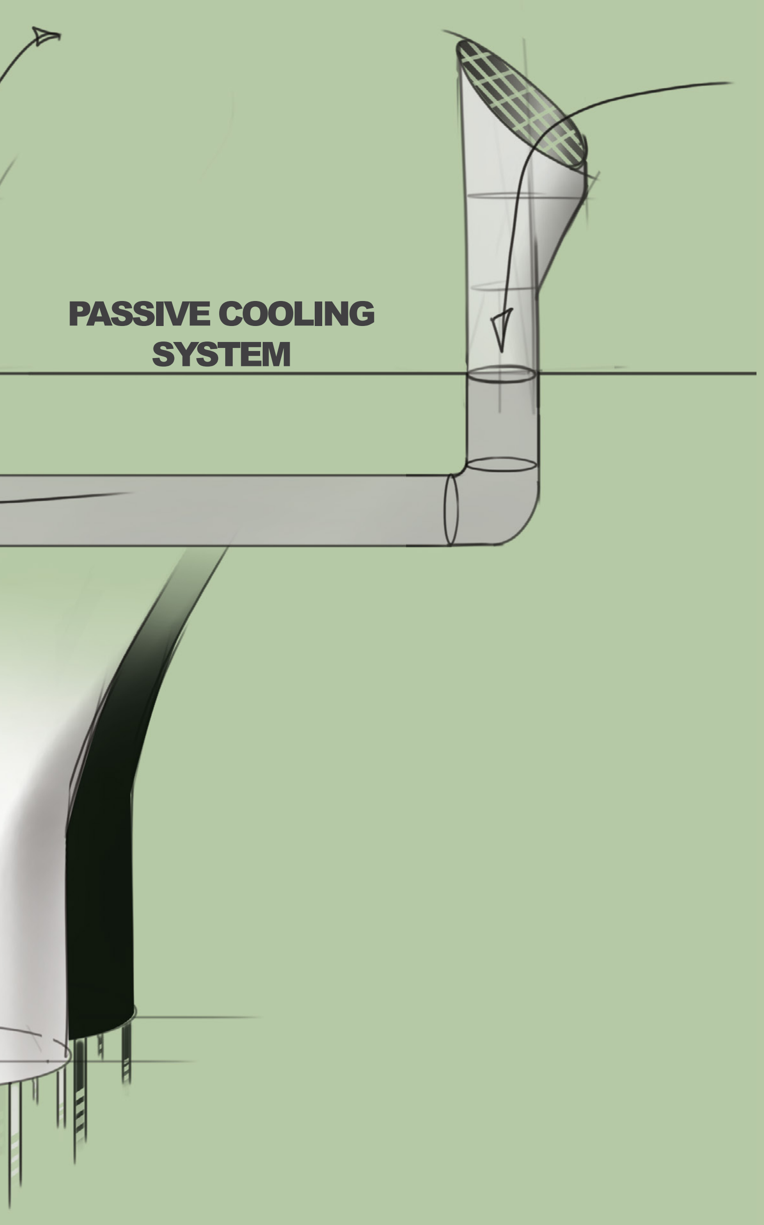
3. VENTILATION SYSTEM

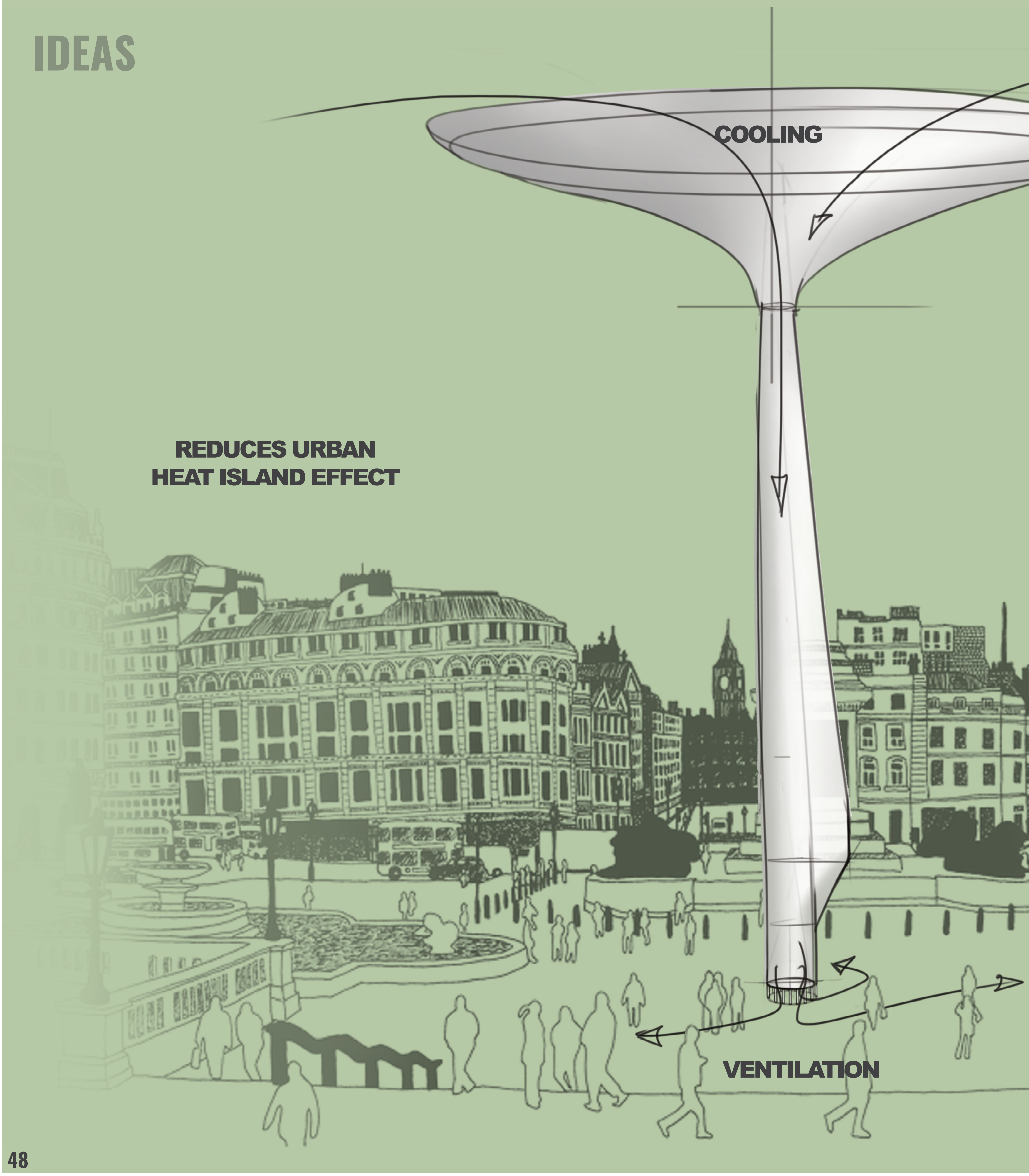
As the middle class of China and India earn more money, a huge increase in energy consumption from air-conditioning is expected in the coming decades. According to the BBC (2017), this problem is so big that they consider it to be one of the biggest energy challenges facing humanity.

Fortunately, much more effective cooling systems exist that can greatly reduce this energy consumption. The hollow shape of the wind turbine blade is very well suited to act as a ventilation shaft in such a system. It can easily be combined with heat recovery systems, passive cooling systems using earth tubes and geothermal heating/cooling systems.

The result is an eye catcher that can be applied in large atriums and easily communicates the past life of the blade. The wind from which it used to power a turbine now flows through the system to reduce energy consumption.

When used in combination with a passive cooling system, a root can be used as a wind catcher, showing also the outside world this innovative system with reused materials.




COOLING
REDUCES URBAN
HEAT ISLAND EFFECT
VENTILATION

4. URBAN MICRO-CLIMATE

Continuing on the idea of an indoor ventilation system, ventilation shafts can also be used in an urban environment. Here, the size and weight of the blade result in fewer construction problems and significant problems exist too. If rain is captured, a cooling system can be designed that draws air through the cold water and brings it to ground level. Such systems have been applied in the past with success, for example in the canopy trees in Singapore's Clarke Quay neighbourhood (Figure 32).

A similar ground connection is used as in the transmission tower and ventilation system, but using longer bolts, the blade is raised above the ground. Ventilation tha tis drawn down can move onto a square freely.

This idea takes the eye catcher qualiities of the ventilation shaft and places it in an urban environment for everyone to see.

Figure 32: Canopy trees in Clarke Quay

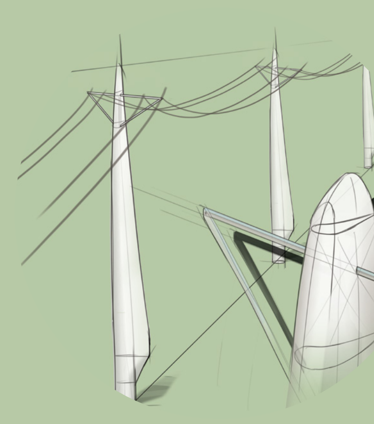
SELECTION

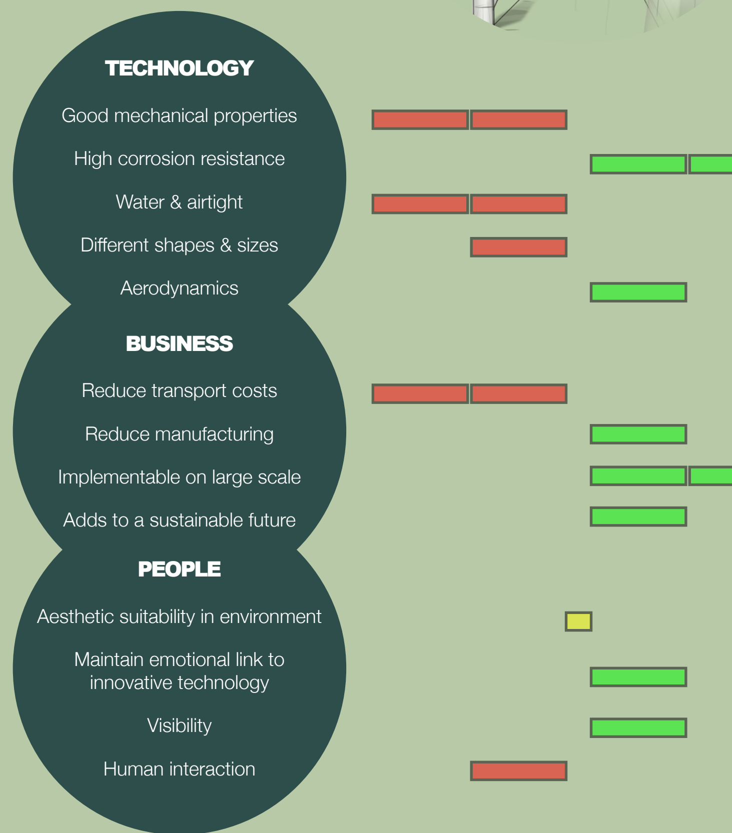
Again, the evaluation criteria generated in the analysis phase were used to make a choice between the ideas. Based on all pillars of a good design, technology, business and people, the best solution to the project problem was found.

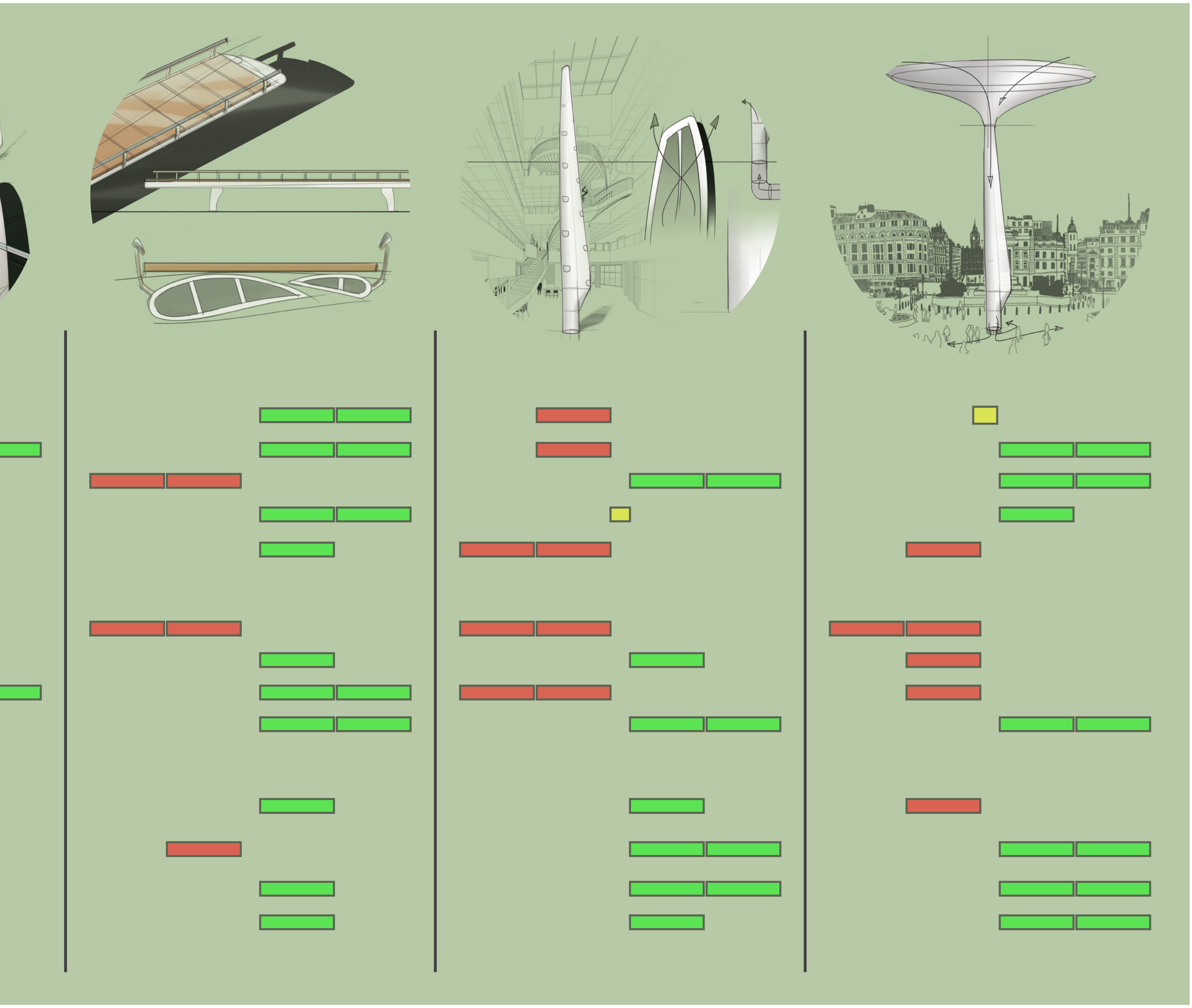
Idea 1 offers an interesting emotional link to the energy system. The most important problem with this idea is the unpredictable swaying of the blade tip. Some manufacturers say that their blade tips may deflect a few meters in strong winds. Although the blade can withstand these forces, it can be very dangerous when the cables sway this much.

Ideas 3 and 4 offer excellent qualities on human interaction grounds. A problem with these systems is the difficulty of on-site assembly. In an architectural design, these problems may be disregarded. However, once one architect has applied this 'gimmick', the emotional benefits are greatly reduced and applying the product in multiple markets becomes a problem.

Although idea 2 does not communicate the emotional values of a blade as much as the others, its gains on technology and business level make it a product that can be economically valid. The deflection problem is solved by mounting the structure on both ends. In the end, the trade off between technology, business and people have resulted in the choice for idea 2: a slow traffic bridge. The bridge will from here on out be referred to as the Bridge of Blades.







4.

CONCEPT DEVELOPMENT

Based on the chosen idea of the slow traffic bridge, the Bridge of Blades is developed. Information is shown regarding bridge design, to be able to identify the product's potential in the market and the requirements that must be met.

All findings are then combined into a concept design. The concept was developed with a focus on aesthetics, user interaction, structural performance and the end-of-life. All components and connections were developed into detail with people, technology and business in mind, to create a realistic design.

MARKET

As of now, the Bridge of Blades concept has only been compared to other ideas/concepts and current EoL practices.

To understand whether reusing the blades in bridges works well in practice, two things must be established:

- The slow traffic bridge market is large enough to enable a significant stream of EoL wind turbine blades to be reused.

- A slow traffic bridge that uses EoL blades offers important advantages over other bridges and is therefore (in some situations) preferred.

Note: Bridges come in many different shapes and sizes. Ideally, the concept would be able to fit all types of bridges, including bridges designed for heavy traffic. However, the deflection and fatigue loads would be too great for the EoL blades. For slow traffic bridges, fatigue loads are much less critical which is why no NEN/EUR norms exist regarding fatigue loads for slow traffic bridges. The wind turbine blades can perfectly perform their load carrying function in such bridges.

SIZE

It is very difficult to get an idea of the market size for slow traffic bridges. According to Simon de Jong (2018), CEO/founder of InfraCore Company, his company once tried to get a grasp of the market in the Netherlands, when a PhD researcher did a four-year research on the topic. From this, only a very rough estimate resulted.

According to Simon de Jong (2018), approximately 2000 slow traffic bridges are (re)placed annually in the Netherlands. This is quite a promising number, if you consider that at the moment of writing, 2322 wind turbines are in operation in the Netherlands (WindStats, 2018). Assuming that nearly all turbines have three blades, approximately 7000 blades are in operation, and will reach their end-of-life in the next 20 years. If during those 20 years, 8,75% of all slow traffic bridges are constructed of wind turbine blades (unlikely), all blades would be used in bridge construction (Figure 33).

How is this market opportunity distributed over the coming years? To find an answer to this question, data about the installation of wind turbines in the Netherlands from year to year was analysed (CBS, 2017).

AMOUNT OF OPERATIONAL BLADES

$$\frac{7000}{2000 \cdot 20 \cdot 2} \cdot 100\,\% = 8.75\,\%$$

BRIDGES/ YEAR — **YEARS** — **BLADES PER BRIDGE**

SHARE OF SLOW TRAFFIC BRIDGES IN THE NETHERLANDS THAT SHOULD BE MADE WITH BLADE S TO REUSE ALL DUTCH WIND TURBINE BLADES

Figure 33: Market calculation

Between 1997 and 2016, the amount of annually installed blades ranged between 28 (2010) and 200 (2003), as can be seen in Table 1. These numbers were translated to the amount of blades that are expected to be decommissioned between 2017 -2036 (Figure 34). Although fluctuating, no clear upward trend is shown, which may come as a surprise. The reason for this could be that as technology develops, the power of the individual wind turbines is increased rather than the amount of wind turbines.

Comparing these to the amount of bridges that are (re)placed annually in the Netherlands, the results are similar to what was presented before.

Looking at the numbers year by year, we see that the pairs of bridges that can be expected to be decommissioned range between 42 (2030) and 300 (2023). If used in bridges within the year, in those years, 2% and 15% of bridges would need to be made of blades respectively.

A more elaborate overview of these data can be found in appendix A.

Since we have relatively many bridges, de Jong expects countries such as Germany and France to only have twice as many bridges, even though the countries are much larger. For other countries, such as China, no data was found.

Note: The data presented are meant as an indication of the market opportunity for reusing wind turbine blades in bridges. It is not an accurate representation.

Year	Turbines installed
1997	89
1998	62
1999	70
2000	47
2001	60
2002	153
2003	200
2004	168
2005	125
2006	121
2007	123
2008	131
2009	52
2010	28
2011	47
2012	65
2013	111
2014	62
2015	148
2016	98

Table 1: Installed wind turbines in the Netherlands 1997-2016 (CBS StatLine, 2017)

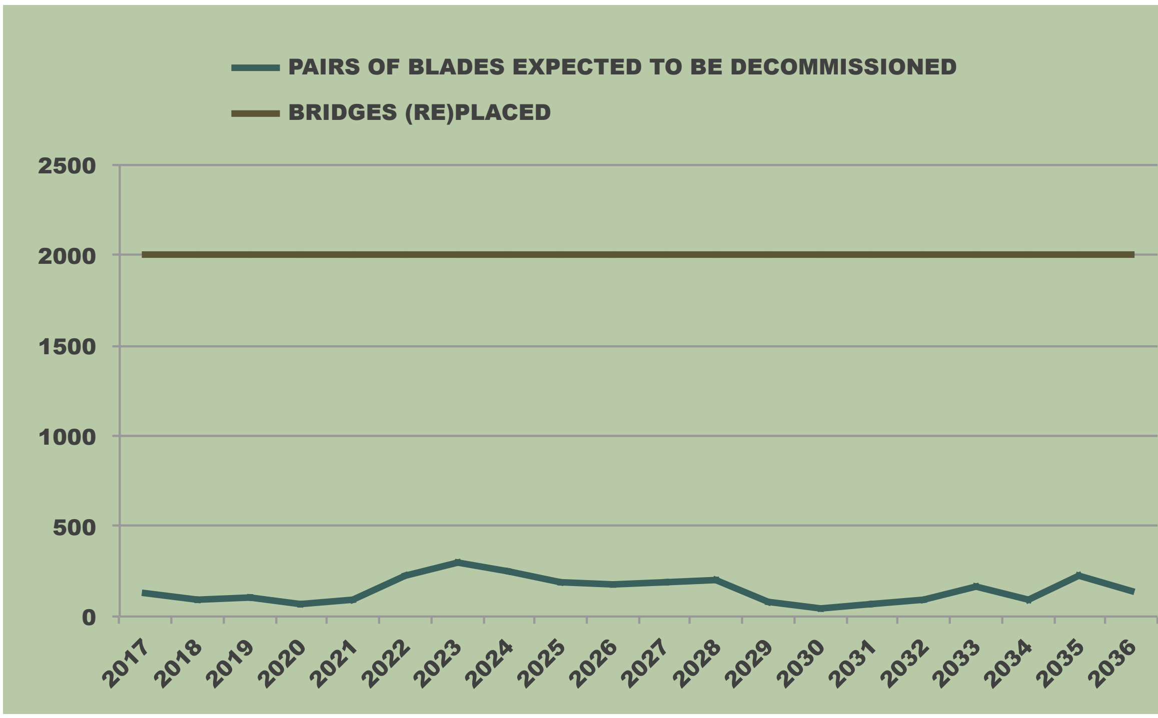


Figure 34: Market calculation (own interpretation from CBS, 2017)

MARKET

WHO

Most often, bridges are purchased by the municipality of a city/town. They are often part of a bigger plan and many different parties can be involved. Important issues to the municipality are cost, safety and suitability in the environment. Lately, environmental considerations have become more apparent in politics which can have a positive influence on this project.

WHERE

At the moment, the product is designed for the Dutch market, because of the interest in wind energy and EoL strategies that has been found in the Netherlands during this project. High-quality products can be made and all components can be designed and produced locally.

In the future, this product can offer opportunities for developing countries, where the wind turbine market is expected to grow and the reduced cost of the bridges can be even more important than in the Netherlands.

SUSTAINABLE COMPETITIVE ADVANTAGE

The market opportunity presented in the previous chapter is promising. However, in order for the Bridge of Blades to utilize this opportunity, it is important that it has a clear sustainable competitive advantage.

The bridge is more than just a solution to the blade waste problem. After some research, it was found that the Bridge of Blades offers two clear advantages, compared to similar slow traffic bridges (Figure 35).

OTHER IMPORTANT QUALITIES

LIGHTWEIGHT | LOW MAINTENANCE

Due to the nature of the blades, these two qualities are also inherited in the blade construction. These qualities are valuable but not unique to this construction. For example, FRP bridges and Ultra-High Performance Concrete (UHPC) bridges offer these qualities too, probably even more so. However, these qualities are important to consider throughout the rest of the project and will be discussed in the deck and parapet design.

CABLES

Bridges are often used to transport electricity and utility cables across water bodies. Because of the hollow structure of the blades, they are naturally very well suited for this purpose.

LOWER ENVIRONMENTAL IMPACT

Material reuse of the blades as construction elements. All other components are also designed according to this principle, as will be explained in this chapter.

COST REDUCTION

On average, material costs for bridges are 5-20 €/kg and the production costs can be as much as 50% of the entire project costs (Pavlovic, 2018). By reusing the blades, which would otherwise cost €100/tonne to dispose of, these material costs are reduced.

Figure 35: Sustainable competitive advantage

REQUIREMENTS

USE

1. The bridge should be accessible to slow traffic: pedestrians, wheelchairs, bicycles and mopeds.

2. The bridge should allow slow traffic to cross a body of water, valley, road, railway or other obstacle safely and comfortably.

3. Depending on the context, a two-way bicycle/moped path with a width of at least 2,5 meters (Fietsersbond, 2004) should be present.

4. Depending on the context, a path with a width of at least 0,9 meters, preferably 1,2 meters, (Bouw Advies Toegankelijkheid, 2017) should be present to accommodate pedestrians and wheelchairs.

5. Any present slope should comply with NEN 1814 and is preferably no steeper than 1:25 (Bouw Advies Toegankelijkheid, 2017).

DESIGN

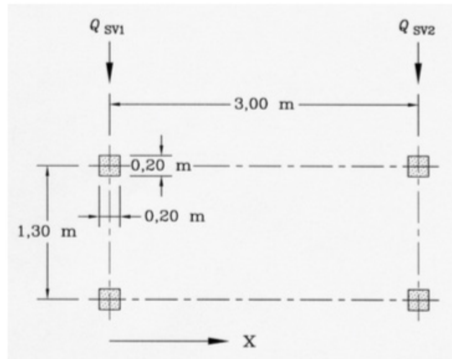
6. A design should be made, that allows wind turbine blades with different shapes, materials and dimensions to act as a load bearing structure in the bridge.

7. The bridge should be applicable across different countries, environments and span widths.

8. The wind turbine blades should be visible when approaching, crossing or passing under the bridge

PERFORMANCE & SAFETY

9. No structural failure should occur under any of the following extreme loads acting on the bridge deck (NEN-EN 1991-2, 2003):
- A distributed vertical pressure (q_{fk}) of 5 kN/m^2
- A service vehicle (Q_{serv}) with a load distribution as such:



Key
x : Bridge axis direction
Q_{sv1} = 80 kN
Q_{sv2} = 40 kN

- A horizontal force (Q_{flk}) that is equal to the greater of the following two values:
    - 10% of the total load q_{fk}
    - 60% of the total load Q_{serv}
- A combined load that is equal to the greater of the following two values:
    - $q_{fk} + Q_{flk}$
    - $Q_{serv} + Q_{flk}$

10. The maximum deflection of the bridge should be no more than 1/200 of the span length due to pedestrian loading (q_{fk}) (Neaco, 2016)

11. The fundamental frequency without loading should be more than 3.0 Hz (WSDOT, 2009).

12. In the lateral direction, the fundamental frequency of the pedestrian bridge shall be greater than 1.3 Hz.

13. Parapets should be placed on the structure with a minimum height of 1450mm, measured from the adjoining pedestrian walking surface (DN-STR-03011, 2016).

14. If the bridge crosses a railway, parapets with a minimum height of 1850mm should be placed (DN-STR-03011, 2016).

15. No structural failure should occur when a line force of 1kN/m acts either vertically or horizontally on the parapet (EN 1317-6).

16. The service time of the bridge should be at least 50 years.

MANUFACTURING AND INSTALLATION

17. At least 80% of the material volume of two wind turbine blades should be functionally applied in the bridge.

18. The bridge should be manufacturable off-site, so it can be transported and installed as a pre-fabricated bridge.

19. No joints may cause water leaking into the blades.

ENVIRONMENTAL IMPACT

20. The environmental impact should be significantly lower compared to conventional bridge alternatives in a Life Cycle Assessment.

21. All other materials than the blades should either have had a previous use in a different product or be reusable according to Circular Economy standards.

22. Any other material than the blades should be easy to separate with simple tools or machines.

FORM

A consideration must be made with regard to the aesthetics of the structure between the following two influences.

The mission for this project was to achieve *'commercially viable processing of used wind turbine blade materials into new products, while retaining their high-end characteristics.'* In order to facilitate commercially viable processing, the design must be implementable in many different environments. An aesthetically pleasing design is desired that is easily recognizable as a bridge and performs its function efficiently.

At the same time, one of the goals for this project was '*to develop a product that communicates the qualities of this material, making it obvious that it has had a previous life as a wind turbine blade.'* This is far from typical for a bridge, but an important part of the project.

Through a combination of analysis, sketching, design drawing and modelmaking, the final form was created. The models can be seen on the next pages and some interim designs can be found in appendix D.

In order to utilize the quality of the blades, their load carrying function was analysed and applied logically. The spar and shear webs are designed to carry most loads and should therefore also have this function in the bridge design. This load-carrying structure can be considered a box profile and runs from the root to the tip of the blade. In some smaller blades, only one shear web exists and the load carrying structure resembles an I-profile.

The blades are placed with 180° rotation, to make the bridge more symmetrical and distribute the loads more evenly across the bridge span.

The loads should be translated from the deck to these profiles directly and with as little extra material as possible, and so two orientation possibilities arise naturally. Unlike the root, the tip of the blade is not designed to withstand huge moment loads. It is much thinner and therefore less strong and stiff. In order to reduce deflection, the tip of the blade is removed.

By removing the tip of the blade, a hollow structure with openings on both ends is created. This makes it easier to guide electricity and phone cables across a span.

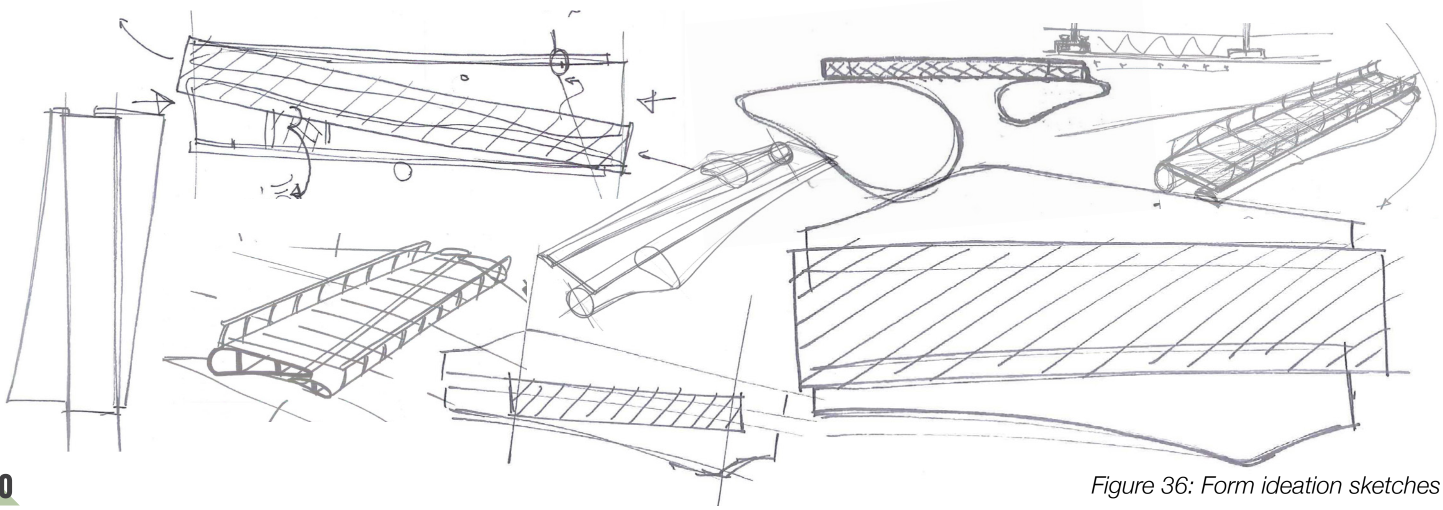


Figure 36: Form ideation sketches

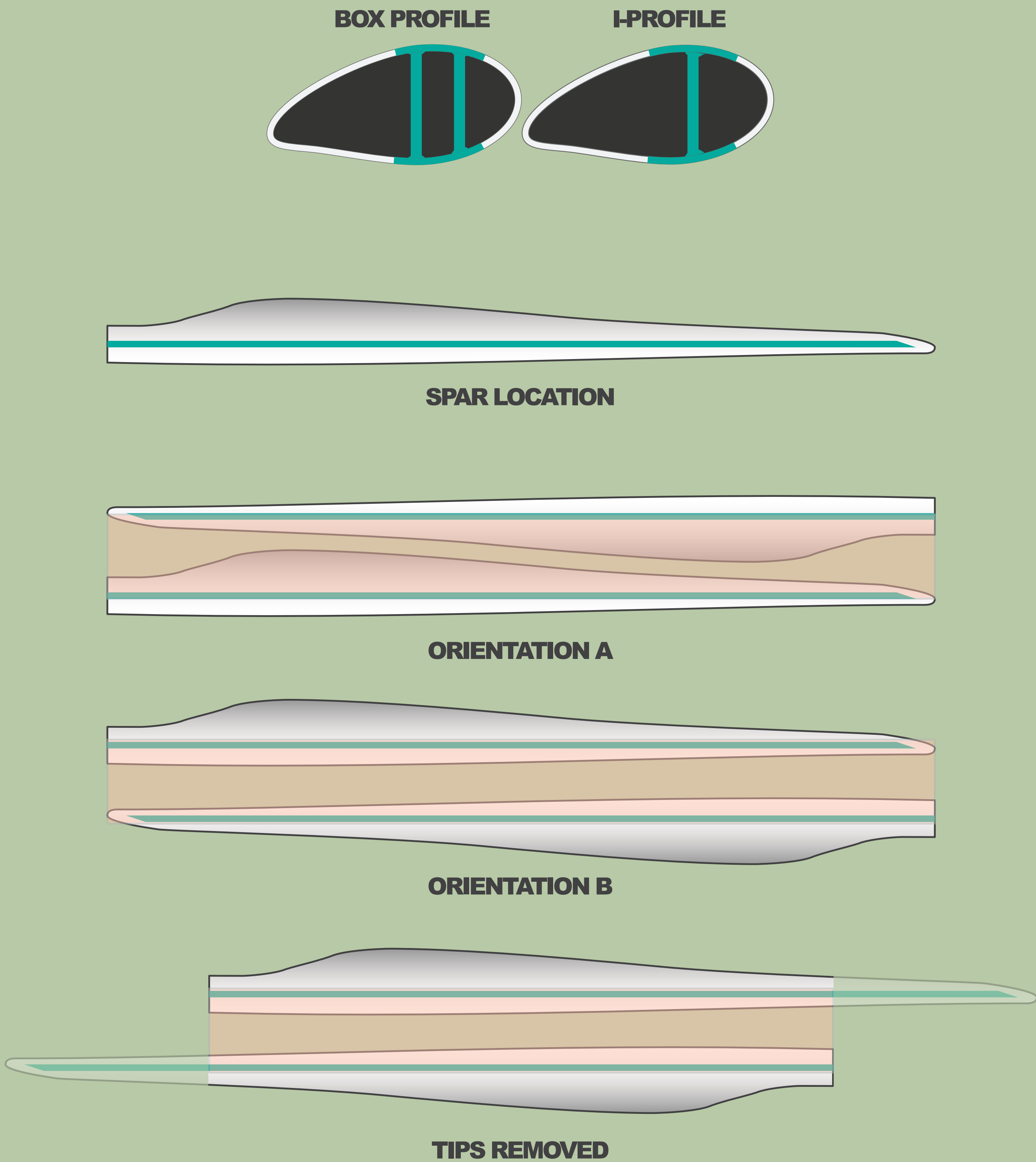
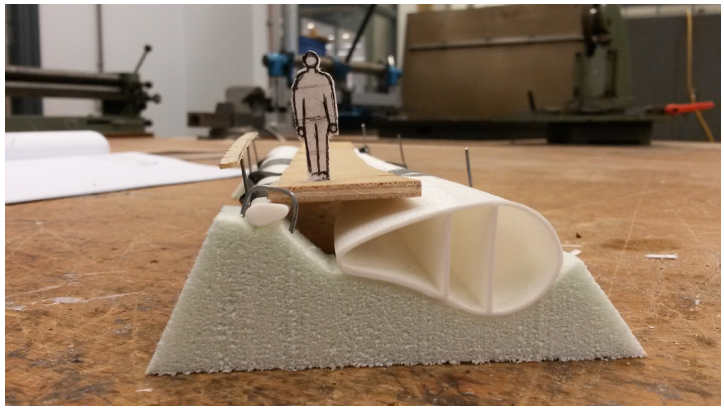
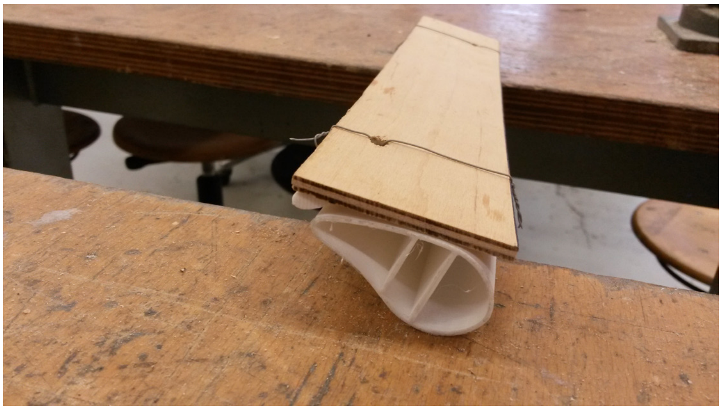
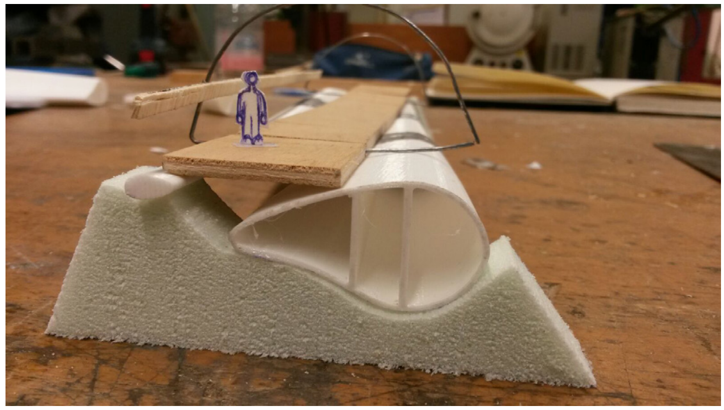


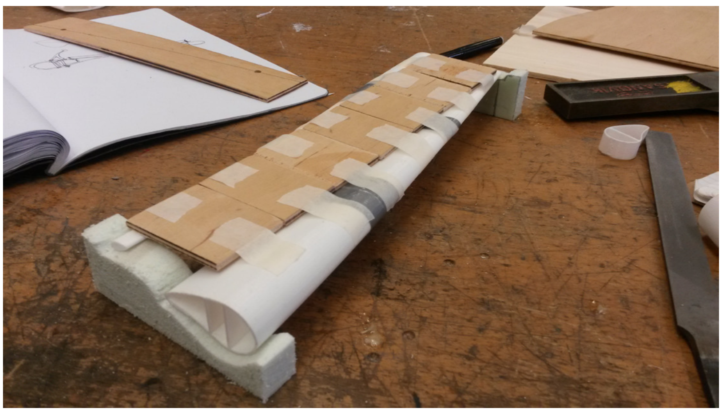
Figure 37: Form development

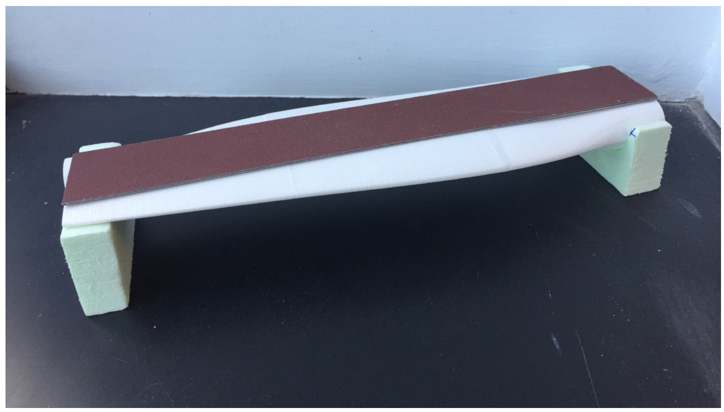
FORM

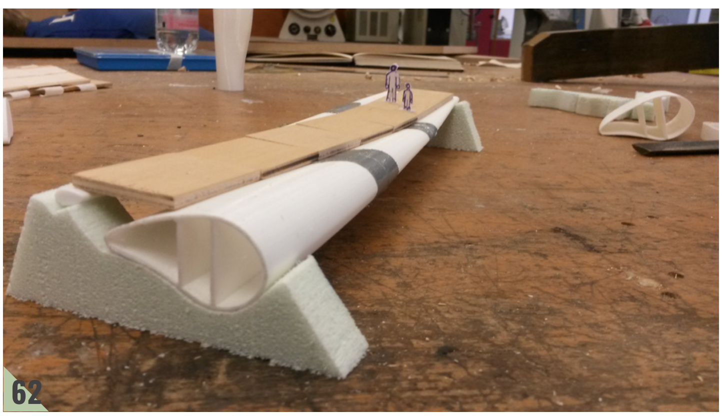


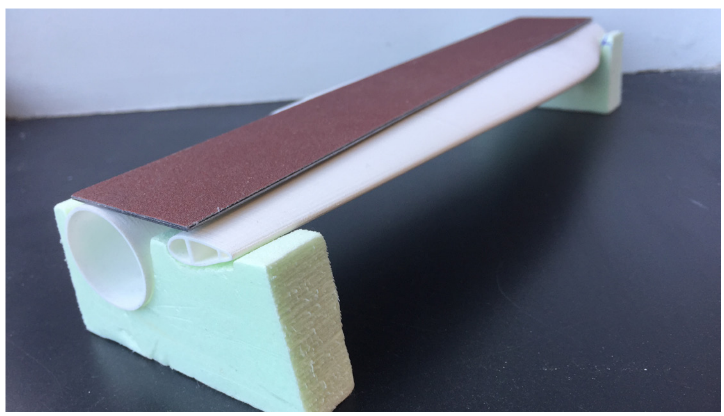


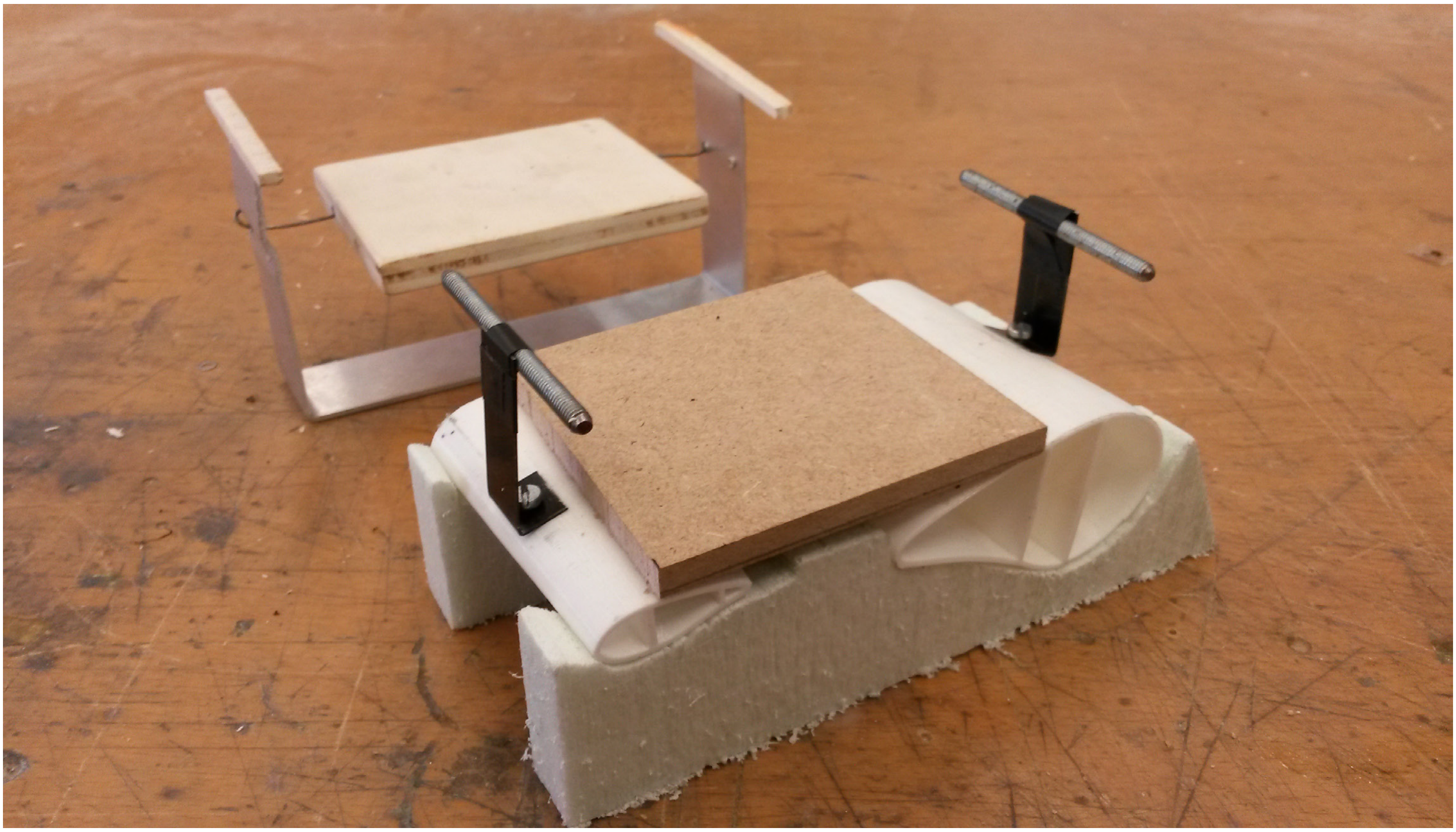


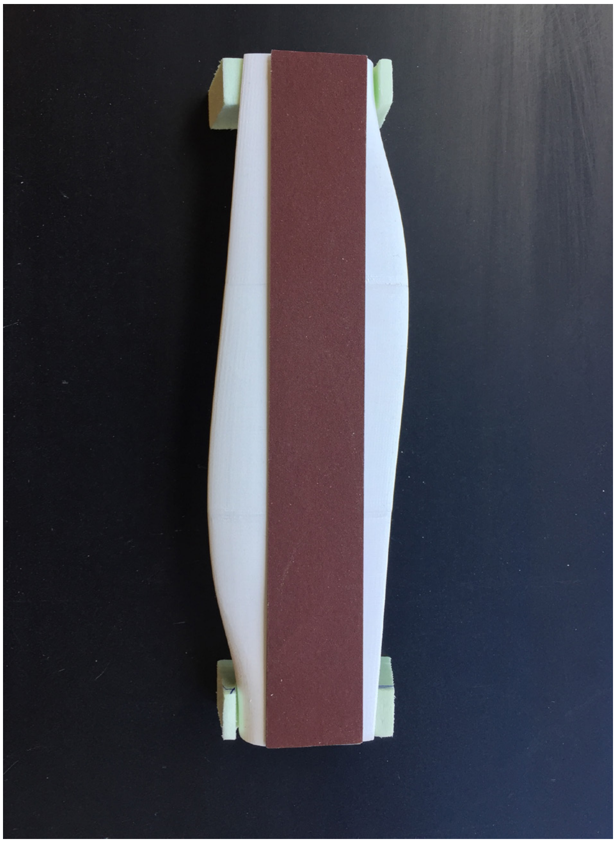


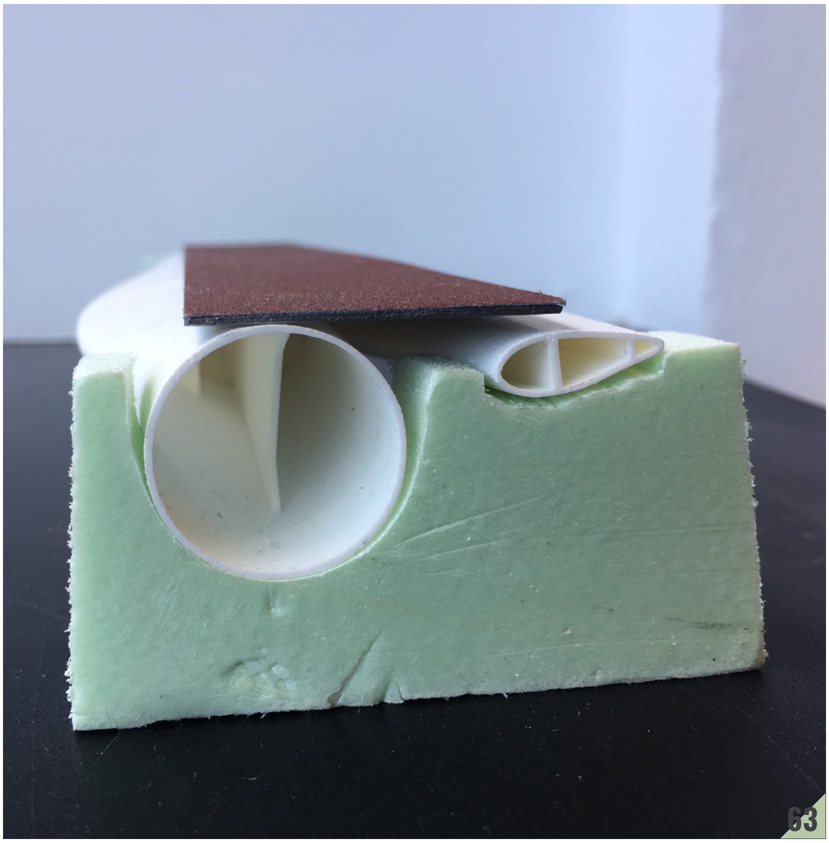












FORM

BLADE INTERACTION

In the current design, the previous life of the blades is communicated explicitly. When approaching the bridge or passing under or over it, the distinctive blade curves catch the eye.

Unfortunately, the blade surface itself is not fit for pedestrians (Pavlovic, 2018; Peeters, 2018). Pedestrian bridges are always subject to surface wearing. In this particular case, it is also important to prevent de-lamination, which may occur due to peak loads caused by heels. Moreover, the original surface of a wind turbine blade is too slippery to walk on. Combined with the sloped/curved surface this may be dangerous.

In order to solve these problems, a non-slippery, load distributing, wearing layer would need to be applied. As a result, the blade surface would become invisible, the actual interaction with the blade would be greatly reduced and a monstrous hybrid of materials would be created, causing environmental problems at the end-of-life of the bridge.

Therefore, the choice has been made to keep the emotional reference with the blade a visual one. The parapets are joined to the deck, creating a physical barrier between the pedestrians and the blades. Parapets are chosen with few materials, that constrain the pedestrian's vision as little as possible.

SIZE

According to de Jong (2018) and Pavlovic (2018), slow traffic bridges are generally approximately 10-30 meters long. For this project scope, the blade size was determined at 10-60 meters. Considering the fact that not the entire blade is used, blades between 12 and 40 meters can be used in the bridge design. This can solve a significant part of the waste problem.

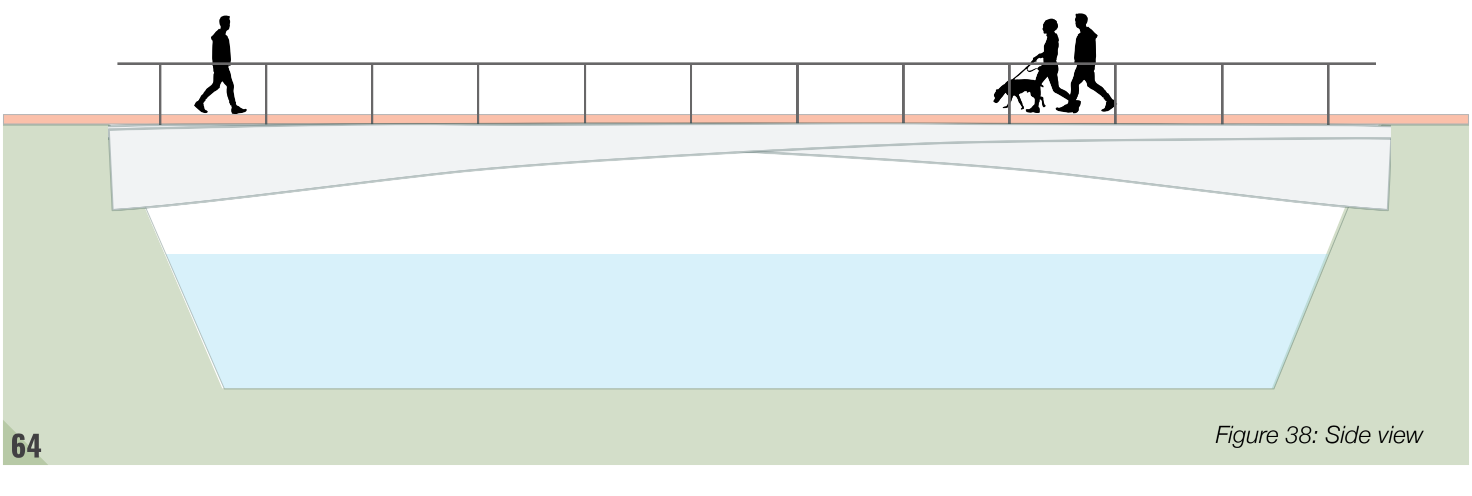


Figure 38: Side view

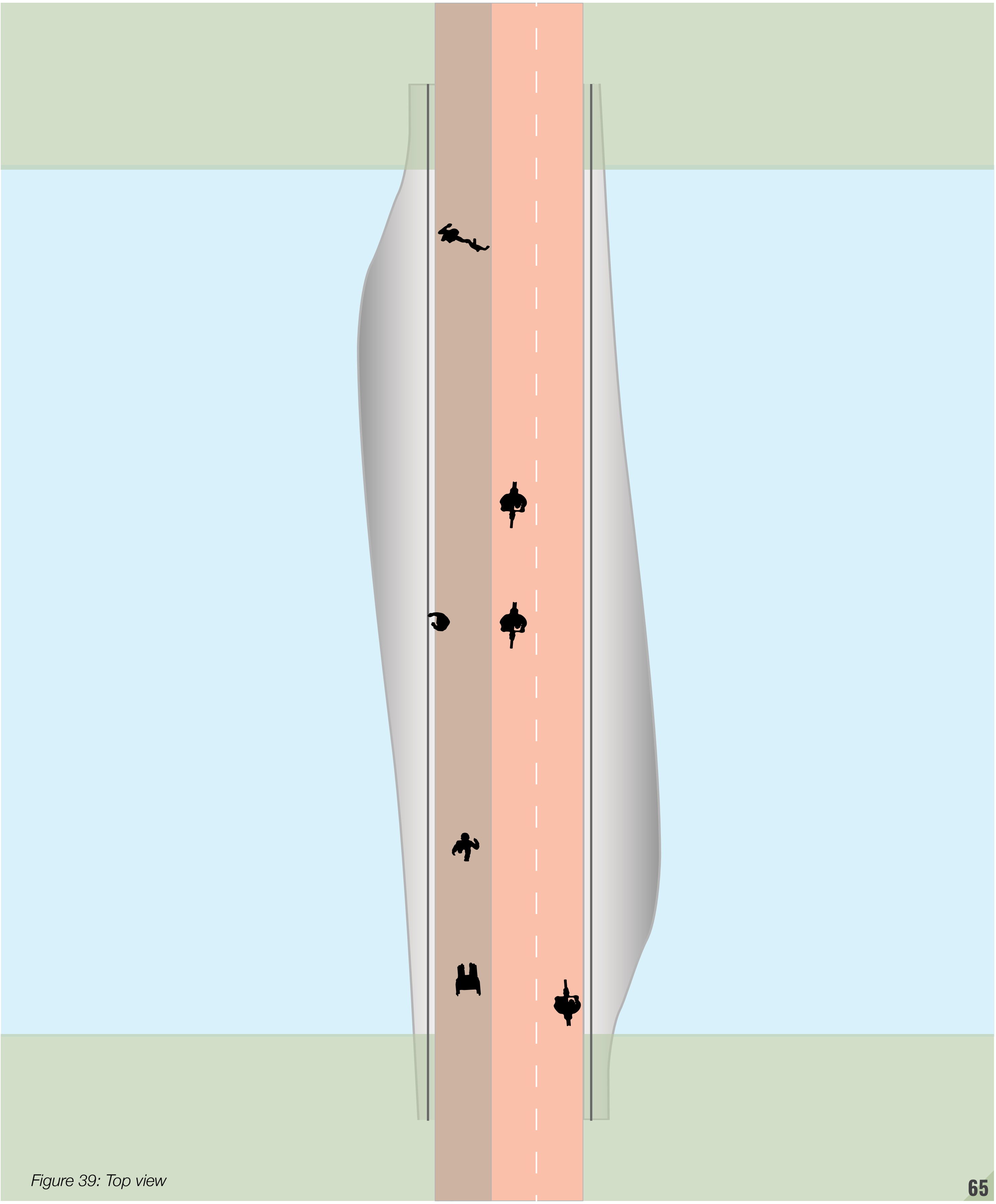


Figure 39: Top view

DECK & PARAPET DEVELOPMENT

REQUIREMENTS

In order to make the bridge suitable for many different applications, the deck should be designed to comply with the following requirements:

A two-way bicycle/moped path with a width of at least 2,5 meters (Fietsersbond, 2004) should be present .

A path with a width of at least 0,9 meters, preferably 1,2 meters, (Bouw Advies Toegankelijkheid, 2017) should be present to accommodate pedestrians and wheelchairs.

Accordingly, the desired width of the deck is approximately 4 meters, which is quite a large span.

In order to utilize the advantages of the Bridge of Blades, as mentioned before, the deck must comply with the following requirements:

- Low maintenance
- Materials have a high strength-to-weight ratio
- All materials are separable (with low-energy consuming disassembly processes)
- Materials are re-usable/recyclable
- Use of re-used/recycled materials is preferred
- Easy to install on-site
- A modular system is preferred, to utilize a single design in bridges with different lengths

For the parapet, the following requirements are relevant:

Parapets should be placed on the structure with a minimum height of 1450mm, measured from the adjoining pedestrian walking surface (DN-STR-03011, 2016).

If the bridge crosses a railway, parapets with a minimum height of 1850mm should be placed (DN-STR-03011, 2016).

No structural failure should occur when a line force of 1kN/m acts either vertically or horizontally on the parapet (EN 1317-6).

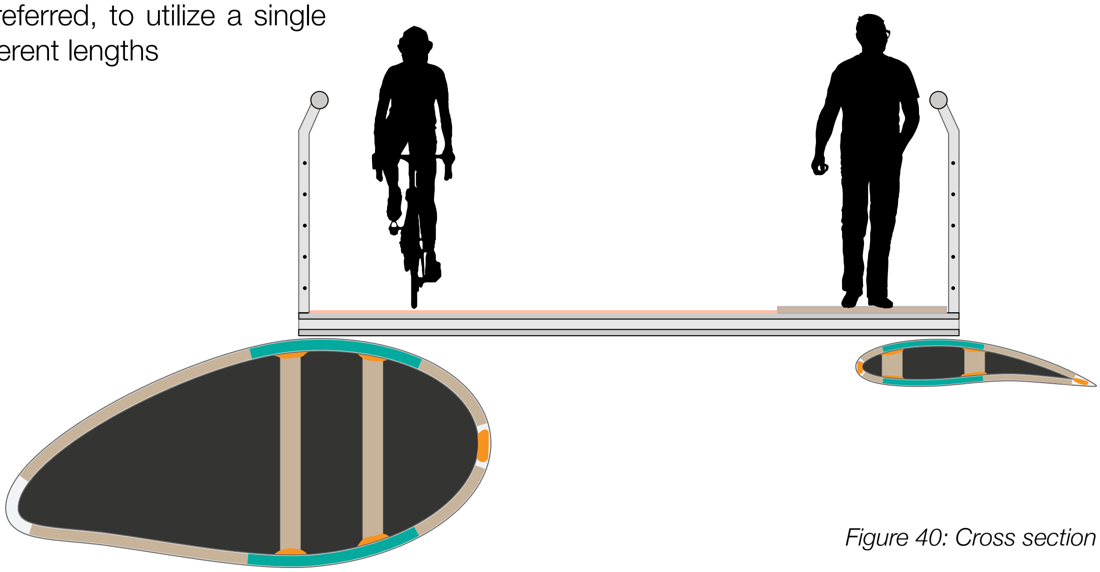


Figure 40: Cross section

VERSATILITY

Bridges are generally designed by architects and most bridges are unique. This bridge is designed to be applicable in different environments. However, in any given bridge project, specific (aesthetic) wishes may need to be taken into account. Therefore, the bridge is designed to allow different decking and standard parapet solutions to be applied.

For the decking, a simple hollow profile can be used to accompany different materials (Figure 41). The profile could be extruded from aluminium or pultruded from FRP material.

Within this project, aluminium was identified as the preferred material, because it requires little energy to recycle and has excellent corrosion resistance (Table 2). Many lightweight aluminium decking profiles exist with high recycled material compositions. Neaco's Neatdek, for example, contains 85-100% recycled content and is 100% recyclable (Neaco, 2016).

No life cycle assessments (LCA) exist that compare decking materials so it is difficult to say what would have the least environmental impact. In some cases, architects or project planners may prefer to use FRP decking, for example for aesthetic reasons. This freedom is supported in the design. It is advised that more research is done (in the form of an LCA) to compare the impact of the different materials. Steel, for example may offer similar results as aluminium.

For the parapet, it was decided that different parapets should be applicable. Again, this allows for architects to offer different kinds of solutions with the same blade basis and ultimately allows the Bridge of Blades to be applicable on a commercial sclae in different environments.

Based on these criteria, three ideas were investigated for the deck/parapet joints, as is explained on the next pages.

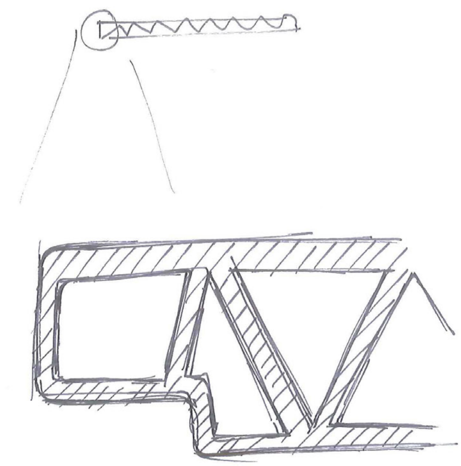


Figure 41: Hollow deck profile

TYPE	MAINTENANCE	INITIAL COSTS	WEIGHT-TO-STRENGTH RATIO	RECYCLABILITY
Steel reinforced concrete deck slab	Occasional	Low	Poor	Poor
Steel grid deck + wearing layer	Rarely	High	Good	Good
Wood deck	Regular	Low	Good	Medium
FRP deck	Very rarely	High	Excellent	Very poor
Aluminium deck	Very rarely	High	Good	Good

Table 2: Deck material comparison

DECK & PARAPET DEVELOPMENT

1. CONNECTORS

Based on the blade's CAD model, connectors are customly produced that are placed 2 meters apart. These connectors are bonded to the blades with an adhesive. The deck profiles are designed with a raised space for the connectors, to make sure the loads are distributed evenly to the blades, rather than creating peak loads where the connectors are.

PRO'S

- Little extra material is needed
- Custom components are relatively small
- Loads are evenly disttibuted

CONS

- Connectors need to be made customly.

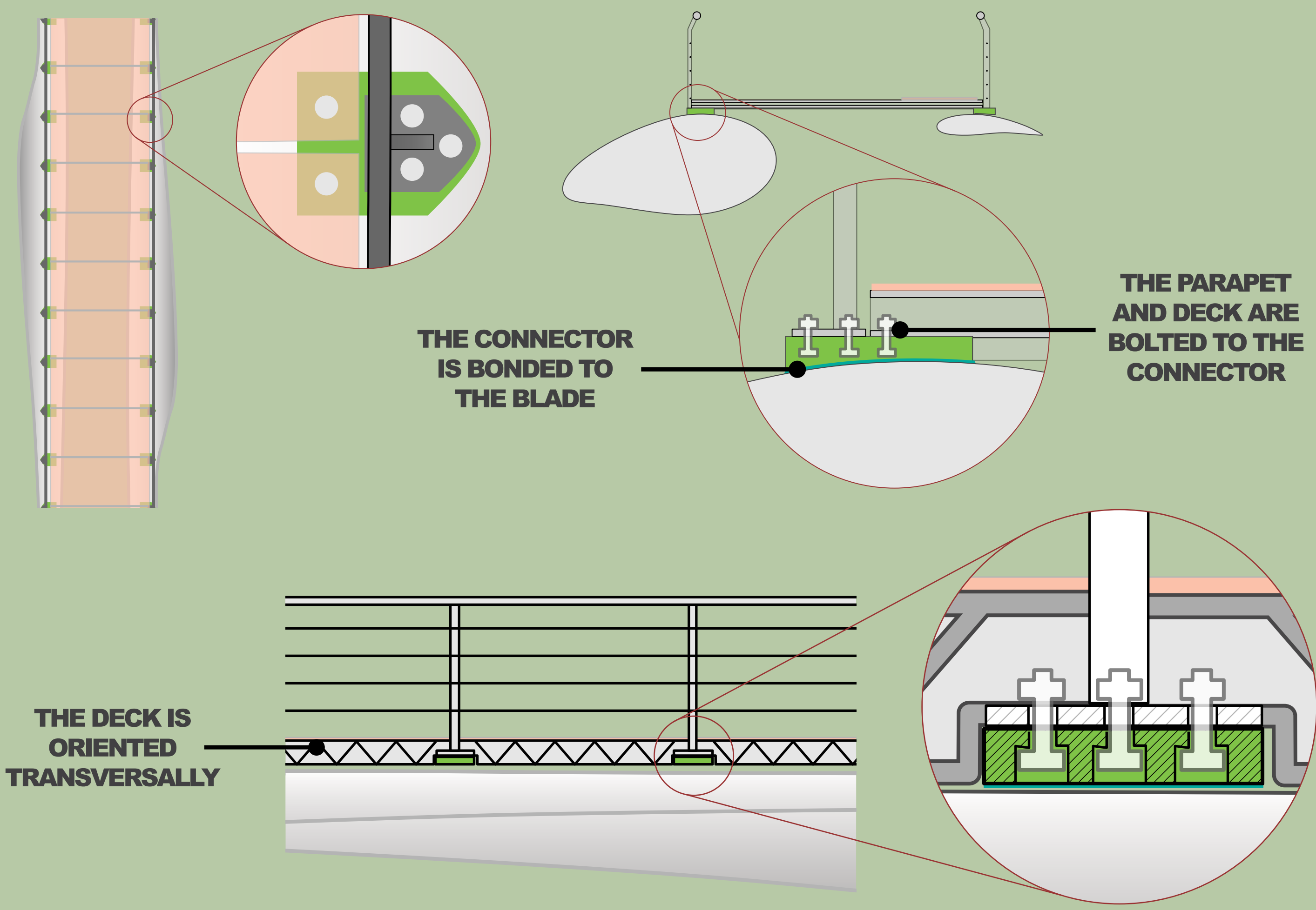


Figure 42: Idea 1: Connectors

2. FORM-FITTED GIRDERS

In an attempt to remove the need of any kind of fixed connection to the blades, the following design was made. By producing girders that fit the exact blade shape based on CAD models, a self-supporting structure is made.

The deck can simply be placed onto the girders and the parapets can be bolted onto the girder ends to withstand the horizontal loads.

PRO'S

- No fixed connection with the blades > improved recyclability
- Reduced installation time
- If the blades don't offer enough stiffness, the girders can provide structural support

CONS

- When the blades offer enough stiffness, the structure is unnecessarily heavy and material-consuming.
- Expensive
- Large custom components
- Structural performance without joints can be questioned

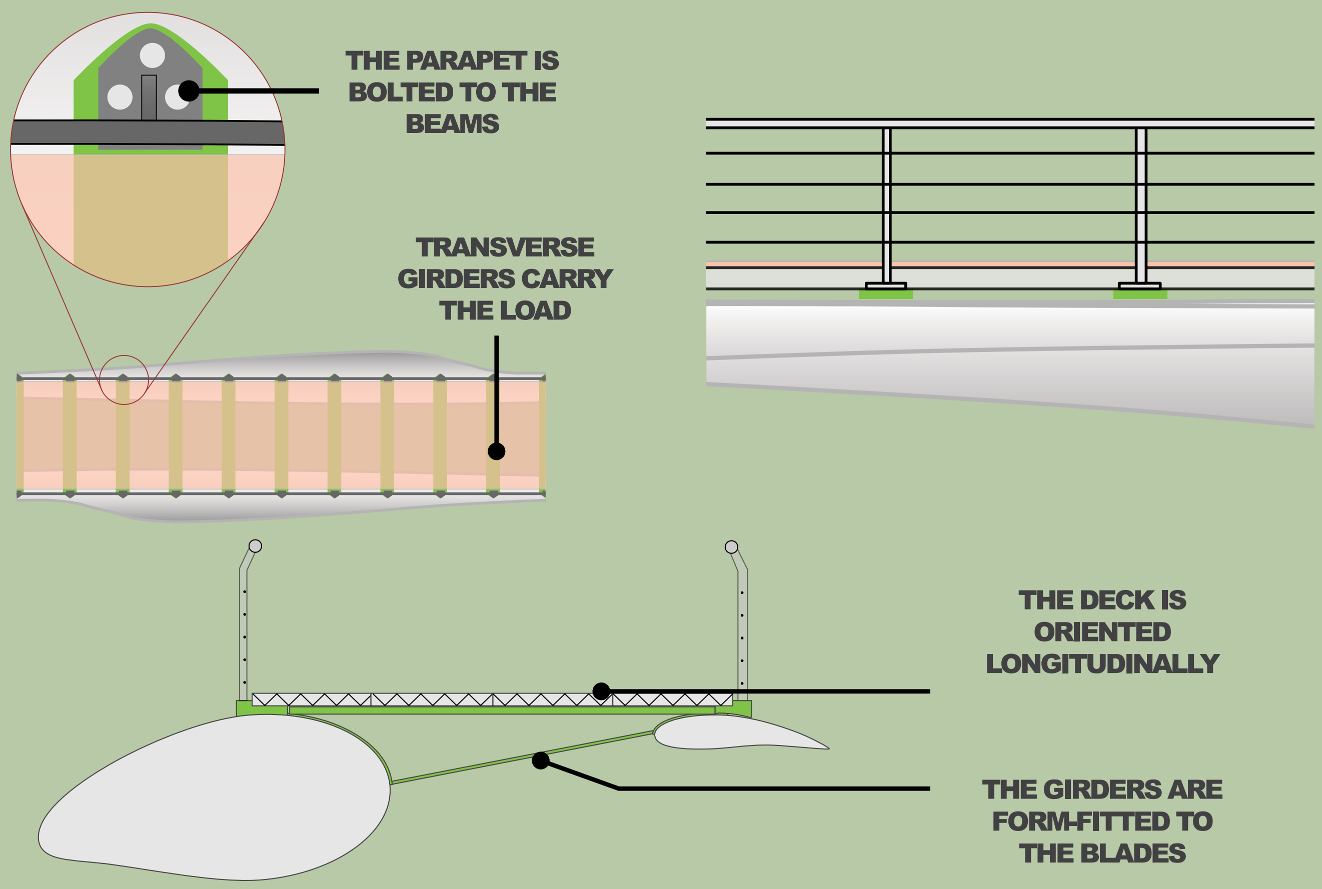


Figure 43: Idea 2: Firm-fitted girders

DECK & PARAPET DEVELOPMENT

3. ONE-PIECE DECK & PARAPETS

Another way to avoid fixed connections across the blades is to make a one-piece structure for the deck & parapets. Extruded deck panels can be (friction stir) welded to each other and the parapets.

PRO'S

- Little extra material is needed
- No fixed connection with the blades - improved recyclability
- No custom components needed

CONS

- Lifting the structure during transport and installation can cause serious problems for the welded bonds.
- Small damages can't be locally repaired
- Not suitable for FRP materials

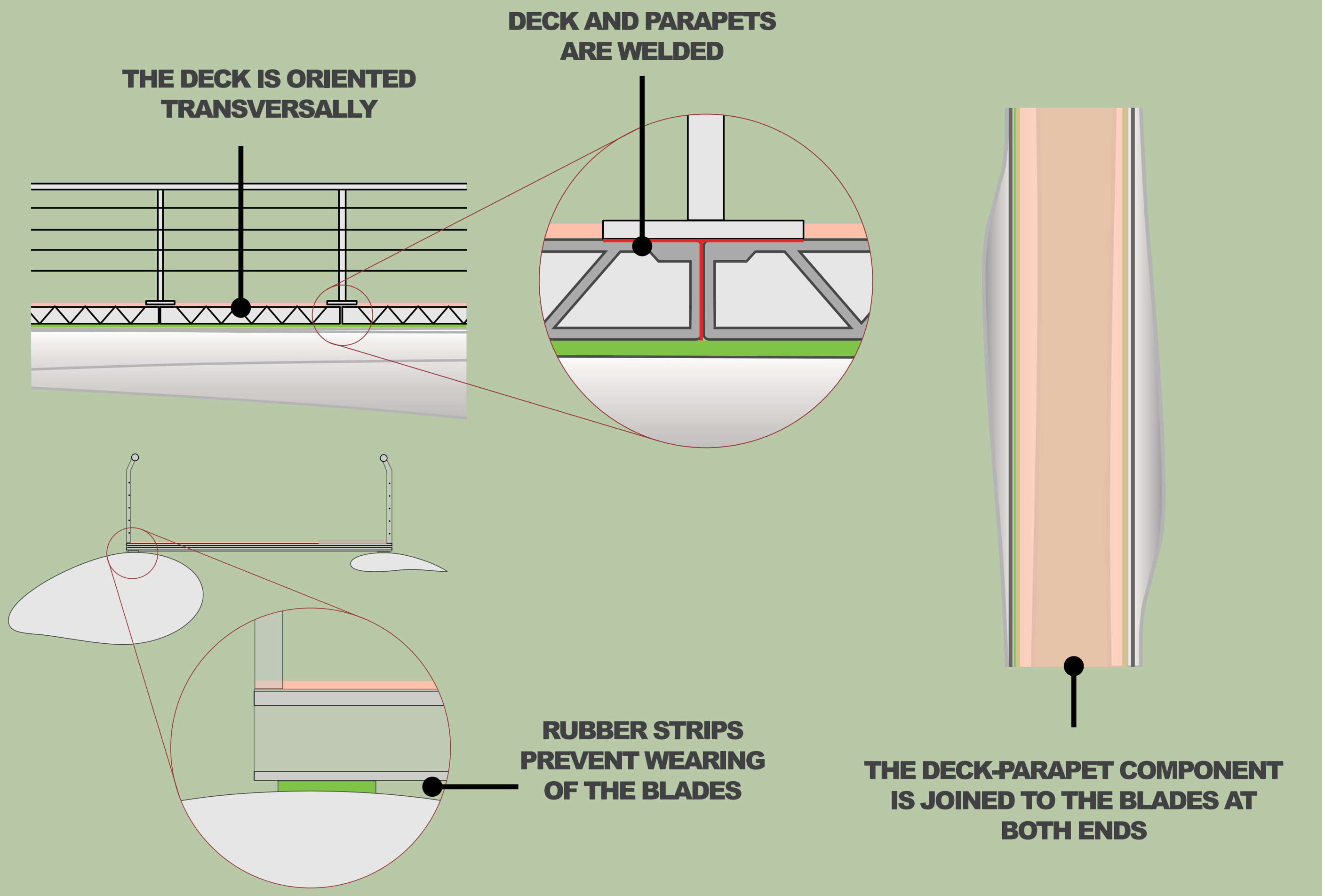


Figure 44: Idea 3: One-piece deck & parapets

CHOICE

In order to make a decision on the deck & parapet design, Dr. Marko Pavlovic was consulted. The advantages and disadvantages of each solution were discussed and finally, the conclusion was found that the first solution is the most promising.

Although each solution can be valid, the first idea offers a solution that makes excellent use of the blades as load bearing structure, without requiring material-costly girders. The system consists of small components, that are easy to transport and install. In the case of a local damage, one component can easily be replaced. Moreover, the system utilizes the strong connections that can be made between FRP components by bonding, while allowing for different (standard) decking and parapet materials to be used.

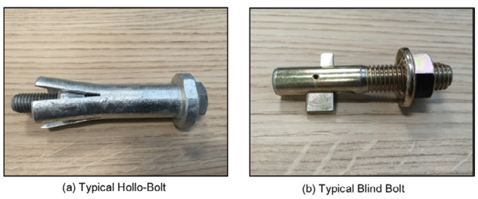


Figure 45: Hollo and blind bolt (Kidd et al., 2016)

Figure 47: AJAX fastener

ALTERNATIVES

Adhesive bonding of the connectors to the blades is not the only possibility within this idea. Alternatively, bolts could be used to join the deck and parapet to the blades. Bonding the deck to a bridge superstructure is common practice in bridge development.

Because of the large hollow shape of the blades, the bottom of the bolts will not be accessible. Therefore, blind fasteners would need to be used. Two blind fasteners are most common: the Hollo bolt and the blind bolt (Figure 45). Another blind fastener that could be used in the AJAX fastener (Figure 47).

These connections are typically designed to connect steel plates and no literature exists that compares their performance in FRP structures. According to Pavlovic (2018), he will perform tests this year at the Delft University of Technology to compare the different fasteners.

The strongly curved shape of the blade may cause problems for the integrity of a bolted joint. Moreover, the bolted joint would cause water to enter the blades, which could cause problems. Bonded joints for FRP structures have proven themselves over the past years and so are at the moment preferred.

The bolted connection can be an alternative to the bonded connector if this is not a problem. Further research (lab tests) should be done to compare the performance of the different alternatives.

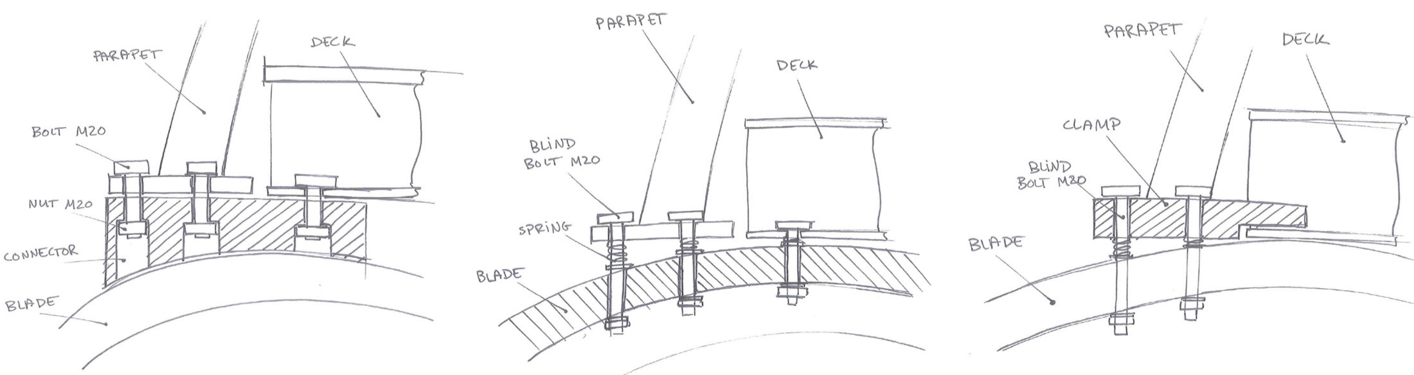


Figure 46: Bonding alternatives

DECK & PARAPET FINAL DESIGN

As mentioned previously, different alternatives are possible and should be investigated further. Within this project, the bonded connectors were used for further detailing because they seem most promising at the moment.

DECK

The deck consists of a hollow profile that can either be extruded from aluminium or pultruded from FRP material. The extruded parts can be cut to the desired length, which corresponds with the width of the deck. A 4 meter wide deck will need to be approximately 140mm high, to comply with the NEN norms (BRS, n.d.).

Decks that are less wide (shorter extrusion length) require a lower height. Producing different profiles would lead to extra investment costs because multiple extrusion dies are then required. Instead, the higher deck could be applied. Which of the two options is preferred can be decided during a project.

The deck has a space on top for a wearing layer. These wearing layers are common practice in such structures and are often made of a resin (e.g. epoxy, PU) and a granulate (e.g. asphalt, EPDM) (BRS, n.d.; Qian et al., 2013).

From an end-of-life perspective, this is not ideal. EPDM can be recycled, but when bonded with a thermosetting resin, it is not separable. Therefore, it is recommended that research is done to discover the possible use of a thermoplastic resin in the wearing layer. Because of the heating of the bridge, a maximum service temperature of approximately 100 °C is required (Pavlovic, 2018). A polycarbonate resin has a service temperature of 120 °C (Figure 48) and should theoretically be sufficient.

Resin Family	Continuous Service Temp. (°C / °F)	Cure Time (min)	Tens Stren (ks
Thermoset Resins			
Phenolic (PH)	170 / 340	60+	6.9
Epoxy (E)	180 / 350	60-240	9.7
Cyanate ester (CE)	180 / 350	60-180	7.4 - 1
Bismaleimide (BMI)	230 / 450	120 - 240+	10.
Polyimide (PI)	370 / 700	120+	16.
Thermoplastic Resins			
Polycarbonate (PC)	120 / 250	< 20	9.4
Polyphenylene sulfide (PPS)	240 / 464		13.
Polyetherimide (PEI)	200 / 390		6
Polyetheretherketone (PEEK)	250 / 480		14 -

Figure 48: Comparison of Selected Aerospace Thermoset and Thermoplastic Resin Matrices (Red, 2014)

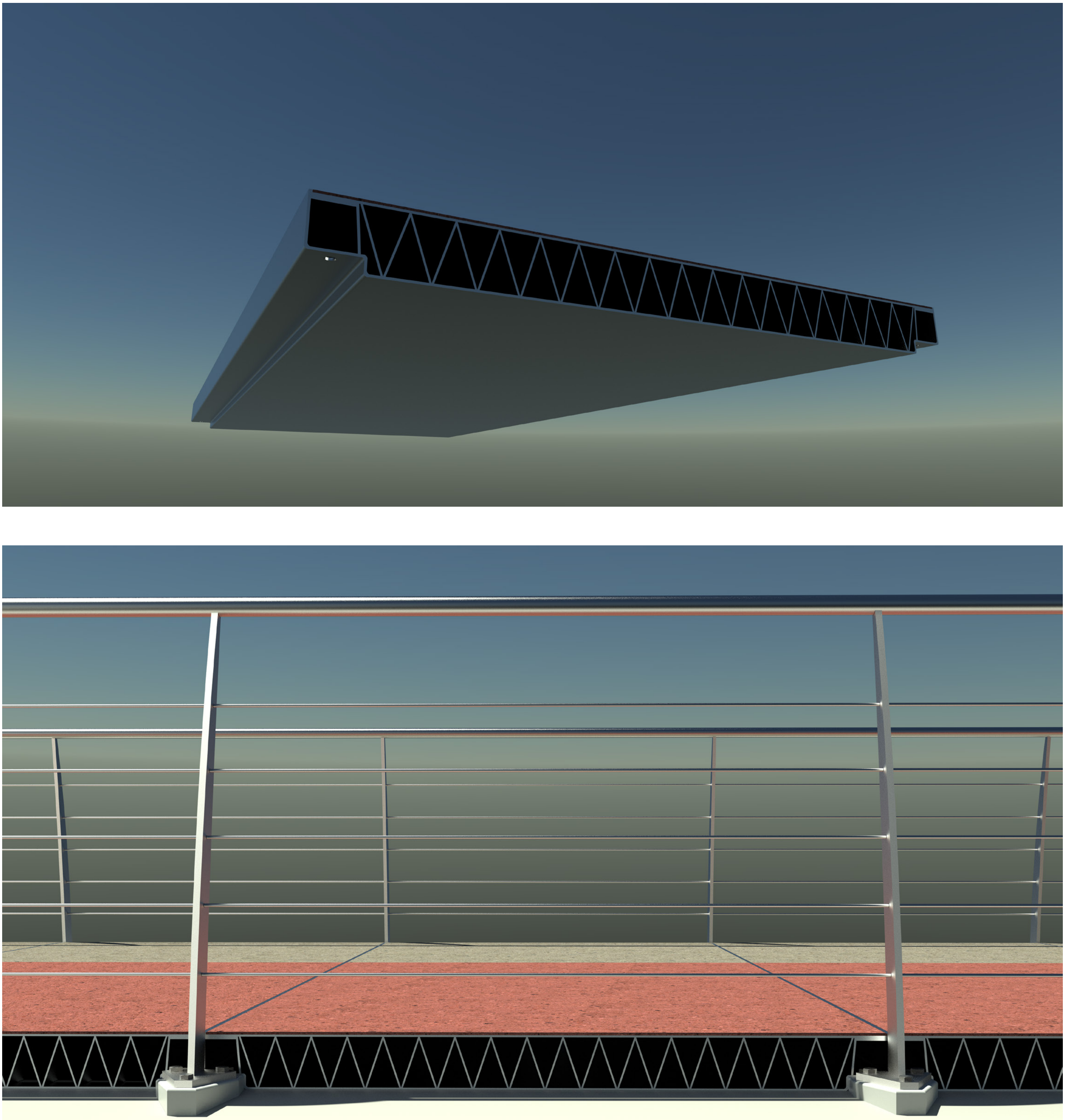


Figure 49: Deck & parapet renders

DECK & PARAPET FINAL DESIGN

CONNECTOR

The connector is designed to precisely follow the blade shape at the bottom to allow a strong adhesive bond with a maximum thickness of 2mm (Pavlovic, 2018). Cavities in the connector allow for a bolted connection with the deck and the railing. The deck requires one hole at each corner. For the parapet connection, standard parapet dimensions were used (Figure 50).

At the moment, thermal expansion and contraction have not yet been taken into account in the connection design. More research and development is required to allow for changes in the dimensions due to temperature. It is highly likely that the connection will need to be altered. Examples of integrating this is by making slots instead of circular holes for the bolts, and offering more space between the deck and connector.

By designing the connectors with plastic (composite) material, a strong adhesive bond can be made with the blades. It is also corrosion resistant and durable.

Because this project aims at closing the loop for such materials, the possibility of using end-of-life materials was investigated. As mentioned in the research at the beginning of this report, Conenor (n.d.) is currently developing thermoset FRP-waste reinforced composites. One of the sources for their material is wind turbine blade waste. A finite elements analysis was done to get an estimation of the connector's performance if it were produced from Conenor's material. The analysis showed that the stresses in the material did not exceed the yield strength of the material (by a small margin) so the material could potentially be used (Figure 54). The full FEA can be found in appendix B.

To produce the connectors (Figure 52), the material is extruded with the outer dimensions and M20 bolt holes integrated. It is then cut to the maximum height. In the final production step, the connectors are CNC milled (upside down). Based on the blade CAD file, the required shape is calculated and milled from the block. A hexagonal profile is milled for the M20 nuts and, if necessary, the M20 nut hole walls can be milled to provide smaller tolerances.

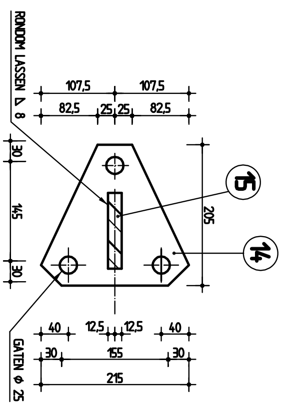


Figure 50: Parapet standard detail
(Rijkswaterstaat Dienst Infrastructuur, 2009)

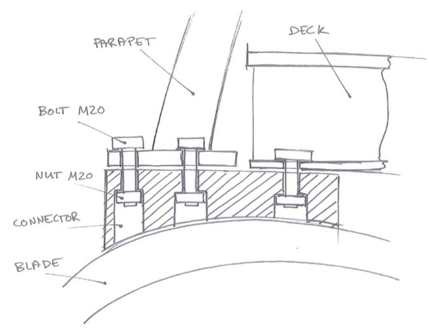


Figure 51: Connection detail

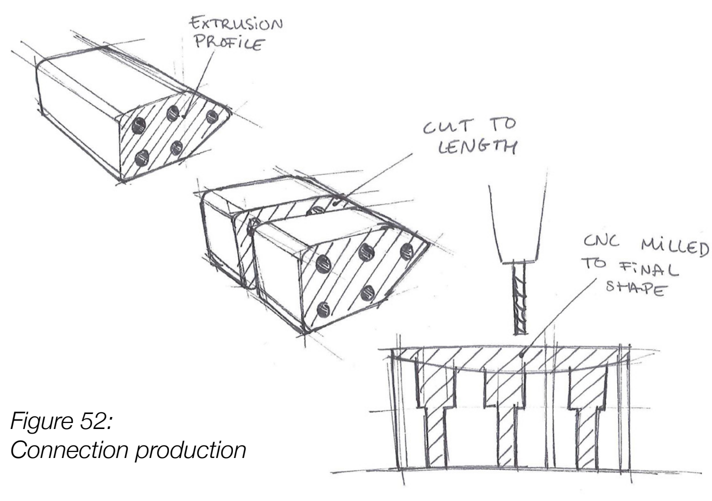
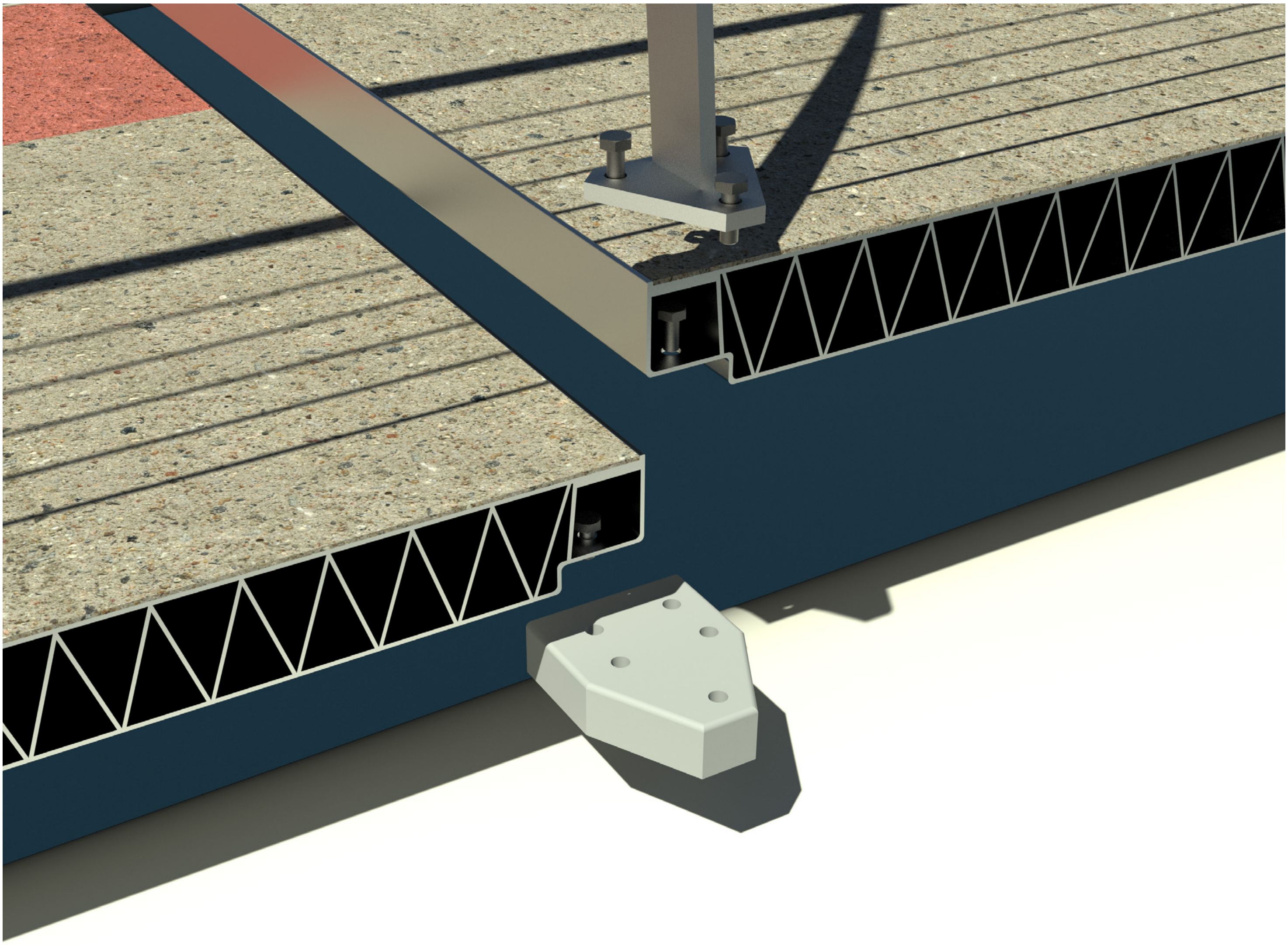
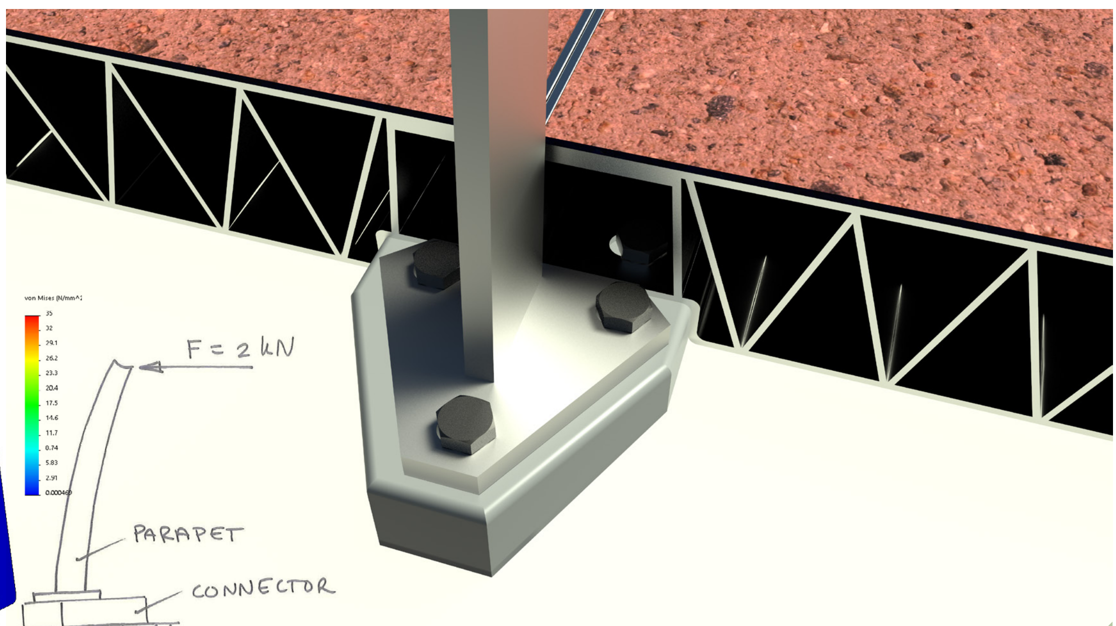


Figure 52:
Connection production





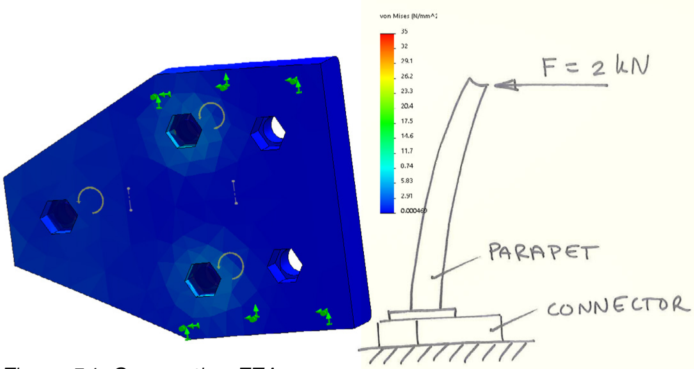


Figure 54: Connection FEA

Figure 53: Connection renders

LAND INSTALLATION

Based on similar slow traffic bridges, a land installation detail is shown in Figure 55. The transition slab, piles and road can be produced and installed according to regular practice. The abutment, however, needs to distribute the forces between the blades and ground evenly. To do so, it is important that the abutment has the same shape as the blade surface (Figure 56).

This means that for every blade model, a new abutment must be made. Using blades as a mould for the abutment was considered. However, because of thermal expansion and material creep, the concrete can't be poured onto the blades on-site (Pavlovic, 2018). This would cause cracking of the abutment or movement of the blades over time. To prevent this, the abutment is poured separately and a rubber layer is placed between the abutment and blades. Using the blades as a mould is not desirable, because either the entire blades would need to be accurately placed, or the functioning cross sections would need to be cut from a third blade, creating useless waste material.

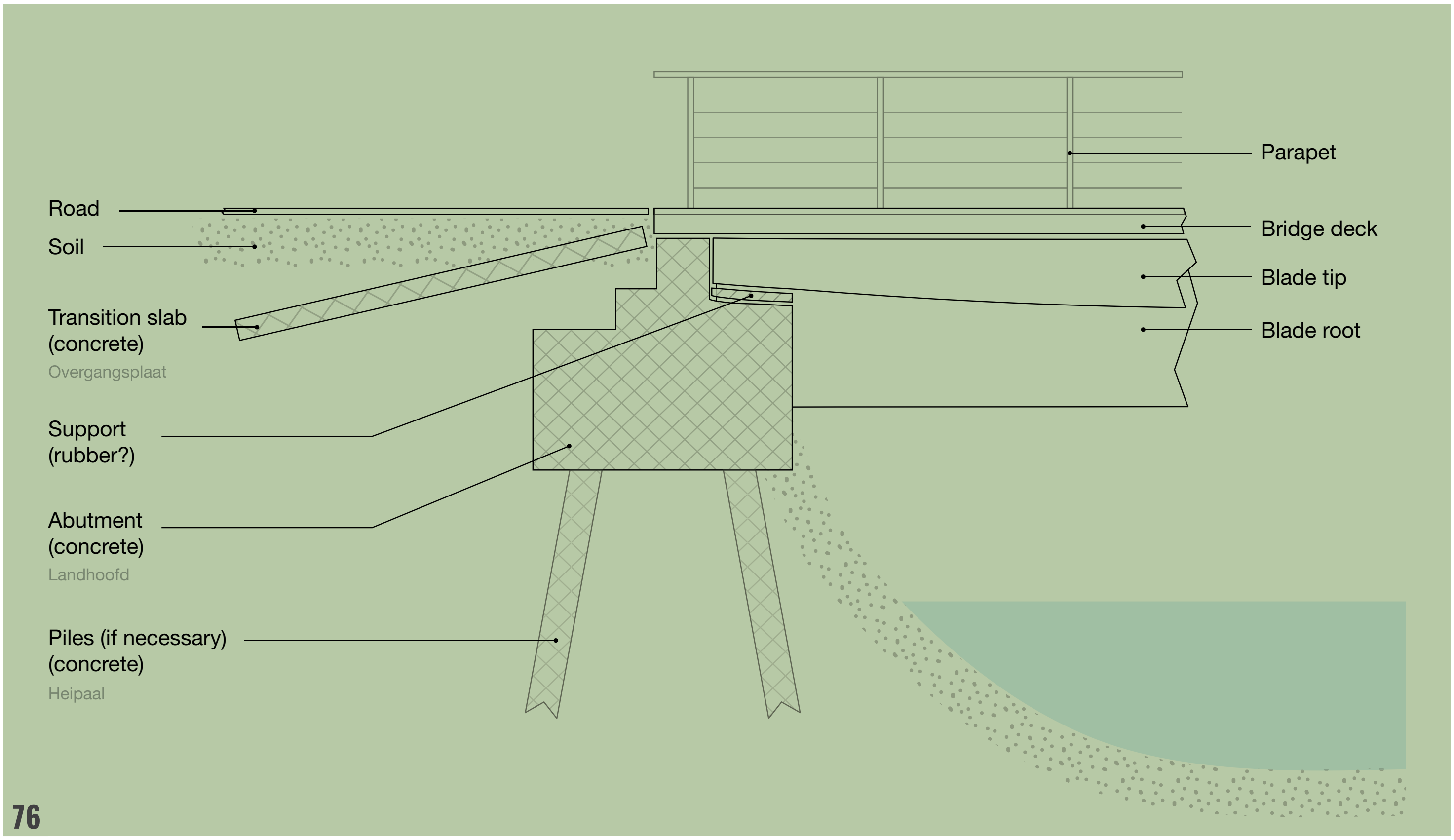


Figure 55: Land installation

Therefore, it is more effective to cast the concrete in a production facility. The bottom- and side walls of the abutments can be made with the same mould walls. The odd top shape can be varied by using a reconfigurable mould wall (Pavlovic, 2018). The abutment orientation is rotated 90° and the mould walls are clamped firmly to a bottom plate. The concrete can then be poured without needing walls that have the outline as shown in Figure 57.

This way, multiple abutments (of approximately the same size) can be made using the same tools.

The blades could be bolted into the abutment, but according to Simon de Jong (2018), it is often cheaper and easier to simply place the blades onto the abutment. it can be argued that in the rare case of a collision with a boat, the bridge is more likely to be moved and reduce severe damage. It can then simply be placed back in position (De Jong, 2018).

These considerations are an attempt by an industrial designer to create an inclusive, scalable design solution. Likely, these aspects will need to be reconsidered/calculated in cooperation with an engineering company.

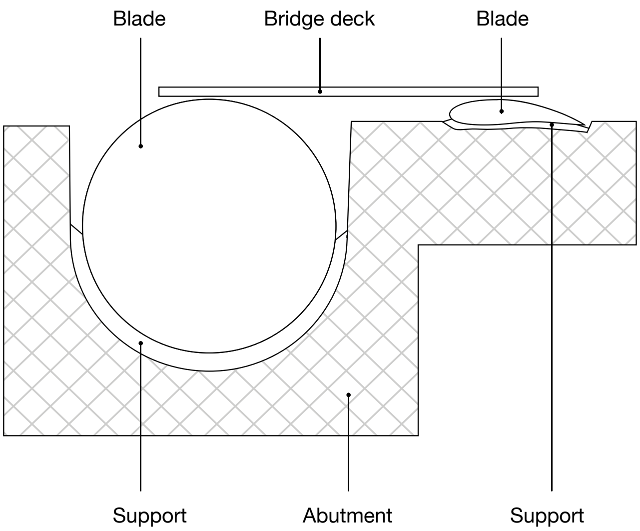


Figure 56: Blade installation

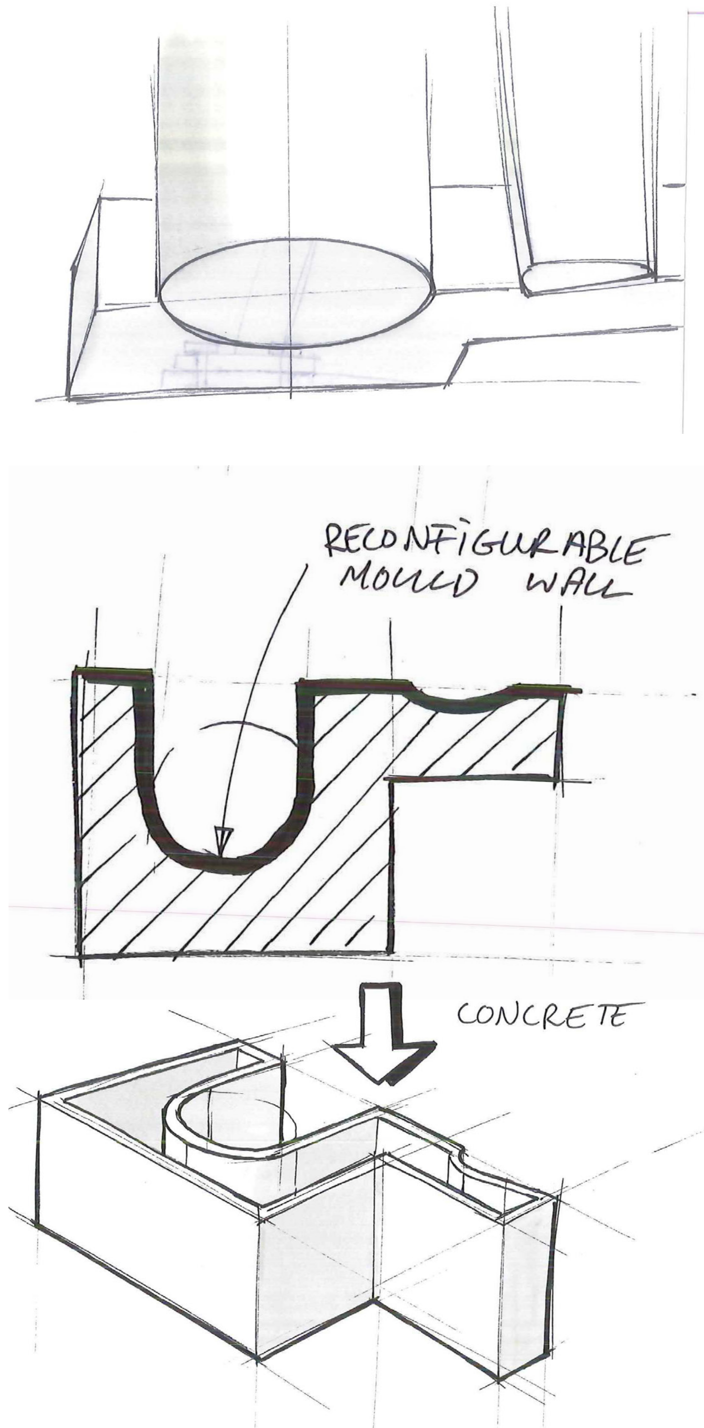


Figure 57: Abutment production

PRODUCTION PROCESS

BLADE SELECTION
It is uncertain whether all blades are structurally sufficient at the end of their life to be used in bridge construction. Also, the blades that are chosen should fit the bridge dimensions that are required. Therefore, it is important to consider the following aspects when selecting the blades:

CAD MODEL
In bridge designs, safety is extremely important. Before any bridge is built, it most comply with the norms for structural performance. CAD models of the blades are a prerequisite for the development of the bridge, so that accurate finite elements analyses can be done to calculate the performance of the bridge. Blade manufacturers must be contacted to retrieve these files.

As explained before, these CAD models are also used for the entire blade design and connector production.

BLADE LENGTH
The blades must be long enough to support the bridge, but at the same time should not be over-dimensioned for their purpose. A bridge length of ±75-85% of the blades is suggested, which is based on the rough finite elements analysis that can be found in the chapter evaluation. Further research is needed to find a more accurate requirement.

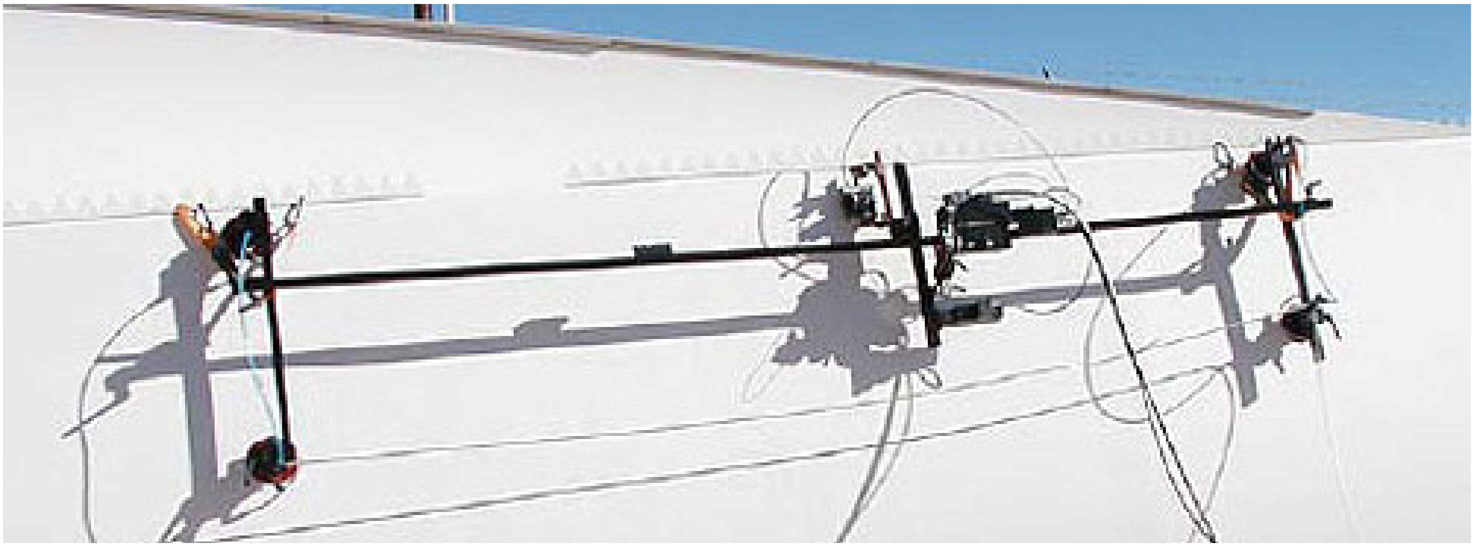


Figure 58: Ultrasonic blade inspection

CONDITION

Because of the safety measures involved with wind turbines in operation, the blades are likely to be in good condition until/at their EoL. However, for safety reasons, condition inspection is recommended.

With visual inspection and simple tapping tests, the blade condition can be inspected to some extent, as is done in regular inspections (Jüngert, 2008). To find more accurate results, other non-destructive inspection techniques can be applied, such as the following (Chady et al., 2016):

- Infra-red thermography,
- Ultrasonic testing,
- Digital radiography,
- Acoustic emission,
- Vibration analysis,
- Microwave and terahertz techniques.

BLADE COLLECTION

Because of the length of blades, transport is not an easy task. In order to reduce the complexity and costs of transport, the blades are cut to their final size at the location of decommissioning. To do so, a diamond circular saw can be used. They are then transported by truck to the production site, where the blades are prepared for construction.

Figure 59: Transporting the world's longest blade

PRODUCTION PROCESS

BLADE PREPARATION

As shown in the previous chapters, the bridge consists of the following components:

- Blades
- Deck
- Parapets
- Connectors

Additionally, to install the bridge, the following components are needed:

- Abutment
- Transition slab
- Support
- Piles (if necessary)

The transition slab, support and piles are common building materials and can be purchased to fit the desired situation. The production methods for the deck, parapet, connectors and abutment have been discussed in the previous chapter.

The blades require some processing before they can be used in the bridge structure. This needs to be done in a clean environment and so a large production facility is needed. After the initial non-destructive inspection and sawing of the blades on-site, further steps at the production facility are as follows:

1. Clean the entire blade. Pressure water guns can be used for this purpose.

2. Inspect the blade for any damages that need to be repaired.

3. Prepare the blade tip that was sawn for laminating. A smooth, straight surface is desired to allow the resin to bond.

4. Sand the blade surface where the connectors will be placed to roughen the surface. This will allow a better adhesive bond.

5. Remove any dust and mark the exact location of the connectors, based on the CAD model.

5. Perform repairs and bonds. Using a resin, repair damages where necessary, cover corrosion-sensitive areas (blade tip) and join the connectors on their pre-determined location. Before bonding, nuts are placed in the connectors where they can be reached by deck and parapet bolts.

TRANSPORT

According to Simon de Jong (2018), an important problem with prefab bridges is transport. Because of the combined length and width of prefab bridges, they are very difficult to transport, especially in dense urban areas. By keeping the blades separated from the deck and parapets during transport, these problems are reduced because the components are not as wide as the entire bridge.

INSTALLATION

When arriving on-site, the abutments, transition slabs and road can be placed according to common practice. Using the connectors, the blades can be joined to the deck and parapets on a flat piece of land.

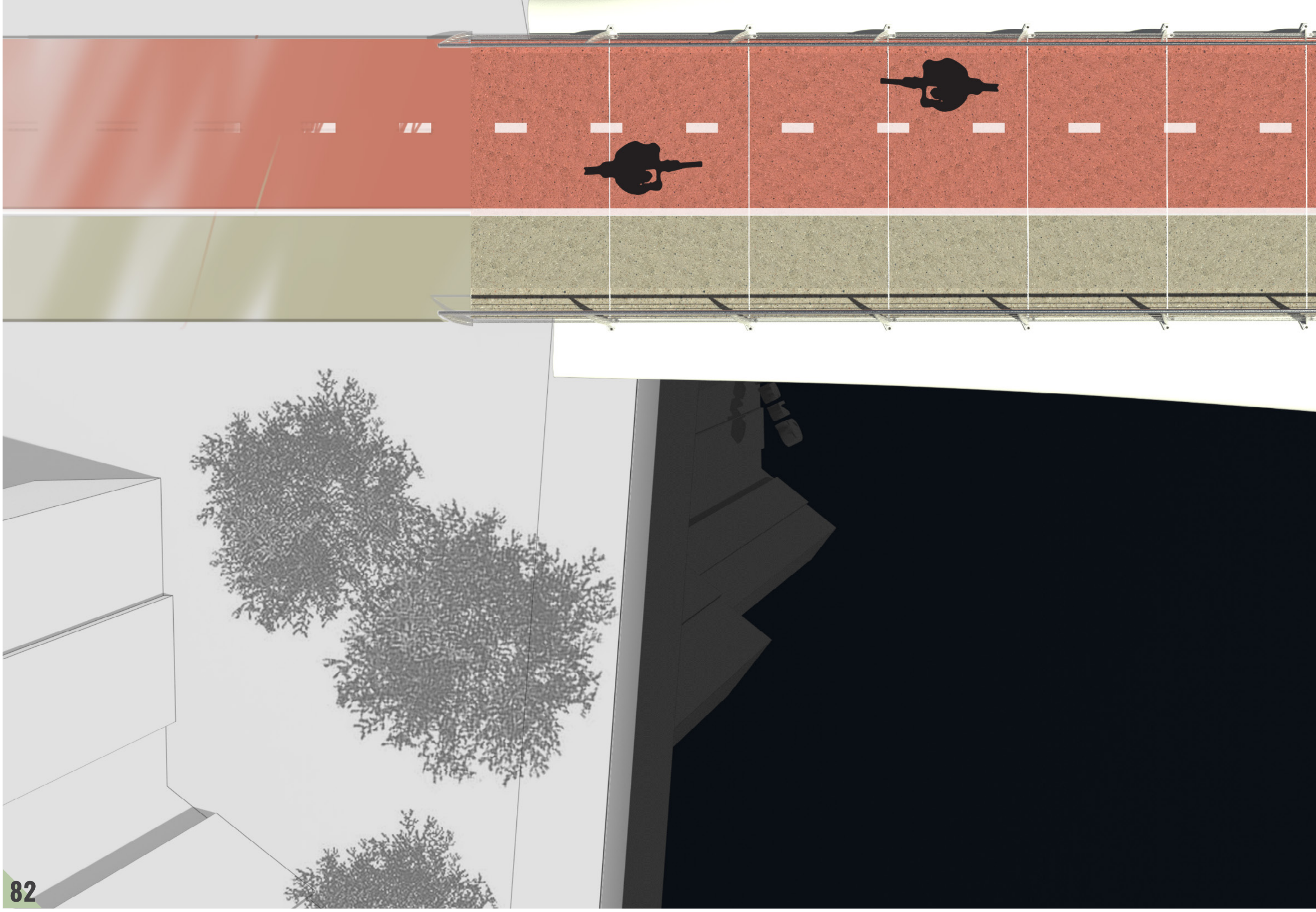
When the components are assembled, the entire bridge can be lifted into place by two cranes.

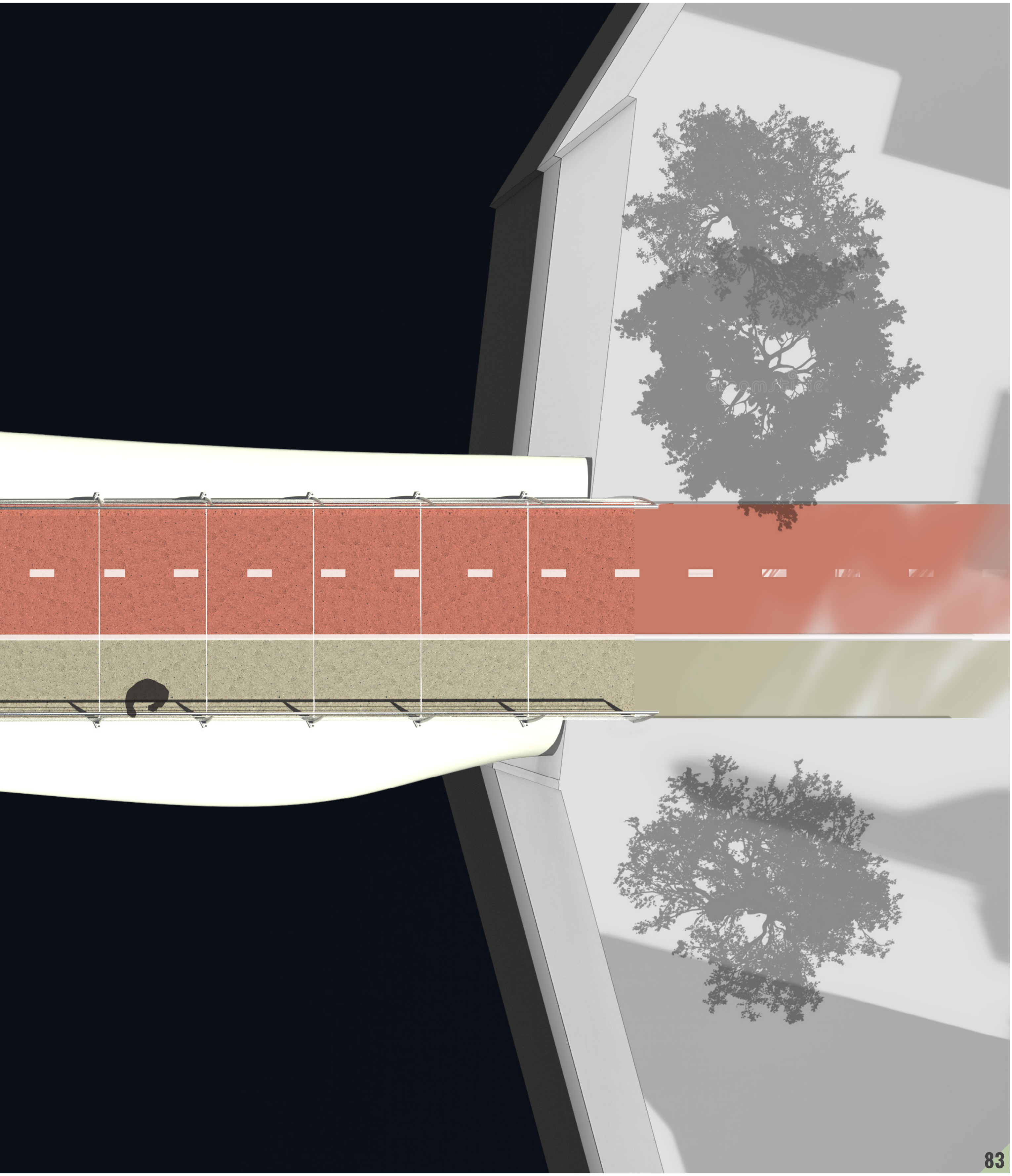
Figure 60: Installation of a prefab bridge.

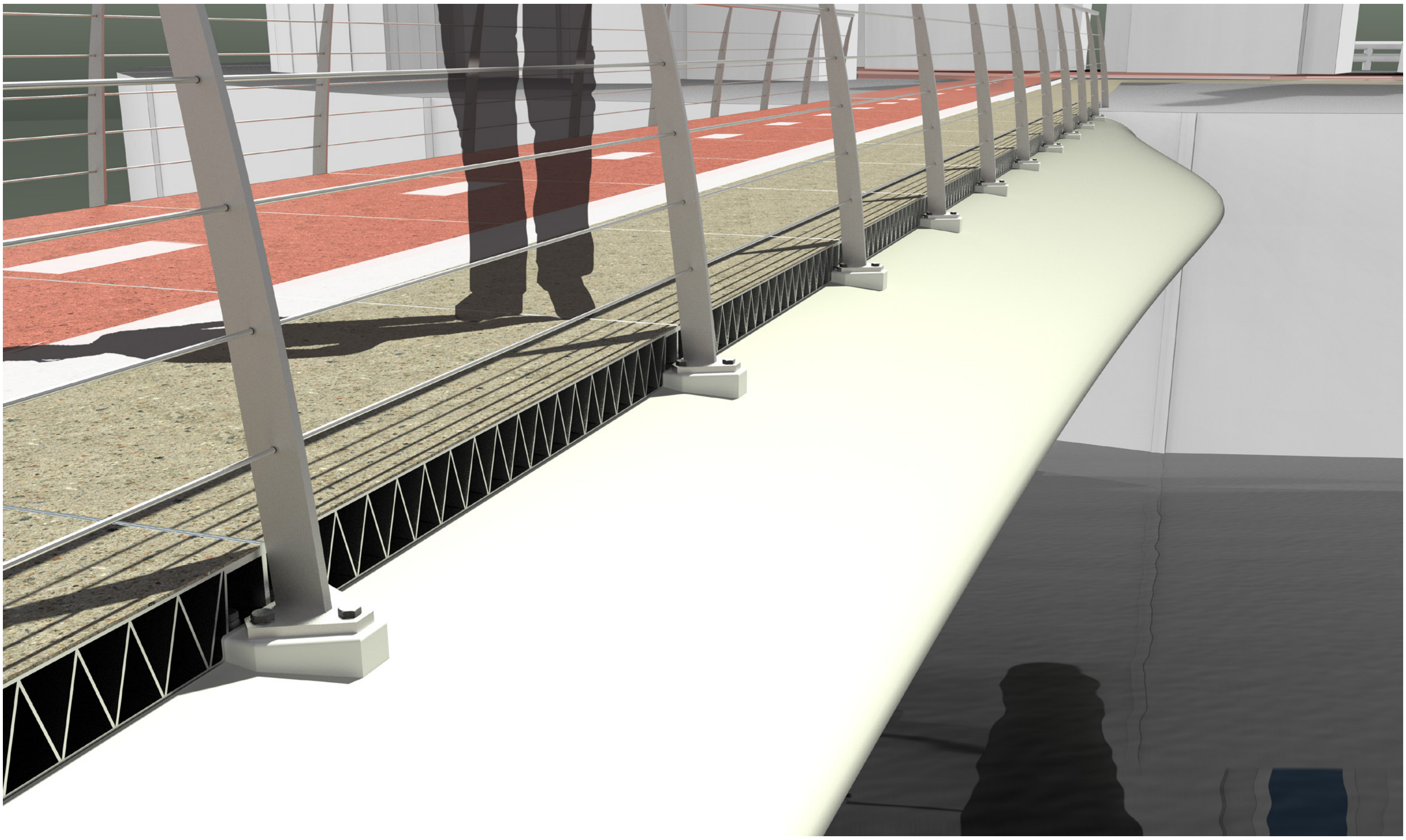
FINAL DESIGN

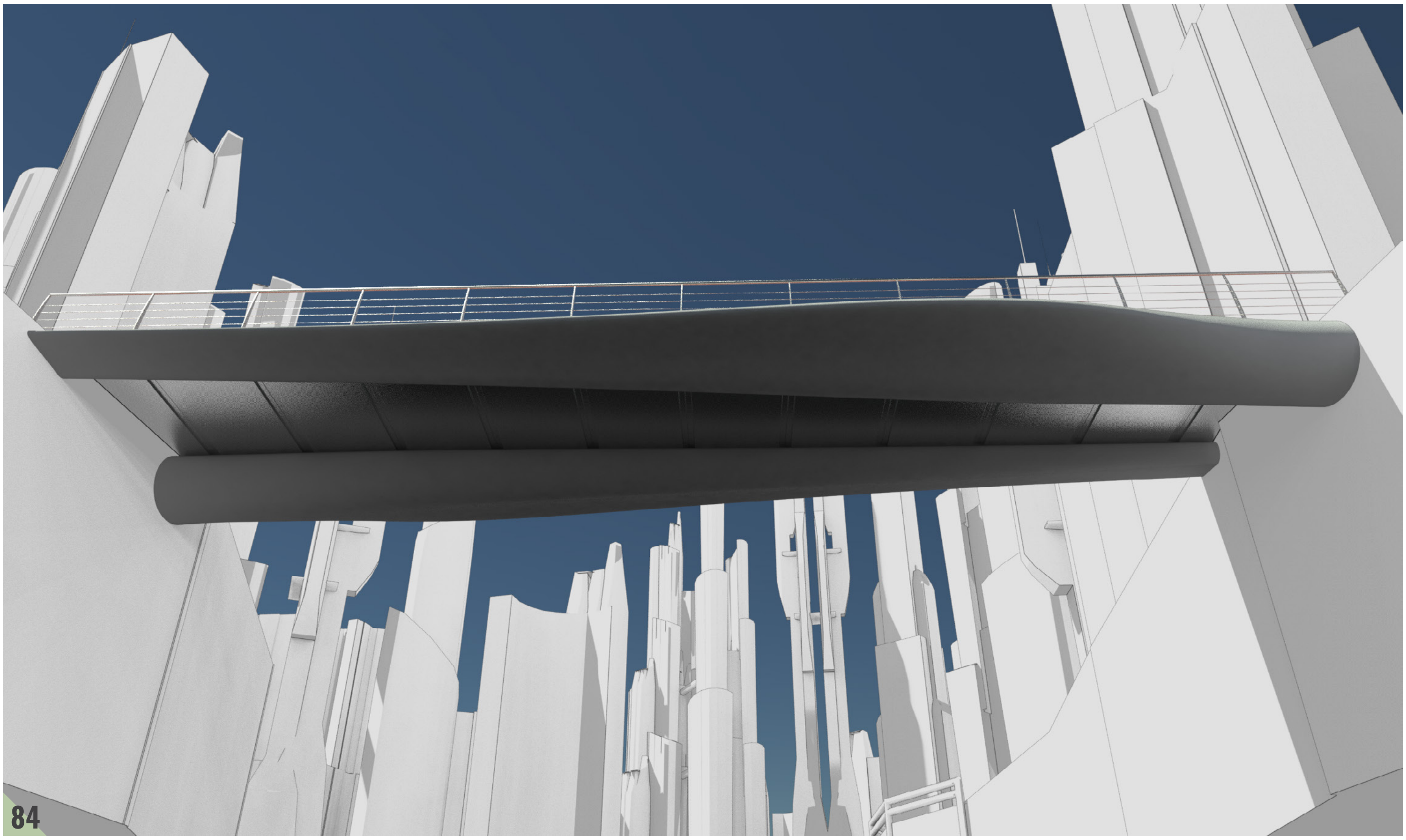
An artist impression of the final design is shown, that communicates the aesthetic and functional qualities of the Bridge of Blades.

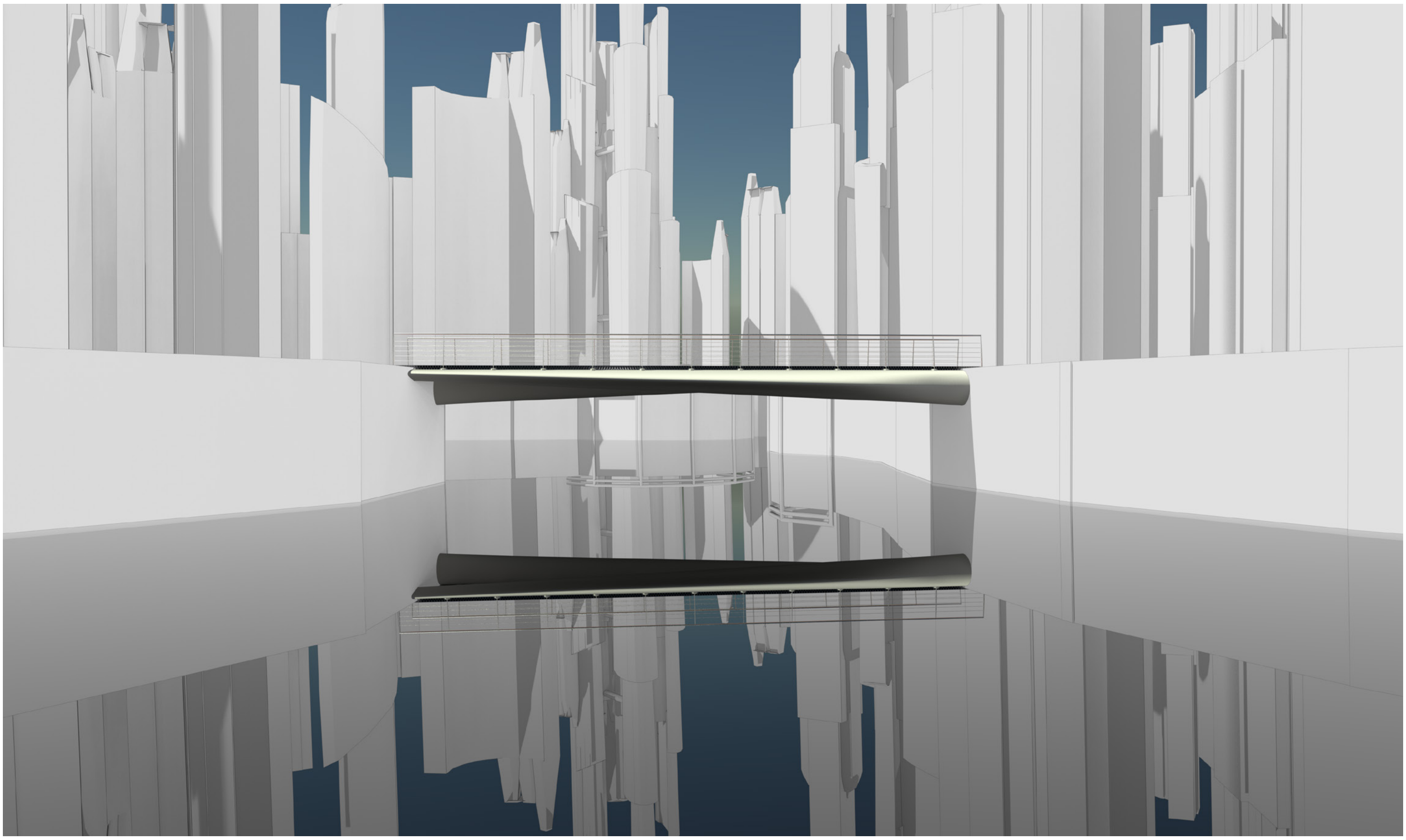
From all viewpoints, the previous life of the blade is visible. The design is playful, dynamic and tells the story of how high performance materials can be re-used in a commercially viable solution. This will help to fuel debate regarding material use in the technologies of the future.

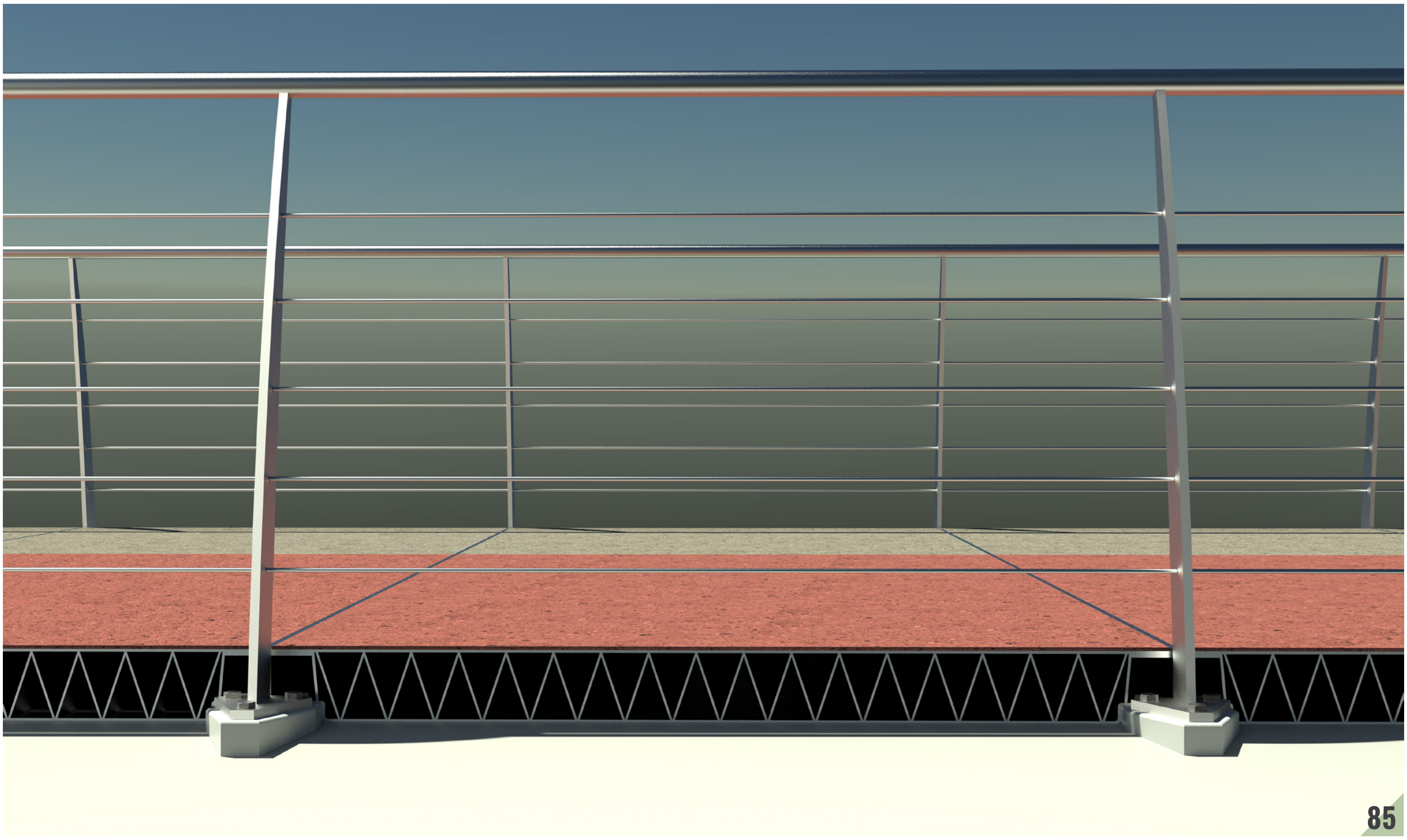


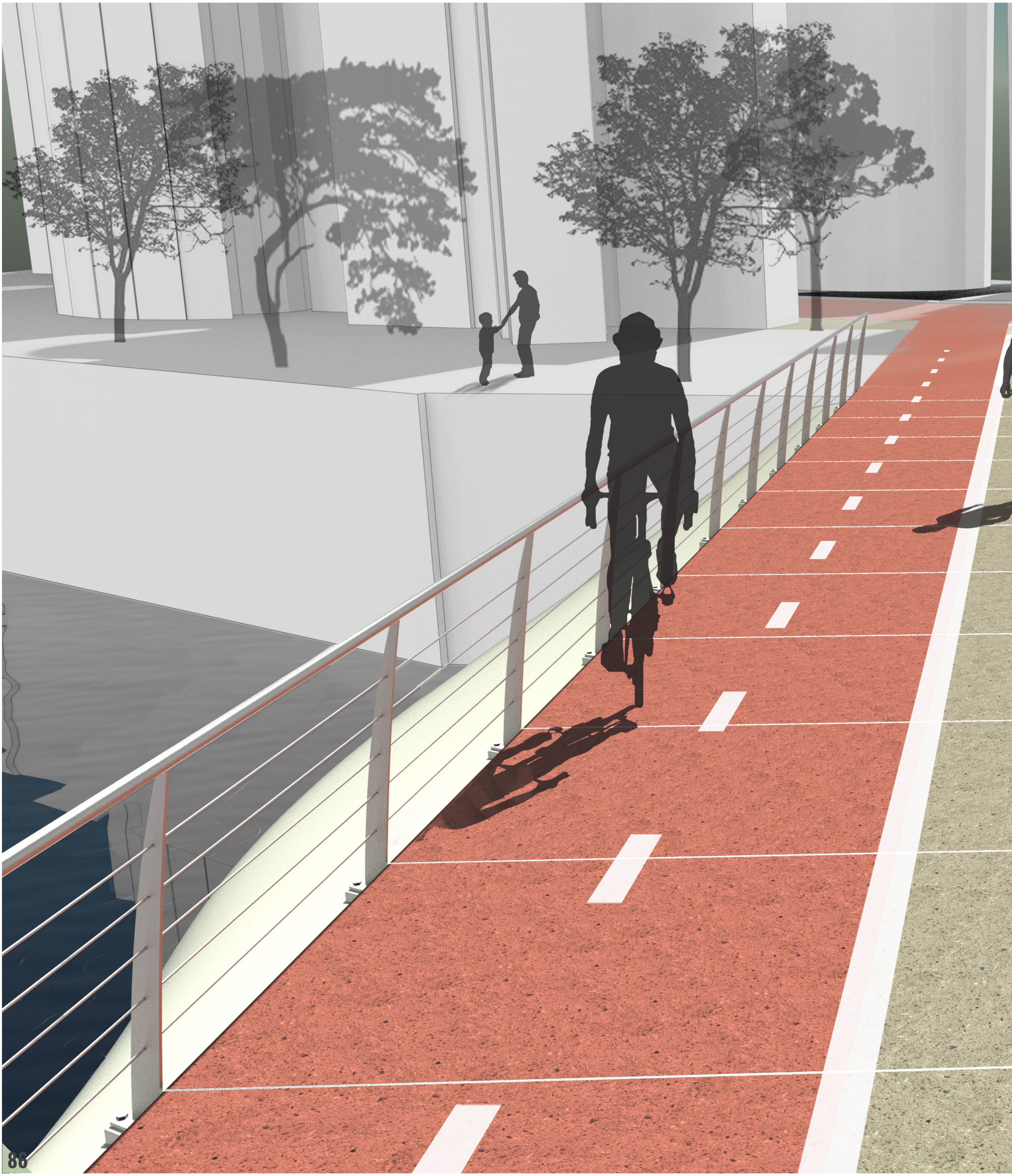


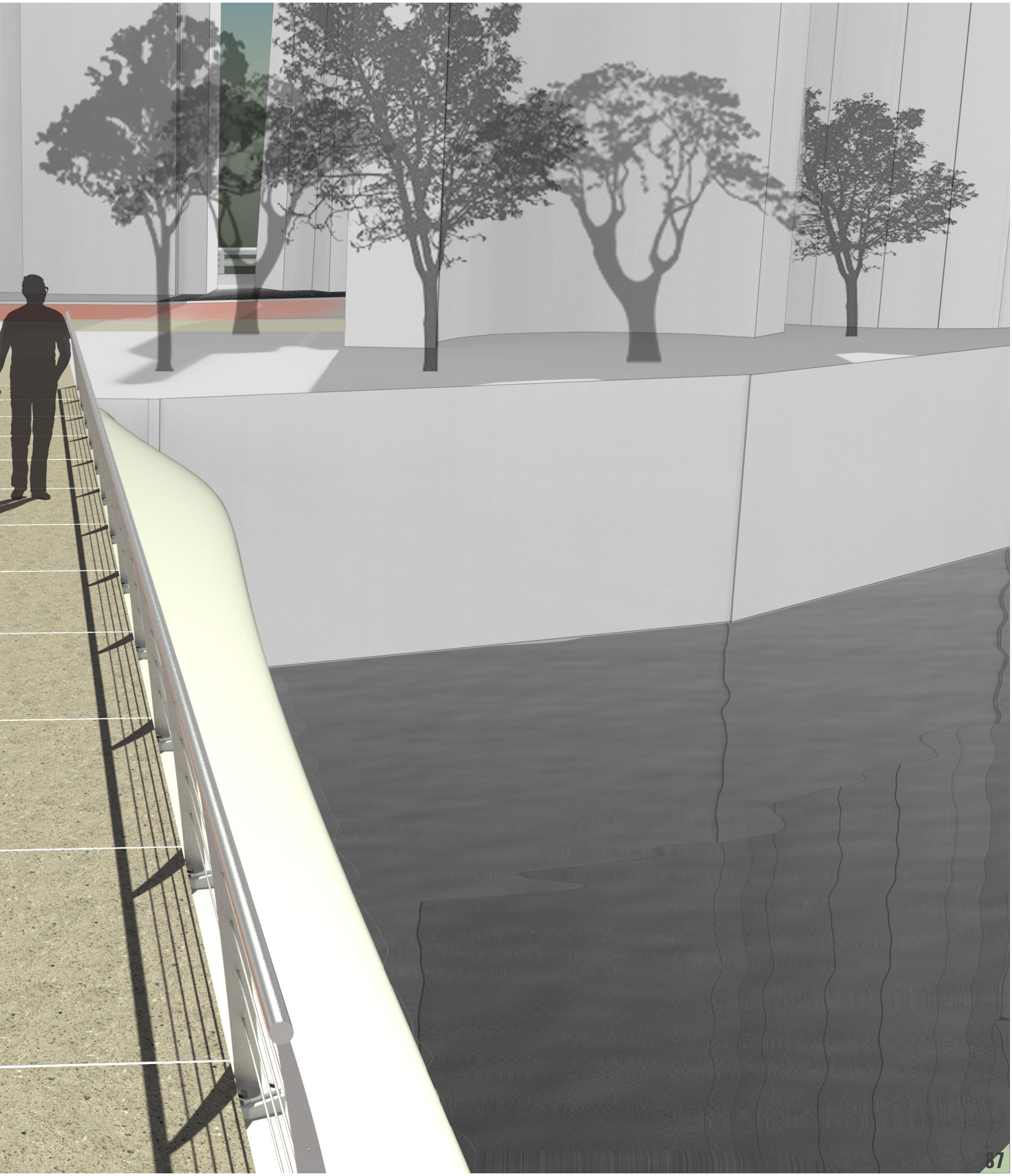












5.

EVALUATION

The viability and effectiveness of the concept must be evaluated, to predict how it could perform in its context. Within this project scope, no detailed quantified data was generated to represent the product structural and environmental performance. Instead, approximations are shown and a qualitative analysis.

Further development is required to make this concept reality, as is explained in this chapter.

STRUCTURAL ANALYSIS

In order to offer a commercialy scalable solution, it is important that the the bridge's structural performance is sufficient. Strict regulations make sure that a bridge will perform well in any context when subjected to extreme loads. In the Netherlands, any bridge that operates in a public space must comply with NEN-EN 1991-2, 2003, which is sufficient for European norms too.

To estimate whether the bridge can comply with these norms, a finite element analysis (FEA) was done. It is important to note that the analysis that was performed can't give an accurate calculation of the stresses and deflection that would occur in the bridge, because of the following two reasons:

- For each bridge that is built, the performance is dependent on the blade models that are used, the span of the bridge and the age of the blades. Therefore, for each individual bridge, a new calculation must be done to make sure the bridge can safely be built.

- An accurate FEA of this model is very complex due to the amount of different materials and the extreme length-to-thickness ratio of the materials. This requires a lot of time and expertise and is outside the scope of this project.

However, it is important to predict whether the structure is at all possible, and so a rough approximation of the results is desired. According to Pavlovic (2018), for a slow traffic bridge, the two most important structural factors to consider are the maximum deflection and the fundamental frequency of the bridge.

The maximum deflection was calculated with an FEA, using a heavily simplified CAD model of the blades and material composition. The maximum allowed deflection of the span is 1/200 of the span length, in this case 125 mm.

The analysis showed that with a solid FRP shell, the maximum deflection would be 83.5 mm, well below the limit. Because the shell consists of both FRP material and balsa wood, a calculation was also done in which the entire shell was composed of balsa. In this case, the maximum deflection was 163 mm, which too much to comply with the NEN norms.

The full FEA analyses can be found in appendix .

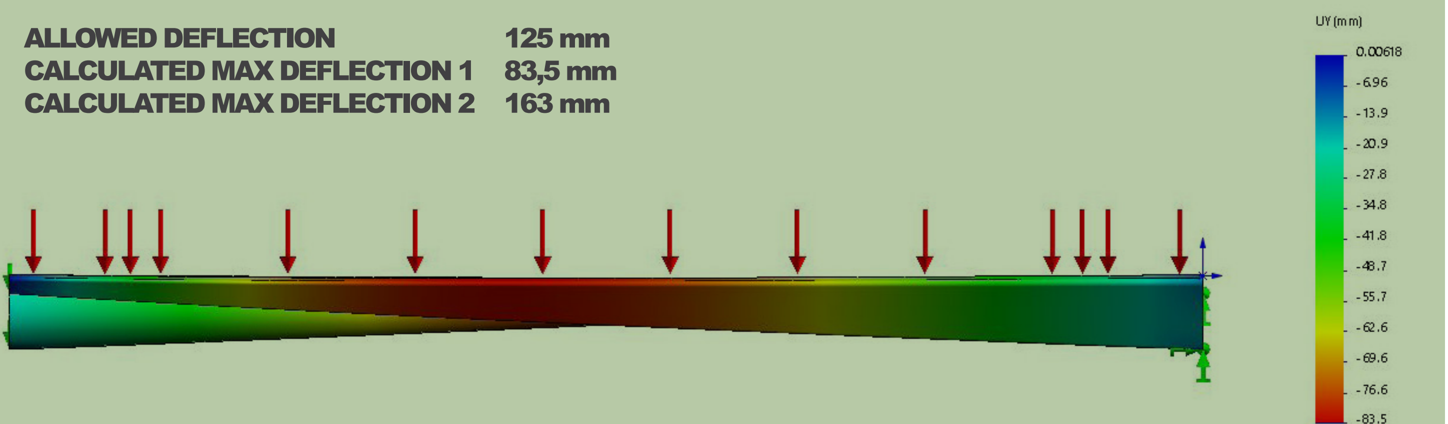


Figure 61: FEA analysis

As for the fundamental frequency of the bridge, the following applies:

The fundamental frequency without loading should be more than 3.0 Hz (WSDOT, 2009).

In the lateral direction, the fundamental frequency of the pedestrian bridge shall be greater than 1.3 Hz.

Unfortunately, with the materials available within this project (SolidWorks student license), a fundamental frequency FEA was not possible. Because of the complexity of the design, a mathematical calculation of the fundamental frequency was not within the scope of this project.

If, in the future, an analysis would show that the fundamental frequency does not meet the requirements (e.g. is too low), this could be solved by adding weight or pre-stressed cables to the structure, changing the deck dimensions etc.

It is clear that the blade's performance reaches the limits of the NEN norms, it could just be sufficient or come short. Because of the huge insecurity in the analysis, it is important that more calculations are done, using official blade CAD models. Additionally, a non-destructive analysis (accelerometer, strain gauges etc.) of an end-of-life blade would be required to understand the performance of an EoL blade. If the performance is insufficient, the norms can still be met, for example by one of the following solutions:

- Using a larger blade to cross the same span
- Applying girders or a thicker deck to improve the overall stiffness of structure
- Extra unidirectional GFRP material can be added to the spars to increase the blade stiffness
- Add a pier halfway down the bridge span. The roots of the blades may be very suitable for this

Figure 62: Fundamental frequency problems

ENVIRONMENTAL IMPACT

Designing a bridge that uses EoL wind turbine blades as construction elements proved to be a valid way to reduce the blade waste problem. It is good to have a solution for this problem, but at the same time, it is important not to create problems in other fields. During this project, the opportunity has risen to introduce the world to an entirely new way of designing bridges. Across the entire project, designing for the Circular Economy has been considered. All components, materials and joints in this bridge were carefully selected and designed.

In order to understand how the environmental impact of the bridge compares to its competitors, they were analysed in a qualitative way. Doing the comparison in a quantitative way (with a life cycle assessment) could provide strong data and was therefore considered. However, such an assessment relies heavily on the scope/boundary conditions that are chosen. In this particular case, the scope of material sourcing of the structure can be interpreted in many different ways, which would have extreme consequences for the results. Because of the influence of the assessor and the conflicting interests that may arise, this is not a desirable approach for this project.

As shown in the previous chapters, the bridge consists of the following components:

- Blades
- Deck
- Parapets
- Connectors
- Bolts

Additionally, to install the bridge, the following components are needed:

- Abutment
- Transition slab
- Support
- Piles (if necessary)

These four components are roughly the same for different bridge types and can therefore be neglected in the comparison. Because no piers exist in the current design, only the superstructure, deck and parapets are compared.

Traditionally, bridges are made of stone, timber, steel and concrete. In most modern bridges, the beams, girders and deck are made of steel, reinforced concrete or a combination of the two (Lin & Yoda, 2017). Due to recent developments, FRP and ultra high strength concrete are increasingly used in pedestrian bridge superstructures.

Steel, (ultra high strength) concrete and FRP bridge structures are very different in amount of required material and environmental impact (embodied energy, CO2 footprint, toxicity, recyclability etc.). As an example, Steel currently has 40-44% recycled content, whereas concrete is only applied in amounts of 12,5-15% in the current supply and thermosetting GFRP materials are not recyclable (CES EduPack, 2018). The environmental impact reduction that the Bridge of Blades offers varies, depending on what it is compared with.

In any case, by reusing the blades in the bridge superstructure, the beams and girders are no longer required. This means that, regardless of the material, environmental impact is reduced. The processing of the blades to be used in the bridge requires only cleaning, sawing, laminating the tips, and sanding the surface for adhesive bonding. Although no quantitative assessment has been made, it is highly likely that the environmental impact of these processes is much smaller than the production of a new structure.

As for the rest of the superstructure; the deck, parapets and connections, these components have been carefully designed to be separable and re-usable in the circular economy.

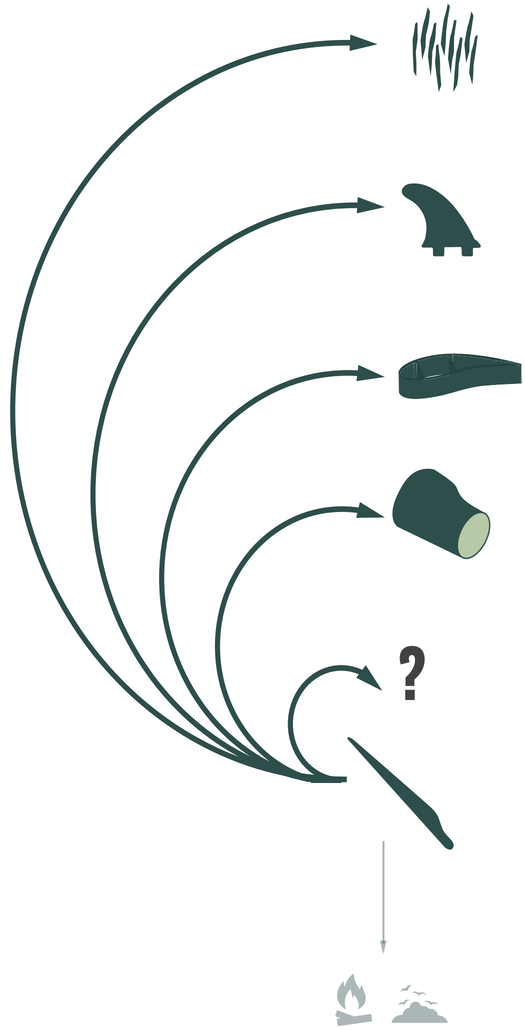


Figure 63: Circular Economy (Adapted from the CE model by the Ellen MacArthur Foundation)

In addition to the reuse of the blades in the bridge structure, all other components and joints were carefully picked and designed to allow for re-use of materials. At the end of the lifespan of the bridge, all materials can be separated and find a new use in the circular economy.

6.

CONCLUSION

To finalize this report, the project is evaluated. A reflection of the process is shown, that could be interesting for similar projects.

Finally, recommendations are given for two markets. A summary is given of the steps that need to be taken in order to further develop this project. Finally, recommendations for blade designers are given, to make sure the problems that were faced in this project can be avoided in the future.

PROJECT EVALUATION

This project was very interesting to do, because it was quite different from other Industrial Design Engineering projects. It was odd to start with an EoL material, that is of high quality, but at the same time difficult to process and therefore not valuable. This required the implementation of a new method, that could possibly be used by other designers in similar situations.

I have noticed in this project that materials that seem to have no value may offer surprising opportunities. Although the project seemed odd at first, I have approached this project the same as other design projects. The process was structured with analysis, ideation and concept development phases that sometimes happened simultaneously.

Maybe even more so than in other projects, I have combined multiple influences in the idea generation. Creative sessions were supplemented by literature analyses, interviews and rapid prototyping. In the idea development and choices, the process has led the outcome, which resulted in a project I was completely unfamiliar with.

Because I knew so little about both wind turbines and bridge design, I contacted many experts. Multiple architects, wind turbine (blade) designers and civil engineers were consulted at Delft University of Technology. I've also had a number of interviews with experienced companies in the field of waste management, FRP bridge design and decking producers. This was extremely valuable to the project.

RESPONSES

By doing these expert sessions, I have also gotten a lot of feedback on the design and the viability of the project. The reactions were generally very positive and it was clear that the approach of an industrial designer can offer benefits compared to civil engineers/architects etc.

On March 15, I was given the opportunity to present the idea at the 'Bruggendag'. It was clear that the topic of re-using materials in bridge constructions was new to the audience. However, the reactions were very positive and gave the impression that the Bridge of Blades has serious potential.

In the end, I think the critical and creative input from an outsider can help to create radical innovation in any market. Realizing the Bridge of Blades still requires a lot of work, but based on the positive feedback from people with different expertises, I think the idea has a lot of potential.

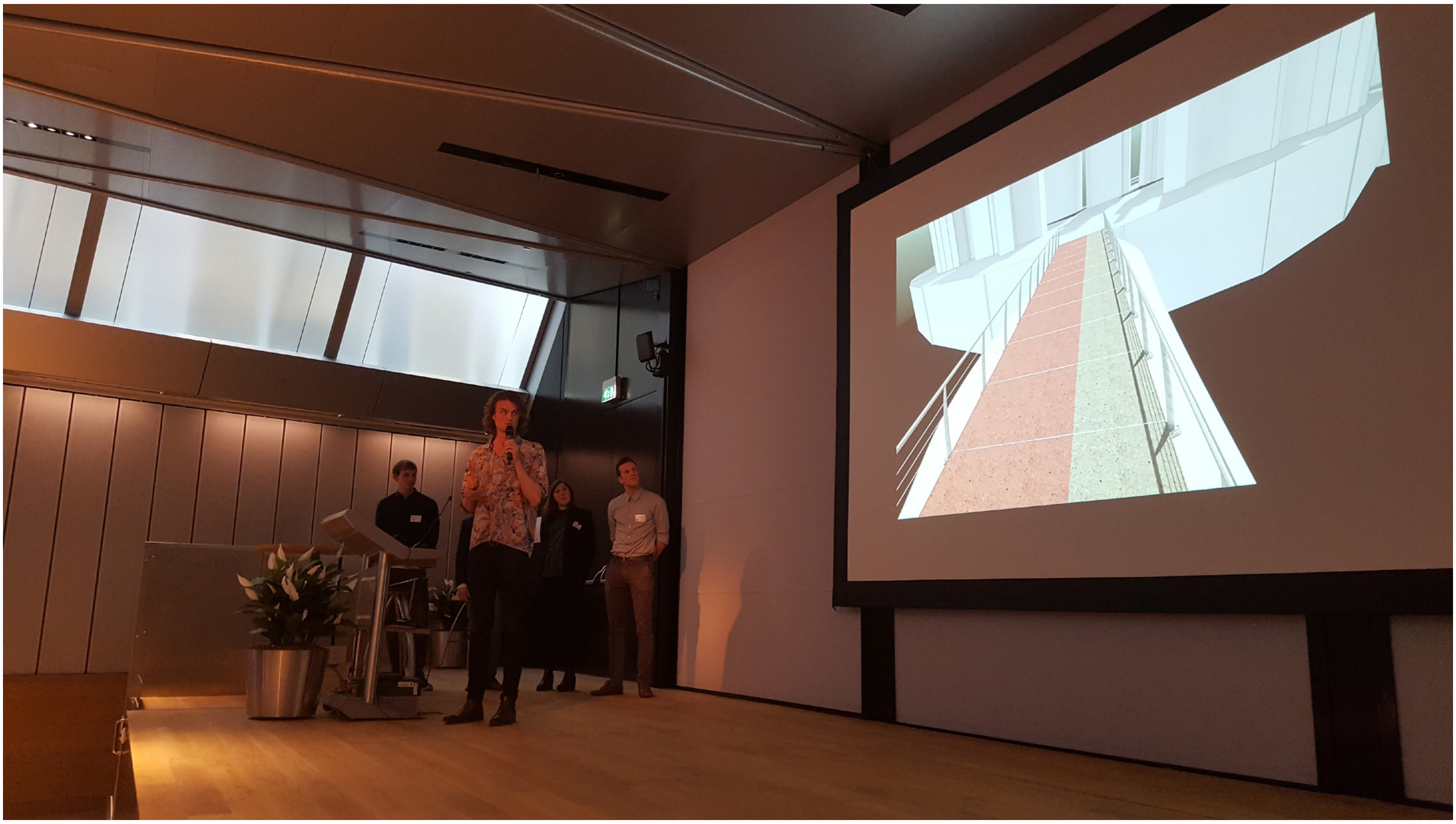


Figure 64: Presenting at the ‘Bruggendag 2018’ (Image courtesy: Joris Smits)

Figure 65: Audience at the ‘Bruggendag 2018’

RECOMMENDATIONS

BRIDGE OF BLADES DEVELOPMENT

Because of the nature of this project, the resulting design details are not final. There are still a number of issues that should be considered to finalize the design and make it suitable for (large-scale) production.

Most importantly, the structural analyses need to be improved to get a better indication of the bridge performance. Because each bridge is different, no definite result can be given for all bridges made with blades. One case study could be done to perform the necessary analyses.

The maximum deflection under load should be found. This could be done by means of an FEA. Using the right CAD models, the fundamental frequency must also be found to meet the NEN norms. Also, the influence of the wind on the structure has not yet been investigated. Due to the size and shape of the bridge, this is important to do. The best way to discover the influence of the wind is to perform a wind tunnel test, using a scale model.

As mentioned before, expansion and contraction due to temperature changes have also not yet been considered in the design. These are important influences and should be integrated in a more detailed design.

When the design is finalized, it is important to calculate the production costs. As mentioned in this report, the expectation is that the bridge will be relatively cheap to manufacture. It is not within the scope of this project to calculate these costs, which is a very complex calculation that involves material, transport, production, installation, environment preparation, testing costs and more. It is recommended to do these calculations in cooperation with a construction company, that can accurately estimate most of the involved costs.

During this project, the possibility to apply this product in developing countries was encountered. This could be very interesting because a second hand market in blades exists there and regulations are very different from the European norms. Here, costs and production facilities have great influence on the viability of such a project.

Finally, it is noteworthy that in the current design not the entire blades are used. Some thought has been given to find new uses for the blade tips. If proven to be possible, some of the blade tip material can be used in the connectors. Additionally, a tip could be placed on the ground next to the bridge, showing information about the origin of the bridge materials. This way, interested pedestrians can be informed about the problem we are facing and further fuel debate about material use in the technologies of the future. In order to maintain a functioning circular economy for wind turbine blades, it is recommended that more design projects are done to find uses for all parts of the blades across many life cycles.

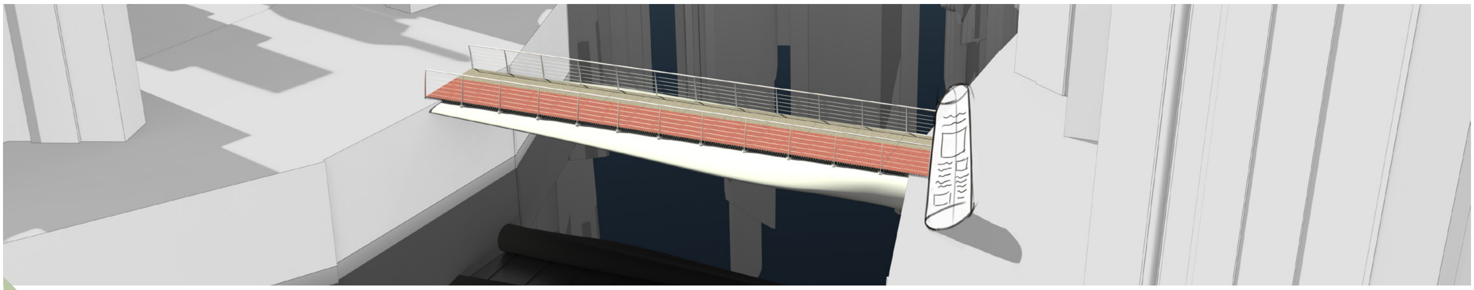


Figure 66: Blade tip as information pillar

FUTURE BLADE DEVELOPMENT

Although it is nice to have found a solution to the blade waste problem, it is just as important to prevent problems like these in the future. Therefore, blade designers and manufacturers must start considering the end-of-life of the products they produce, as is common in other markets.

Some developments have been discussed during this project. A very promising development is the potential use of thermoplastic resins in blades. These could allow for efficient recycling of the blades after their intended use, because the resins can be melted. It is likely that this will (at first) only be applicable to the shell of the blades, while the spars are still made with thermosetting resins (Teuwen, 2018). This has the potential to recover the resin and fiber sheets from the shell and produce construction beams from the spars.

Because of the increased costs and complexity of using such resins, it will take quite some time before this is realistic. In the meantime, other solutions can be considered. For example, the blades can be designed with a second life as a bridge in mind. Making the tips easier to remove can improve the processability into a bridge, while at the same time making transport easier. A more effective connection system can also be designed, that are produced when the blades are first made. This way, reusing the blades will be much easier.

Currently, the relatively low stiffness of the blades (compared to strength/durability) may prevent them from being used in other applications. By increasing the spar thickness, this can be resolved. Post-processing of the blades by laminating material onto the spars can make this possible.

Thankfully, the waste problem is becoming more apparent amongst blade designers. The responsibility of disposing the blades is increasingly put in the manufacturer's hands (financially). The largest global blade manufacturer LM Wind Power already has a small design team working on the subject. With a bit of luck, wind turbine blades may ave their share in the circular economy in the near future.

REFERENCES

Adaramola, M. (2014). *Wind Turbine Technology: Principles and Design*. CRC Press.

Albers, H. Greiner, S., Seifert, H. & Kühne, U. (2009). *Recycling of Wind Turbine Rotor Blades.* Institut für Umwelt und Biotechni: Hochschule Bremen.

Andersen (2015). *Wind turbine end-of-life: Characterisation of waste material.* Faculty of engineering and sustainable development: University of Gävle.

AVK (2010). *Sustainability of Fibre-Reinforced Plastics*. AVK - Industrievereinigung Verstärkte Kunststoffe e. V.

Arkema Group (2017). *A wind turbine blade recyclable with Elium®*. Retrieved December 8, 2017, from https://www.youtube.com/watch?v=UQ1Vo7FcW44.

Asmatulu, E., Twomey, J. & Overcash, M. (2014). Recycling of fiber-reinforced composites and direct structural composite recycling concept. *Journal of Composite Materials 2014 Vol. 48(5)* 593–608.

BBC (2017). The *Biggest Energy Challenges Facing Humanity*. Retrieved December 22, 2017, from http://www.bbc.com/future/story/20170313-the-biggest-energy-challenges-facing-humanity

Beauson, J., Bech, J. I., & Brøndsted, P. (2014a). *Composite recycling: Characterizing end of life wind turbine blade material.* In Proceedings of 19th International Conference on Composite Materials

Beauson J, Lilholt H, Brondsted P. (2014b) Recycling solid residues recovered from glass fibre-reinforced composites – a review applied to wind turbine blade materials. *J Reinf Plast Compos 33*: 1542–56.

Beauson, J. & Brøndsted, P. (2016). *Wind Turbine Blades: An End of Life Perspective. 421-432*. 10.1007/978-3-319-39095-6_23.

Bouw Advies Toegankelijkheid (2017). *Voetpaden voor iedereen.*BAT: Utrecht.

Buijs (2012). *The Delft Innovation Method: A Design Thinker's Guide to Innovation*. TU Delft.

Breakbulk (2016). *LM Power delivers record turbine blade*. Retrieved October 27, 2017, from http://www.breakbulk.com/lm-power-delivers-worlds-longest-blade/

Brøndsted, P., Lilholt, H. & Lystrup, A. (2005). Composite materials for wind power turbine blades, *Annual Review Material Research, No. 35*, 505–38.

BRS (n.d.). *BRS Decksystems brochure.* Retrieved February 9, 2018, from https://brs.nl/downloads/

Callister, W. D. (2010). *Materials science and engineering: An introduction*. New York: John Wiley & Sons.

CBS StatLine (2017) *Windenergie op land; productie en capaciteit per provincie.* Retrieved February 23, 2018, from http://statline.cbs.nl/StatWeb

Chady, T., Sikora, R., Lopato, P., Psuj, G., Szymanik, B., Balasubramaniam, K., Rajagopal, P. (2016). Wind Turbine Blades Inspection Techniques. *PRZEGLĄD ELEKTROTECHNICZNY, ISSN 0033-2097*, R. 92 NR 5

Conenor (n.d.). *Recycling Thermoset FRP-Waste*. Retrieved December 14, 2017, from http://www.conenor.com/recycling-thermoset-frpwaste/

De Jong, S. (2018). *[personal communication]*

Fietsersbond (2004). *Over breedtes van fietspaden.* Ketting 173, p 4-6.

Diepeveen, N. (2017). *[personal communication]*.

Dolan, S.L. & Heath, G.A. (2012). Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power. *Journal of Industrial Ecology, vol. 16*, no. 1

EU Publication Office (2017). *Circular Process for Eco-Designed Bulky Products and Internal Car Parts.* Retrieved October 2, 2017, from http://cordis.europa.eu/project/rcn/210181_en.html

EWEA (2012). Research note outline on recycling wind turbine blades. The European Wind Energy Association, Brussels.

EWEA (2015). *Wind energy scenarios for 2030*. The European Wind Energy Association, Brussels.

GenVind (2014). *Mission*. Retrieved October 26, 2017, from http://genvind.net/Legal/Mission_EN.htm

Halliwell (2006). *End of Life Options for Composite Waste Recycle, Reuse or Dispose?* National Composites Network.

How It's Made (n.d.). *Wind Turbine.* Retrieved October 27, 2017, from https://www.sciencechannel.com/tv-shows/how-its-made/videos/wind-turbine

Job, S., Leeke, G., Mativenga, P.T., Oliveux, G., Pickering, S. & Shuaib, N.A. (2016). *Composites recycling: Where are we now?* Composites UK

Jüngert (2008). *Damage Detection in Wind Turbine Blades using two Different Acoustic Techniques.* 7th fib PhD Symposium in Stuttgart, Germany.

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

Kidd, Matthew & Judge, Ryan & Jones, Stephen. (2016). Current UK trends in the use of simple and/or semi-rigid steel connections. *Case Studies in Structural Engineering. (6)* 05.004.

Lin, W. & Yoda, T. (2017). *Bridge Engineering: Classifications, Design Loading, and Analysis Methods*. Butterworth-Heinemann: Oxford. ISBN 9780128044322

Liu, P. & Barlow, C. (2015). *An update for wind turbine blade waste inventory.* In: EWEA Annual Conference. EWEA, Paris.

Liu, P. & Barlow, C. (2017). Wind turbine blade waste in 2050. *Waste Management 62*, 229–240.

Mara, V. (2015). *Development of connections for fibre reinforced bridge elements and an analysis of sustainability.* Chalmers University of Technology: Gothenburg, Sweden.

Neaco (2016). *Neatdek 188. Retrieved February 8, 2018, from https://neaco.co.uk/downloads/*

Pavlovic, M. (2017). *Joints in FRP structures*. CIE5128, Lecture 10: Delft University of Technology.

Pavlovic, M. (2018). *[Personal communication].*

Peeters, J. (2018). *[Personal communication].*

Peeters, M., Santo, G., Degroote, J. & Paepegem, W.V. (2017). The Concept of Segmented Wind Turbine Blades: A Review. *Energies 10*, 1112.

Qian, Z. Chen, C., Jiang, C. & de Fortier Smit, A. (2013). Development of a lightweight epoxy asphalt mixture for bridge decks. *Construction and Building Materials (48)* 516-520, ISSN 0950-0618.

REFERENCES

Red, C. (2014). *The Outlook for Thermoplastics in Aerospace Composites*. Retrieved March, 18, from https://www.compositesworld.com/articles/the-outlook-for-thermoplastics-in-aerospace-composites-2014-2023.

Rijkswaterstaat Dienst Infrastructuur (2009). *Standaarddetails voor betonnen bruggen.* Rijkswaterstaat: NBD-00730.

Sayer F, Bürkner F, Blunk M. (2009) Influence of Loads and environmental conditions on material properties over the service life of rotor blades. *DEWI Mag 34*: 24–31

ten Busschen, A, Bouwmeester, J., Bosman, P. & Schreuder, P. (2016). *Hergebruik van thermoharde composieten -Onderzoek van mogelijke producten en toepassingen.* Windesheim: Zwolle.

Teuwen, J. (2017). *[personal communication]*

WindStats (2018). *Statistieken.* Retrieved February 5, 2018, from https://windstats.nl/statistieken/

Wiser, R., Hand, M., Seel, J. & Paulos, B. (2016). *Reducing Wind Energy Costs through Increased Turbine Size: Is the Sky the Limit?*. Electricity Markets & Policy Group: Berkeley Lab.

WSDOT (2009). LRFD Guide Specifications for the Design of Pedestrian Bridges: Final Draft. NCHRP 20-07 TASK 244

Yang, Y., Boom, R., & Irion, B., van Heerden, D.J., Kuiper, P. & de Wit, H.(2012). Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification. 51.* 53–68. 10.1016/j.cep.2011.09.007.