BLADE BARRIER

Sound barriers from decommissioned wind turbine blades

Master Thesis Adriaan Przespolewski

SUPERUSE

TU Delft

BLADE BARRIER

Sound barriers from decommissioned wind turbine blades

May 2022

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

Graduate Student
Adriaan Przespolewski

Chair
Prof. Dr. Balkenende, A.R.
Delft University of Technology
Department of Sustainable Design Engineering

Mentor
MSc. Willemen, A.M.
Delft University of Technology
Department of Design, Organisation and Strategy

Company Mentor
MSc. De Krieger, J.
Blade Made & Superuse Studios
Architect, Partner and Head of Interventions

Report Summary

This report covers the development of the Blade Barrier: A sound barrier constructed using decommissioned wind turbine blades.

The ever-growing wind industry faces a composite waste problem. Wind turbine blades only last a few decades, and are difficult and therefore not economically desirable to recycle.

One proposed solution to this issue, is to repurpose the blades. Over the last years, several small-scale projects (such as playgrounds and urban furniture) have been realised that show how these high-end objects can serve new purposes successfully.

As the wind industry has grown exponentially over the last two decades, the resulting composite waste stream is expected to follow this same growth in the coming decades. For this reason, more impactful solutions are required.

To this end, the Blade Barrier is proposed by Blade Made, a spinoff startup from Superuse Studios. A roadside sound barrier has the potential to incorporate a large number of blades into its construction, and extend their life-in-service for another two to five decades, simultaneously eliminating the need for virgin materials.

The blades represent the starting point of the project, while the sound barrier is the final goal. The project is about connecting these two points through various research and design methods. Analysing the blades offers an understanding of the opportunities and limitations of the material, while research into sound barrier design yields insights into what makes a well-performing barrier. Throughout the project, the expertise of experts has been consulted to be able to expand this understanding and make well-grounded design decisions.

Based on this research a design vision is formulated, focussing on aesthetics, circularity and scalability. After the creation of three concepts, the idea for a *green urban corridor* was selected. This concept has the potential to transcend the simple idea of a sound barrier, and fulfil multiple purposes. It could offer a cleaner and more biodiverse urban area, and create an enjoyable surrounding on the resident side of the barrier.

Through an iterative process, this concept was further developed. The result is a design that is adaptive to the availability of blades and the requirements of the barrier location. Acoustic simulations are used to validate the performance of the design, and physical prototyping steps were taken in order to elaborate upon the production process. Vegetation is incorporated into the design to enhance its aesthetics and acoustics, and to stimulate biodiversity.

The design is applied to a location in Rotterdam to show how it integrates within the urban environment. The flexibility of the design enables it to be constructed in various different locations with varying types of blades. This way, it offers a solution to the blade waste problem anywhere on the planet.

The design was presented to the wind industry at the 2022 WindEurope conference in Bilbao. The design was received well there, and several parties are currently in touch with Blade Made to explore the possibilities for the construction of a Blade Barrier.

To this end, the report concludes with several recommendations toward the realisation of the design.

Acknowledgements

This project marks the end of nearly seven years at the TU Delft. During this time, I have been able to develop myself on a personal and professional level thanks to the many opportunities that I have been offered. Studying in England for a semester, and being a full-time part of the Delft Hyperloop team are only a few of the wonderful adventures that I got to experience.

I am very grateful for this, and would like to use this page to thank a few people that supported me along the way.

Family and friends
Thanks to my mom, dad and brother for everything, and always encouraging me to try new things.
I am lucky to have lovely friends who are always ready to help out or have fun.
During most of my studies, I lived with some great people at the Buitenwatersloot in Delft. Thank you guys and gals for this unforgettable time.
Finally, I am unable to express how amazing my girlfriend is.

Project-specific
Maurits Willemen: For your clear and to-the-point coaching. Our conversations helped me greatly to prioritise, get inspired and find direction.

Ruud Balkenende: For your razor-sharp feedback and new perspectives on various facets of the project. Your expertise has helped me to challenge myself to dig deeper.

Jos de Krieger: For helping me through this process in which so many things were new to me. You were always there to help out and answer any question that I had.
Thanks to all at Superuse and Blade Made for welcoming me into the wonderful office. I hope to see you all again in the future.

I could not have finished this project without the help and input of many others.
Thanks to: Jelle Joustra, Martin Tenpierik, Arthur van der Harten, Joris Smits, Stijn Speksnijder, Silvia Viola, Aidan Wyber, Albert ten Busschen, Meike Kolthof, Rieneke van Noort, Tonny Wormer, Jan-Willem de Laive, Joost Tielken, Casper van Alfen, Van der Jagt Sloopwerken, Jaco van Herk, Hessel Klein Schiphorst and more.

Table of Contents

Figure I: Wind turbines being decommissioned (WindEurope, 2020)

1. General introduction

Context
Since the 1970's, wind turbines have become iconic in the shift toward renewable energy. The wind energy sector is expected to continue to grow exponentially in the coming years, with a projected sevenfold increase in offshore wind capacity in the coming decade (Global Wind Energy Council, 2021).

In recent years it has become clear that along with the solutions that wind energy offers, new problems have also arisen (Grantham Research Institute, 2018).

One major issue is the fact that wind turbines generally have a lifespan of 20 to 30 years (Beauson, 2014; Liu & Barlow, 2017; SmartPort, 2020). Once a turbine reaches the end of its service, it is decommissioned and often replaced by new - and generally larger - models (GWEC, 2021). This phenomenon, combined with the exponential growth of the industry, results in an ever-growing stream of waste materials (SmartPort, 2020). For many of these materials - such as iron, steel and copper - recycling capacity is widely available (Tang, 2021). The problem lies with the blades.

Problem description
Wind turbine blades are designed to handle the extreme forces that result from gravity, wind and rotation. The blades are required to be stiff, yet lightweight. Therefore, they are generally made from composite materials. They comprise various materials, with strong permanent bonds. While composites offer unique material properties, they simultaneously complicate recycling at the End of Life (EoL). Recycling the blades is possible, but complex. The capacity for reprocessing the material is small, and the recycled material does not offset the costs (Oliveux, 2015). This results in a waste stream that has yet to find a proper destination. In some parts of the world, they directly end up in landfills (Tang, 2021).

As sustainability gradually becomes the norm, industries are under public and political pressure to abide by environmental laws and green principles. It is therefore reasonable to expect companies in the renewable energy sector to have sound plans to mitigate the EoL issues caused by their activities.

The root of this problem is the same one that causes issues across most industries globally: the linear economy. The blades have been designed through a 'make, use, dispose' framework. As material shortages are encountered on one end of the line and waste problems on the other, a new framework has been proposed: the circular economy (Ellen MacArthur Foundation, 2021)

Current solutions
Superuse Studios is an architecture firm that has pioneered circularity in the built environment for nearly 25 years. Using locally reclaimed materials, they have been able to construct various buildings, interiors and installations (Superuse Studios, 2021).

One principle from the circular economy that Superuse has constantly applied, is to see value in existing products and materials that are often seen only as waste. They 'harvest' materials from various sources, and give them a new purpose. To minimise the impact made on the environment, materials are left 'as-is' as much as possible, utilising the existing material properties to their advantage. This process is unofficially called 'Superusing' by the company. So far, wind turbine blades have occasionally been applied in this way. Playgrounds, bus shelters and furniture are a few examples of this. These constructions are valuable as they offer proof that the blades can indeed be used to fulfill a great number of different functions. Next to this, they raise awareness concerning the problem with the EoL of composites. It should be stated that Superuse is not the only company to use blades in this way (Speksnijder, 2018).

On a purely material level however, these projects have made only a small impact in terms of the surplus of composite waste material from wind turbines. To make a significant dent in this waste stream, a scalable solution needs to be found. This is not a novel idea. Various designs and solutions have been proposed toward this end, such as shelters and slow-traffic bridges (Re-Wind Network, 2021). Due to various reasons however, such solutions have yet to make a significant impact on the problem.

Scalable approach
Superuse, and their spin-off Blade Made in particular, have made it their mission to work toward this scalable application of the blades. They have proposed the Blade Barrier: A road- or railside acoustic barrier predominantly constructed using decommissioned wind turbine blades.

Initial design impressions were made (Figure 1.1), and tentative cost calculations were done by their partner company GKB Groep (who have been involved with nearly all Blade Made projects). The proposed barrier had not yet been researched or developed further (De Krieger, 2021).

This barrier - if executed well - would promote the principles of reuse and circularity in people's minds, as millions of people would pass it every year. This could help the shift toward a more circular economy, and a world in which we are conscious of the resources we use and the impact that we can make. At the start of the project, the following design goal was formulated:

Design goal
"Design an acoustic barrier that offers a scalable application for decommissioned wind turbine blades. The design should be functional, reliable, realisable and reflect Superuse's values of circularity and sustainability."

The design will incorporate circular design principles as much as possible to maximise the sustainable potential of 'Superusing' windblades. For example, EoL considerations should be incorporated in any new design for these blades. Additionally, potential remaining parts of the blades not used in the design should be considered, so that the entire blade is accounted for.

Reading guide
This report describes a creative and iterative process where different processes run parallel, and much back-and-forth happens between design and research. These activities are partitioned into the four main parts that make up the bulk of the document:

Problem exploration
In this part, the problem of the waste stream is analysed. The causes and size of the problem are elaborated, and current solutions are discussed.

Research toward the solution
The next part covers the research with the design goal in mind. It is roughly split into two components: material and barrier related research. The first dives deeper into the composition and properties of the material, how circular and sustainable principles can be applied to the waste stream, and what can be learned from previous builds. The second examines barrier design considerations and acoustic principles. Finally, based on the conclusions from the research, design principles are formulated.

Concept development and selection
The third part covers the creative process from initial ideation to concept selection.

Development and final design
The final part describes the development of the chosen concept toward the final design. The design is further detailed, prototyped and evaluated.

Throughout the report, insights that are key to the project are summed up briefly in grey boxes like this one.

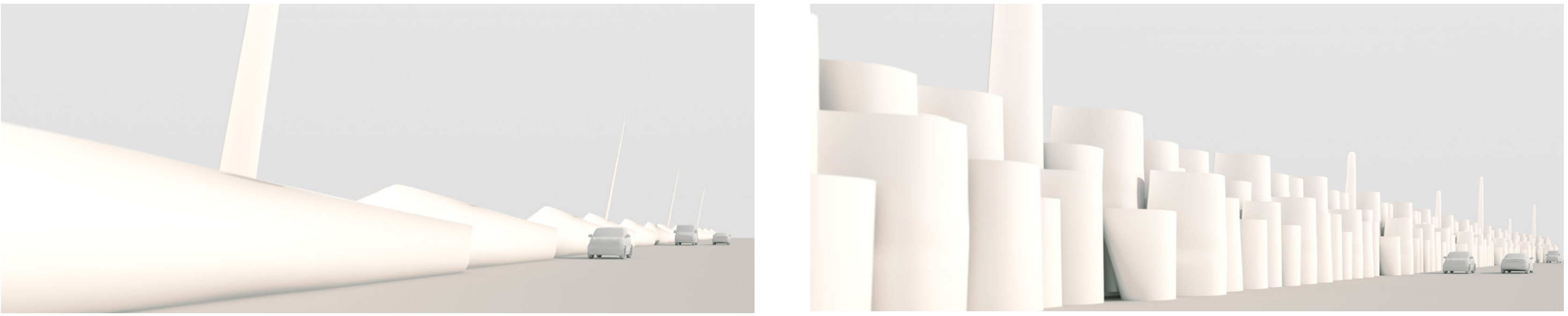


Figure 1.1: initial Blade Barrier impressions (Superuse Studios, 2021)

2. General method

This project - although in collaboration with an architecture firm - was approached primarily as an industrial design challenge. The first obvious reason is that this project concludes my curriculum at Industrial Design Engineering. The second reason is to offer the client company Superuse a new perspective on their Blade Made projects and approach these challenges with a different skillset.

The project is structured in four stages, following the double-diamond framework: Discover, Define, Develop, Deliver (Design Council, 2019). These stages are represented in the four parts of the report, and can roughly be grouped in a research phase and a development phase (see Figure 2.1).

My personal modus operandi during any project is to start designing from the very start. This helps to run into problems early on, and to discover new topics to be researched.
This is why - parallel to the research phase - a continuous cycle of design loops takes place.
Where relevant, additional research and evaluation methods are further elaborated throughout the report.
Following is a short description of the four stages.

Discover
The goal of this phase is to gain a thorough understanding of the context of the design challenge. It therefore entails research into a broad range of topics, such as material, locations, previous builds, acoustics, stakeholders, and design for the circular economy.

Define
The next step is to convert the findings into tangible insights, principles and requirements. This offers the basis for evidence-based idea generation and selection. The findings range from practical boundary conditions, to design principles for the intended aesthetics.

Develop
This phase is primarily focused on working toward feasible concepts that comply with the previously identified principles. Various creative methods are applied, such as How-To's, brainstorming, braindrawing and SCAMPER (Zijlstra & Daalhuizen, 2020). The method of tinkering (experimenting with the material to understand its properties, constraints and potential) from the Material Driven Design framework (Karana et al., 2015) is also applied in this stage of the project. This phase concludes with the concept selection.

Deliver
In the last phase, the chosen concept is developed toward the final design. A comprehensive CAD-model is created, and a prototype model is constructed. The results are evaluated and recommendations for further development and implementation are formulated.

It is my firm belief that creativity does not take place in a vacuum. Through expert interviews, brainstorm sessions and design reviews, fresh perspectives are applied to the development of the design. Details of these sessions are found in appendices F and G.

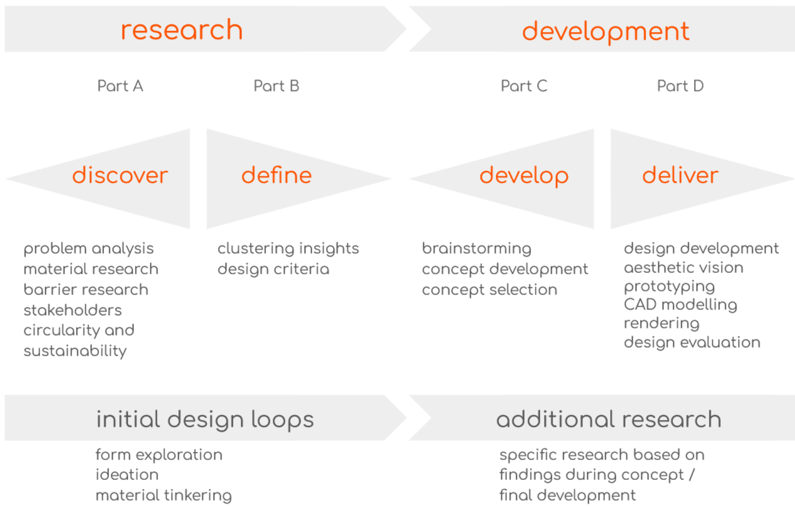


Figure 2.1: general project structure

PART A

Problem exploration

PART A

Problem exploration

The surplus of decommissioned wind turbine blades. That is the problem that this project aims to tackle.

The general introduction covers how this became an issue: the blades have not been designed and produced with the EoL in mind, and recycling capacity is insufficient to efficiently deal with this wastestream.
While the blades themseles have a high intrinsic value, the material is generally only seen and treated as waste. As a consequence, a great deal of potential for reuse and sustainability is wasted.

“How large is this waste problem? What currently happens to this material? What solutions have already been proposed, and how effective are these?”

The following part dives deeper into the problem space in order to answer these questions.


Figure II: Landfilling of turbine blades in Wyoming, USA (Bloomberg, 2020)

3. Blade waste

To be able to fully grasp the urgency of the issues, it is vital to look at the grand scheme of things. The following chapter deals with the size of the waste stream, and how the problem will evolve in the coming decades.

Worldwide, most blade waste is expected to come from onshore wind turbines in the immediate future. However, the offshore wind industry is expected to grow at a much higher rate (Liao, 2020).

In Europe, the offshore industry is already much more prominent. Recent research illustrates the projected growth of the offshore wind industry in the North Sea area (see Figure 3.1). This current waste stream is estimated to be around 500 tonnes annually (SmartPort, 2020), which translates to roughly 100 blades of various sizes.
Based on the research from SmartPort (2020) and Roelofs (2020), the following broad predictions can be made:

2030: 8000 tonnes per year, corresponding to 1600 blades annually.
2040: 25000 tonnes per year, corresponding to 4900 blades annually.
2050: 53000 tonnes per year, corresponding to 10500 blades annually.

These numbers illustrate the problem in the North Sea area alone. As wind farms are located throughout the world, this is a global issue. Recyclable wind turbine blades are currently in development that aim to prevent these EoL problems altogether (Siemens Gamesa, 2021; GE News, 2021). This is essential to stop the problem from becoming ever larger. However, it does not solve the problem of the existing blades. Moreover, it is expected that non-recyclable blades will continue to be installed for the coming two decades at least (Ten Busschen, 2021). It should also be noted that in this context 'recyclable' means that the material can be separated back to pure materials that can be used again for various purposes. Immediately reducing a blade back to its materials still means a loss in potential for the structure. Therefore, repurposing wind turbine blades as an intermediate step will remain the preferred option, even after this development has taken place.

Another expected development in the industry is the continued increase in wind turbine size. This is because constructing larger turbines proves to be more cost-efficient (Wiser, 2016). Future applications for these blades after decommissioning should be developed to take this growth into account.

Subsequent chapters will explore why this waste stream forms a problem on a material level, and what the current situation looks like in terms of End of Life.

Main insights:
- EoL applications of the material should aim to incorporate as many blades as possible, to overcome the surplus of blade waste.
- A scalable solution EoL application should incorporate the general increase in size of wind turbine blades.

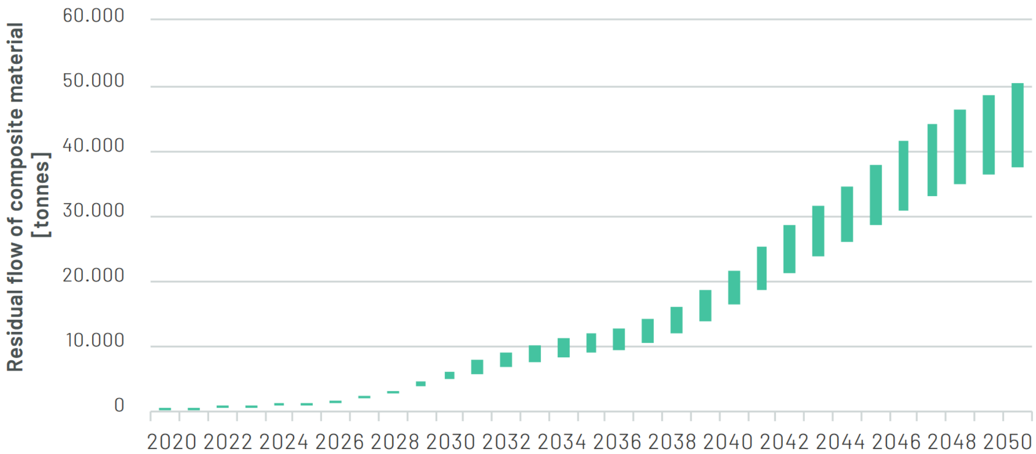


FIGURE 3.1: The projected size of the composite waste-stream coming from offshore wind farms in the Southern North Sea (SmartPort, 2020) (the increasing sizes of the bars represent increasing uncertainties in the future)

4. Blade anatomy

To be able to deal with the material surplus, it is essential to understand the material thoroughly. The following chapter offers an analysis of the construction of the blades and its various components.

Blade construction
As mentioned previously, wind turbine blades come in varying shapes and sizes. Therefore, many differences can be found in the build-up of the structures. Still, most blades follow a similar blueprint to achieve the desired properties. Figure 4.1 shows a typical breakdown of the blade construction.

The blades are mainly constructed using Glass Fibre Reinforced Plastics (GFRP). Glass fibre is what mainly gives the structure its lightweight, strong and stiff properties. To shape the fibres, a matrix material is needed. Thermoset polymers, such as epoxy and polyester, are used to this end. Thermosets are cost-effective and relatively straightforward in the manufacturing process. A sandwich structure is made using two layers of GFRP and a light core material, most commonly foam or balsa wood (Joustra, 2020). This sandwich is applied to a large part of the shell, as well as the shear webs (see Figure 4.2).

Figure 4.2: blade cross section (Bloomberg, 2020)

To further reinforce the structure and provide stiffness to the longitudinal axis, the spar runs along the blade. Near the hub, a thick layer of GFRP is used to create a strong root. Two halves of the blade are produced separately, and are joined together using strong adhesive bonds. Finally, the entire blade is finished using polyurethane surface coating to protect the internal components and prevent premature material degradation (Joustra, 2020).

Inherent recyclability issues
The large number of different materials, and strong permanent bonds contribute to the low recyclability of the blades. Moreover, due to the use of thermosets the GFRP cannot be melted or remoulded to form other products. The potential use of thermoplastics - that can be remelted - has been researched but not implemented on a significant scale yet, presumably due to higher costs and inferior material properties (Gardiner, 2017).

Blade geometry
Wind turbine blades are generally designed in a similar way to aeroplane wings: as an airfoil. One side of the profile is more curved than the other. Air flowing around the curved side is forced to travel faster, resulting in a lift force that causes the blade to move (Hansen, 2015).
The root is shaped in a cylindrical way for a strong connection to the hub. Next, the profile of the blade quickly starts to resemble the foil shape. The blade gradually narrows down toward the tip. These form variations give the blades their iconic shape. Even when segmented, their original purpose can easily be recognised.

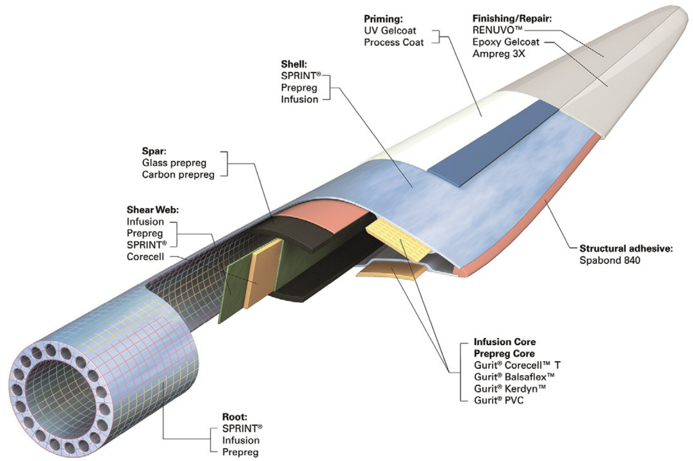


Figure 4.1: Common blade build-up (Gurit, 2021)

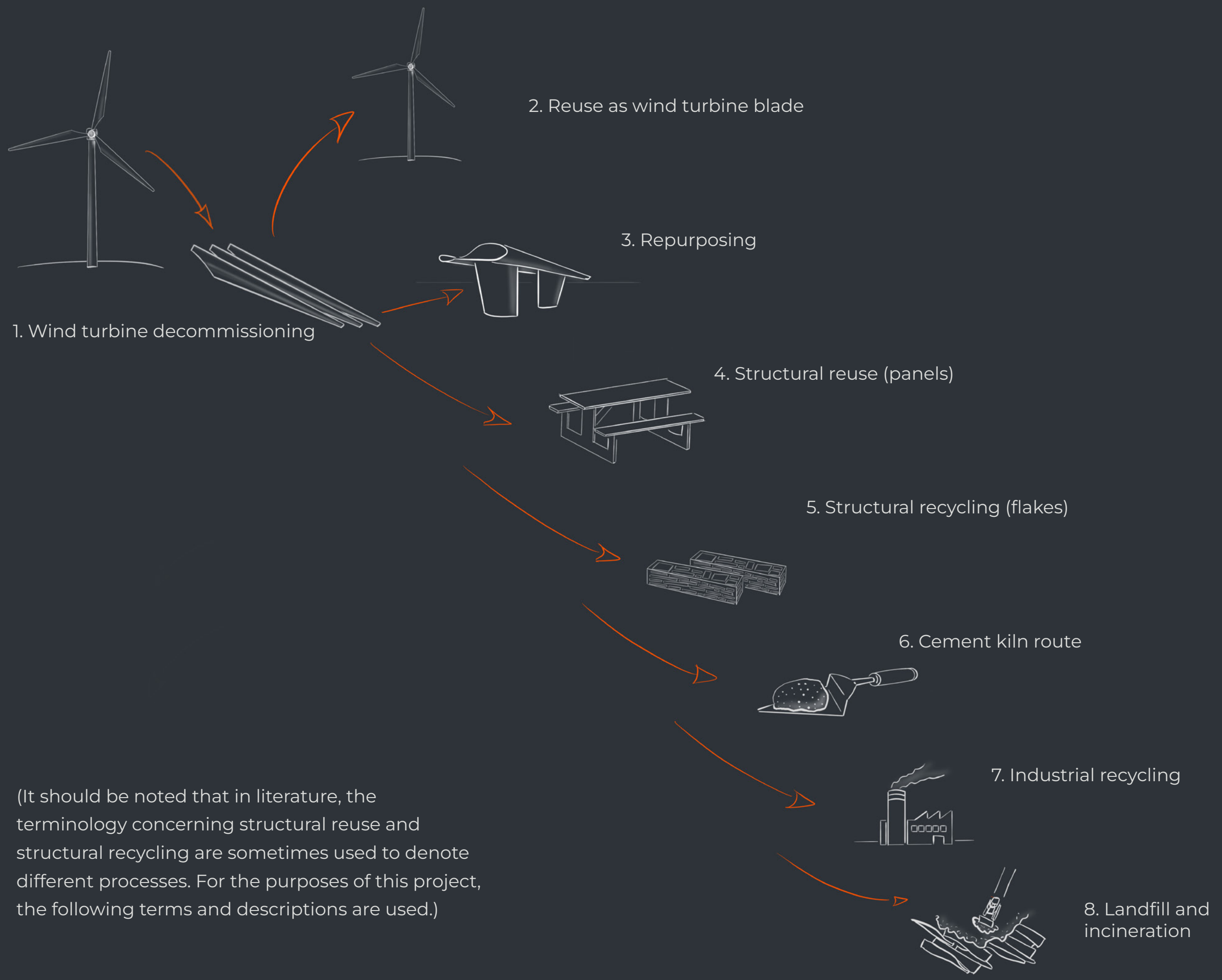
Main insights:
- A challenge for the design is to retain and utilise the valuable material properties, while suiting the blade to a greatly different purpose.
- Physical testing might be required to validate the material's suitability for the new application in terms of material degradation.
- The unique and therefore recognisable shape offers opportunities regarding aesthetics, while potentially posing challenges in terms of construction.

5. Current material journey

This chapter explores what currently happens to the material during its lifetime, and what End of Life solutions exist.

The material journey starts with the sourcing of the original virgin material. During its initial use, the blades are not only exposed to gravity, wind and rotation, but also to the elements (Tavner et al., 2012). Frost, heat, humidity and UV radiation are examples of the external influences that work on the blade in a slow but constant manner. The combination of all aforementioned factors causes the limited lifespan of the blades. However, the blades are generally not decommissioned for being close to failure. Most commonly, blades are replaced as manufacturers cannot guarantee proper performance after a period of 20 to 30 years (Ziegler et al., 2018), or the entire turbine is replaced for economic reasons (Ruitenburg, 2017). The result is that the vast majority of decommissioned blades are in sound condition, and offer great potential for reuse due to their high-end structural and material qualities. During the decommissioning process, or transport to storage facilities, damage to the blades might occur. Usually, they are cut to more easily transportable pieces (Kolthof, 2022). This means that edges get exposed and material degradation might occur.

From this point on, there are several routes that the material could follow (see Figure 5.1), and sometimes these processes occur in series.
Following is a description of these, generally ordered in preference from a Circular Economy standpoint (Campbell-Johnston et al., 2020).



(It should be noted that in literature, the terminology concerning structural reuse and structural recycling are sometimes used to denote different processes. For the purposes of this project, the following terms and descriptions are used.)

Figure 5.1: Current material journey diagram (own illustration)

Reuse as wind turbine blade
The most ideal scenario would be to use the blade again for what it has initially been designed and produced for. However, this has so far not happened on a significant scale due to a lack of standardisation and location-specific design choices (SmartPort, 2020). The increase in turbine size could further complicate this path.

Repurposing
Blades can serve a new purpose, either in their entirety or cut into major segments. The original functionality of the material - being a wind turbine blade - is still clearly discernible from the new application. Examples are the REwind urban furniture (Figure 5.2) and Wikado Playground in Rotterdam (Superuse, 2021), and the slow traffic bridge by Anmet in Poland (Mason, 2021). Blade repurposing is further elaborated upon in chapters 6 and 8.

Structural reuse
This route is defined as transforming the material into smaller segments that are no longer recognisable as coming from a wind turbine blade. This method is described by Joustra et al. (2021). As the resulting parts are relatively flat and rectangular in shape (see Figure 5.3), they can be used for various applications. Following this method, the previously mentioned researchers explored the design of a picnic table to evaluate the implications of this method for design with these segments.

Structural recycling
This method, as described by Ten Busschen (2020), is based on maintaining the desirable properties of the EoL composite (such as strength, stiffness and water resistance) as much as possible. This is done by machining the product into strips or flakes, while not altering the composite structure. Virgin material (approximately 30%) is added in the form of resin to create new products (see Figure 5.4). Flaking the structure does result in reduced strength and stiffness.

Cement kiln route
This is currently the most common method in Europe. Since 2012, it has become a widespread method of recycling the composite material (Ten Busschen, 2020). In this process, the material is processed so that fibres are mixed in with cement (Figure 5.5), while the resin is used as fuel during the process.

The method is expensive, and it could be argued that it does not benefit from the structural potential of the material.

One benefit of this method is that due to the added fibres, parts produced using this process are less likely to break or damage during transport (De Krieger, 2021).


Figure 5.2: Urban furniture by Superuse (2012)

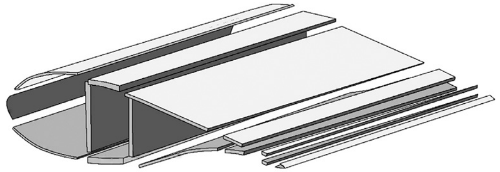


Figure 5.3: Proposed segmentation by Joustra et al. (2021)

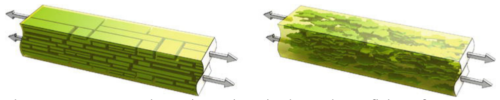


Figure 5.4: Beams and panels produced using strips or flakes of composite materials (Ten Busschen, 2020)


Figure 5.5: Shredded blades for cement production (Recharge, 2020)

Figure 5.6: A blade segment treated in a pyrolysis reactor (Larsen, 2009)

Industrial recycling
These processes use chemicals, often in combination with heat to break down the structure into raw materials (Mattsson et al., 2020), as seen in Figure 5.6. The available literature shows that the quality of glass fibres in current chemical recycling processes deteriorates significantly and can no longer be used for applications in which strength requirements are imposed on the materials (Larsen, 2009).

Landfill and incineration
These methods are the last resort when other paths are not feasible. In most countries across the globe, landfilling the blades is still legal. In Europe only four countries - Austria, Germany, the Netherlands and Finland - have so far banned the activity (Reuters, 2021). There are indications that a continent-wide ban on landfilling the blades is at hand (Tang, 2021). In the Netherlands, the incineration of blades is allowed if the transfer costs to the waste processing party exceed €205/tonne (SmartPort, 2020). Both methods pollute the environment while contributing little to compensate for this. Incineration has the benefit that power may be generated in the process (Ten Busschen, 2021).

Figure 5.7 shows the envisioned material flow based on all aforementioned methods.

Main insights:

- Decommissioned blades are generally in sound condition. Local damages can occur during the decommissioning process. The design should consider these potential damages.
- To use the material to its full potential, the different reprocessing methods could be performed subsequently, with the material only slowly degrading in terms of quality and application. The design should take this ‘cascade’ into account.

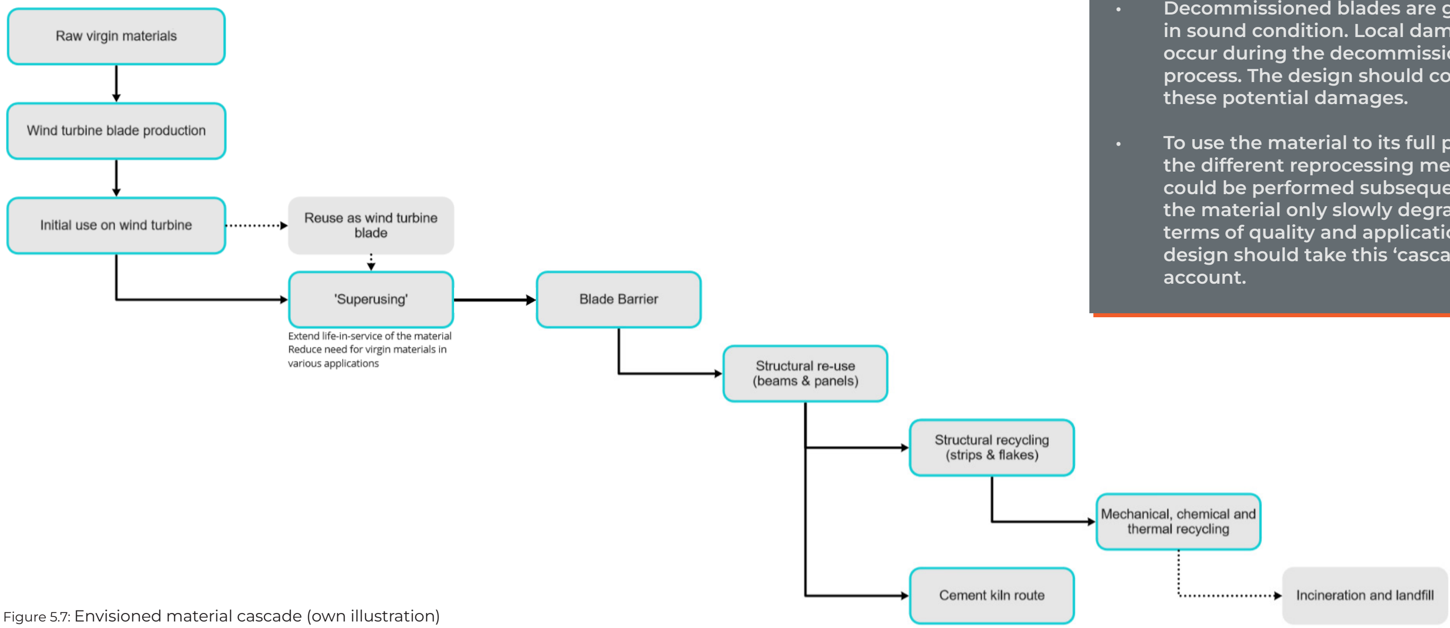


Figure 5.7: Envisioned material cascade (own illustration)

6. Proposed blade repurposing solutions

Throughout the past two decades, several designs have been proposed and realised that repurpose the blades. This chapter presents an overview of the most well-known projects, and offers an explanation as to why these have so far not succeeded in becoming more widespread.

Current projects

On several occasions, blades have been repurposed without being altered significantly. Only a new layer of paint and a foundational concrete block were required to create urban furniture and a store signpost, see Figure 6.1.

Apart from these, several playgrounds such as the Wikado (Figure 6.2) and a bus shelter were created. Siemens Gamesa was asked by the Danish government to repurpose one of their blades. This collaboration resulted in a bike shelter, as seen in Figure 6.3.

Urban furniture is a common use for the blades, as the material is frequently described as being 'vandal-proof'. Polish recycling company Anmet has created several pieces of furniture, often in combination with wood (see Figure 6.4). This company has also constructed the first blade bridge by connecting two blades together at their root, and placing the bridge deck on either side, as seen in Figure 6.5.

Alternative bridge designs have been proposed by Superuse Studios, the Re-Wind Network, Stijn Speksnijder and others.

The Re-Wind network, based in Ireland, has released a catalogue containing several proposed designs. These include several bridges, boardwalks, shelters (see Figure 6.6) and sound barriers. The Re-Wind sound barrier designs are discussed in further detail in chapter 12.

A diverse range of designs has been successfully realised. One striking similarity is that virtually all of these are still one-off projects. Even though these companies are open to scaling up the production, there is no application in existence that uses a large number (>100) of blades.

Figure 6.1: Store signpost in the Netherlands (Superuse, 2014)


Figure 6.2: Wikado playground in The Netherlands (Superuse, 2009)


Figure 6.3: Bike Shelter in Denmark (Siemens Gamesa, 2021)


Figure 6.4: Blade furniture (Anmet, 2021)


Figure 6.5: Slow traffic bridge in Poland (Anmet, 2021)

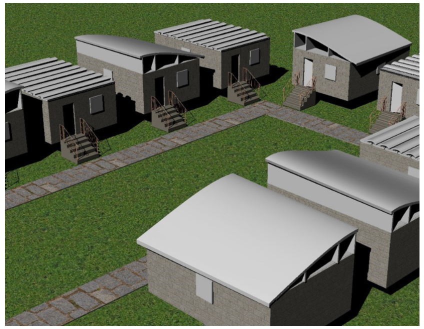


Figure 6.6: Proposed low-cost shelters (Re-Wind Network, 2021)

Simply put, the demand for applications like these has remained low, and the 'blade throughput' of these constructions is meagre. For example, for a relatively simple pedestrian bridge, a long process involving planning, permissions and finally construction is required, while the number of used blades remains low (bridge designs usually comprise two blades). Another limiting factor is that current bridge designs are horizontal, while for many locations a concave pedestrian bridge is required for traffic to pass underneath it (Speksnijder, 2021).

The potential for a Blade Barrier
The previously mentioned applications fail to make a significant dent in the waste stream due to two main reasons. Firstly, most designs incorporate only a handful of blades. Secondly, the designs have so far failed to be produced and replicated on a larger scale.

A promising direction to solve this is to design an application that incorporates a great number of blades in a single construction, that can simultaneously be scaled to fit the needs of various clients and locations.

An acoustic barrier lends itself well to this direction, as they span long distances and need to be vandal-proof and weather-resistant. Moreover, there is a steadily growing worldwide demand for these structures (Global Market Insights Inc., 2022). Blade Barriers offer an opportunity for governments to lower the ecological footprint of their infrastructure.

Location-specific requirements can be incorporated by designing standard modules, or custom solutions for a specific location feature. The unique shapes of the blades offer opportunities in terms of aesthetics and creating a more visually pleasing urban environment.

Main insights:

- To impact the blade surplus, it is important to design an application that uses many blades effectively in a single project; design for a high 'blade density'.
- Acoustic barriers lend themselves well as a scalable application

PART B

Research toward a solution

PART B

Research toward a solution

This part of the report covers the research that was performed with the solution in mind: applying the blades to create acoustic barriers. It is divided into two main topics: **material** (chapters 7 and 8) and **barrier** (chapters 9 to 12).

“How can we use repurposed blades to create effective sound barriers?“

The first part explores all aspects relating to the material. The technical characteristics of the blades are explored, previous Blade Made projects are further analysed, and key principles of sustainability and the circular economy are examined.

The second part deals with the aspects relating to sound barrier design. Topics such as acoustics and different methods of reducing traffic noise, current barriers, and barrier construction are covered here.

The goal of part B is to gain a thorough understanding of how the blade material can be used to create an effective and desirable acoustic barrier. These insights will subsequently be used in the development phase, to formulate design principles and evaluate ideas.

7. Sustainable design

Circular design principles

To design a barrier with a minimal impact on the environment and utilise the material at hand in an effective way, several principles need to be taken into account. The following chapter offers a perspective on how to integrate circularity and sustainability into the design.

In an ideal circular economy model (see Figure 7.1), waste is designed out of all products, and each product, component and material is continuously reused to preserve its value and functionality. (Ellen MacArthur Foundation, 2013). In the case of the composites at hand, this scenario is currently unfeasible, as the blades are not designed to fit within this circular framework. Developments in improving wind turbine design in terms of EoL are focused on facilitating better recycling, not on designing out waste altogether.

The next best course of action would be to preserve the integrity of the material as much as possible, and therefore keep the material close to its original form. It is inevitable that all applications have a finite lifespan, and that each time an EoL strategy is needed. In any subsequent step, the material properties should be redeemed wherever possible to benefit optimally from the material. When reuse is no longer feasible due to material degradation, recycling is the way forward to process the material.

Combining these cascading methods would prolong the life in service of the composites significantly. For this to be feasible, each application of material should be designed so that the best subsequent process remains feasible. This generally means altering the structure as little as possible and preventing degradation of the material.

The main advantage that this lifetime prolonging brings, is the significant drop in the need for virgin materials. Combined with locally sourcing the blades, a major potential for reducing environmental impact is created. The fact that fewer new materials are needed, does not result in a drop in employment. New local jobs would be created when large-scale repurposing is possible via a circular wind hub (Scheepens, 2021).

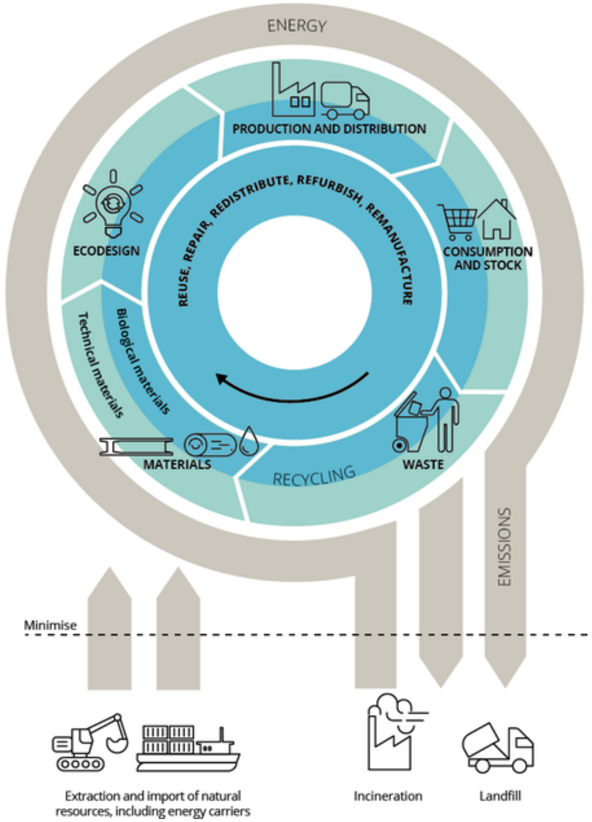


Figure 7.1: Circular economy system diagram (European Environment Agency, 2020)

Superuse methodology

Superuse Studios is an international architecture firm that has been pioneering circularity and sustainability in design for nearly 25 years. Using locally reclaimed materials, the studio has been able to construct various buildings, interiors, installations and playgrounds (Superuse Studios, 2021).

The company outlines several strategies to reach its sustainable goals. Four of these strategies that are relevant for this project are elaborated upon here:

Harvesting Materials
Simply reusing materials does not guarantee a lower carbon footprint, if - for example - the material has to be transported across the globe. Much can be gained by sourcing reusable materials locally. Superuse has developed a so-called 'Harvest Map' to this end.

Circular Materials
This strategy guides the selection of materials, see Figure 7.2. As each material choice is unique and various factors come into play, the decision tree serves as a guideline rather than a fixed set of rules.

Demountable Construction
Materials should be able to be reused many times. Therefore, detachable connections should be used whenever possible.

Material Driven Design
In this strategy, the design largely follows the available material. The designer is guided by the characteristics of the material, and suitable applications are selected based on these (Karana et al., 2015).

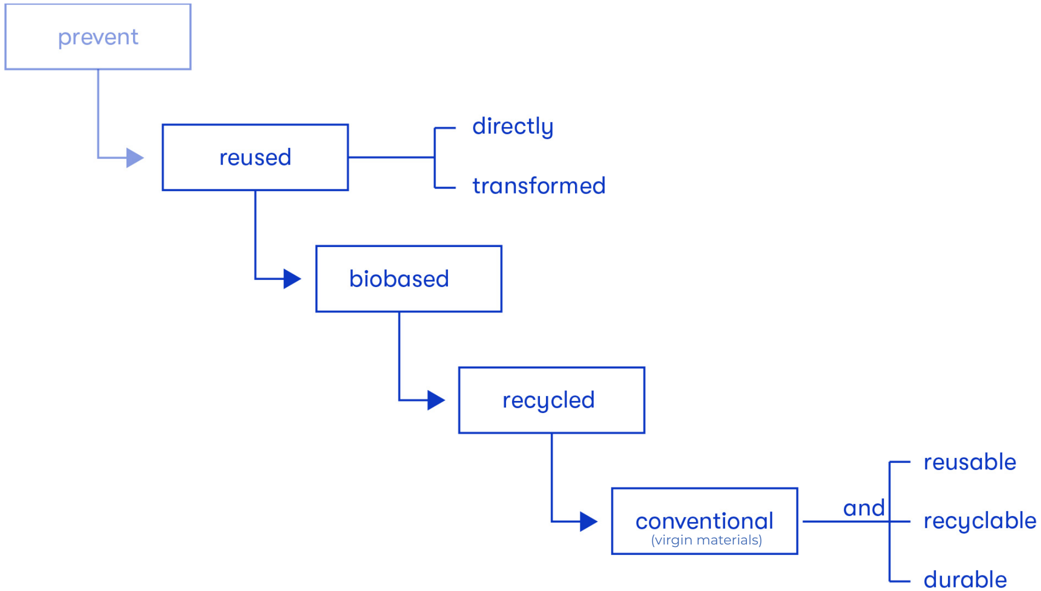


Figure 7.2: Superuse material decision tree (Superuse, 2021)

Main insights:

- Scalable applications that aim to repurpose as many blades as possible should be developed so that unpredictable damages are accounted for in the overall process. Damaged parts might still be suitable for structural recycling.
- The design should focus on prolonging the life-in-service of the material
- The application should be designed in such a way that it does not complicate subsequent reuse or recycling methods.
- The design should allow for locally 'harvested' blades to be used.
- The design should be made to be fully demountable.

8. Blade repurposing considerations

After serving on a wind turbine, the blade can be repurposed in various ways, as described in chapter 6. These projects offer valuable insights that would support any new design, and help to answer the following questions. These key questions have been determined in collaboration with Superuse, and are essential to answer in order to create feasible designs.

- What modifications to the structure are suitable?
- What are the considerations regarding transport?
- What is needed to safely erect new structures with the material?
- How can designs stand the test of time?
- What design opportunities do the unique qualities of the blades offer?

The Wikado Playground was visited to closely observe the construction, and see how the material has performed over the past 15 years. Photos from the site visit can be found in appendix B. From all current applications, this playground is the most diverse and contains most different features.

Modifications
Many applications for repurposed blades require modifications to the objects in order to acquire the desired shapes and dimensions. This increases the versatility of the material.

For segmenting the blades it is strongly preferred to only use straight lines (as seen in Figure 8.1). The practicality saves time and allows for more precise dimensioning (de Krieger, 2021).

Capping off a segmented piece can be done in a relatively straightforward manner. A panel - such as a wooden plank - can be cut to size, inserted, laminated and finished. Small segments can also be capped without adding panels.

Any small load-bearing additions to the segment (such as climbing holds or eyebolts) can be conveniently connected to the spar caps. Alternatively, a reinforcement should be added to the interior of the blade to prevent tearing the sandwich structure (van Herk, 2021).

For visual appeal and to protect the material, the blade is cleaned and given a new coat of paint.

Figure 8.1: Segmenting a blade using straight cuts (GKB Groep, 2021)

Transport
Getting the material to the right location is not to be overlooked, and has the potential to greatly influence the design.

There are two main options for transporting the blade material. In the first scenario, the material is small enough to be transported using regular trucks. In the second, special transport is needed when large blades or blade segments are to be moved, and exemptions are needed. In the Netherlands, the limits are a width of 3.5 metres, with a length of up to 14 metres (van Herk, 2021).

The vehicles used to transport large sections are comparable to the truck in Figure 8.2. The blades are secured using straps and protected against damage using shock-absorbing mats.

To be able to lift the segments on and off the trucks, a mobile crane or excavator may be used. Straps are again employed in this step. For segments with a narrowing top, eyebolts need to be added to the structure in order to lift the object from the truck and place them in the desired location. For segments with a widening top, a strap alone is often sufficient for this step (van Herk, 2021).

Construction
Depending on the use of a blade or blade segment, a foundation might be required. For blades that are placed diagonally or horizontally elevated from the ground, a concrete foundation is commonly used. Moreover, vertical structures that stand alone, and/or are subject to significant forces from the wind are also anchored to the ground through a foundation (see Figure 8.3).

For other designs, a foundation is not required. For example, the blades in the Wikado playground are simply dug into the ground to create a stable construction. Attaching any upright segments to other structural components adds to the overall rigidity of the build.


Figure 8.2: Blade segment lifted using eyebolts (GKB Groep, 2021)


Figure 8.3: Signpost blade foundation (Superuse, 2014)

Technical properties and design opportunities
As discussed in chapter 4, the wind turbine blades have unique and high-end technical properties. This chapter examines these characteristics, based upon which several design opportunities are identified.

Firstly, the blades are designed to be strong and lightweight. Toward the root of the blade, the walls are thickest, and a circular steel flange facilitates the bolted connection to the hub.

Design opportunity:

- The blade could be bolted in any orientation to a sturdy structure, such as a concrete block. This makes it possible to devise a barrier design in which the blades are positioned in virtually any orientation. An overhanging barrier (comparable to Figures 8.4 and 8.5) could well be designed in this manner.

To achieve the required strength, the shear webs and spar caps are needed. These reinforcements run along the length of the blade.

Design opportunities:

- The spar caps offer a rigid surface for mechanical connections. Complementary material to construct a barrier could be connected in this area of the blade, or the blades can be interconnected to each other.
- It is possible to cut the blades along the length. The inner reinforcements should be considered to retain some of the strength properties of the blade (see the Danish bike shelters, Figure 8.6).

Main insights:

- It is favourable if the blades are segmented to be suitable for regular transport.
- Additions such as eyebolts might be required for transportation.
- The necessity for foundations might be prevented if the blades or blade segments are either subject to negligeable wind forces, or structurally connected to surrounding components.


Figure 8.4: Wielwijk barrier (van Heeswijk architects, 1997)


Figure 8.5: barrier Parkstad Limburg (ipvDelft, 2018)


Figure 8.6: Bike Shelter in Denmark (Siemens Gamesa, 2021)

9. Acoustics

Now it is time to shift the focus toward barriers. This chapter explores all relevant aspects regarding acoustics. Factors that influence the effectiveness of noise barriers are examined in order to gain a thorough understanding of what is required for the design to perform well.

The first acoustic barriers emerged in the United States in the middle of the twentieth century. In the following years - as highways became more and more widespread - noise barriers became common in all developed countries. Simultaneously, advances in acoustical science helped to design increasingly effective barriers.

Sound levels are measured in decibels. For example: An average highway produces a sound level of 70 to 80 dB when observed from a 15-metre distance. A barrier of around 6 metres high would achieve a noise reduction of 15 to 20 dB (Corbisier, 2003). This corresponds to a perceived noise reduction of 65 to 70% (Acoustical Surfaces, 2018).

How exactly do acoustic barriers achieve this sound reduction?

Firstly, the basic working principle of acoustic barriers is discussed.

Between the source of the sound and the observer, a physical barrier is placed. The purpose is to reduce the level of sound perceived by the observer.

The first factors that play a role:

- The horizontal distance between the source and the barrier
- The horizontal distance between the barrier and the observer
- The height of the source, barrier and observer
- The width of the barrier

The sound that directly collides with the barrier can either be **reflected, diffused** or **absorbed** (see Figure 9.1). This depends on the material of the barrier. While a smooth surface generally reflects the sound in the opposite direction, a bumpy surface diffuses the sound in many different directions. A porous material is able to absorb (part of) the sound.

Sound reflection is generally less desirable than absorption, as the reflected sound can actually cause increases in noise levels (Bernhard, 2021). An exception is when reflected sound can be directed toward absorbing materials, such as soil or the track ballast (crushed rocks underneath railway tracks) (Tenpierik, 2021). Therefore, the angle of the barrier should be considered when designing for reflection.

Another factor that plays a role is the frequency of the sound. While traffic noise in the city is mostly due to engine noises (>500 Hz), the sound produced by highways is mostly due to the contact between the tires and the road, and aerodynamic noise (500 - 1000 Hz). Therefore, noise barriers are designed mostly to deal with these higher frequencies. According to Tenpierik (2021), diffusing traffic noise is rather difficult as this strategy drops in effectiveness when different frequencies are present. Therefore, the overall shape of the barrier surface is less critical. Absorption is preferred in this scenario.

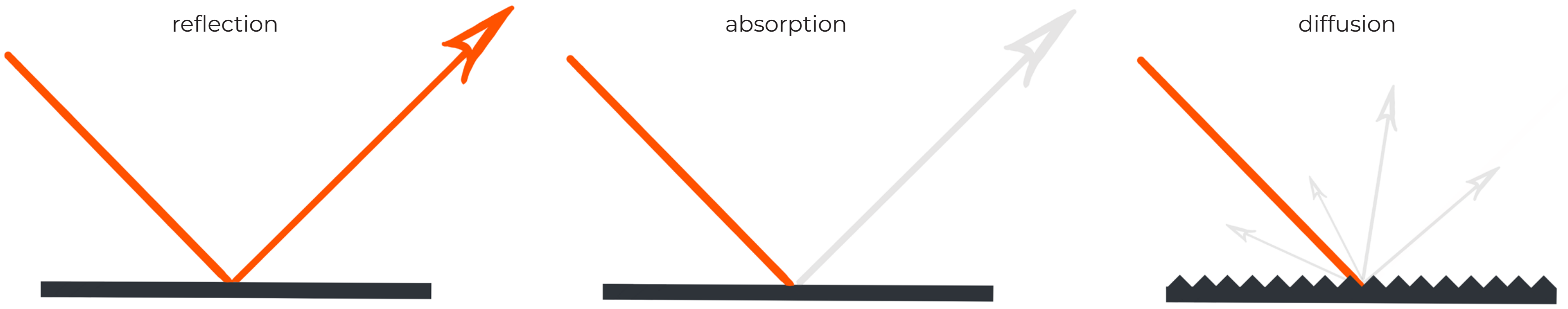


Figure 9.1: Reflection, absorption and diffusion (own illustration)

While it perhaps seems obvious, it is important to note that a noise barrier should be a mostly closed structure. A general rule of thumb: If the observer can directly see the source, no effective noise reduction will occur. However, it is possible to create openings in noise barriers while preserving their performance. This is done by installing overlapping barriers. Recommended is to create an overlap that is 4 times as wide as the opening between the to layers (TfNSW, 2021).

The barrier stops most of the sound from directly reaching the ears of the observer. Most of the sound that the observer still hears does not travel through the barrier, but around it.
The main reason that some of the sound still reaches the observer, is the phenomenon of **diffraction**. Sound waves will bend around edges that they pass, similar to how waves in water will bend around obstacles. As sound waves reach the top of the barrier, they will bend downwards toward the observer behind it.

The effects of diffraction can be evaluated using the Fresnel-number. The difference in distance is divided by the wavelength of the sound (see Figure 9.2). Therefore, increasing the height of the barrier, and increasing its proximity to the source is generally effective in reducing the perceived sound. Moreover, the sharper the edge, the more diffraction will occur. Creating a 'soft' edge (by using vegetation for example) will reduce the effects of diffraction (Tenpierik, 2021).

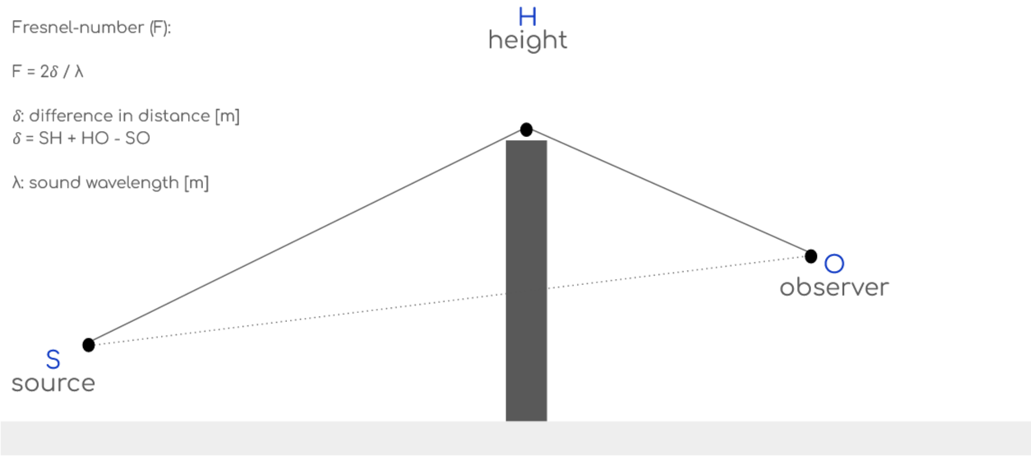


Figure 9.2: Sound barrier acoustics (own illustration)

Another phenomenon that bends sound downwards is **refraction**. This effect is due to heterogeneous properties in the atmosphere. Differences in wind speeds or air temperatures will alter the course of the sound waves, comparable to how light can be bent to create fata morganas.

Main insights:

- A closed structure is essential for effective noise reduction, but there are ways to create openings using overlaps.
- The barrier should be placed close to the source, with a substantial height.
- The surface shape should be considered, but is less critical.
- The angle of the barrier should be considered for its effects on sound reflection.
- Absorption is generally preferred over reflection
- Vegetation should be considered to reduce the effects of diffraction, and for its sound-absorbing properties.

10. Aesthetics

Acoustic barriers should not be regarded as purely functional objects. Studies show that the aesthetic design of the structures can significantly influence the experience of travellers as well as residents (Arenas, 2006).

Therefore - in addition to the concise Spoorbeeld (2016) handbook - two extensive sound barrier design guideline documents were consulted, compiled by researchers from the University of Michigan (Farnham et al., 1990) and the New South Wales government (TfNSW, 2021). The following is a summary of the most relevant principles and best practices for the purposes of this project.

Firstly, it is important to reiterate the distinction between the traveller and resident side of the barrier. These two perspectives result in different requirements.

For the traveller, viewing the barrier is a more fleeting experience. The overall shape, colour and rhythm (i.e. recurring elements) are therefore of most concern. This is due to the speed of the traveller, and the fact that his/her attention should be on the road.

For the resident, the barrier is a more permanent part of their surroundings. A larger focus lies on detail, and how the structure blends into the local environment.
Inconsistencies should be avoided, as they often cause a jarring effect to the beholder. However, it is equally inadvisable to construct monotonous walls that stretch into the distance. This can in fact cause boredom and disorientation in the traveller.

The advice is to appropriately employ rhythm to create an interesting, yet coherent barrier. This can be done in numerous ways: slight variations in the height of the barrier, planting trees or shrubs, varying the distance between barrier and road, and so forth (see Figure 10.1). The average speed of the highway should be considered when determining the frequency of the rhythm.

When inconsistencies are unavoidable, for example when a bridge interrupts the barrier, the barrier should be designed to transition into this.

It is generally considered pleasant for the traveller if the barrier is slightly tilted away from the road in terms of spatial perception. It should be noted that this might negatively impact the acoustic performance of the barrier.
Transparent barriers are generally used on bridges (for their low weight, and to mark the crossing to travellers), to allow for more light, or not to block the sight to notable landmarks. If possible, it is advised to tilt the panels away from the traffic to allow the rain to wash away dirt that builds up over time due to the traffic. This means that the barrier is tilted toward the resident side, creating an uninviting area there.

Generally, the resident side of sound barriers is often experienced as an unappealing place (Foderaro, 2005).

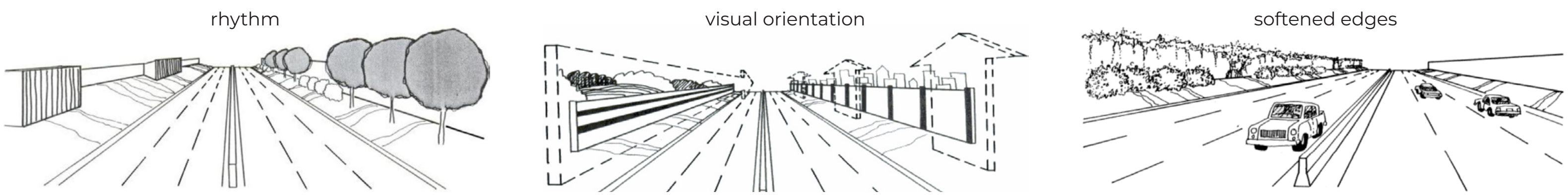


Figure 10.1: A selection of aesthetic principles in barrier design (Farnham et al., 1990)

To prevent this, the use of plants is highly advised. They give the barrier a natural and appealing look while providing acoustic and ecological benefits. They help to blend the barrier into the landscape from both perspectives (see Figure 10.2). Care should be taken when selecting the plant species regarding aesthetics, maintenance and suitability to the local climate. It is advised to select evergreen species that require minimal maintenance.

Another important element is light. On the roadside, the barrier should take into account where lampposts are located, and how this affects the aesthetic during nighttime. On the resident side, proper lighting should be considered when it borders publicly available areas.

Main insights:

- **The barrier should be coherent, while offering visual interest to the traveller. Distracting elements should be avoided. Attention to the overall experience is most important.**
- **For the resident, attention to detail is essential. Local (urban) landscapes, demographics and history should be considered for this side of the design.**
- **The resident sides are generally experienced negatively. This presents an opportunity for a design that serves all users.**
- **Evidence shows the versatility and added benefit of vegetation. Species should be selected carefully.**

Figure 10.2: Example of a well-exectuted barrier near Amersfoort that is functional, visually pleasing yet not distracting. (Google Maps, 2021)

11. Current barrier- and location types

To understand how the previously discussed acoustic and aesthetic principles are currently applied, an analysis of current sound barriers is performed. Different types of locations and their specific requirements are also discussed.

Sound barriers can be divided into the following general types (as seen in Figures 11.1 to 11.5):

- Transparent screen
- Cassette screen
- Gabion
- Earth mound
- Overgrown screen

Following is a brief description of each type, and their most prominent advantages and drawbacks (Spoorbeeld, 2016).

Transparent screen
These barriers are designed to obstruct the vision of travellers and residents as little as possible. Acrylic panels are attached to a metal support structure. They are relatively prone to vandalism.

Cassette screen
Concrete or wooden slabs are stacked between vertical profiles. These barriers are relatively straightforward to install and maintain. In their bare form, they offer little in terms of aesthetics and are sensitive to vandalism.

Gabion
Gabions are large metal baskets, usually filled with stones. They offer a generally natural and pleasant aesthetic. Moreover, their rough surfaces diffuse sound and discourage graffiti artists.

Earth mound
These barriers are artificial slopes, generally constructed using earth. They are generally covered with grass. Occasionally, an additional barrier is placed on top of the mound to increase its height. The main disadvantage is the space required to construct this type of barrier.

Overgrown screen
This type is any barrier that has been significantly covered by plants. This type of barrier is preferred due to its natural appeal, and is less prone to vandalism. Often, additional steps need to be taken to stimulate plant growth.

It should be noted that innovation in the area of acoustic barriers has far from stagnated. Companies such as WacerWall and 4Silence have developed concepts that offer new sustainable and technical advantages.

WacerWall has created a design using recycled EPS blocks, that has a 70% lower carbon footprint compared to similar barriers (Waterstaat, 2020). These lightweight blocks are anchored to the ground using integrated poles or straps.

4Silence has developed a technology that uses resonance to bend sound upwards, making it possible to lower the height of sound barriers, without compromising on overall performance (Bak, 2021).

Figure 11.1: Transparent screen (Holland Scherm, 2013)

Figure 11.2: Cassette screen (CivilEngineer, 2018)

Figure 11.3: Gabion (Benjamins, 2022)

Figure 11.4: Earth mound (Google Maps, 2021)

Figure 11.5: Overgrown screen (Gramm Barriers, 2022)

Effectiveness of sound barriers
Roughly speaking, the aforementioned barrier types perform similarly in terms of sound reduction. The height primarily determines the effectiveness of the barrier. While applied materials and their potential reflecting, diffusing or absorbing properties can increase the effectiveness, the selection between the different barrier types is typically decided based on location-based requirements. These include aesthetic considerations and the available space for the structure (US Department of Transportation, 2021).

Locations
Acoustic barriers are generally used along railways and highways. This distinction comes with specific requirements. The most significant difference is the preferred form of noise reduction.

For railways, it is common to construct angled barriers that reflect sound waves down toward the absorbing track ballast. A constraint is that railways generally offer little space for barriers to be constructed.

For highways, more different types of barriers (and therefore noise reduction principles) are used. Frequently more space is available for wide barriers, such as earth mounds. Downward sound reflection is not common, as asphalt does not absorb sound as well as track ballast.

Recently, ProRail (Dutch railway infrastructure management) has rejected proposals for a railside blade barrier, mainly based on the previously mentioned limitations.
This is one of the main reasons that the project will predominantly focus on roadside barriers.

Roadside barrier locations can be divided in the following way. Three 'dimensions' are identified: location type, urban density and available space.

Location types:
- Regular (i.e. straight road)
- Under bridge
- Over bridge
- On- and off-ramps
- Emergency exits

Urban density:
- Sparse (small town)
- Medium (suburbs)
- Compact (city)

Available space:
- Narrow (x < 5 m)
- Standard (5 m < x < 10 m)
- Wide (10 m < x)

The 'narrow, standard and wide' distinction has been made based on an analysis of existing barriers in The Netherlands. The available space is defined as the total width of the area between the road and the next feature in the landscape, such as buildings, streets or bodies of water. This includes the space used for guardrails and such. The practical space that is available is therefore often smaller, depending on the location.

An overall pattern can be found in the location analysis: The available space is broadly reversely proportional to the urban density, and therefore to an extent to the barrier height.

Generally speaking, dense areas yield more artificial and industrial barriers in terms of aesthetics, while sparser areas contain more natural and grounded ones. The full location analysis can be found in appendix C.

For the Blade Barrier, the dimensions of the material rule out the most narrow barriers. A target type for the barrier design is formed, as seen in Figure 11.6..

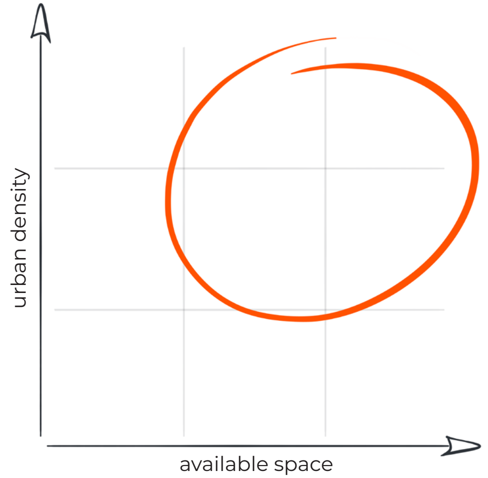


Figure 11.6: Identified location-type for Blade Barrier potential

Main insights:
- The project will focus on roadside barriers, as this offers more potential for a blade barrier.
- Transparent and/or green barriers are considered desirable as they integrate well with the landscape and offer a natural aesthetic.
- An opportunity is to target the design at the standard and wide areas for medium and wide urban density.

12. Existing blade barrier designs analysis

Creating a sound barrier from wind turbine blades is not a new idea, as other parties than Superuse have proposed this application. This chapter serves to briefly analyse these, and identify conceivable shortcomings to the designs.

The Re-Wind Network (2021) from Ireland has so far been the only party to publish several concepts for a blade barrier, as seen in Figures 12.1 to 12.4. While these designs are visually appealing, they contain several shortcomings that prevent these designs from being suitable.

Barrier 1
This barrier contains many openings between the row of segments, which prevents proper sound reduction. Only the mid-sections of the blades are used, so still a lot of by-product is created that needs a separate purpose.

Barrier 2
A lot of labour is needed to process the blades. The material is degraded significantly by producing curved panels like these, and a lot of structural integrity is lost. Therefore, a thin structure like this might suffer under fierce winds. Panelling the blades like this takes away the original aesthetic of the shape of the blades.

Barrier 3
A lot of work is needed to cut the blades while removing the shear webs and therefore losing much of the structural integrity (COWI Engineers et al., 2015). Gaps are still apparent in the design, and connecting elements seem to be absent.

Barrier 4
This is an efficient design in terms of space and construction. Only a limited part of the material is suitable however, while identical blades are needed. The material is degraded significantly by creating panels like these, and a lot of work is needed. Even more so than barrier 2, the blades are reduced to parts that are hardly recognisable as coming originating from wind turbine blades. As a result, the aesthetic value is diminished.


Figure 12.1: Barrier 1 (Re-Wind Network, 2021)


Figure 12.2: Barrier 2 (Re-Wind Network, 2021)


Figure 12.3: Barrier 3 (Re-Wind Network, 2021)


Figure 12.4: Barrier 4 (Re-Wind Network, 2021)

Main insights:

- The designs show that there are numerous different ways in which the blades can be transformed into barriers in terms of shape.
- The main challenge is to design a barrier that is simultaneously functional, space-efficient and visually appealing, while limiting the amount of work needed to process the blades into their new shapes.

13. Conclusions and design principles

Designing an acoustic barrier using decommissioned wind turbine blades is not a straightforward endeavour, especially when sustainability is an important factor.

A large and ever-growing waste stream of blades needs to be processed. Research indicates that repurposing the blades as large constructive elements is an advisable solution from the standpoint of sustainability. A sound barrier is a suitable application to use great quantities of this material in a meaningful way. The differences and inconsistencies in type, size and material quality call for a flexible design that can incorporate these variations effectively, and across different location types.

Previous builds offer a solid frame of reference for the development of blade barrier designs. The simpler and fewer modifications are needed, the better.
The previous statement also comes into play when considering sustainability and circularity. The design should repurpose the material in such a way that the material potential at its subsequent EoL is compromised as little as possible. Segments should be able to be reused for other purposes such as furniture, or to be reprocessed into panels and beams.

To create a functioning noise barrier, a closed structure must be realised. Significant heights must be possible, while being cognizant of space limitations. Sound absorption is generally the preferred form of noise attenuation, and the use of plants can assist in this area. Additional benefits of vegetation are ecological and aesthetic in nature.

More than half a century of barrier construction worldwide has resulted in a vast knowledge of the various factors that come into play in the design of a sound barrier. Aesthetic principles have been analysed in order to make well-founded decisions in terms of the form of the design.

It is important to consider the life-in-service of the barrier, and therefore allow for the required maintenance to happen in a convenient way.
Current repurposing projects have shown the potential of the material, but have so far not succeeded in making an impact in terms of material quantity. Previous proposals for a blade barrier are generally found to be lacking in one or more of the identified needs, so a renewed effort is needed to conceive an adequate design.

The findings from the research form the basis for the following set of design principles:

Effective noise reduction
This is the main purpose of the Blade Barrier. A general sound reduction of 15 dB is required to be competitive with standard barriers. The placement and height relative to the source of the sound are crucial. Studies show that sound diffusion and absorption are generally more effective than sound reflection for roadside barriers.

Circularity
In a circular economy, resources can be used and reused indefinitely. To approach this model, the blades should be kept intact as much as possible. That way, the material keeps its potential for subsequent applications. Preventing degradation of the material, and limiting cuts per kilometre (length of cuts in the blades for a kilometre of barrier) should be limited.

Aesthetics
The barrier would be a large structure in the public environment. It is therefore required that the barrier is pleasing to the beholder, being travellers and residents.

Scalability
To deal with the large surplus of blades, it is advantageous if the barrier is suitable for a range of different locations.

Secondary functionalities
The Blade Barrier has the potential to fulfil more than one purpose. Social and ecological perspectives should be considered too.

Ease of transport, installation and maintenance
The barrier should be designed to keep transport and installation relatively simple. This would reduce the time and cost to build the structure.

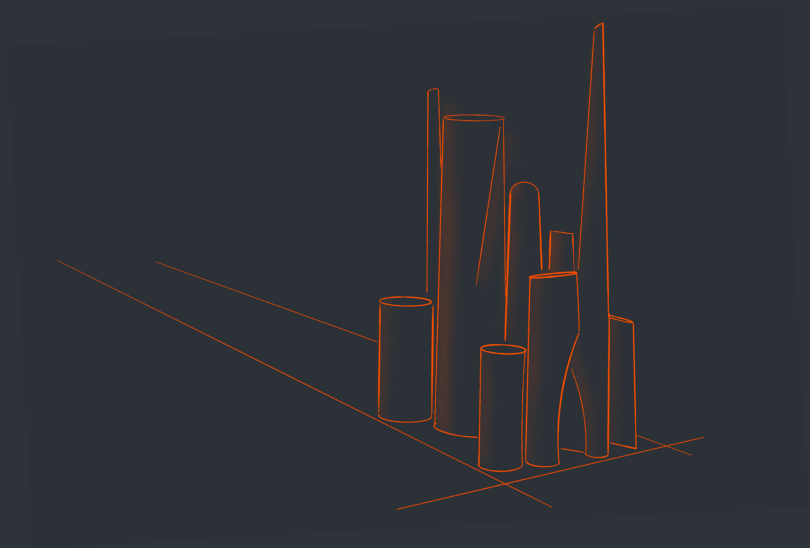
Suitability for unpredictable blade-stream
As the blades come from a waste stream, the availability of blades is unpredictable. The barrier should ideally be designed to be suitable for a wide range of blade types and sizes.

Blade density (blades/km)
To deal with the large surplus of blades, it is advantageous if the barrier has a high density of blades used per kilometre.

Use of unique blade properties
The blades are high-end structural objects. The characteristics of the blades could offer unique possibilities if applied in a suitable way.

PART C

Concept development and selection



PART C

Concept development and selection

This part starts with a vision for the final design, and offers an overview of the ideation phase, concept generation and the final three concepts. Subsequently, in collaboration with Superuse, one concept is chosen based on the previously established criteria.

While this part follows the research parts in this document, it should be noted that the ideation and early concept generation ran parallel to the research phase.
This process is also referred to as the co-evolution of the problem- and solution space (Dorst & Cross, 2001). Therefore, the early designs are not yet in line with conclusions from the research.

14. Ideation and concept generation overview

Design vision
The design vision describes the three main areas of focus for the design of the Blade Barrier:

Wind turbine blades have an inherent and unique value in terms of material and shape. The **aesthetics** of the barrier design should follow from the inherent qualities of the blade, instead of forcing the blade into a pre-existing notion of barrier design.

The design of the barrier should conform to established **circular** economy design principles. Minimising material loss, preserving value and considering the entire material journey will be leading in all key choices in the design process.

To increase the potential impact of the barrier, the design should be **scalable** and adaptive to factors such as blade type and local requirements, and integrate seamlessly with the surrounding land- or cityscape.

Form exploration
During this phase, various methods were employed to create ideas, such as sketching, tinkering, CAD modelling and brainstorming (see appendix G).

In the initial ideation phase, various activities were undertaken to get acquainted with the unique shape of the blades. By tinkering with the orientation, repetition and potential segmentation of the blades, they can be combined to form different barrier typologies.

From an early point in the process, CAD tools were applied to do this, as this clarifies what is spatially possible with the complex and three-dimensionally curved shapes. 3D prints were made to make the form more tangible and to experiment with the shape.

Figure 14.1 shows a sample of the form exploration (for all images, refer to appendix E). It should be noted that a mono-stream of blades was used here. A relatively simple parametric model was created to be able to systematically generate a great number of variations. (Appendix H elaborates upon the parametric models that were created during the project.)

Parametric models
The potential for a parametric model for the design was analysed further. This time, blades were considered that vary in shape and size. A parametric design was created that would place segmented blade parts onto a plane that represents the appropriate landscape and available space (see Figure 14.2). Factors such as blade density, rotation and distance from the border can be altered. One problem that the model quickly encountered is the overlapping of segments. A system needs to be in place to prevent this 'collision problem'.

Therefore, a new model was created that approached the problem differently. A 'volume-box' can be created based on the desired height, length and width. Separate 'no-go' volumes are added to be able to control the shape of the overall output.

Next, segments are placed into this volume and packed as densely as possible. This creates a more coherent output that resembles a plausible blade barrier. The rotation of the segments can be individually altered at random, and any segments that do not fit within the established volume will be listed.

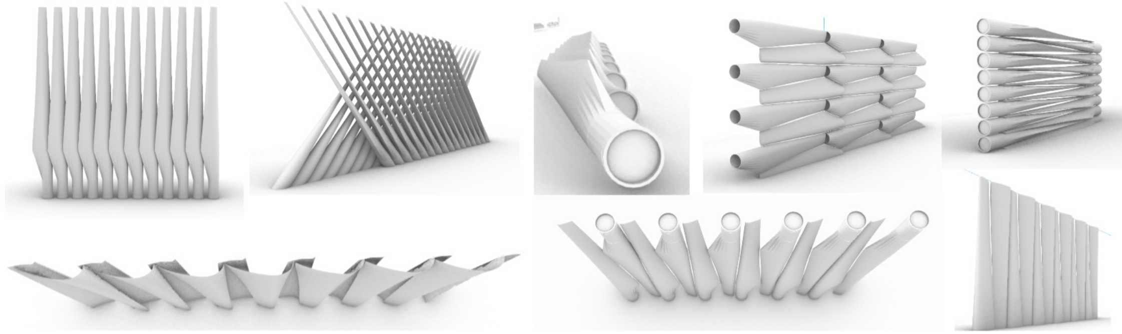


Figure 14.1: A sample from the form exploration


Figure 14.2: Parametric model that places segments onto a surface

The aforementioned collision problem could alternatively be seen as a potential advantage. Horizontal incisions could be made so that segments could lock into each other, as seen in Figure 14.3. This would add rigidity to the structure, and ensure a closed barrier. Upon further evaluation however, the idea was discarded. The needed incisions introduce much complexity to the construction process and degrade the material to a great extent. Moreover, locking shapes together in this way is complicated further by the double-curved nature of the blades.

Additional materials

Another approach to construct a functioning barrier would be to introduce a second material. One variant of this idea is to construct a transparent wall in which the blades act as the main structural component (see Figure 14.4). To be able to construct such a barrier, either identical blades need to be used, or a mounting system needs to be devised that can mitigate the inconsistencies in the blades. Acrylic panels act as the main sound-reflecting components. Due to their structural properties, the blades can be installed at an acute angle, provided they are connected to an adequate foundation. This opens up the potential for an overhanging barrier design.

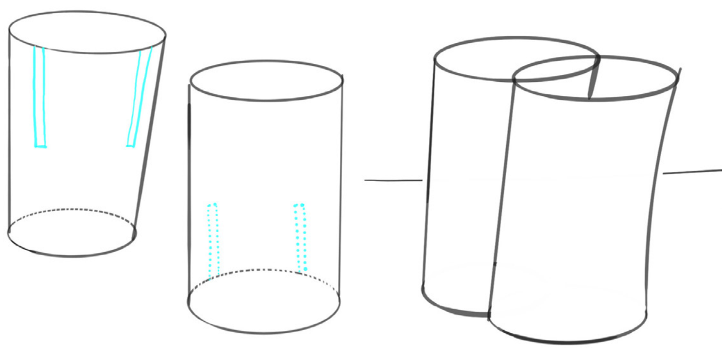


Figure 14.3: interlocking segments using incisions

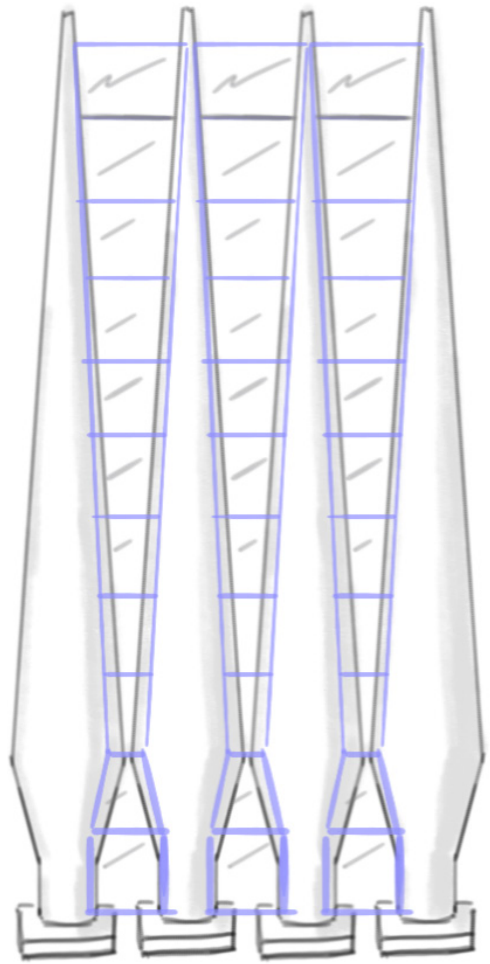


Figure 14.4: barrier with transparent panels

Alternatively, the blades can be combined with gabions, as shown in Figure 14.5. Gabions offer more flexibility in terms of connections and slight inconsistencies. However, gabions are designed to be supported by an inner structure. Substituting this structure for the blades does not yield a significant advantage in terms of material use.

A third way to introduce a second material in order to achieve a closed shape, is to incorporate the earth mound barrier type into the barrier (Figure 14.6). The main advantage is that such a barrier would require roughly half of the space required for a traditional mound, while maintaining its advantageous characteristics.

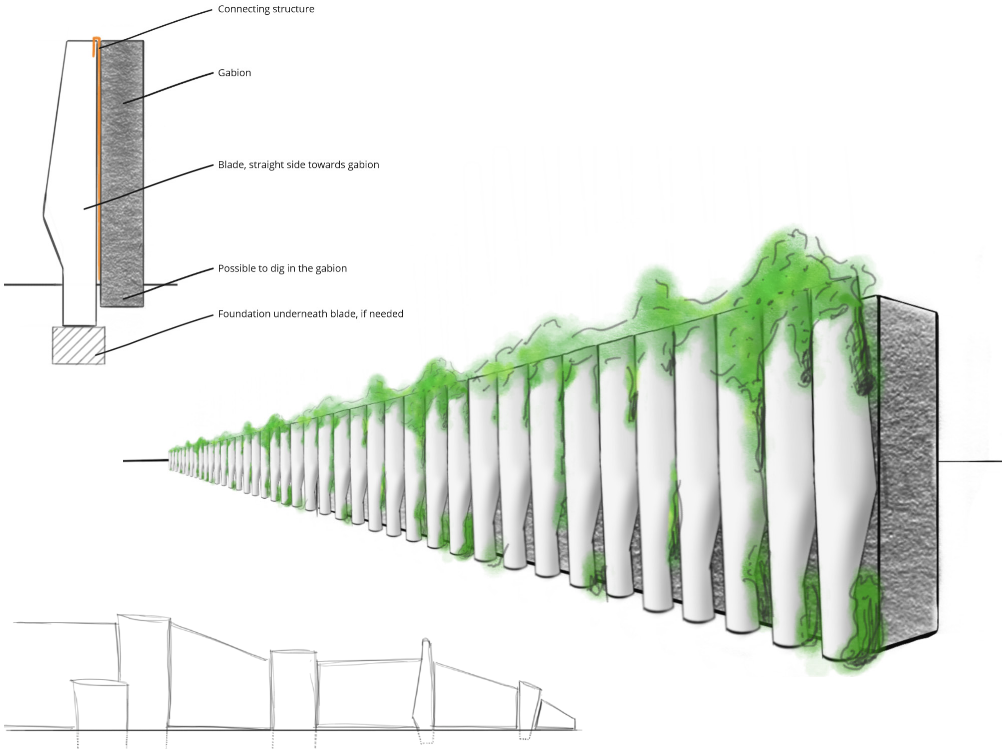


Figure 14.5: Blades as constructive elements in gabions

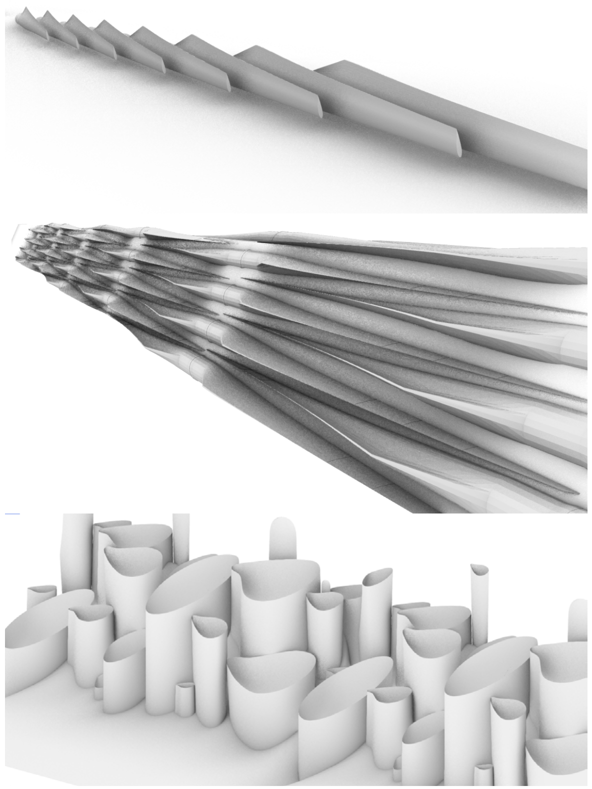


Figure 14.6: Integrated earth mound barriers

Clustering, evaluating and elaborating upon these ideas lead to the concepts that are covered in the next three chapters.

15. Concept I - Parametric design

For creating a fully scalable design, parametric models can offer significant benefits. In essence, a design is generated based on given data and instructions (see Figure 15.1).

A detailed set of input values can in theory result in optimal designs that adapt themselves to any suitable location.

This concept is an exploration of how parametrics can be applied to our design challenge. It does not constitute a clear design, but rather an algorithmic approach to the design challenge.

The main advantage that this approach offers is that it can automate various steps in the detailing of the barrier. Damages to the structure can be circumvented, blade density can be optimised, technical drawings can be generated, and so forth. All this could be done without an architect needing to do this 'by hand'. It is estimated that for barriers that exceed 10 kilometres in length, this approach would be worth the investment.

Details on the created parametric models can be found in appendix H.

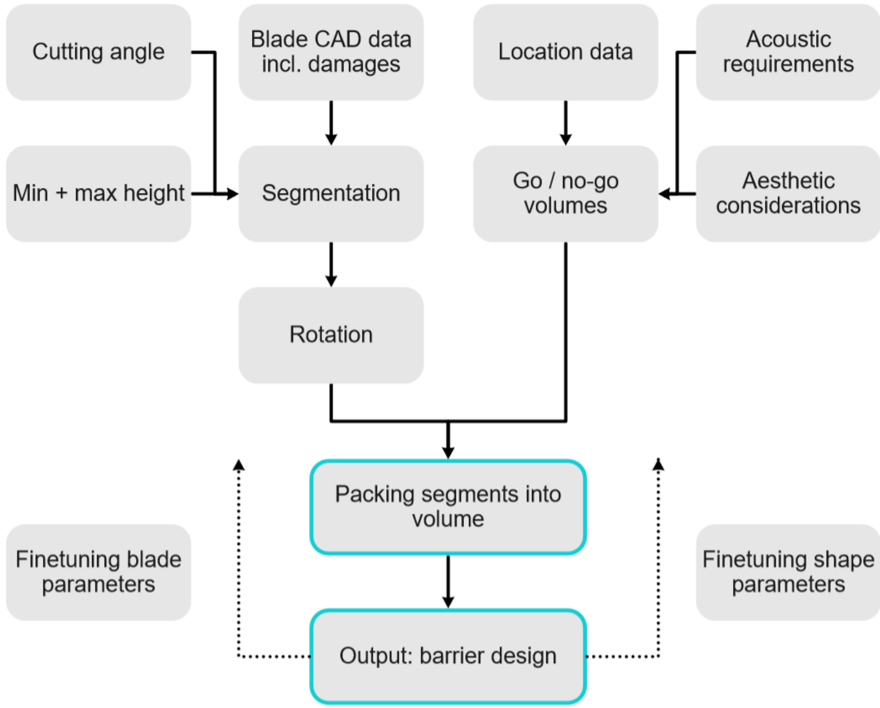


Figure 15.1: Parametric model flowchart

Depending on the availability of blades, an inventory is made. CAD models of all blades are required. These could be obtained from the original manufacturer or created using 3D scanning techniques. Potential damages should also be included.

The blade models are segmented based on the desired minimum and maximum heights. Damaged parts are avoided. The angle of segmentation can be altered in this step.

Based on the requirements that follow from the location, acoustics and aesthetics, 'go / no-go' zones are created. An algorithm then packs the segments as tightly as possible into the designated space. By slightly altering input values, such as the axial rotation of the blades, a virtually infinite number of different variations can be generated. Figure 15.2 serves to illustrate this process.

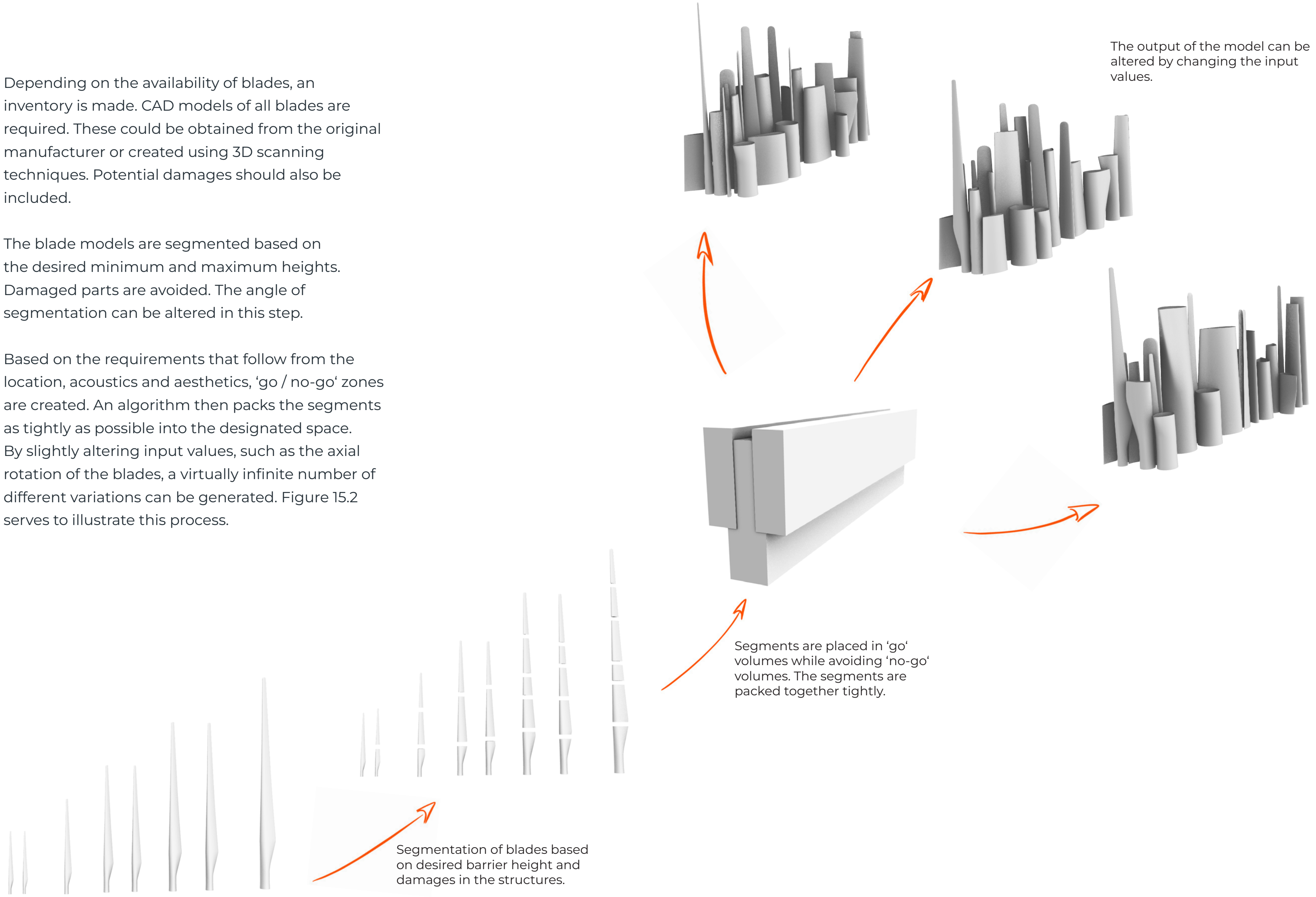
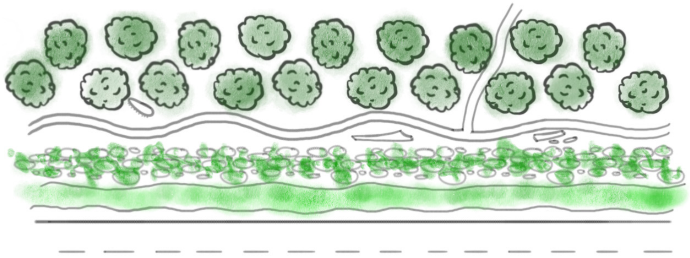


Figure 15.2: Visual representation of parametric design

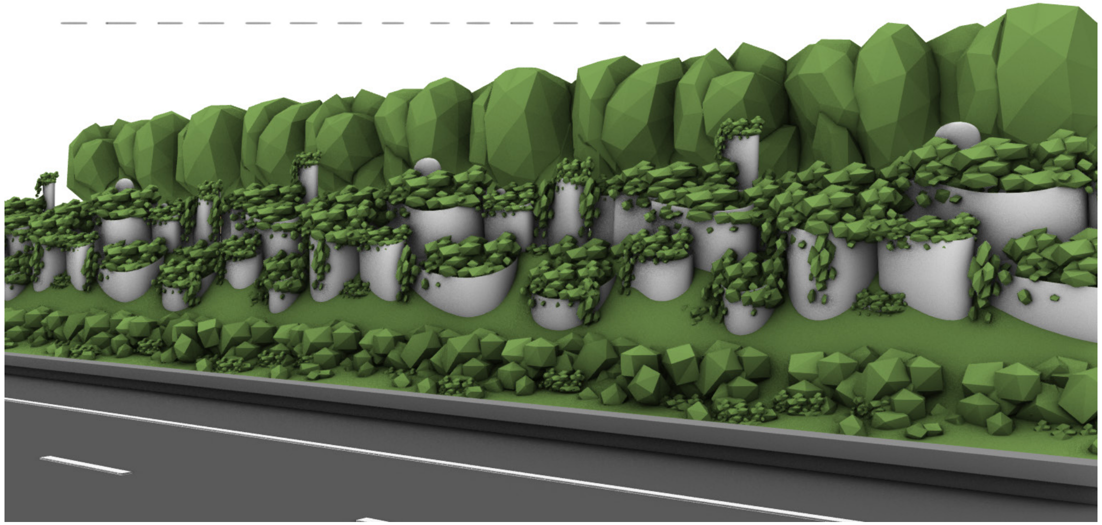
16. Concept II - Green corridor

This concept is a barrier that aims to fulfil a holistic role in its environment. Sound attenuation is simply one aspect of what a sound barrier can be. Social and ecological factors have been given much focus, and result in a design that includes these perspectives to a great extent.

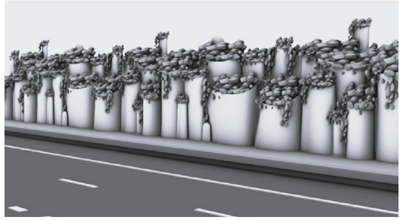
The barrier consists of five main components (see Figure 16.1) that combine to form a green strip that functions as a natural corridor in the urban environment. While offering a pleasant and natural aesthetic to the traveller, the resident is offered a unique green linear park that is designed to suit the local area. The design can be adapted to larger or smaller spaces, and therefore integrate well with the existing infrastructure.



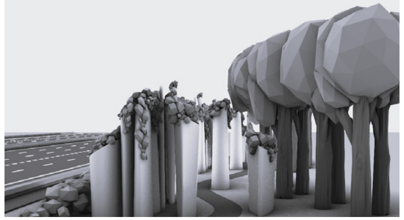
1. Canopy layer
2. Curvilinear path
3. Optional blade furniture
4. Elevated ground layer
5. Ground layer



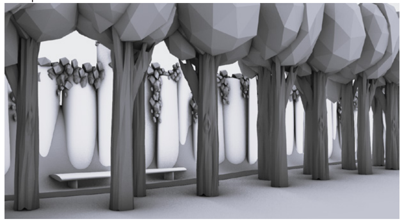
Simplified linear corridor for more limited spaces



Path interwoven with the barrier



Simple blade furniture



Elaborate furniture to create hubs and parks

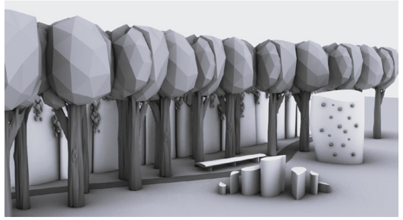


Figure 16.1: Green corridor concept images

17. Concept III - Structural potential

This concept results from the design opportunities identified in chapter 11. As mentioned previously, the blades have sophisticated structural properties as they are originally designed and produced to be lightweight, but withstand extreme forces.

The blades can be mounted in any orientation, as they have been designed for this purpose. Any potential structural downsides from changing the axial rotation can be mitigated by connecting the blades to each other structurally. This makes it possible to construct overhanging barriers that can be as steep as desired, provided that a sound foundational structure is also built (see Figure 17.1).

The reinforcing spar caps that run along the blade offer surfaces that can be used to connect the blades to each other, and connect panels to close off the barrier, as seen in Figure 17.2.

As the blades are designed to be flexible along their slender axis (parallel to the road), the connections between the blades likely need to provide structural reinforcements to prevent unwanted flexion.

The main advantage of the concept is that it can offer high performance in a small space. Downsides are the lower blade density, and that only undamaged blades can be used.

The barrier is best suited for identical blades, which reduces its versatility regarding the blade waste stream.

As the angle increases, the foundational structure needs to handle a larger moment, and the connection with the blade needs to be increasingly high. For a horizontal overhang, the tips of the blades could be connected to the opposite foundations, relieving some of the force on the main foundation.

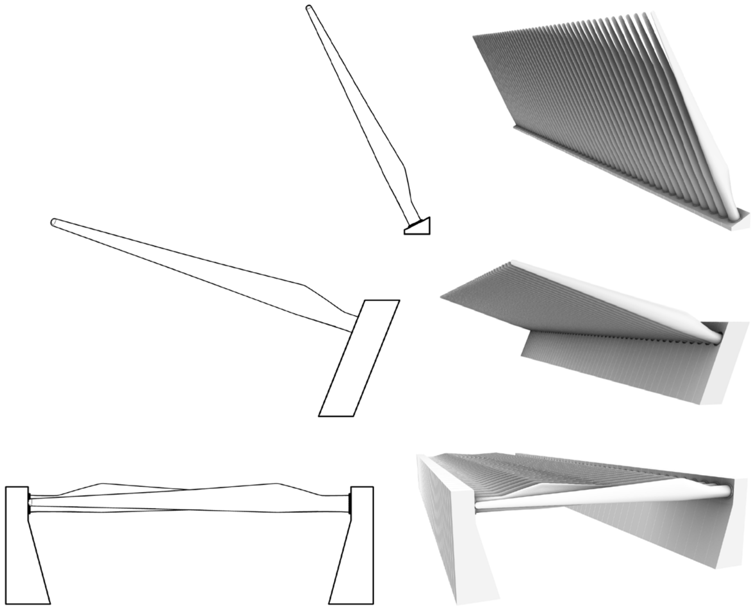


Figure 17.1: Freedom in barrier angle

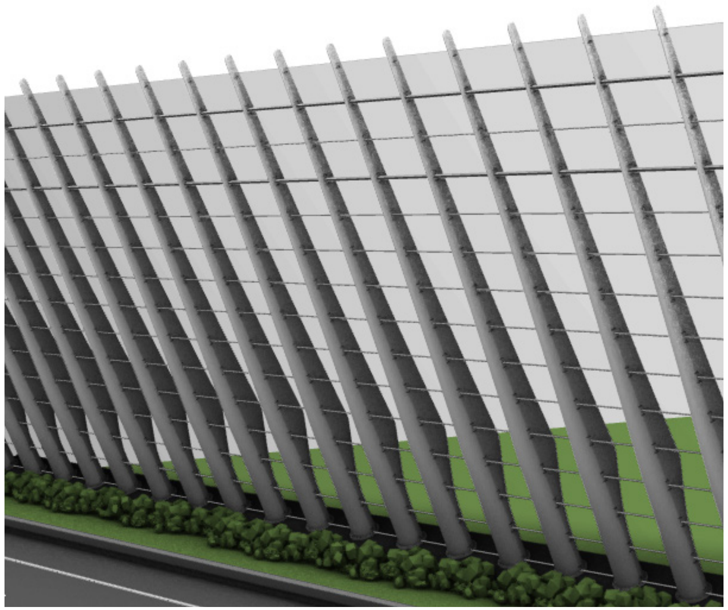


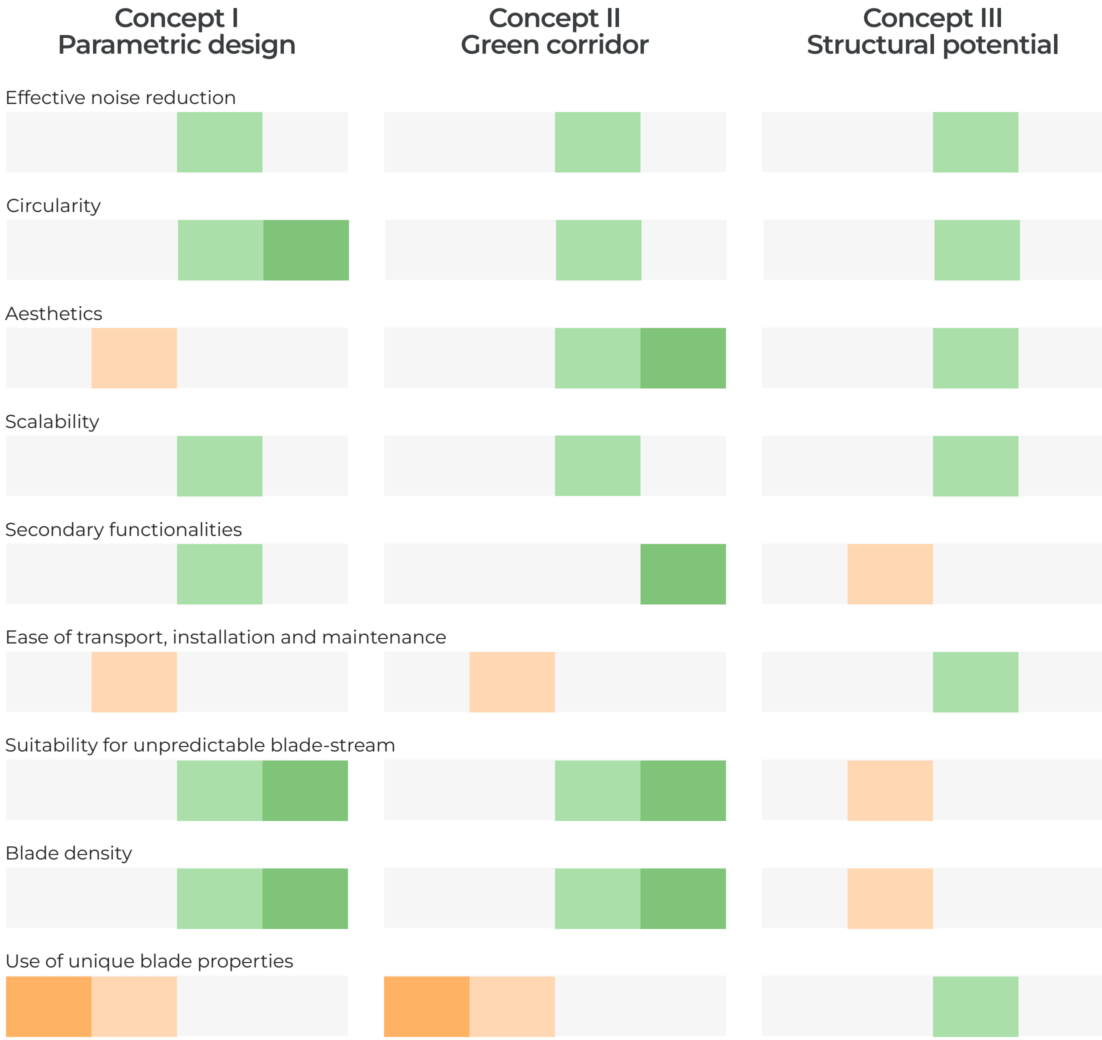
Figure 17.2: Semi-transparent barrier design

18. Concept selection

The three concepts represent three different approaches to the design challenge; a parametric, landscape and technical perspective.

In order to select the most suitable concept for the design challenge, a Harris-profile (Zijlstra & Daalhuizen, 2020) is made. The principles that resulted from the research (see page 35) are ordered in terms of priority, and the concepts are scored for each principle. Explanations for each rating are given on the next page.

The profile is used to evaluate the concepts in collaboration with Superuse to come to a definitive choice.



The following is a brief description of the reasoning behind the scoring of the concepts.

Effective noise reduction
The concepts score equally here. While Concept III (C3) has the advantage of height and placement, it relies on reflection while the other concepts have the benefit of diffusion and absorption.

Aesthetics
In terms of aesthetics, C2 has the upper hand. The concept takes the most advantage of the creative potential of the material, and is designed to contain much greenery. While this is also possible with C1, the parametric nature of the design complicates creative freedom and therefore makes it less suitable for detailed form-giving. In C3 the overall style is comparable to many existing barriers, reducing its novelty.

Circularity
C1 scores highest in this area. While the blades are cut into smaller segments, potential damages can be effectively circumvented in the algorithm, resulting in a minimised material waste. This sets it apart from C2. C3 has the advantage that blades are not segmented. However, the connections will affect the material quality along the entire length of the blade. This would make structural reuse (creating beams and panels) at its EoL more difficult.

Scalability
C1 and C2 score positively here as they are built around adaptability for various locations. The nature of the design does limit it in terms of width, so the barrier is not suitable for narrow spaces. This is where C3 has the upper hand. While this concept can be placed virtually anywhere, it is limited in length as there is limited availability of identical blades.

Secondary functionalities
C3 is limited in its other purposes, even though vegetation could be added on the ground level. C1 is similar to C2 in the sense that a lot of plants can be included for ecological benefits. C2 excels in its recreational potential, and the possibility to adapt the design to the perspective of the residents.

Ease of transport, installation and maintenance
The main difference here is that packing segments closely together is a disadvantage regarding maintenance, as certain areas might be hard to reach. C3, on the other hand, resembles current barriers and its surfaces are more straightforward to clean. While C3 is more uniform (and therefore more systematic in terms of installation), a foundational structure is required where C1 and C2 do not need this.

Suitability for unpredictable blade-stream
C3 is mostly suitable for identical blades. Adapting the design so that a wider range of blades is useable within the same barrier can be done, but would complicate the structure significantly. C1 and C2 are designed in such a way that virtually all types and sizes of blades can be incorporated. Only the bottom parts of the largest blades are potentially too wide to be used in these concepts.

Blade density (blades/km)
As C1 and C2 are constructed using densely packed blade segments, they score well on this principle. C3 is constructed using a single row of blades alternated by transparent panels, reducing its density.

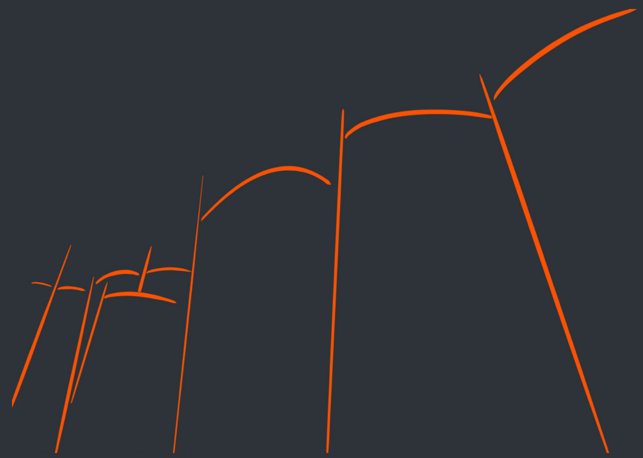
Use of unique blade properties
C3 is designed based on two main technical attributes of the material, and therefore scores well here. C1 and C2 do not employ these properties to a great extent.

Outcome:
1st place: Concept II - Green corridor
2nd place: Concept I - Parametric design
3rd place: Concept III - Structural potential

The *green corridor* concept is chosen as the most promising concept. It is further developed in the continuation of the project.

PART D

Final design



PART D

Final design

In this part, the final design is presented. First, the main features are shown succinctly, and the barrier is showcased in a proposal for a location in Rotterdam.

Next, the various aspects of the full design are covered in more detail. Finally, several recommendations for the realisation of the design are presented.

Figure III: Resident side of the Blade Barrier

Figure IV: Traveller side of the Blade Barrier

19. Blade Barrier 'at a glance'

A quick look at the Blade Barrier design:

1. Segmented blades are placed together tightly to form a closed wall

2. Barrier modules allow for relatively sharp bends in the barrier

3. The adaptive design seamlessly integrates with existing infrastructure

4. Traveller side and resident side differ in aesthetic and functionality

5. Different modules for features such as escape routes

6. Custom transitions into the existing surroundings

7. Where possible, Blade Made features like playgrounds or fitness parks can be included

8. The resident side is designed to form a *green urban corridor*

9. Vegetation enhances the aesthetic of the barrier, improves its acoustic performance and stimulates biodiversity

10. Smaller pieces such as bridges and urban furniture connect the barrier to the environment

20. A20 barrier proposal

This chapter presents the proposed design for an initial Blade Barrier in Rotterdam, the Netherlands. It shows how the design can be tailored to the requirements of any location.

Based on the location type analysis and insights from the design development, a target location type (being a location with a high urban density, and an average to high level of available space) was identified.

A site was found that is highly suitable for a Blade Barrier prototype. It is a strip of land (ca. 350 metres long) on the Northern side of the A20, bordering the allotment association “Eigen Hof”. This location is close to the central borough of Rotterdam Noord. It is connected to multiple cycling and walking routes and offers ample space for a linear park to supplement the barrier.

Moreover, the current noise barrier is in dire need of replacement. The structure is rusty, contains a great number of holes and has a collapsing inner structure. In certain spots, the steel cladding has fallen off as well (see Figure 20.1).

A significant benefit of Rotterdam as a location for a prototype is Superuse’s strong connection to the municipality, and the city’s tendency to embrace innovation and novelty in the built environment.

The scalable design of the barrier (developed to suit various locations) is adapted to the area, and a linear park is proposed that integrates with the existing surroundings. This park includes additional Blade Made structures such as a fitness park, benches and a pedestrian bridge. The additional features are mostly made from leftover pieces from the barrier construction, to illustrate Blade Made’s *full blade strategy*. Figures 20.2 to 20.4 showcase the proposed barrier design.

Further details on the envisioned barrier are found in appendix N.

Figure 20.1: Current barrier at selected location

Figure 20.2: Envisioned barrier blending into existing surroundings

Figure 20.3: Blade Made fitness court

Figure 20.4: End point of the barrier, integrating with existing structures

21. Blade to Barrier

In this chapter, the method of creating the barrier from wind turbine blades is explained. The focus lies on the geometry and functionality. Physical production steps are elaborated upon in chapter 27.

The barrier consists of four different *modules* that repeat themselves indefinitely. Each module is made up of the same set of *blade segments*. Variations in how the segments are placed result in the four different modules.

Segmentation and orientation

For one set of blade segments (and therefore one module), four blades are required. To create a barrier that conforms to aesthetic and acoustic considerations, a systematic way of cutting the blades is developed. This method is in essence a series of steps describing how exactly to cut the blades, and how to orient the resulting segments properly. The method is described more elaborately in appendix J.

Essentially, the method alternates between straight and angled cuts, and repeats itself after four blades. The segments are oriented so that all angled cuts face upwards. Alternating the tapered shapes allows for a tight sequence of segments.

The four different modules are based on the four combinations in which the largest segments can be arranged (see Figure 21.1). From large to small, the remaining segments are placed in front of each other in an overlapping manner.

In this example, a common blade design of 29 metres is used, but this method can be applied to any blade type. This is important as blades are expected to keep increasing in size.

It was found that the bottom part of the blade is rather unsuitable for use in the barrier due to its shape, as incorporating it would result in a wider barrier and a less tight sequence of segments. Unless they are used as poles for streetlights, the tips of the blades were found to add little functionality to the barrier due to their thin geometry. Fortunately, both of these parts are highly versatile when it comes to urban furniture and installations such as playgrounds. Therefore, these parts are excluded from the design of the barrier itself.

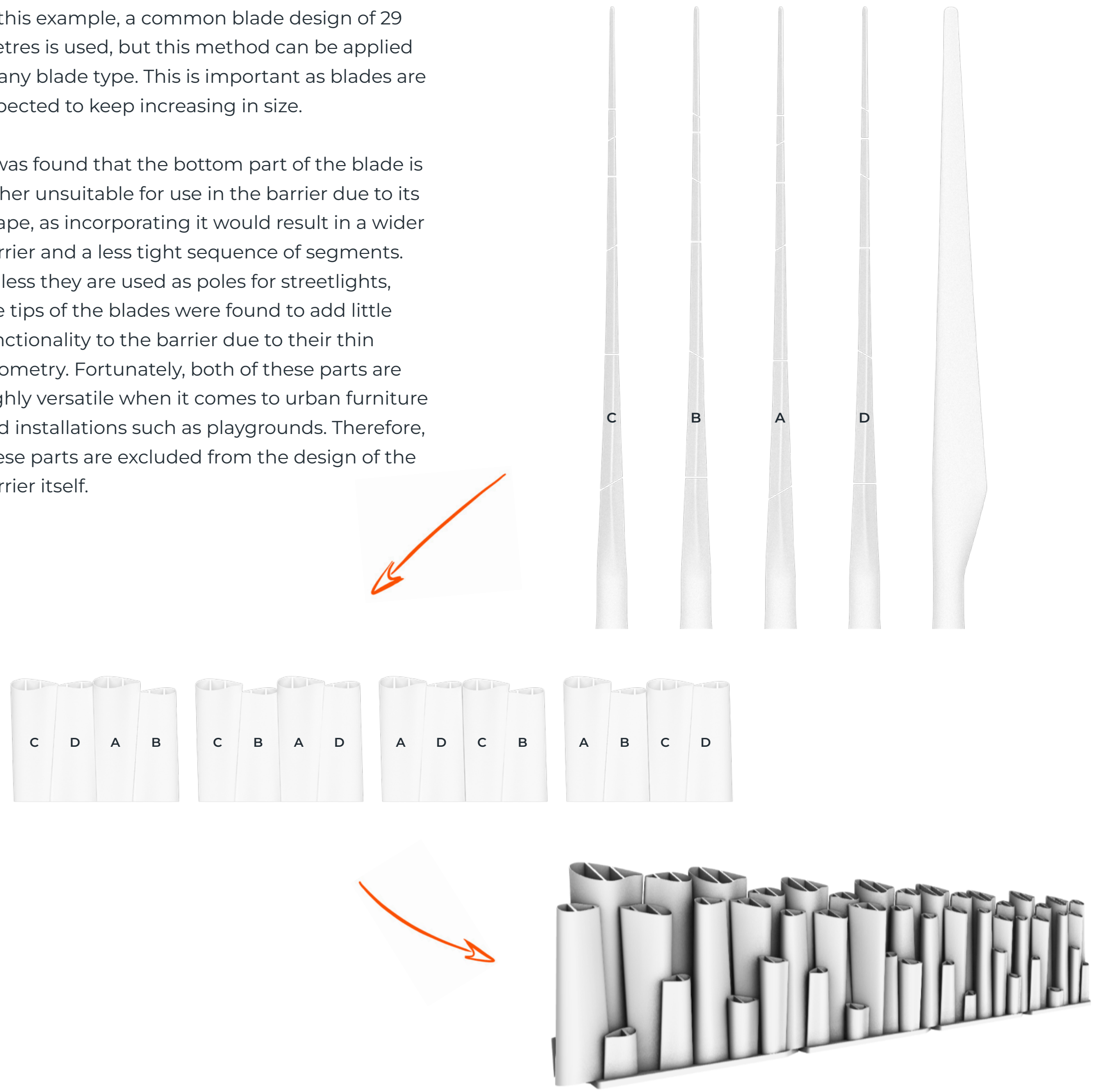


Figure 21.1: Simplified segmentation and orientation schematic

Module foundation

It should be noted that for the barrier to perform as intended, precise placement of the segments is required. If gaps between the segments are significantly larger than intended in the design, the acoustic performance is affected (see chapter 24 on the acoustics of the barrier). Therefore, a foundation is designed to serve as the basis for each module.

The foundation is a reinforced concrete slab to which the segments are attached using metal brackets. Markings on the foundation will clearly indicate which segment needs to go where, creating a prefabricated solution that simplifies the building process. The foundations are to be dug in so that the foundation and brackets are covered with earth.

The foundation is perforated so that rainwater can simply run down into the soil. The pattern of the holes is designed so as not to collide with the reinforcements within the concrete. The slabs are shaped in such a way that they slightly interlock with each other, and allow for curvatures in the overall barrier layout, see Figures 21.1 and 21.2.

The exact way that the barrier is anchored to the ground will depend on the specific location and its soil type (Van Noort, 2022). In most cases, driven piles will be needed to construct a barrier that can deal with the wind forces that are exerted on the structure. The piles are placed at the end of each module so that they can simultaneously form the connecting element between the foundations. This is visualised in Figure 21.3.

Lastly, the dimensions of the foundation are chosen so that they do not require special transport permits, and are suitably small for the installation on site.

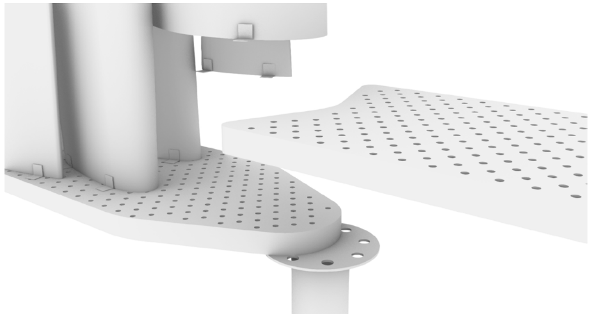


Figure 21.3: Interface between the driven piles, foundations and blade segments

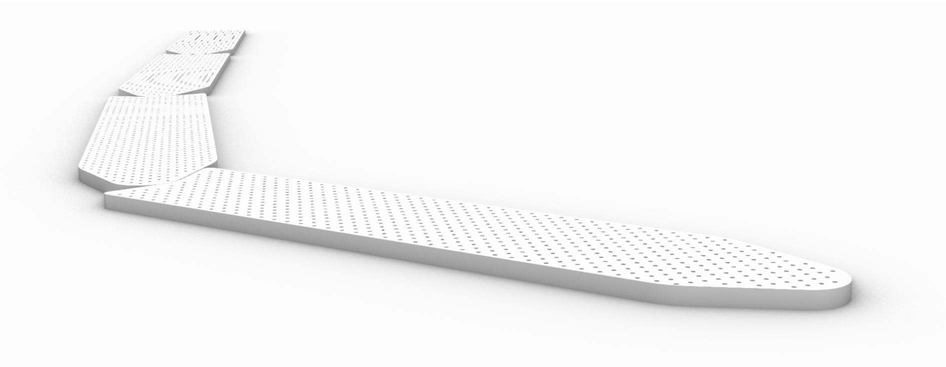


Figure 21.1: Example of how modules can be placed to create turns of max. 45°

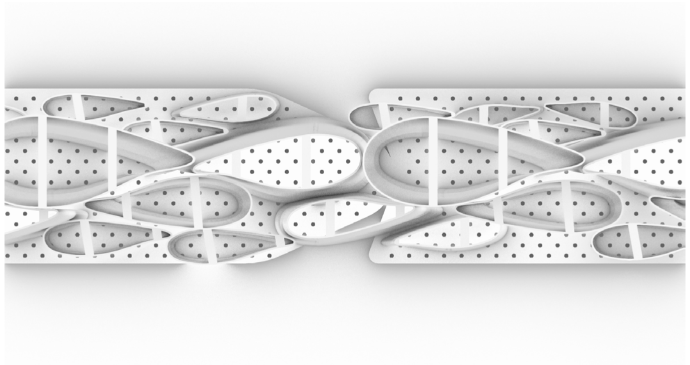


Figure 21.2: Topview of the foundations interface with the sequence of blade segments

22. Barrier module adaptations

The four modules that are covered in the previous chapter form the basis of the entire barrier design, and are therefore henceforth called the *base-modules*. There are various situations in which the base-modules are not functionally suitable, or at least do not fulfil aesthetic requirements.

This chapter shows how these modules are adapted to suit various location features and requirements.

Standard starting module
For the start of the barrier (for example right after an off-ramp), it is advised not to start with a base-module. Rather, a simple adaptation is made to the first module. The segment heights are adapted so that they gradually reach the desired barrier height. This module can be customised by adding a few small segments to further emphasize the transition into the landscape (Figure 22.1).

Sharp corners
For angles between two base modules that exceed 10°, the placement of the smaller segments must be evaluated to prevent potential 'collisions'. The maximum angle between two modules is 45°, as this is what the foundation is designed for. Therefore, if a sharp corner of 90° is desired, this bend should be made over three modules (as seen in Figure 22.2).

Under bridges
Overhead bridges come in two common types. They are either supported by earth mounds up until the highway, or they are supported by pillars in the run-up. In the former, the barrier can be integrated by a standard starting module (potentially using a sharp corner). For the latter scenario, the barrier would continue underneath the bridge. In this case, large straight-cut segments are used that extend to the bottom surface of the viaduct. This prevents sound reflection from this surface toward the resident side. Additionally, vegetation is not installed due to a lack of sunlight and rain. Therefore, only large segments are used (see Figure 22.3).

On bridges
In the scenario where a sound barrier is required on top of a viaduct, the standard design of the Blade Barrier is likely too wide and heavy. Moreover, often transparent barriers are preferred for this location type. For these reasons, a custom solution (such as the one in Figure 22.4) is proposed. Unused blade tips are suitable for this module.

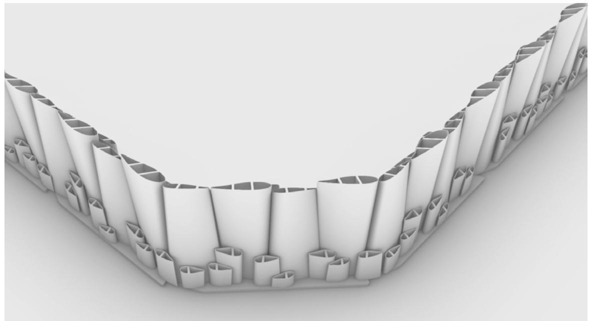


Figure 22.2: Sharp corner using two 45° turns

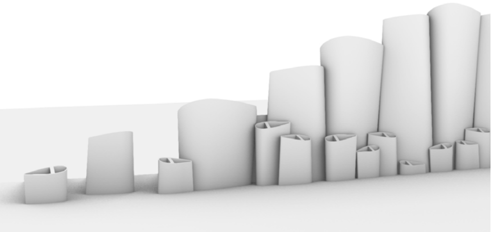


Figure 22.1: Starting module with additional small segments

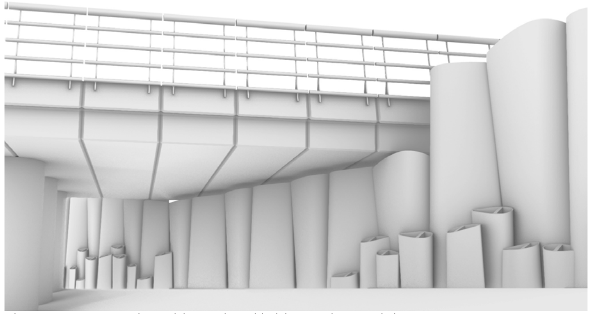


Figure 22.3: Integration with overhead bridges using straight-cut segments

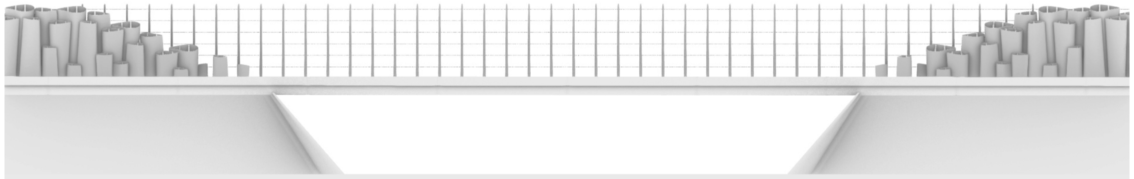


Figure 22.4: Custom lightweight and semi-transparent module for use on bridges (using left-over blade tips)

Emergency exits
For escape routes, two main variations are developed. For limited available space, it is recommended to place a door that allows for safe passage, similar to current escape doors (see Figure 22.5). The second variation requires more space, and relies on a second layer of barrier to overlap with the first (Figure 22.6). This creates an opening that conforms to barrier design guidelines as described by the TfNSW (2021).

Obstacles
If signposts or other objects are in the way of the intended course of the barrier, several options are possible.
The least disruptive way would be to remove a few small segments, as seen in Figure 22.7. This would not drastically affect the barrier's performance. This is however not possible in all cases.
Other options include redirecting the path of the barrier slightly, or including a second layer of barrier, similar to the second exit variation.

Custom transitions
The modules are all attached to foundations. However, segments can be installed without any foundation if they are dug in (as seen in previous Blade Made builds). Combining these two offers limitless possibilities for custom transitions designed for specific locations. Figure 22.8 shows an example of how this can be used to integrate the existing landscape with the barrier in a unique way.

These modules are both functional and aesthetic in nature, to integrate with the surrounding landscapes. The next chapter dives into the appearance of the barrier, and the steps taken to integrate with the needs of the users as well.

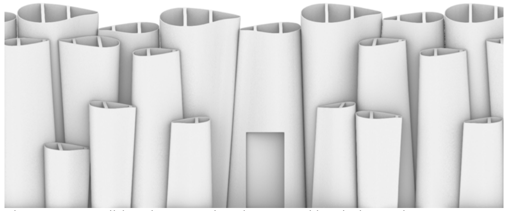


Figure 22.5: Traditional escape door integrated in Blade Barrier

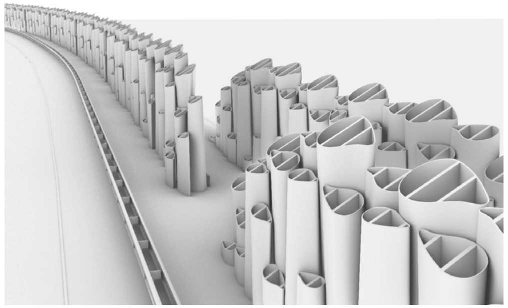


Figure 22.6: Emergency exit using overlapping barriers

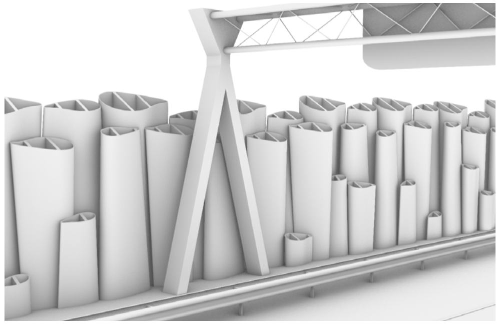


Figure 22.7: Integrating with signposts by removing small segments

Figure 22.8: Envisioned barrier blending into existing surroundings

23. Aesthetic design

This chapter serves to elaborate upon the aesthetic considerations taken in the final design of the Blade Barrier. The perspectives of the traveller and resident are key in the development of the appearance of the design. For the former, their speed and task at hand are considered in the visual design of the barrier, while for the latter a more engaging surrounding is envisioned.

Natural look

The aesthetic potential of plants is significant. While living and commuting in a green environment is generally experienced as pleasant (Foderaro, 2005), plants also offer more subtle ways of adding aesthetic value. A low layer of plants in front of the barrier can be used to decrease its apparent height, and visually create a barrier that is tilted away from the traveller. This last effect is also achieved through the way that the segments are placed from low to high. Both examples are shown to improve the spatial experience of the traveller (Farnham et al.,1990). Plants can be used to smoothen out any irregularities or imperfections.

Angled cuts

Apart from having acoustic benefits (these are covered in the following chapter), cutting the blades using 30° angles gives the resulting segments a more dynamic and purposeful aesthetic. Currently, landfilled blades are often segmented for practical reasons, using perpendicular cuts. The angled cuts set these segments apart from the idea of being a ‘waste material‘, and give it a new appearance with a higher design value.

Organic repetition

The design is based on four modules that slightly differ from each other. Visual evaluation shows that these modules can be repeated indefinitely, without it being visually obvious that these are indeed the same repetitive units. This effect of ‘apparent randomness‘ is further strengthened by the application of plants, as each plant is unique in shape. Slight variations in height add to the natural and organic feel of the structure.

Visual contrast

The monolithic blade segments, with their continuous surfaces and smooth lines, are contrasted with the natural and random aesthetic of the vegetation that is placed inside.
While the segments are still recognisable as coming from wind turbine blades, they have taken on a new role in this design and have become something new.

Segment height and width ratio

It was found to be most effective and visually attractive to follow a segmentation pattern in which the segment widths and heights roughly correspond to the same ratio.
In other words, the broad parts of the blade will be cut longer, while the narrower parts of the blade will be used for the shorter segments. This ratio creates a visually harmonious barrier, even when the resulting segments are distributed in a visually random manner. For this visual harmony to occur, the ratio (r) between segment height (h) and average width (w) needs to roughly sit between 2 and 3 (see Figure 23.1).

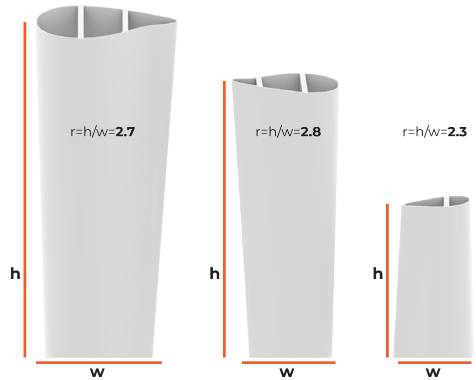


Figure 23.1: Segment height and width ratio example (2 < r < 3)

Traveller side

In terms of rhythm in the appearance of the barrier, the traveller side is designed to offer enough variation to be visually pleasing, without being distracting at high speeds. Variations in segment heights span the entire height of the barrier.

Resident side

For the resident side, more visual variation is allowed as traffic is slower. In terms of segment height, a large difference (of at least 2.5 metres) is required between large and small segments to prevent climbing onto the barrier. Furthermore, the small segments are placed in such a way that they (along with the added vegetation) disrupt the smooth surfaces of the large segments, making the barrier less attractive as a canvas for graffiti artists.
Depending on the location, the barrier can be equipped with sensor-activated lights to illuminate the area at night.

24. Acoustic performance

The main purpose of the barrier is to reduce the perceived sound levels in the areas surrounding the highway. This chapter covers the ways in which the barrier aims to achieve this sound reduction. Acoustic simulations were performed to validate the performance of the design.

Acoustically closed barrier

The first rule of barrier acoustics is 'if you can directly see the source, you will hear the sound'. This means that any barrier should at least be a visually closed structure. This is achieved by placing blade segments in an overlapping sequence. This is helped by the fact that the wide part of the segments is oriented along the length of the barrier, and that the tapered shapes of the segments are alternated.

This leaves us with a visually closed barrier, but that still contains gaps between all segments. Initially, ideas were generated for closing these gaps (such as incorporating soil or rubber strips). However, after deliberation with Dr Tenpierik (2022) - an authority in this field - it was found that the narrow gaps between the segments, in combination with the curved funnel-shaped slits would be enough by themselves to sufficiently cancel out any sound that might penetrate these gaps by absorption and diffusion. This is confirmed in the next step using acoustic simulations. Any sound that would still pass through the barrier would be negligible compared to the dominant path of the sound, being the sound that travels over the barrier.

In short, the closely packed sequence of blade segments is deemed to be acoustically closed.

Acoustic simulations

To assess the performance of the design, a series of acoustic simulations were performed. Following is a brief description of the set-up, results and conclusions. For full details, please refer to appendix M.

Set-up

A CAD model was constructed in which the sound source (being the highway) was modelled as a line. The sound from the highway was based on busy traffic, with speeds of 120 km/h. The sound is measured in the observer points, which are placed close, average, and far from the barrier. The sound is measured in the following situations: no barrier, generic barrier (5 m), generic barrier (6 m), and the blade barrier. Figure 24.1 shows the setup of the simulation.

The functional height of the blade barrier was not certain due to the slight variations in segment height. Therefore, the barrier is compared to generic counterparts of both 5 and 6 metres in height (see Figure 24.2). The thickness of the generic barrier is set to be 0.7 metres as this represents an average of the five main types of barriers.

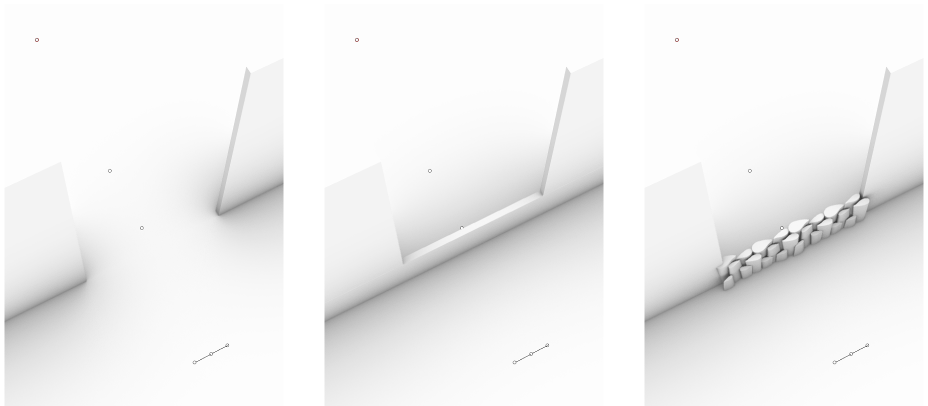


Figure 24.1: CAD set-up for acoustic simulations

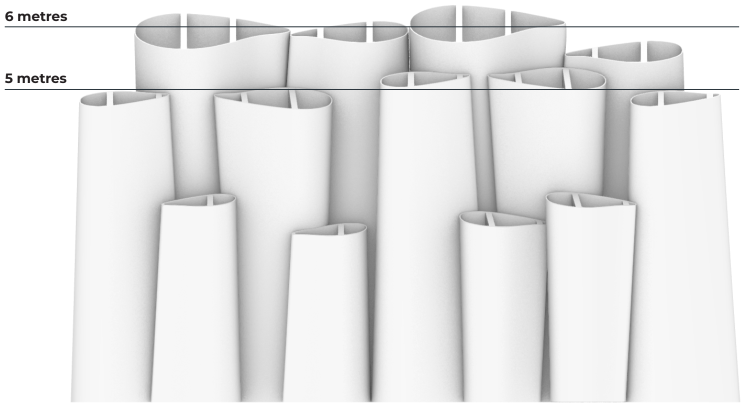


Figure 24.2: simulated barrier heights

Results
The measured SPLs (sound pressure levels [dB]) are shown in Figure 24.3.

Firstly, it should be noted that the addition of all of the three barriers results in a large decrease in perceived SPLs, being approximately 14 decibels. This corresponds to a perceived sound decrease of more than half: a decrease of factor 2.6 to be exact (Sengpiel, 2020).

Secondly, the Blade Barrier is shown to perform better than the 5m generic barrier. This indicates that the functional height of the barrier lies higher than the area in which the segments overlap. On average, the Blade Barrier achieves an additional 1.6 dB decrease, corresponding to a 10% decrease in perceived loudness.

The differences between the 6m barrier and the Blade Barrier are considered negligible. Therefore, the functional height of this design is shown to lie only ±5% under its maximum height.

Simulations show that the distance between segments is vital for the performance of the barrier. Generally, the closest distance between adjacent segments is ±5 cm. When this distance is more than doubled, the performance is significantly affected. Therefore, the tolerance for blade segments is set at 5 cm. This is why enabling precise segment placement is key in the success of the design.

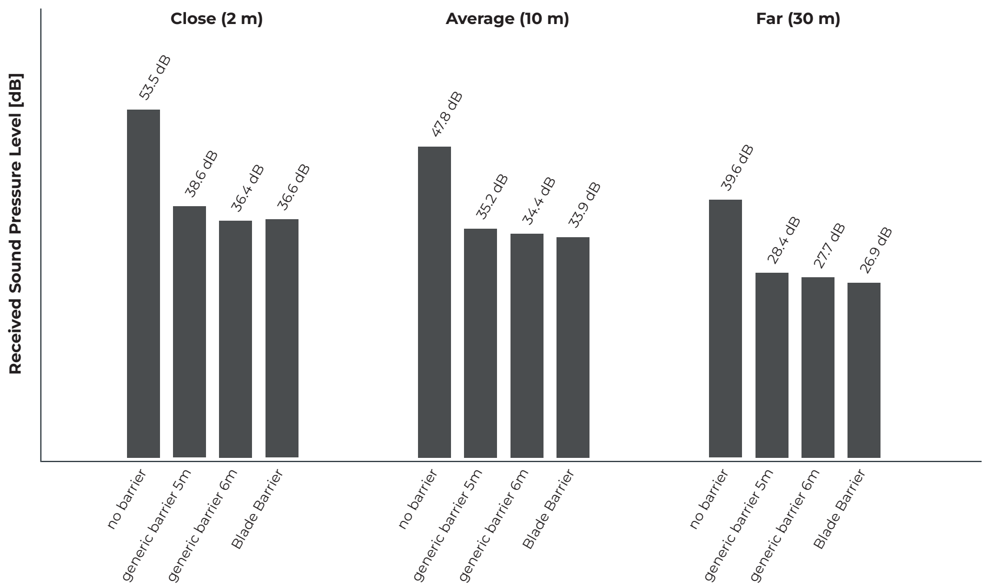


Figure 24.3: simulation results averages

Vegetation
Thus far, the effect of vegetation has been left out of the equation. The reasoning is that even without this addition, the barrier should function as intended in terms of acoustics. The added layer of vegetation is meant to further enhance the performance of the barrier. It is difficult to precisely pinpoint the acoustic effect of vegetation. Sound absorbing qualities of grass and soil, and the diffusing effects of thickets have the most impact on the nearby observer, while reductions in diffraction can influence the noise levels that are experienced relatively far away. It is estimated that adding a layer of vegetation to an existing barrier structure can increase its effectiveness by 1 to 2 dB (Kalansuriya et al., 2009).
Experts agree that soil serves to absorb sound (Viola, 2021)(Tenpierik, 2021). This last point is the main reason that the segments are cut under an angle. This way, the surface of the soil is turned toward the source of the sound, increasing the contact area between soundwaves and soil.

Chapter 26 will cover the application of vegetation in more detail.

25. Segment prototype

The following two chapters will cover the envisioned placement of vegetation and the overall production process. These steps were informed by physical prototyping steps that led to the final segment prototype (see Figure 25.1).

An actual blade segment was cut to size, processed and coated, and equipped with vegetation bags and vegetation.

The prototype is a tangible representation of the final Blade Barrier design. Included as addendum to this report is a video of the production process.

Figure 25.1: Final prototype and its place in the overall design

26. Vegetation

This chapter reiterates why vegetation is incorporated prominently into the design, and how this can be done effectively.

Firstly, the benefit of incorporating vegetation is threefold:

- Aesthetic: Green and natural elements in the urban environment are broadly experienced as pleasant and beautiful.
- Acoustic: Vegetation and soil can be applied to further enhance the performance of the barrier.
- Natural: Green berms are shown to stimulate biodiversity (mainly insects and birds) and help to improve urban air quality.

The first two benefits are described in previous chapters in more detail. The third is elaborated upon here:

Natural benefits

Implementing vegetation can be an effective way of contributing to the biodiversity of the area. All too often, infrastructure projects eliminate green areas in the urban environment (Biodivers, 2021). Research indicates that creating wild berms (Figure 26.1) through natural landscaping can effectively reverse biodiversity loss in urban areas, especially when great care has been taken to select indigenous plants (Threlfall et al., 2017). Also, the use of plants next to traffic routes has been shown to have a positive effect on air pollution (Rai, 2016).

Plant selection

The plants are required to be evergreen, low-maintenance and resilient to changing weather conditions. Based on these main requirements, a preliminary selection of plants is made in collaboration with S. Viola (2022), many of which have a proven track record in green roofs:

- Juniper
- Siberian Cypress
- Sempervivum
- Sedum Album
- Sedum Floriferum
- Holly
- Ilex

This selection is shown in Figures 26.2 to 26.8.

Figure 26.1: Wild berms in The Netherlands

Figure 26.2: Juniper

Figure 26.3: Siberian Cypress

Figure 26.4: Sempervivum

Figure 26.5: Sedum Album

Figure 26.6: Sedum Floriferum

Figure 26.7: Holly

Figure 26.8: Ilex

Vegetation bag design
Developments in the area of green roofs offer a grounded basis for the application in the Blade Barrier. For the plants to thrive, a few conditions are necessary. Soil depth should be limited, and roots should not be allowed to grow too deeply. It should not be possible for moisture to accumulate and cause rotting. Therefore, a barrier is needed that contains the soil and roots while allowing for water to flow through.

Through prototyping with an actual blade segment, it was found to be most suitable to use a vegetation bag as a basis. This way, the plants can be installed and replaced in a convenient way. Moreover, the flexibility of the bags offers an adaptive solution for the unique shapes and sizes of the 'blade compartments' in the segments. This way, only 3 to 5 different bag sizes are enough to equip the entire barrier with vegetation.

Appendix L describes the low fidelity prototype of the vegetation bag, which is the starting point for the final bag design. While the prototype managed to safely carry 30kg more than the calculated load on two of the four connection points to the structure, it was chosen to further increase the load-carrying capacity of the bag to be able to safely carry all intended volumes of soil over an extended period of time. Therefore, 5 cm wide nylon straps are selected to reinforce the bag (see Figure 26.9).
The bag itself is made from a geotextile fabric that allows for water and air to pass through. This allows for optimal root growth, and prevents moulding. The fabric keeps the soil warm during winter and helps cool it during summer. The material lasts many years and is resistant to the effects of UV rays (Biosolutions, 2021). This material, in combination with the nylon reinforcement straps, make it so that the bag can withstand many years of ageing and weathering.
The bag is connected to the segment in four locations. In these four spots, eye-bolts are connected to the blade structure. These bolts are connected to the eyelets in the bag using carbine hooks (see Figure 26.10). This allows for easy installation and - if necessary - replacement of the bags.

In short, evergreen and resilient plants are placed in the unique blade compartments using flexible reinforced geotextile bags that are attached to the segments durably and conveniently.


Figure 26.9: Final vegetation bag prototype


Figure 26.10: Installed vegetation bag

27. Production process

This chapter serves to describe how the production of the barrier is envisioned practically; from turbine decommissioning to barrier EoL. The process is visualised in Figure 27.1. The reasoning and testing behind several choices is elaborated in appendix K. The process is designed to suit all involved stakeholders. Appendix D offers an overview of the interests of each party.

Decommissioning
Wind turbines are decommissioned, usually by hired contractor companies specialised in these operations. The components are brought ashore (in the case of offshore turbines) and prepared for the next step in the process: recycling. In practice, this means that large components are cut to smaller parts so that they can be transported to the intended facilities (Kolthof, 2022). Blades are commonly cut several times to create more easily transportable pieces.

Segmentation
In the envisioned scenario, the entire blades are segmented using a lint-saw in accordance with the subsequent application immediately after decommissioning. A port-based circular wind hub, as proposed in recent research (Scheepens, 2021) would be most suitable for this, and would simultaneously offer potential for many other circular strategies. Such a hub would enable various parties in the wind- and reprocessing industry to invest in and use necessary equipment together.

Post-processing of segments
After segmentation, the resulting exposed edges need to be sealed and coated. While this would traditionally be done at the premises of the hired contractor, it could be beneficial to explore the possibility of performing all post-processing and preparatory steps in the proposed hub too, as this would reduce the financial and environmental costs of transport.
Further necessary steps are to apply a new layer of finish to the segments, and to drill holes for the interfaces with the foundations and vegetation bags.

Production of foundation
The foundation slabs are poured in moulds, internally reinforced by a steel mesh. The drainage holes are designed with a generous draft angle so that they can be included in the design of the mould. It is proposed to produce four unique tops for the mould, so that the location for segment connections for each base-module can be indicated on the concrete surface.

Production of bag
The vegetation bag is to be produced from bought-in geotextile grow-bags that are subsequently reinforced using nylon straps. Finally, metal eyelets are punched into the straps. It is suggested that these production steps be performed in the textile workshops that are part of the In-Made program in Dutch penitentiary institutions. This would give the project an opportunity to also generate a positive societal impact.

Transport
All components of the barrier are designed to be transportable using regular transport, meaning that no exemptions are required for any step in the process. After the segments and foundation slabs are transported to the construction site, they can be placed using straps and a small crane or excavator arm.

Installation
A strip of 2 metres wide and 0.3 metres deep will be excavated and levelled for the foundation. The piles are installed, onto which the foundation slabs are connected in a row. From large to small, the segments are then bolted to the foundation using brackets. The segments are connected to each other using bolts to prevent collisions due to wind. Next, the vegetation bags are placed in the tops of the segments. A ladder or aerial work platform are required for the tallest segments.

Maintenance
Due to the sturdy nature of the material, the main maintenance tasks will be aesthetic in nature.
After installation, it is estimated that an average of 20% of the vegetation will die in the first few years, and will need replacing. Afterwards, the plants will settle more permanently (Viola, 2021). While measures to discourage graffiti artists have been taken, visual vandalism will likely take place during the intended decades of service of the barrier.
Recoating segments will therefore inevitably be necessary at some point. An alternative approach could be considered in which street art is actually encouraged, and some segments are designated as a canvas. A similar approach was used for the NDSM-werf in the Netherlands (I Amsterdam, 2022).

End of Life
The barrier is designed so that various EoL strategies are possible at EoL, such as repurposing segments or creating panels from the structure. The next chapter will go into more detail about the EoL of the barrier, and the positive impact that the material journey can have.

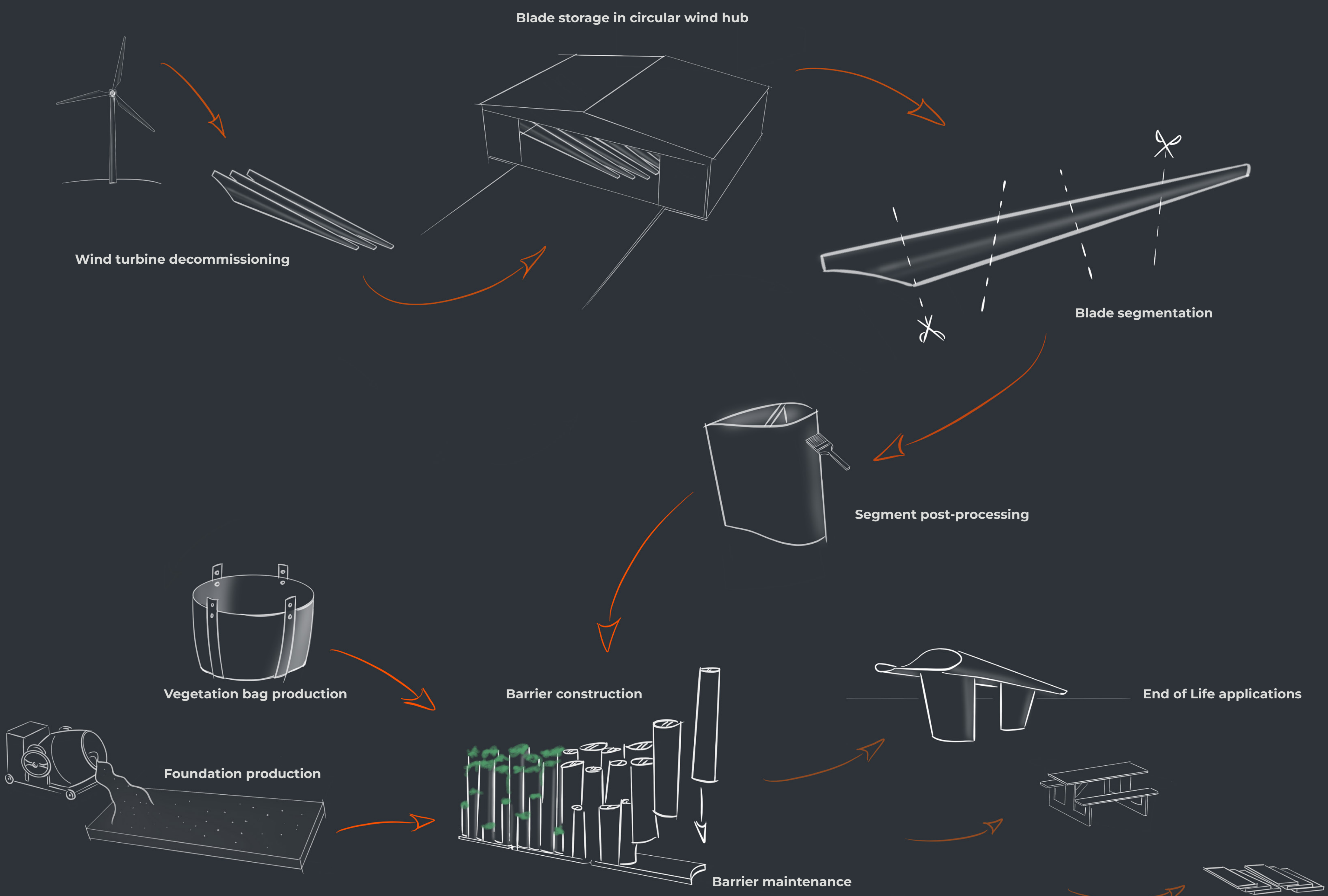


Figure 27.1: Envisioned material flow and production steps (own illustration)

28. Environmental impact

The *raison d'etre* of the Blade Barrier project lies in its potential for positive environmental impact. It approaches this goal by extending the lifetime of the material and reducing the need for virgin materials.

Firstly, the life-in-service of the composite material is extended. As noise barriers are generally required to last several decades, the lifespan of the blade material is at least doubled by applying it in the form of a Blade Barrier. Moreover, the material journey does not end there.

The Barrier is designed to preserve the integrity of the material to a great extent (by preventing material degradation and limiting the number of modifications such as cuts and drilled holes), meaning that various subsequent applications of the material are still possible after the EoL of the barrier. The segments could be used to produce pieces of urban furniture, or be processed into panels and beams as proposed by Jellema et al. (2021).

The next step would be to process the material into flakes and use them in new composite applications as described by Ten Busschen (2020).

Following this cascade, the value of the material is preserved for as long as possible before the material is eventually disposed of.

The result of this approach is that for each new application of the blade material, fewer virgin materials are needed. In the case of the Blade Barrier, the vast majority of the structure is made using pre-existing material.

The viability and environmental impact of constructing sound barriers using repurposed wind turbine blades was researched by Dura Vermeer and Rotterdam University of Applied Sciences (2022). Results from this study show that repurposed blades are overall a significantly more environmentally friendly material than currently used virgin materials.

Furthermore, the study indicates that it would be financially profitable to use repurposed blades instead of traditional materials.

To put things in perspective, the following data is considered:

- In the Netherlands, approximately 20 kilometres of noise barrier is placed along highways every year (CLO, 2022).

- In the year 2023, an expected number of 400 to 500 blades is expected to be decommissioned in the Netherlands (de Krieger, 2022).

- The Blade Barrier has a density of approximately 450 blades/km. (based on a 29m blade)

This means that if next year, 5 percent of the required barriers are constructed using blades, we can nearly eliminate the blade waste steam for that year, and simultaneously vastly reduce the need for virgin materials.

The only virgin materials in the barrier include concrete, metal and fabric. For some of these components, reused materials can be considered as well, such as concrete with a high concentration of recycled content.
The barrier is designed in such a way that all components can be separated at EoL, and used for new applications.

In short, the aforementioned points illustrate how the barrier has the potential to contribute to a durable and more circular world in which inherent material value is preserved, and the need for new materials is reduced.

29. Discussion

This chapter serves to take a step back and observe the process and results of the project. The final design is related to the initial project brief, and a general reflection on the project is offered.

Project structure

It should be noted that the Blade Barrier project has been an unconventional one in several regards:

- The design challenge was tackled by an industrial designer, using methodology and techniques taught at the faculty of Industrial Design Engineering in Delft. On the other hand, the subject matter is for a large part architectural and urban in essence.
- Using an existing material or object as a starting point for the design process is not commonplace in the world of industrial design.
- The endpoint of the project was clear from the start, namely a noise barrier design. The project has generally been all about connecting the starting point (the blade material) to this endpoint (the barrier).

Furthermore, the project was approached using a wide scope, so that all of the most relevant factors can be included in the design process. This resulted in a design that is informed by various divergent topics, such as the decommissioning process of wind turbine blades, aesthetic considerations for noise barriers, and the acoustic value of vegetation to name a few.
Due to this wide scope, many experts have been consulted throughout the project to be able to make informed design decisions.

This project structure, with many different aspects, along with the uncertainties that come with any design project, needed to be managed very actively. The resulting challenge was that a balance needed to be found so that each topic would be covered thoroughly, without straying too far into a single facet of the design.

In the project planning, idea generation was included from the start of the process. This has helped to guide the research phase, and accelerate the creative process. As a result, one concept had already been chosen at the midterm, and a significant portion of the project could be dedicated to developing a well-rounded design.

Validity of the design

In the process, the focuss was on making grounded design-decisions based on research, the expertise of various experts and on previously realised constructions. Research led to the formulation of design principles and a design vision, that were closely adhered to in the development of the concept.

For the aesthetics of the design, it is inevitable that the personal preferences of the designer play an influential role. However, objective sources have been consulted to create a well-based design that aims to serve all users of the barrier. For example, the aesthetic differences between the two sides of the barrier and the prominence of vegetation are guided by established design guidelines.

In lieu of a physical full-scale barrier prototype, acoustic simulations have validated the performance of the barrier to a great extent. In short, it is possible to create a functioning barrier in the envisioned way. Results show that the design performs as well as current barriers, and is therefore a competitive alternative.

The segment prototype is made to showcase several practical aspects of the design, such as cutting, processing and the placement of vegetation. Furthermore, several practical tests have offered proof that the intended application is possible, such as mounting plants and substrate in the cavities of the segments.

Applying the design into an actual location illustrated the adaptive nature of the design, and proves that it can be integrated flexibly with pre-existing infrastructure.

In April 2022, the Blade Barrier was included in the Blade Made exhibition at the WindEurope Conference in Bilbao (refer to appendix O for more details).
The design was well-received among parties in the industry. The main reaction was it is not just about reducing harmful aspects of the sector, but actually achieving positive impact.
People saw the need for ambitious yet achievable solutions to the blade waste issue, and the scalable Blade Barrier fits this demand. Having detailed renders of the design helped greatly to convey the design and garner enthusiasm. As a result, several organisations are in contact with Blade Made to

explore the possibilities for their blade EoL issues. This shows that relevant parties in the wind industry see the great potential for scalable repurposing of blades, and that the design is in line with their vision of a more sustainable future.

Shortcomings in the design
Even though circularity has been a major influence in design decisions, the environmental impact of the Blade Barrier compared to generic barriers is still quite ambiguous. Research concerning this very topic was performed by other parties at the same time as this project. While the results indicate that barriers from repurposed blades are indeed favourable overall in terms of environmental and financial costs, no quantitative indications can yet be given concerning its life-cycle.

In terms of construction, the design is still rather conceptual. This facet of the design would have benefitted if the prototyping steps had been performed earlier on. However, due to external factors, these steps had been delayed. More time spent on the physical prototyping could have yielded a more detailed design in terms of the foundation and the connecting interfaces.

The aesthetics of the design could be explored further. For example, the visual impact of the barrier when viewed by travellers at high-way speeds could have been evaluated using simulations. That way, the rhythm in the barrier could be improved upon.

Finally, the use of colour has not been explored. Currently, it is chosen to keep the segments white to preserve their recogniseability. Experimenting with colour use could have yielded new perspectives on the aesthetics of the barrier, and could be an answer to potential vandalism in the form of graffiti.

Role of industrial designers in this field
In essence, industrial design engineers are equipped with a toolkit to tackle problems in a certain way: design thinking. Industrial designers are trained to bridge the gap between various fields such as technology, human interaction, aesthetics, materialisation and sustainability.
Where industrial design was traditionally about designing physical products, the last decades have revealed a trend that designers can contribute to solving various societal problems (social, ecological, etc). This project is an industrial designer’s attempt to contribute to solving the issue of blade EoL. Judging by the response from within the industry, the attempt has succeeded in garnering enthusiasm and starting the conversation about large-scale repurposing. This is not surprising, as the main difference between this project and common design projects simply lies in the physical scale. This is not such a big difference when the similarities are considered. In the end, architects and industrial designers share many traits, such as a technical inclination, an eye for aesthetics and a thorough understanding of human-centred design.

30. Recommendations

In order to realise the envisioned Blade Barrier, several recommendations are given here. Also included is a broader perspective on the wind industry and the waste issue in general.

Design detailing

The final design is not a final blueprint for the Blade Barrier, but rather a detailed vision for Blade Barrier constructions. Various aspects of the design need further development before the actual construction of the barrier.

There are a virtually infinite number of ways to cut and orient the blade segments and create a blade barrier design. The described method was performed manually until the requirements were met in a satisfying way. It follows that other configurations are conceivable that fulfil the requirements to a similar extent, and that this is not an optimised result yet. If a specific blade type is found for a barrier construction, the method should be evaluated and potential optimisation steps could be made.

More research will need to take place to fully evaluate the impact of using increasingly large blades, as this could affect the portion of the blade that can be used.
The width of the larger segments would require more space, so the location needs to allow for this. Otherwise, the largest parts will need to be used for other applications. For example, for a 2 metre wide barrier, the bottom thickness of the large segments should not exceed an approximate 1.5 metres, as creating an acoustically closed barrier would then be impossible using the proposed method.

As the construction of the barrier differs from previously realised projects, the stability of the structure should be further evaluated by civil engineers. In the final design, the structure is anchored to the ground using driven piles, and the segments are connected to each other using bolts. These two precautions are taken to withstand strong winds. Further engineering should further determine the design of the piles and the connections between all components.

In terms of aesthetics, further steps could be taken to develop the orientation and geometry of the blade segments. Additionally, the specific placement of plants and their impact on the overall appearance should be evaluated.

When it comes to acoustics, it should be noted that the performance of the barrier is simulated without the inclusion of vegetation. The application of plants is expected to further enhance the performance of the design. Ultimately, only a full-scale prototype of the barrier will offer decisive information regarding the exact acoustic performance of the design.
For the vegetation, it is advised to run a trial with the segment prototype to analyse the performance of the vegetation bag and to test whether the plants thrive as intended.

In terms of developing a parametric model of the design, an expert should be approached to weigh in on further possibilities, and potentially recruit a specialised party for a large scale blade barrier design. Please refer to appendix I for more details about the potential for parametric design.

Barrier production

For the production process, it is advised to involve wind farm owners, decommissioners and logistical parties early on in the process. That way, an integrated approach can be realised. For example, large blades are usually cut into easily transportable segments in the decommissioning process. An integrated production plan would allow for this segmentation to happen in accordance with the design of the repurposing solution. Thus fewer actions and transport would be needed in the entire process. Researchers have proposed so-called 'circular wind hubs' (Scheepens, 2021), where these activities could take place.

For the production of the vegetation bags, an interesting opportunity worth exploring would be to approach social or penitentiary workshops. In this way, the barrier could have a positive social impact, as well as an ecological one.

If a selected site for a Blade Barrier already contains a lot of vegetation, it is advised to consider reusing the vegetation in the new construction, or finding a new place for these plants, similar to how Stichting Struikroven (2022) works toward reducing waste when it comes to urban vegetation

Considering the EoL of the barrier, all components are demountable. These should be harvested and used optimally. The design was made to preserve the integrity of all involved materials. The condition of all parts should be evaluated, and subsequent applications can be found that optimally retain the value of the material.

A20 Blade Barrier proposal
About the potential realisation of the barrier in this location, the following can be said.
In the early stages, it is key to garner enthusiasm for the project among relevant parties. Firstly, the municipality would be contacted to inquire about the current situation and potential development plans for the area. The proposal would then be presented to the relevant parties (such as the municipality, Rijkswaterstaat, and local neighbourhood representatives) to convey Blade Made's sustainable mission and the added benefits of the Blade Barrier for this location.
When sufficient enthusiasm and momentum are achieved, the first steps toward realisation can be made. The proposal would be further refined based on requirements and wishes from stakeholders, and the technical details further engineered. A more in-depth study of the location could yield insights that would assist in further tailoring the design of the linear park to the surroundings.

This build would serve as a proof-of-concept for larger Blade Barrier constructions. The prototype would be used to further evaluate and improve the design in terms of performance, aesthetics and cost-effectiveness.

Toward future Blade Barriers
After an initial Blade Barrier is built, the door will be open for larger barrier constructions. These could be built anywhere in the industrialised world. Therefore, location-specific requirements (climate, regulations, cultural aspects) all need to be considered, and the design altered accordingly. It would be advisable to consult local architects and developers in the process of tailoring the design. The impact of local sourcing of blades and the substitution of virgin materials should be made clear before scaling up the design, so that the design could be optimised for sustainability. It is therefore advised to perform an extensive LCA to evaluate the environmental impact of the Blade Barrier.

Recommendations for the wind industry
Based on the understanding of the wind industry that was gained during the project, several recommendations can be formulated for the industry at large.

Currently, manufacturers are not directly responsible for the material at the EoL, and the problem usually lies with wind farm owners and waste processing companies. Due to this situation, manufacturers have not been strongly incentivised to invest in EoL solutions.

However, due to recent trends and new environmental laws, the industry has taken significant steps toward solving EoL issues. The most known example is the development of recyclable blades in which resin can be separated from the fibres.

To further improve the ecological performance of the industry, it would be beneficial if manufacturers became more involved in the world of repurposing. It is a good start that Blade Made was invited to the WindEurope conference. This is a start in bridging the gap between the wind industry and the parties that seek to reduce the negative impacts of composite waste.
When partnerships between these parties are formed, designers and engineers from both sides should cooperate toward feasible solutions in terms of repurposing and structural reuse, by sharing information and expertise.

In terms of blade design, manufacturers could accelerate repurposing and structural reuse by publishing detailed technical and logistical data regarding blades that reach the decommissioning stage. That way, repurposing solutions can be developed ahead of decommissioning, based on the information regarding the material and geometry of the blades. Moreover, manufacturers can preserve their competitive edge, as details of their designs would only be disclosed approximately two decades after initial production.

These steps would further strengthen the positive impact of the renewable energy sector, and inspire other industries to be more involved in sustainable challenges.

31. Conclusions

This report has presented the design process and result of the Blade Barrier. With the discarded blade as a starting point and a noise barrier as desired application, a multi-faceted process was started to connect these two points.

Research into the waste issues, current solutions and the construction of the blades has provided a solid understanding of the material at hand. Next, the desired application was analysed. Acoustic principles, aesthetic considerations and noise barrier types and locations were investigated. Meanwhile, early ideation activities were performed to gain an understanding of the potential that the unique shapes of the blades offer.
The research led to the formulation of several key design principles.

Next, three concepts were developed and evaluated using the aforementioned criteria. The selected concept was elaborated upon in the final stage of the project.

The main question that this project aimed to answer is:

“How can we use repurposed blades to create effective sound barriers?“

The proposed solution is to create segments from the blades in a systematic way, and to create barrier modules by placing these segments in a deliberate sequence on modular foundations. This creates an acoustically closed barrier that is enhanced acoustically and aesthetically by the addition of vegetation. The modules are adapted to suit various location-based constraints. The design is detailed to integrate all aspects in a well-grounded design based on contemporary research and knowledge from the industry.

The barrier is designed to do more than just reduce sound levels. The barrier has the potential to create a green corridor in the urban environment in which people can relax and play, and where nature can find a place. The resident-side is equipped with a pedestrian path and urban furniture, while biodiversity is stimulated through the prominent inclusion of vegetation in the structure. The design was validated through acoustic simulations and physical testing and prototyping.

A physical prototype was made that serves as a tangible representation of a part of the full design.

To illustrate the scalability and flexibility of the design, a detailed proposal was made for a specific location in the Netherlands (see Figure 31.1).

The answer to the main question is that it is in fact possible to use repurposed blades to create functional and desirable sound barriers. The final result is a design that incorporates all relevant aspects for an all-encompassing design. Various steps for further development are listed in the recommendations.

Figure 31.1: Final design implemented in the north of Rotterdam

Figure V: Blade Barrier illuminated at night using slightly green-tinted lights

References

Acoustical Surfaces. (2018, 5 december). *Noise dB Levels*. Retrieved 17 Januari 2022, from https://www.acousticalsurfaces.com/soundproofing_tips/noise_reduction.htm

American Lung Association. (2021). *Living Near Highways and Air Pollution.* Lung.org. Retrieved 13 Januari 2022, from https://www.lung.org/clean-air/outdoors/who-is-at-risk/highways

Arenas, J. (2006). *Sound barriers and environmental impact studies.* 13th International Congress on Sound and Vibration 2006, ICSV 2006. 1. 42-57.

Bak, L. (2021, 24 december). *4Silence gives noise a twist and you barely hear it anymore.* Innovation Origins. Retrieved 14 Januari 2022, from https://innovationorigins.com/en/4silence-gives-noise-a-twist-and-you-barely-hear-it-anymore/

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

Bernhard, R. J. (2021). *How Highway Noise Barriers Can Make Traffic Louder - Cheddar Explains* [Video]. YouTube. https://www.youtube.com/watch?v=e0naL8eJmLA

Biodivers. (2021, March 9). *Bermen.* Retrieved 10 December 2021, from https://biodivers.nl/bermen/

Biosolutions. (2021, October 27). *Grow bag | Planten groeien beter dan in een bloempot.* Retrieved 17 March 2022, from https://biosolutions.bio/grow-bag/

CLO. (2022). Geluidsschermen en ZOAB in Nederland| *Compendium voor de Leefomgeving.* Retrieved 19 March 2022, from https://www.clo.nl/indicatoren/nl040503-geluidsschermen-en-zoab

Campbell-Johnston, K., Vermeulen, W. J., Reike, D., & Brullot, S. (2020). The Circular Economy and Cascading: Toward a Framework. Resources, Conservation & Recycling: X, 7, 100038. https://doi.org/10.1016/j.rcrx.2020.100038

Corbisier, C. (2003). *Living With Noise*. FHWA. Retrieved 17 januari 2022, from https://highways.dot.gov/public-roads/julyaugust-2003/living-noise

COWI Engineers, Superuse Studios, Citizens Group, Siemens Wind Power A/S, Fiberline Composites, Kærsholm Diamantboring ApS, Public Roads, & Municipality of Aalborg. (2015). *Lindholm Blade Park Bridge Preliminary Sketch Design.*

De Krieger. J. (2021). [*personal communication].*

Design Council. *What is the framework for innovation? Design Council's evolved Double Diamond.* (2019, September 10). Retrieved 8 December 2021, from https://www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies, 22*(5), 425–437. https://doi.org/10.1016/s0142-694x(01)00009-6

Dura Vermeer, Rotterdam University of Applied Sciences. (2022, januari). *End-of-Life Solution for Wind Turbine Rotor Blades.* https://drive.google.com/file/d/1WGPj-0Y4BGnIjK8gw31S0D9Q8nNHTMG8/view

Ellen MacArthur Foundation. (2021). New to circular economy overview. Retrieved 7 December 2021, from https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Ellen MacArthur Foundation, 2013. Toward the Circular Economy 1. Ellen MacArthur Foundation. https://doi.org/10.1162/108819806775545321.

Farnham, J., Beimborn, E., United States. Dept. of Transportation, Technology Sharing Program (U.S.), & University of Wisconsin--Milwaukee. Center for Urban Transportation Studies. (1990). *Noise Barrier Design Guidelines.* U.S. Department of Transportation.

Foderaro, L. W. (2005, 12 juni). *It's the Big Ugly, but Life Behind Walls Is Quieter*. The New York Times. Retrieved 28 april 2022, from https://www.nytimes.com/2005/06/12/nyregion/thecity/its-the-big-ugly-but-life-behind-walls-is-quieter.html

GE News. *Circular Economy: Wind Turbine Blade Maker Is Working To Turn Waste Into A Resource. GE News.* (2021, November 29). General Electric. Retrieved 9 December 2021, from https://www.ge.com/news/reports/circular-economy-wind-turbine-blade-maker-is-working-to-turn-waste-into-a-resource

Gardiner, G. (2017, 18 september). *Thermoplastic Wind Blades: To be or not?* CompositesWorld. Retrieved 12 Januari 2022, from https://www.compositesworld.com/articles/thermoplastic-wind-blades-to-be-or-not

Global Wind Energy Council. (2021, september). *Global Offshore Wind Report 2021*. https://gwec.net/wp-content/uploads/2021/09/GWEC-offshore-wind-2021-updated-1.pdf

Global Market Insights Inc. (2022, March 4). *Sound Barriers Market Size, COVID-19 Impact Analysis, Regional Outlook, Application Development Potential, Price Trend, Competitive Market Share & Forecast, 2022 – 2028*. Retrieved 15 March 2022, from https://www.gminsights.com/industry-analysis/sound-barriers-market

Grantham Research Institute. (2018, January 12). *What are the pros and cons of onshore wind energy?* Grantham Research Institute on Climate Change and the Environment. Retrieved 7 December 2021, from https://www.lse.ac.uk/granthaminstitute/explainers/what-are-the-pros-and-cons-of-onshore-wind-energy/

Gurit. (2021). *Wind Energy.* Retrieved 8 December 2021, from https://www.gurit.com/en/our-business/industries--markets/wind

Hansen, M. O. L. (2015). *Aerodynamics of Wind Turbines* (3rd ed.). Routledge.

Joustra, J., Flipsen, B., & Balkenende, R. (2020). Structural reuse of high end composite products: A design case study on wind turbine blades. *Resources, Conservation and Recycling, 167, 105393.* https://doi.org/10.1016/j.resconrec.2020.105393

Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. *Composites Part C: Open Access*, *5*. https://doi.org/10.1016/j.jcomc.2021.100137

Kalansuriya, C. M. (2009). Effect of roadside vegetation on the reduction of traffic noise levels. *Proceedings of the Technical Sessions, 25 (2009) 1–6.* http://192.248.16.117:8080/research/bitstream/70130/3262/1/2009Paper19.pdf

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.

Kolthof, M. (2022). [*personal communication].*

Larsen, K. (2009). Recycling wind turbine blades. *Renewable Energy Focus, 9*(7), 70–73. https://doi.org/10.1016/S1755-0084(09)70045-6

Liao, K. (2020, November 25). *The Rise and Future of Offshore Wind Farms*. Global Citizen. Retrieved 14 March 2022, from https://www.globalcitizen.org/en/content/offshore-wind-rise-and-future/

Liu, P., & Barlow, C. Y. (2017). Wind turbine blade waste in 2050. *Waste Management, 62,* 229–240. https://doi.org/10.1016/j.wasman.2017.02.007

Martin, C. (2020, February 5). *Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills.* Bloomberg.com. Retrieved December 9, 2021, from https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills.

Mason, H. (2021, November 2). installs first recycled wind turbine blade-based pedestrian bridge. CompositesWorld. Retrieved 9 December 2021, from https://www.compositesworld.com/news/-installs-first-recycled-wind-turbine-blade-based-pedestrian-bridge

Mattsson, C., André, A., Juntikka, M., Tränkle, T., & Sott, R. (2020). Chemical recycling of End-of-Life wind turbine blades by solvolysis/HTL. *IOP Conference Series: Materials Science and Engineering, 942*(1), 012013. https://doi.org/10.1088/1757-899x/942/1/012013

Ministerie van Infrastructuur en Waterstaat. (2020). *Overzicht alternatieven circulair wegmeubilair. https://www.circonl.nl/kennis/overzicht-alternatieven-circulair-wegmeubilair/*

Ministerie van Infrastructuur en Waterstaat. (2022, February 10). *Taken en verantwoordelijkheden.* Rijkswaterstaat. Retrieved 15 March 2022, from https://www.rijkswaterstaat.nl/wegen/wetten-regels-en-vergunningen/geluid-langs-rijkswegen/taken-en-verantwoordelijkheden-rijkswaterstaat

Neslen, A. (2021, September 10). *Surging wind industry faces its own green dilemma: landfills.* Reuters. Retrieved 9 December 2021, from https://www.reuters.com/legal/litigation/surging-wind-industry-faces-its-own-green-dilemma-landfills-2021-09-10/

Oliveux, G., Dandy, L.O., Leeke, G.A., 2015. *Current status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties.* Prog. Mater. Sci. 72, 61–99. https://doi.org/10.1016/j.pmatsci.2015.01.004. Resources,

Conservation & Recycling 167 (2021) 105393

Rai, P. K. (2016). Biodiversity of roadside plants and their response to air pollution in an Indo-Burma hotspot region: implications for urban ecosystem restoration. *Journal of Asia-Pacific Biodiversity, 9*(1), 47–55. https://doi.org/10.1016/j.japb.2015.10.011

Recharge. (2020). *GE signs deal to turn old 'unrecyclable' turbine blades into a greener form of cement.* Rechargenews.Com. https://www.rechargenews.com/wind/ge-signs-deal-to-turn-old-unrecyclable-turbine-blades-into-a-greener-form-of-cement/2-1-926935

Roelofs, B. M. (2020). *Material Recovery from Dutch Wind Energy.* https://repository.tudelft.nl/islandora/object/uuid%3A164d7900-ef53-4347-be1d-7cd81ed5bc1d

Ruitenburg, R.J. (2017). Manoeuvring physical assets into the future - planning for predictable and preparing for unpredictable change in Asset Life Cycle Management. PhD thesis, University of Twente, Enschede, the Netherlands.

Scheepens, W. S. (2021). *A Circular Hub for End-of-Life Wind Turbine Blades.* Master thesis, Delft University of Technology and Leiden University.

Sengpiel, E. (2020). *Decibel levels and perceived volume change.* Retrieved 5 May 2022, from http://www.sengpielaudio.com/calculator-levelchange.htm

Siemens Gamesa. *Siemens Gamesa pioneers wind circularity: launch of worlds first recyclable wind turbine blade for commercial use offshore.* (2021). Retrieved 8 December 2021, from https://www.siemensgamesa.com/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

SmartPort. (2020, October). *Offshore wind farm decommissioning.* https://smartport.nl/wp-content/uploads/2021/01/SmPo_TNO-Offshore-windpark-decommissioning_v03.final_.pdf

Smits, J. (2021). [*personal communication].*

Speksnijder, S. (2018). *Reuse of wind turbine blades in a slow traffic bridge.* Retreived 10 November 2021 from https://repository.tudelft.nl/islandora/object/uuid%3A5af53410-1be0-43e0-9a6d-2e438b1865f9?collection=education

Speksnijder, S. (2021). [*personal communication].*

Spoorbeeld. (2016). *Handboek Geluidsschermen.* https://www.spoorbeeld.nl/beleid/spoor/handboek-geluidsschermenSuperuse Studios. (2021, November 8). *Selected Projects*. Retrieved 7 December 2021, from https://www.superuse-studios.com/nl/projects/

Stichting Struikroven. (2022). *Werkwijze Struikroven.* Struikroven. Retrieved 12 May 2022, from https://www.struikroven.nu/werkwijze

Tang, A. (2021, June 16). *Wind industry calls for Europe-wide ban on landfilling turbine blades.* WindEurope. Retrieved 7 December 2021, from https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/

Tavner, P., Greenwood, D., Whittle, M., Gindele, R., Faulstich, S., & Hahn, B. (2012). Study of weather and location effects on wind turbine failure rates. *Wind Energy, 16(2)*, 175–187. https://doi.org/10.1002/we.538

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

Ten Busschen, A. (2021). [*personal communication].*

Tenpierik, M. (2021-2022). [*personal communication].*

TfNSW (2021). *Noise wall design guideline.* https://roads-waterways.transport.nsw.gov.au/business-industry/partners-suppliers/documents/centre-for-urban-design/noise-wall-design-guideline.pdf

Threlfall, C. G., Mata, L., Mackie, J. A., Hahs, A. K., Stork, N. E., Williams, N. S. G., & Livesley, S. J. (2017). Increasing biodiversity in urban green spaces through simple vegetation interventions. *Journal of Applied Ecology, 54(6)*, 1874–1883. https://doi.org/10.1111/1365-2664.12876

US Department of Transportation. (2021). *Highway Traffic Noise Barriers at a Glance - Design Construction - Noise Barriers - Noise - Environment - FHWA. Federal Highway Administration.* Retrieved 15 March 2022, from https://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/keepdown.cfm

Van Herk. J. (2021). [*personal communication].*

Van Noort, R. (2022). [*personal communication].*

WindEurope. (2020, 23 juli). *Working towards a European standard for decommissioning wind turbines.* Retreived 15 May 2022, from https://windeurope.org/newsroom/news/working-towards-a-european-standard-for-decommissioning-wind-turbines/

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. Retrieved 8 December 2021, from https://emp.lbl.gov/news/future-wind-energy-part-3-reducing-wind

Zieglder, L., Gonzalez, E., Rubert, T., Smolka, U., & Melero, J. J. (2018). Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK. *Renewable and Sustainable Energy Reviews, 82,* 1261–1271. https://doi.org/10.1016/j.rser.2017.09.100

Zijlstra, J., & Daalhuizen, J. (2020). *Delft Design Guide (revised Edition).* Macmillan Publishers.

Appendix A - Project brief

DESIGN FOR our future

TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Przespolewski 5383
initials: A.C. given name: Adriaan
student number: 4431774
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): ★ IPD ◯ Dfl ◯ SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: Honours Programme Master
specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: A.R. Balkenende dept. / section: SDE
** mentor: M. Willemen dept. / section:
2nd mentor: J. De Krieger
organisation: Superuse Studios
city: Rotterdam country: The Netherlands

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

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

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 1 of 7

TUDelft

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: A.R. Balkenende date: 22 - 11 - 2021 signature: [signature]

CHECK STUDY PROGRESS

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

Master electives no. of EC accumulated in total: 32 EC
Of which, taking the conditional requirements into account, can be part of the exam programme: 32 EC

★ YES all 1st year master courses passed
◯ NO missing 1st year master courses are:

List of electives obtained before the third semester without approval of the BoE

name: J. J. de Bruin date: 23 - 11 - 2021 signature: J. J. de Bruin, SPA — Digitally signed by J. J. de Bruin, SPA Date: 2021.11.23 11:17:17 +01'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED ◯ NOT APPROVED
Procedure: ★ APPROVED ◯ NOT APPROVED

comments

name: Monique von Morgen date: 06 - 12 - 2021 signature:

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7

Initials & Name: A.C. Przespolewski 5383 Student number: 4431774

Title of Project: Transforming decommissioned wind turbine blades into sound barriers

Personal Project Brief - IDE Master Graduation

TU Delft

Transforming decommissioned wind turbine blades into sound barriers   project title

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

start date 25 - 10 - 2021   01 - 04 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

As the world slowly moves towards renewable energy sources and a more circular economy, we see that the End of Life (EoL) of many products, buildings and structures have not yet been considered fully. Even in the renewable sector this problem is a widespread occurrence. Wind energy - that is generated using wind-turbines - is an iconic new way of powering our world. However, so far these turbines have been designed following a mostly linear framework: design, production, use, and finally disposal.
Especially for the turbine blades this forms a problem. As the glass- or carbon-fibre blades have an initial lifespan of 10 to 25 years, these need to be replaced by new ones after this 'guaranteed period' ends. Recycling of these composites is possible, but complex. The capacity for reprocessing the material is small, and the recycled material does not offset the costs (Oliveux et al., 2015; UBA, 2019)

This shortage of recycling capacity and lack of economic incentive to recycle, leave us with a great number of old windturbine blades. In general, the only current ësolutionsí are shredding, incineration and landfill.

As sustainability gradually becomes the norm, companies are under public and political pressure to abide by environmental laws and green principles. It is therefore reasonable to expect companies in the renewable energy sector to have proper solutions for the EoL issues caused by their activities.

Superuse Studios is an international architecture firm that strives to make our built environment sustainable and circular. One of their projects - Blade Made - is set up to incorporate decommissioned windturbine blades in architecture. So far they have realised several one-off structures in The Netherlands, such as a playground in Rotterdam.

This problem should be approached in different ways. One is to drastically redesign the turbine blades from the start, so that the EoL is accounted for. This is not within the scope of this project.

Another way is to tackle the problem of the current blades, and what to do with them once they can no longer safely be used for their intended purpose. This is what the project will tackle.

Research indicates that it would be most beneficial if the blades could be repurposed in a way that requires minimal reprocessing. This is in line with the principles of the circular economy. In this way, the work that was put into the blades is not undone, and little new energy needs to be put into the repurposing. This is why architecture can offer an elegant solution: reuse the blades ëas-isí as much as possible, keeping the structure and recognise-ability of the blades intact.

—— References: ——
Oliveux, G., Dandy, L.O., Leeke, G.A., 2015. Current status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties. Prog. Mater. Sci. 72, 61ñ99. https://doi.org/10.1016/j.pmatsci.2015.01.004.
Resources, Conservation & Recycling 167 (2021) 105393

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

TU Delft

introduction (continued): space for images

image / figure 1: Landfilled wind turbine blades (Source: Bloomberg)

image / figure 2: The WIKADO playground in Rotterdam (Source: Superuse)

Personal Project Brief - IDE Master Graduation

TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

So far, the ©Superusing© of windblades has only happened on a relatively small scale, in the form of one-off projects. If Blade Made is to significantly make a dent in the surplus of old blades, a scalable solution needs to be found.

One of the problems with designing with decommissioned windblades is the uncertain nature of the material. For example, it is unknown beforehand where damages will be in the structure. Also, any design should take into consideration the varying offer of different types and sizes of blades. Different types of blades (in terms of construction) could also complicate the repurposing of the blades.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

I will design a scalable application for decommissioned windturbine blades in road- and railside sound barriers. The design should be functional, reliable and realisable and reflect Superuse's values of circular architecture.

Superuse has developed initial designs for the soundbarriers, but no specific plans have been drawn up. The project will build upon the previously booked progress, and research various factors that come into play.

The design will incorporate circular design principles as much as possible, to maximise the sustainable potential of 'Superusing' windblades. For example, EoL considerations should be incorporated in any new design for these blades. Additionally, potential remaining parts of the blades not used in the design should be considered, so that the entire blade is accounted for.
During the project, the potential for a parametric design will be evaluated. Such a model could possibly generate designs based on the functional and aesthetic design vision, different locations, transport possibilities, available blades, and certain circumstances such as blade damage.

The deliverable will come in the form of a fully-fledged CAD design and a prototype / scale-model to physically showcase the design of the Blade Barrier. Logistical factors such as transport, processing and installation will be incorporated into the design.

Key challenges:
- Developing a design that is aesthetic, functional and realisable in various different locations.
- Striking a balance balance between a large-scale application of the blades, and the aesthetic value that this offers.

Personal Project Brief - IDE Master Graduation

TU Delft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 25 - 10 - 2021 1 - 4 - 2022 end date

link to Gantt planning: https://plan.tomsplanner.com/public/graduationplanning

Additional info on planning and approach:

My aim is to work on this graduation project full-time from start to finish. I have structured the project using the double-diamond framework (discover, define, develop, deliver). This method has helped me structure projects in the past quite well.

I am planning to apply various creative methods to this project. The Delft Design approach offers many tools to enhance our design creativity. I am convinced of the power of co-creation sessions with participants of various backgrounds. Next to this, I plan to set up brainstorming sessions and consult with experts in various fields. Personally, I work a lot using (digital) prototyping techniques to generate and test ideas, and to broaden my understanding of a specific problem.

In the planning, I have left room for the (recommended) holidays. Another unrelated activity takes place on Nov 18th, on which day I am asked to present a previous project at an Ergonomics day. This lost day will be made up for in the weekend.

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS
Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

My motivation for setting up this project is mainly that I love to work on something which I believe to have a substantial purpose. I work best when I am deeply motivated, and I only get motivated if I feel I am making a contribution somehow. Working on a project that tries to solve an ecological problem suits this desire very well.

The second part is my interest in the overlapping area of Design and Architecture. My Bachelor Thesis (for a student housing company) turned out to border on architecture, and I explored this further during my electives in the Master. I followed a fascinating course called Bridge Design at the Faculty of Architecture, and designed a bridge for the Gemeente Rotterdam.

One of my main goals for graduation was to set up a project in collaboration with an inspiring company that aligns with my passions. I am glad to have found Superuse, a company with which I feel I share many values.

In terms of learning, I want to further explore this area between Design and Architecture, and pick up new skills along the way. Specific skills that I aim to improve: (Parametric) CAD-modelling, drawing and illustrating, prototyping, and learning about the challenges of realising a large architectural design.

FINAL COMMENTS
In case your project brief needs final comments, please add any information you think is relevant.

Appendix B - Blade Made site visits

To gain a deeper understanding of the shape, scale and possibilities of the material, two Blade Made constructions were observed closely. The following pictures were taken there, and served as inspiration during the ideation phase.

REWind urban furniture

WIKADO playground

WIKADO playground









Appendix C - Barrier location analysis

Chapter 11 covers the analysis of current barriers and their location types. This appendix is an elaboration of the latter, and shows types of barriers for the three identified ‘dimensions‘, being location type, urban density and available space. Based on this analysis, and insights from the ideation, a target segment is identified.

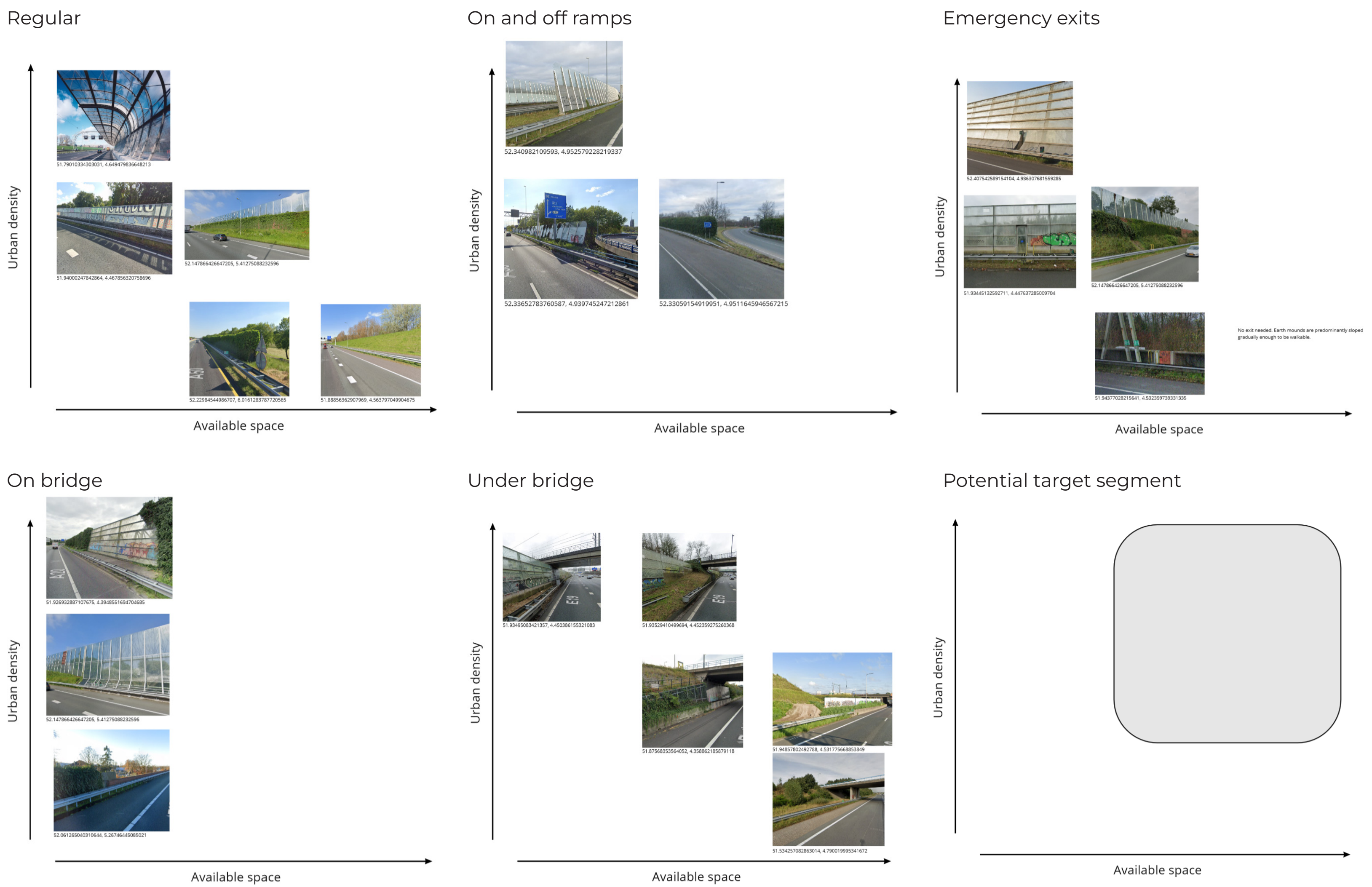


Figure C.1: Barrier location analysis matrices

Appendix D - Stakeholder interest overview

In collaboration with Jos de Krieger (2022) from Superuse, the following stakeholder overview is made. The main purpose is to identify the interests of the involved stakeholders, as all perspectives ought to be integrated into the final design.

This overview is based on roadside barriers. The choice to focus on this, rather than railside barriers is elaborated in chapter 11.

Rijkswaterstaat
This government body is responsible for most infrastructure (such as highways, tunnels, rivers and bridges) in The Netherlands. They are tasked with creating and maintaining a safe, durable, and pleasant living environment. They are usually the principal client (Ministerie van Infrastructuur en Waterstaat, 2022).

Key interests:
- Cost-effectiveness
- Durability
- Safety
- Performance
- Low maintenance

Local municipality
This party is usually the owner of the site where the barrier will be constructed. In some scenarios, the municipality could be the main client (De Krieger, 2021).

Key interests:
- Pleasant, safe and healthy living environment.
- Employment opportunities

Superuse Studios & Blade Made
The studio would mostly be responsible for the final result, so the design should reflect well on them. Their values should be incorporated into the building process and the result, and attract potential new clients and commissions.

Key interests:
- Circular and sustainable impact
- Creating an appealing end-result
- Local sourcing of materials

GKB Groep (and potential other contractors)
As the contractor for most past Blade Made projects, they are expected to be involved in most future builds as well.

Key interests:
- A design that takes the logistics and installation into account
- Clear technical design
- Installation process based on previously gained insights and skills
(Van Herk, 2021)

Blade suppliers
Mostly wind energy companies who seek to dispose of their waste. Finding a sustainable purpose for the blades is desirable as it can lower their environmental footprint. It is ideal if a 'complete blade strategy' is in place, so that all blades can entirely be accounted for (De Krieger, 2021).

Key interests:
- Full blade strategy
- Guarantee that the blades will be put to good use
- Logistical infrastructure in place for after the decommissioning phase

Decommissioning organisations
These parties are hired for the physical decommissioning process. They will take down the structure, and channel the materials to designated waste processing companies (Kolthof, 2022).

Key interests:
- Efficient and safe decommissioning process
- Clear instructions from the client regarding potential reuse or repurposing.

Travellers
In an ideal scenario, no barrier would obstruct the view. When a barrier is needed, either a see-through or green barrier is generally considered pleasant. The environment surrounding the road should however not be distracting. It is common practice to subtly signal changes in the landscape, or complement certain noteworthy elements in the environment (Farnham et al., 1990).

Key interests:
- Attractive roadside environments
- Safety

Residents
Local residents and office workers benefit from a pleasant and healthy environment. Studies show that living close to highways increases the risk of developing various health problems due to noise- and air pollution (American Lung Association, 2021). Additionally, urban areas benefit from green recreational places where people can relax and meet. An attractive 'green urban corridor' could greatly contribute to all aforementioned points (Viola, 2021).

Key interests:
- Effective noise reduction
- Pleasant and healthy living environment

Nature
The environment could benefit from a well-executed blade barrier in various ways. Vegetation could offer a place for various insects, birds and small mammals (Biodivers, 2021). Also, contributions could come in the form of a lower ecological footprint compared to regular barriers, by using locally sourced reusable materials.

Key interests:
- Suitable vegetation for local wildlife
- Air purifying plants
- Minimising the need for virgin materials
- Locally sourced supplies

Appendix E - Form exploration overview

In the beginning of the ideation phase, the possibilities with the blade shapes were explored in 3D. Tinkering with the geometries yielded interesting combinations for barrier designs. This is an overview of the results from this activity.

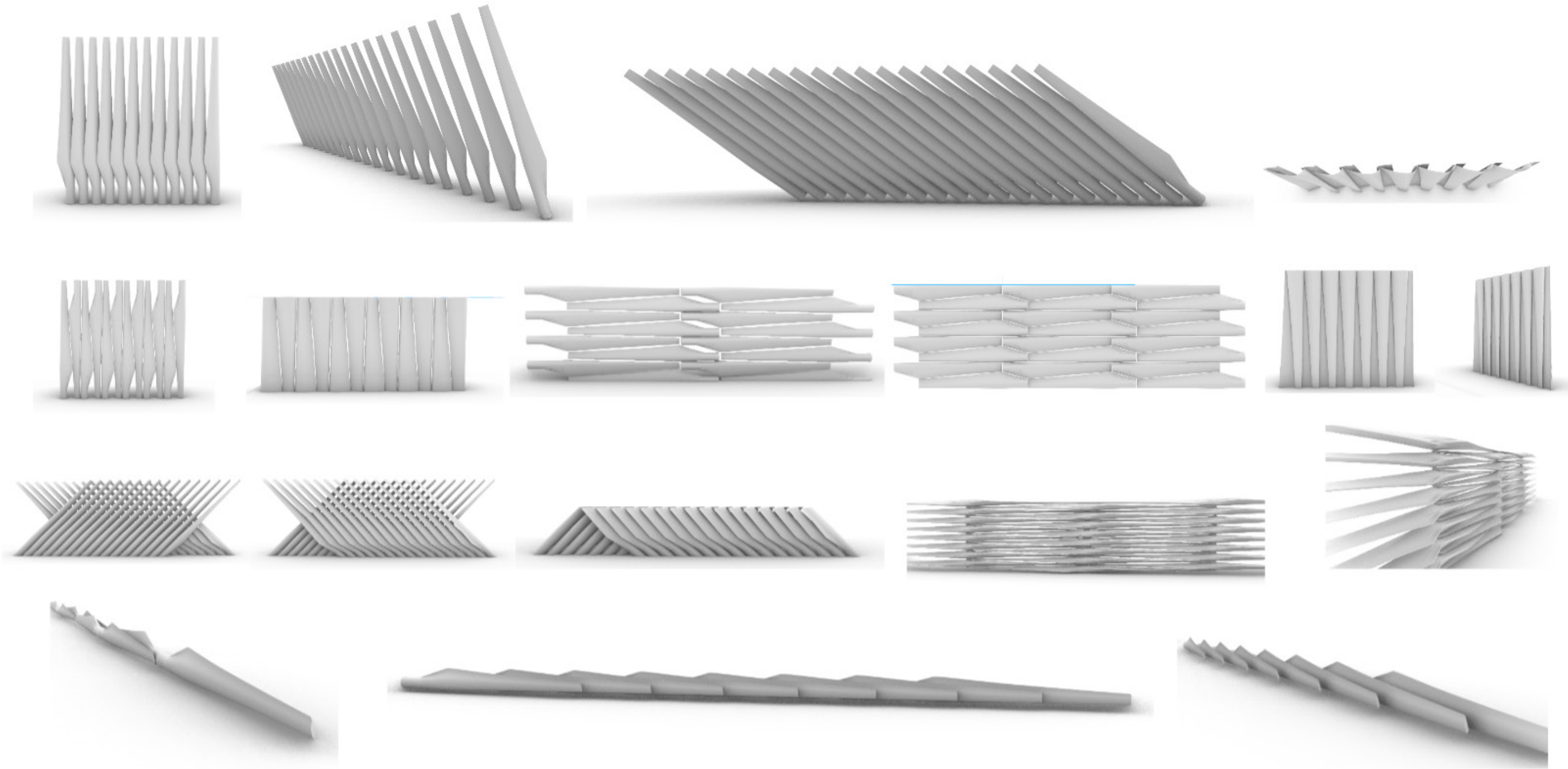


Figure E.1: Form exploration 3D models

Appendix F - Expert interviews insights

The following people all contributed to the development of the project through their expertise. Insights from these conversations are compiled here.

S. Speksnijder (2021)
(Graduated on the Bridge of Blades design)

- The differences between road and railside sound barrier requirements should be researched.
- It is important that the new solution is not significantly more expensive than the status-quo solution. Or it would need to offer great additional value
- Cutting the blades is a topic that should not be underestimated. The logistics and method should be considered. Also, waste from the process should not enter the environment.
- Consider how to integrate the design with limitations in transport possibilities.

A. Wyber (2021)
(Industrial designer, expert on parametric and generative design)

- Parametric design could be used to create barrier designs by packing segments together using 'circle-packing' or by creating bounding boxes around segments.
- It is also possible to first start with a final design, and create a parametric model that is able to approximate this design.
- Perhaps it is possible to generate acoustic elements with the given shapes, like cavities and niches.

A. ten Busschen (2021)
(Engineer and lecturer specialised in composite technology)

- Recycling of composites is wasteful. Keeping the material intact is the way forward.
- While recyclable blades are in development, the prediction is that in the coming 25 years at least, traditional blades will still be installed.
- Even if blades have all become recyclable, it would still be best to first repurpose them before recycling.
- The cement kiln is currently viewed as the best way of processing the composite material, but A does not agree. The material is degraded, and much potential is lost. It is also expensive, also in terms of eco-footprint. The material becomes untraceable after this process.
- Contrary to popular belief, composite material does not degrade in water. Therefore, applications such as quay sheeting are suitable.
- During the life-in-service of repurposed blade solutions, the material is likely to degrade slower than in its initial application. Therefore, the lifetime of the material can be more than doubled. This extension leads to the elimination of virgin material use, and that better recycling methods will be available in the future at the subsequent EoL.
- A circular wind hub would be a very suitable solution to some of the logistical concerns.

M. Tenpierik (2021)
(Engineer and lecturer specialised in acoustics)

- Sound will bend downwards over barriers due to diffraction. The height and position of the barrier relative to the source are key.
- It is key that the barrier is a closed structure.
- It is important to understand the principles of reflection, diffusion and absorption.
- Vegetation has absorbing effects, especially soil, thickets and grass. Leaves can diffuse sound.
- Diffraction can be decreased by creating a softer edge on the top of the barrier. Irregularities in shape and applying plants are recommended.
- The barrier could have additional purposes, such as air purification through vegetation. Also, a layer of titanium oxide could be considered for this end.
- High-way sounds predominantly originate from the airflow around vehicles and the contact between tires and the road.

J. van Herk (2021)
(Projectleader at GKB contractors)

- It is estimated that installing a blade barrier would take three times as long as most current solutions.
- The labour needed for the barrier can be seen as a plus. Social benefits of local production.
- In terms of transport, max. 3.5m in width and 14m in length are suitable for regular transport where no permits are needed.
- It would be best to limit the number of cuts, and to keep them straight. Curved cuts require much more time to get right.
- Watercutting could be considered.
- Additions to the structure - such as eye-bolts - are best placed on the spar caps. This part can handle the largest forces, and there is no risk of the sandwich structure tearing. It is possible to place additions anywhere, but depending on the use-case, some reinforcements might be needed.

J. Smits (2021)
(Engineer and lecturer specialised in infrastructure design)

- Available space is likely to be an issue for the blade barrier. Infrastructure projects tend to get tight.
- It is important to consider the barrier as a construction, and to see how the material and its properties fit in.
- The blades have a unique character and aesthetic. These should be retained and used to their advantage in the design.

S. Viola (2021)
(Landscape architect)

- Vegetation can be used for sound reduction on its own, or in combination with other structures
- Interesting additional benefits such as air purification and enhancing biodiversity. Similar to wild berms in urban areas.
- Three layers of vegetation: ground, shrub and canopy
- It is advised to use low-maintenance and evergreen plants
- Depth of the roots is important. Plants should not root too deeply and become too large. Roots might also damage the blade structure.
- Inspiration should be taken from green roofs, which are becoming more common in urban areas. A barrier is needed to block the roots, but allow moisture to travel through to prevent rotting.
- The soil should be ±10 centimetres lower than the segment edge to prevent it from running out in wet periods and leaving drip marks. Roots will keep the soil together.
- A filler material for the rest of the segment could be considered. Not needed from a vegetation standpoint.
- Recommended trees: cypress, acer, tillia, cedars, platanus.
- Recommended plants: holly, juniper, sedums, succulents. Hedera is also common, but its invasive nature should be considered.
- For acoustic benefits, it would be good to angle the soil toward the sound.
- 20% of plants will likely die after initial planting. This should be taken into account.
- If light is incorporated, green-tinted light is best for the fauna.

J. Joustra (2021)
(PhD candidate on the topic of composite materials in the circular economy)

- The material is currently used in dragline bulkheads. This might be interesting for the foundation of the design.
- Suspension of plants can be physically tested using the blade segment
- How to determine the ‘randomness‘ of the segments in the design?
- It could be possible to perform acoustic tests using a physical prototype. Would require a relatively large set-up and university equipment.
- Using the middle part makes sense, and is in accordance with results from J’s research.
- Research is currently done regarding panel production of blades through machine-learning nesting processes. This could also be done at the EoL of the barrier.

M. Kolthof (2022)
(Engineer, expert in the field of sustainable decommissioning)

- Offshore decommissioning of wind turbines has not happened yet on a large scale in The Netherlands. This is currently starting up.
- A large ship will hoist up the 'jackets' (turbine foundations). These are then transported to shore by smaller barges. There they will be cut into smaller transportable pieces if necessary. After that, a waste processing company takes the material.
- A development in decommissioning is to incorporate EoL considerations into the process. For example, cutting into smaller pieces can be done with the next application in mind. The client does need to give permission for this.
- These processes could potentially be integrated into the proposed circular hubs in harbours.

M. Tenpierik (2022)
(2nd interview)

- Filling the segments completely is not necessary as the curved shapes of the cavities prevent any resonances or reverberations.
- The proposed design with sequenced segments can be considered 'acoustically closed' as the segments are packed together in a tight overlapping way. The funnel-shaped gaps between segments will help to further absorb the sound, and prevent most soundwaves from penetrating the barrier.
- There will be sound that penetrates the barrier, but this would be insignificant compared to the dominant path of the sound, and therefore negligible.

R. van Noort (2022)
(Civil Engineer)

- The type of soil will be key for the final construction and foundation design. Clay soil (prominent in the Netherlands) is tricky to build on, and driven piles are often needed.
- It might be tricky to excavate a lot right next to a highway due to potential subsidence of the concrete. This should be taken into account.
- Connections between the segments are necessary to prevent collisions between them. Otherwise, they would swing back and forth slightly, all in different frequencies due to height differences.
- Driven piles can probably be used in the design in a similar way to how they are used now in regular barrier constructions.

Appendix G - Brainstorm session setup and results

In the development phase of the design, a brainstorm session was organised at the Superuse office to gather new insights, ideas and feedback. The method and results are covered here.

Set-up

Preparation

- Create slides that illustrate the problem to be solved, and essential basic info regarding the material and barrier design.

Introduction

- Welcome the participants
- Introduce them to the project by going through the presentation
- Answer any questions that come up, but do not cover existing ideas and/or concepts yet.
- Establish an environment in which ideas can flow freely, without receiving criticism.

Round 1

- Let the participants come up with ideas, starting with a 'blank slate'
- Stimulate the participants if they are stuck by offering small cues or asking questions to trigger new ideas.
- Discuss the ideas, and elaborate upon each other's thoughts.

Round 2

- Introduce the participants to the previously generated ideas or concepts
- Another round of brainstorming, now focused on discussing, elaborating and altering existing ideas.
- Again, discuss the new ideas and elaborate upon each other's thoughts.

Round up

- Go over the newly generated ideas
- Make sure all ideas and suggestions have been voiced
- Thank the participants

Results

The main results from the brainstorm sessions are clustered and listed below. They are formulated either as opportunities or concerns.

Additional materials:

- Construction waste could be a suitable material if a filler is needed to stabilise blade segments.
- Transparent panels could be integrated into the design, even if varying blades are used. The blades could be positioned behind the panels, and serve mainly as construction. Differences in blade type and size would need to be mitigated by custom / flexible mounting components.

Resident side:

- Optional Blade Made urban furniture ought to be selected in collaboration with local residents, to increase the effectiveness of the barrier, and create a sense of involvement and ownership among the residents.
- A fitness park made partly from blades, potentially containing exercise machines and climbing walls.
- Safety and potential vandalism should be considered.
- Installing lights can be a way to make the surroundings safer, and more appealing. The ecological impact can be reduced by using adaptive green tinted lights.

Durability:

- How does the material respond to being installed into the ground? What precautions need to be taken to prevent the material from rotting or polluting the soil?
- What are the implications for the maintenance of the structure?

Visibility:

- Could it be possible to create a design in which openings are integrated to create direct sightlines, angled sharply in regard to the road? The continuity principles (TfNSW, 2021) should be followed to guarantee proper noise reduction. This would result in a more 'open' and spatial aesthetic.

Figure G.1: 3D prints used in the sessions

Appendix H - Parametric models

Parametric design was explored as a way of tackling the design challenge. Three distinct models were produced in the ideation and concept generation phase. Following is an overview of these with short descriptions of their working principles.

Model 1 places segmented blade parts onto a plane that represents the appropriate landscape and available space. Factors such as blade density, rotation and distance from the border can be altered. The depth in which the segments are dug into the soil can also be changed.

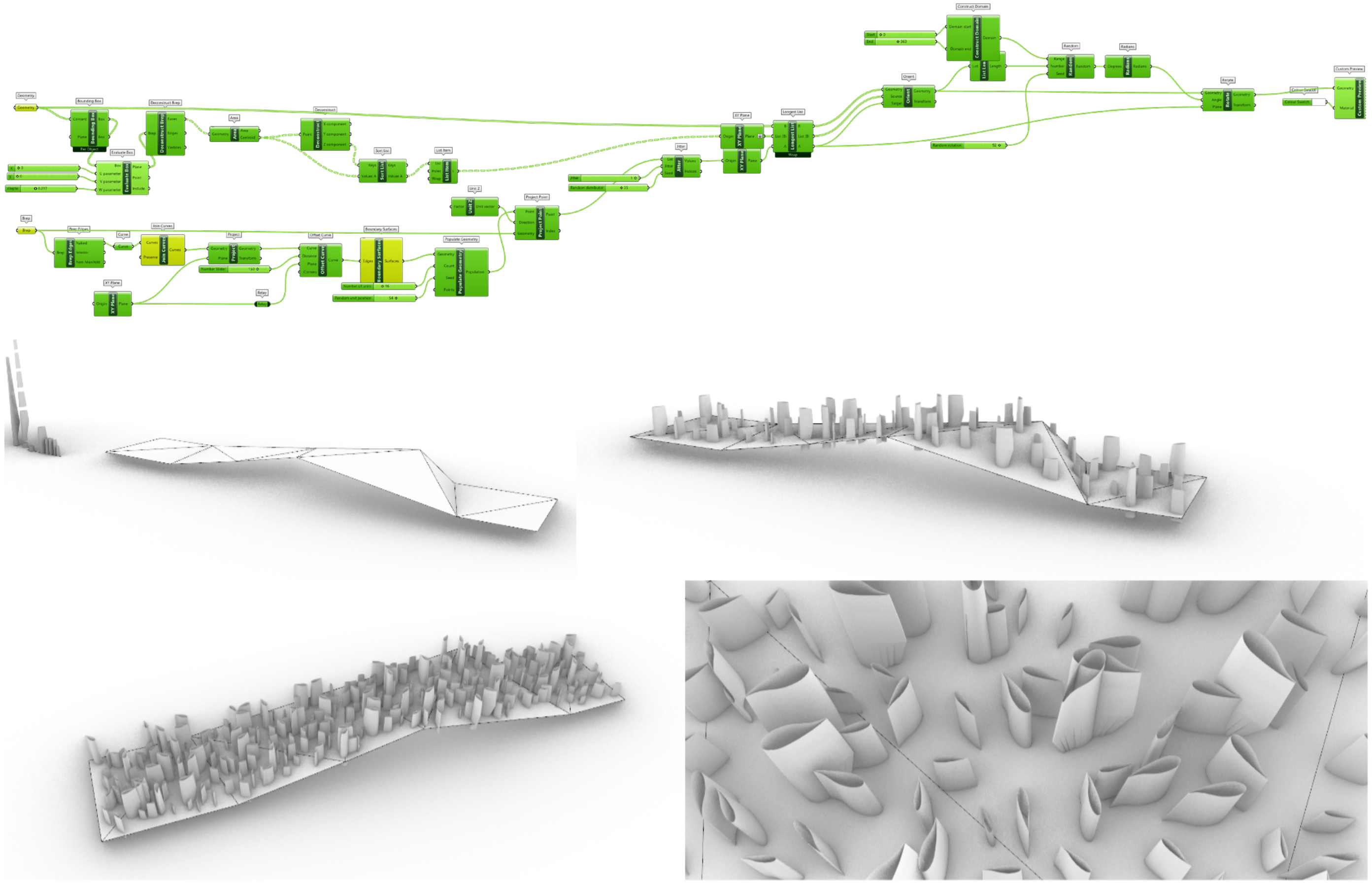
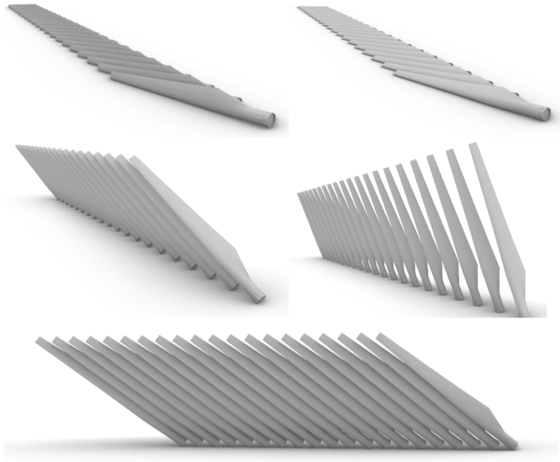


Figure H.1: Parametric model 1

The second model is quite simple. It would take an entire blade and repeat it along a line. The orientation of the blades can be controlled precisely, as well as the distance between each repetition of the blade. The model was also used for the form exploration in the ideation phase.



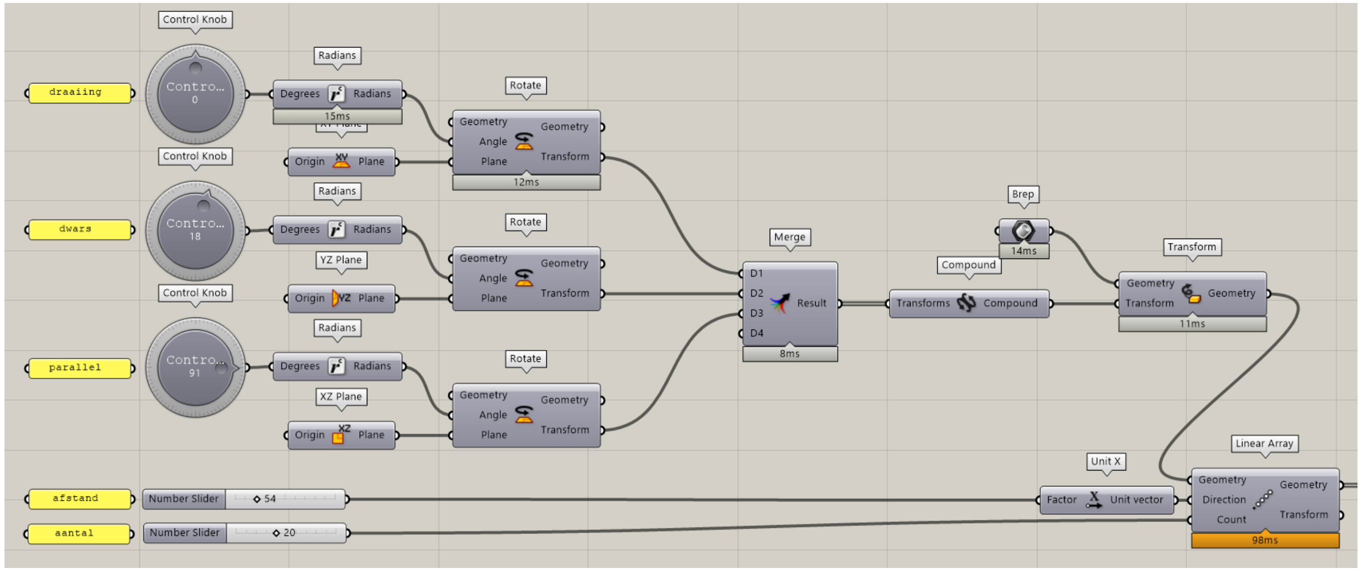
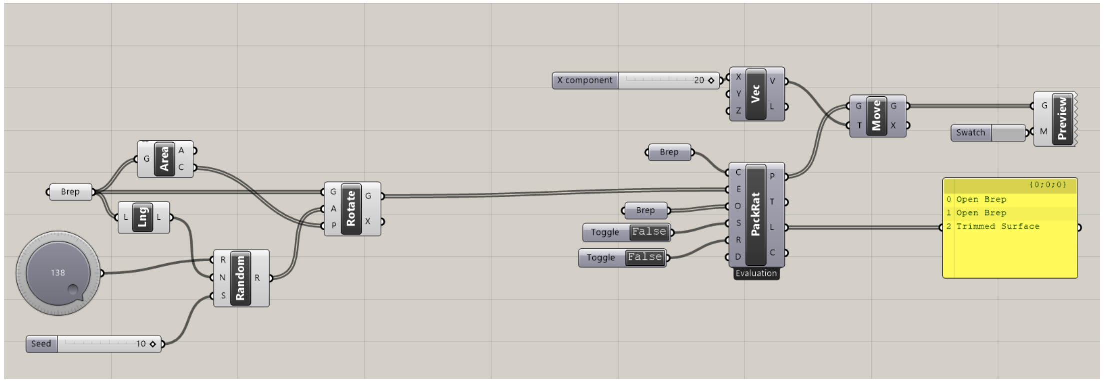


Figure H.2: Parametric model 2

In the third model, a volume-box is created based on the desired height, length and width of the barrier. Separate 'no-go' volumes are added to be able to control the shape of the overall output.

Next, segments are placed into this volume, and packed as densely as possible. The rotation of the segments can be individually altered at random, and any segments that do not fit within the established volume will be listed. Built into the model is a randomisation function, with which a practically infinite number of different combinations can be generated.



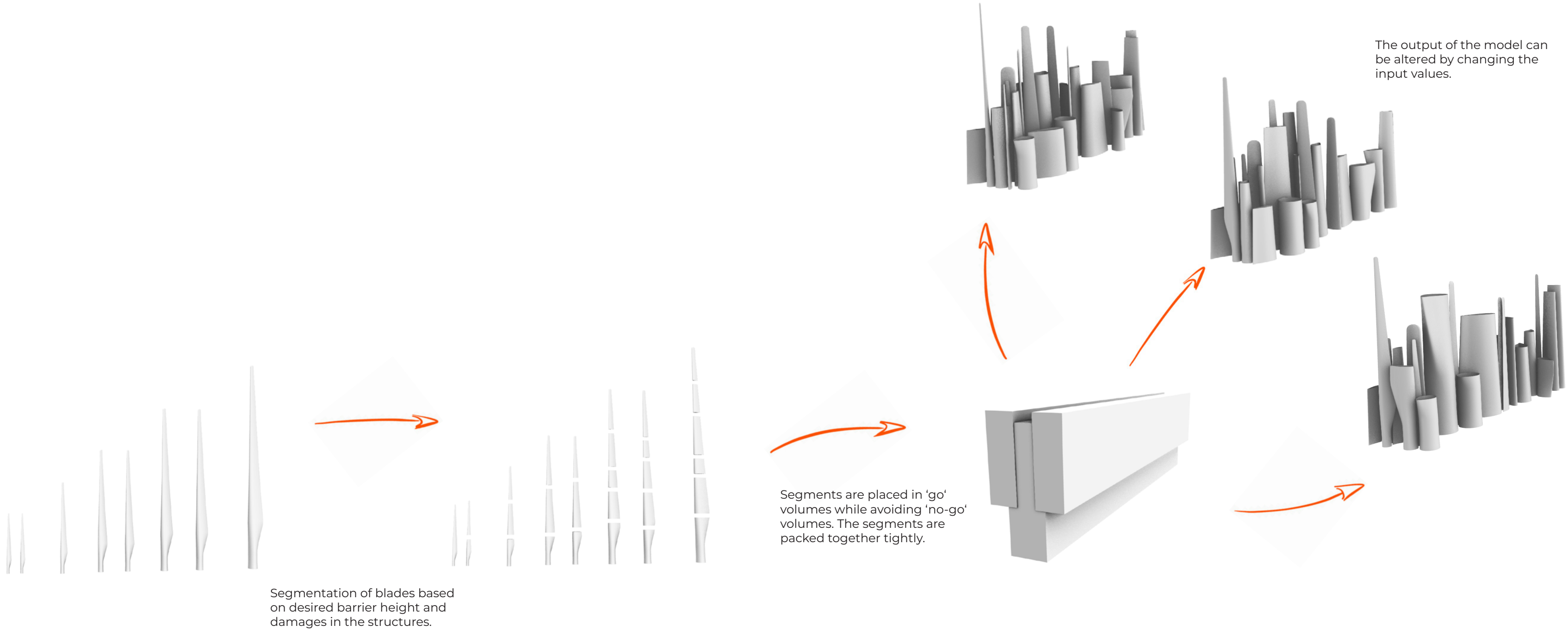


Figure H.3: Parametric model 3

Appendix I - Potential for parametric barrier design

Earlier in the ideation phase, parametric design was explored as a way to automate the design process of a Blade Barrier. Based upon input (blade geometry, material quality data, and location and performance requirements), a suitable design would be generated. For the purposes of this project, this approach was not selected. The current Blade Barrier is designed 'by hand', meaning that the location of segmentations and placement of segments is done manually into the different modules, and repeated appropriately.

Following is a reflection on the potential for parametric design for Blade Barriers.

Based on the experience and insights gained in the project, this manual approach is best suited for relatively small builds. It is estimated that creating a parametric model to automate (a substantial part of) the design process becomes viable for longer barriers in which various different types of blades are to be used. In this case, repetition of manually designed modules is not feasible.

The reason that this method is only viable for large projects, is that several investments would be necessary:

Firstly, in order to create such a model, a specialised party in parametric design will need to be involved. Complex requirements regarding the determination of segmentation locations, and ensuring sufficient 'form-closure' are essential for such a model to fulfil properly.

Secondly, an accurate CAD model, including data on damages would need to be available. 3D scanning methods would need to be applied to generate this data.

In short, parametric barrier design is potentially valuable for lengthy barriers of different blades. It is advised that an expert on parametric design is consulted for the specific project.

Appendix J - Segmentation and barrier formation

Following is an elaborated version of the segmentation method as described in chapter 21. The method is divided into two parts: cutting and orienting.

Factors that are considered:
- The location of the cut
- The angle of the cut
- The dimensions of the segments
- The rotation of the segment
- The variation in cutting pattern over multiple blades
- The portions of the blade to be used

Cutting:

This method repeats itself after four blades.

- The cuts are alternated between horizontal and 30-degree angles (see Figure J.1)

- The lowest cut is just above the widest part of the blade, at the point where the bend in the corner ends.

- The highest cut is at the point where the thickness of the blade is approximately 25cm. This is because the cavities in the segments need to be large enough to install vegetation.

- This leaves us with the middle portion of the blade, as these have ideal geometries for the Blade Barrier. The bottom and top pieces lend themselves better to other Blade Made designs such as furniture, playgrounds and other installations.

- Based on the desired height of the barrier, the height of the first segments (S1) is determined (first segment height = desired functional barrier height + 0.1 [m] that sits under ground level + 0.3 [m] to allow for slight variations in the barrier height). Angled cuts are measured from the middle of the cut.

- The heights of the second segments are based on the first height (first segment height - 0.5 [m]). This allows for enough difference that the second segments are always lower than the first, but still high enough to effectively create an overlapping barrier that is acoustically closed.

- From the remaining part of the blade, the smaller segments are cut. The S3's are cut so that they sit between S2 and S4 in height. Of S4a and S4b it is required that they are at least 2.5 [m] shorter than S1, as this will reduce the possibility of climbing over the structure from the resident side.

It should be noted that for the second blade, the first cut is diagonal, and the angle is mirrored when compared to the previous blade. This method is shown to yield the best results through an extensive process of trial and error.

Lastly, while the height of the cuts might seem the same over the four blades, a slight variation (of max. 0.3 metres) is present. This is included to create a more organic and 'flowing' aesthetic in the look of the barrier.

Orienting:

- The 'backbone' of the barrier is created using the four largest segments (S1). All segments face downwards with their horizontal end, meaning that two of the four segments are rotated 180 degrees relative to their two counterparts. These four segments can be placed in a row to form a nearly closed wall. To do this, four different combinations are possible (see Figure J.1). These form the basis for the four differing 'base-modules'.

- The next step is to place the second segments (S2) in front of the first in an overlapping manner. This is what essentially seals the wall in terms of acoustics (refer to chapter 24 for more details).

- From large to small, the remaining segments are placed, again in an overlapping manner.

- The previously mentioned steps create the roadside part of the barrier. S4's are similarly placed on the resident side of the structure.

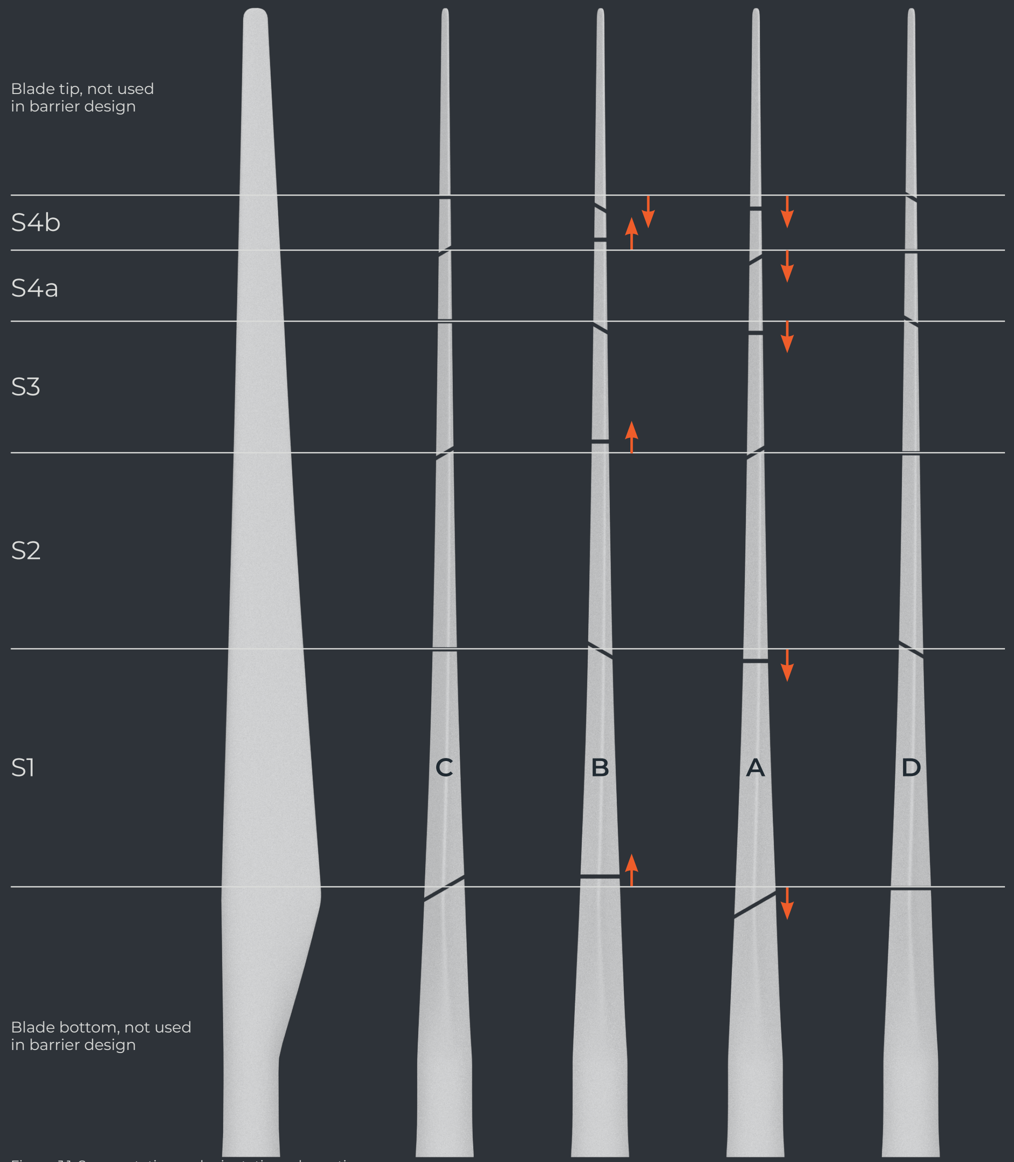
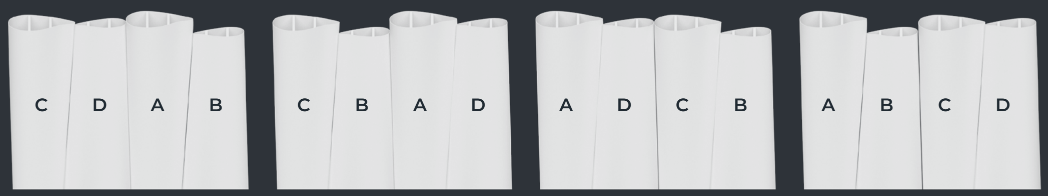


Figure J.1: Segmentation and orientation schematic:

This method results in a distinct look for the two sides of the barrier. The traveller side benefits from an even distribution of the vegetation to leverage the acoustic qualities of the plants and soil.
For the resident side, the placement of the segments is determined so that it is not possible to use the segments as a means to easily climb onto the structure. Moreover, the height of the smaller segments is chosen to discourage graffiti artists from using the large blades as a blank canvas. Plants growing in the small segments will create a thicket in the areas that would otherwise be prone to this phenomenon.

The four different base-modules that are created using the aforementioned method can be repeated indefinitely in the construction of the barrier.

Figure J.1 illustrates the cutting method for the blades. The white lines indicate the general cutting location that is selected based on height requirements. The arrows indicate how the second and third blades are cut in a slightly alternative way. This is essential in giving the design its flowing aesthetic. Each arrow indicates a deviation of 30 centimetres. Finally, the large segments form the basis for the four distinct base-modules.



Appendix K - Barrier construction development

For the design of the Blade Barrier, many insights from earlier projects can be used. However, a few key differences must be identified:

- The barrier is a large-scale application, and thus the time and material used to perform repetitive production steps are more critical.
- The precise placement of the blade segment is critical for its performance.

These differences make it worthwhile to reconsider the way that segments are cut and processed, how these segments are anchored to the ground, and how vegetation is best placed in the structure.

To do this, the following questions are tackled:

- *What cutting method is most suitable for the production of the Blade Barrier?*
- *What is the most suitable way to process the edges?*
- *How to install and anchor the segments to the ground?*
- *How should the plants be mounted to the structure?*

Cutting:

What cutting method is most suitable for the production of the Blade Barrier?

Requirements:

- The blades should be segmented using straight cuts (90° and 60° relative to the longitudinal axis of the blade)
- The cuts should be smooth to require little post-processing
- The selected machinery should allow for a flexible and rapid segmentation process

Approach:
The production process of previous projects is analysed, and the suitability of those methods for the Blade Barrier is evaluated. Next, a physical blade segment is cut using a potentially suitable method using a circular saw (Figure K.1). The effectiveness of the process and the quality of the final result is analysed.

Results:
Previous builds have all been one-off projects, where relatively few cutting steps were necessary. The effectiveness of the cutting process is vital for a feasible production process.
Using a circular saw on a rig did not fulfil the requirements. The process requires many preparatory steps, and the resulting cut is not smooth. This is due to the fact that the diameter of the saw-blade needed to be changed in the middle of the process to ensure a proper cut, as starting with the larger diameter would mean that the blade would initially deflect too much.
A large mobile lint-saw (as used by Anmet) is found to be most suitable, as the position of the saw relative to the blade can be altered in one action. Furthermore, this type of saw is able to make the cut in one go, resulting in a faster cutting process and a smoother result.

Discussion:
This question was answered using limited information. To be able to find a definitive answer for the cutting process, a more thorough analysis should be conducted.

Figure K.1: Cutting the segment using a large circular saw

Processing edges:

What is the most suitable way to process the edges?

Background:
Virtually all existing builds are one-off projects, with an intensive use-case such as furniture and playgrounds, in which people closely interact with the structure). For these projects, it has been most common to process exposed edges due to cutting by laminating them using additional glass-fibre layers. This process is time-consuming and labour intensive. One edge can take up to a day to be processed by a single worker (Anmet, 2022). As for the creation of the Blade Barrier a great number of edges need to be processed, it is valuable to explore options that have the potential to streamline this process.

Requirements:
- The internal material of the blade (foam, balsa wood), should be sealed off to prevent rapid material degradation
- The processing method should require as few steps as possible
- The processing method should require little virgin material
- A final layer of paint should be applied to the edge for aesthetic and protective purposes

Approach:
The first step was to consult experts in the field of glass-fibre structures. The most promising alternative was found to be to treat the edges with pure epoxy, or to mix the epoxy with a filler material (aerosil) to create a more viscous liquid.

The two previously mentioned options were applied to the edge of a physical blade segment, and the process and results were analysed.

Results:
Figures K.2 and K.3 show the applied methods. It was found that the foam in the sandwich structure would absorb much of the pure epoxy, causing many layers to be needed in order to create a smooth sealed surface. This was not the case for the mix with aerosil. This thicker substance could be applied in a more controlled manner, and need only a single layer for a proper seal.
Another disadvantage of the pure epoxy was that it would trickle down the edges, as it was more fluid than the mix. This creates undesirable drips on the sides of the segment. This did not happen with the thicker mix with aerosil. The only disadvantage of the mix was that it would need more time to prepare, but this is compensated by the fact that only one layer is required.

Discussion:
The results between the two options are quite clear in terms of convenience. Mixing epoxy with aerosil creates a thick paste that can easily be applied in a controlled manner.
This method would replace the current practice of laminating all edges with new glass-fibre mats. Contrary to this method, the aerosil mix has not yet been evaluated after a long period of time in use. It could be possible that disadvantages of this method would present themselves over time. It is recommended to evaluate this using the prototype that was built to test this.

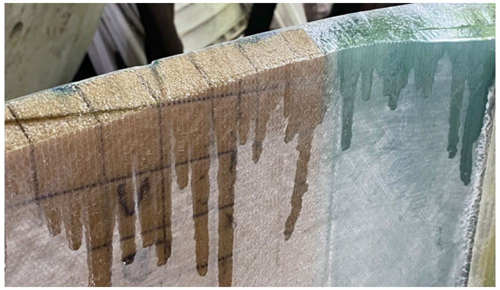


Figure K.2: Treating edge with pure epoxy


Figure K.3: Treating edge with epoxy aerosil mix

Installing segments:

How to install and anchor the segments to the ground?

Requirements:
- The segments need to be placed strictly according to the design, as tight gaps between the segments are critical, and can not be significantly wider than intended
- The installation process should be as straightforward as possible to avoid potential errors
- The blade barrier should not be prone to sagging, as that could impair its acoustic performance
- The segments should be open at the bottom, so that water can run through into the soil

Approach:
Initially, the construction of existing projects with erect blade segments was considered. Usually, these segments are simply dug into the ground, and in some occasions they are attached to a concrete foundation using metal brackets (Van Herk, 2022) (see Figure K.4). It became clear that digging the segments into the ground would be unsuitable, as this process leaves a lot of room for error, and it would not be clear whether a segment is placed correctly or not. Therefore a solution needed to be found that makes the process more straightforward, to speed up the construction and reduce potential errors significantly. Various ways of creating a pre-fab solution were considered.

Results:
The main element of the solution is a reinforced concrete slab that acts as a foundation for the blade barrier segments. Each barrier module (see chapter 21) is installed on one foundation using metal brackets (see Figure K.5). Markings on the foundation will clearly indicate which segment needs to go where, creating a prefab solution. The foundation is perforated so that rainwater can simply run down into the soil. The foundations are shaped in such a way that they slightly interlock with each other, and allow for curvatures in the path of the barrier. The foundations are placed on driven piles to withstand heavy wind forces.

Discussion:
The proposed foundation design is mainly a result of functional requirements, and will therefore require further development using civil engineering and production expertise.


Figure K.4: Installation to a foundation using brackets (GKB, 2021)

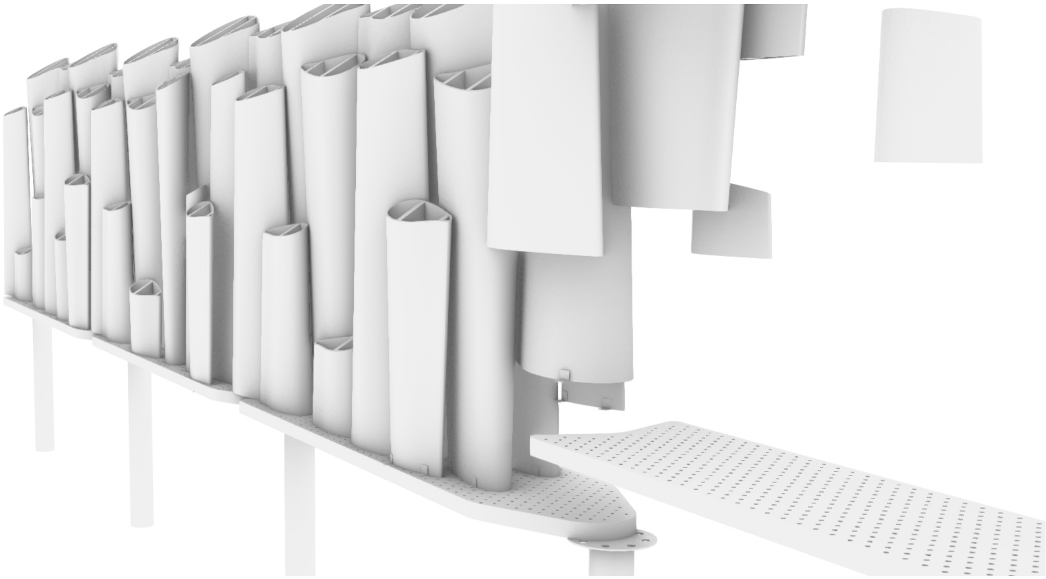


Figure K.5: Interface between foundation slabs, blade segments and connecting brackets

Vegetation

How should the plants be mounted to the structure?

Background:
The application of vegetation is intended to further enhance the barrier's acoustic performance, to contribute to its aesthetics and to stimulate biodiversity in the urban environment.

Requirements:

- The substrate depth should be suitable for the plants used.
- The solution should be flexible so as to suit the varying shapes and sizes of the cavities in the segments.
- The solution should be easily installed, and should be dismountable in case a plant needs to be replaced.
- The solution needs to block roots from getting too large, but allow for water to run through.

Approach:
Green-roof structures are used as a starting point, and translated to a design that is suitable for the barrier. Physical tests were performed using an actual blade segment to find the most suitable way of installing and mounting the necessary structure. Two options were considered: installing a platform inside the cavities onto which the vegetation can be placed, and installing a flexible bag that would be hung from the edges of the segment. Figure K.6 shows the design of both options.

Results:
Very quickly it became clear that the first option was not feasible, as installing bolts and a grated surface that deeply into the structure was cumbersome and time-consuming. On the other hand, a bag could be installed near the edges of the structure, which made it much easier to place the required bolts. Additionally, the fact that the required holes are closer to the edge leaves the segment in a better shape overall in terms of material integrity. This is important considering the EoL applications after serving as a barrier.
The final design of the structure consists of a geotextile bag that is reinforced using nylon straps (see Figures K.7 and K.8). The straps run underneath the bag and are sewn into the fabric. The bags are placed into the segment cavities and mounted to the brim of the segment. Eyelets in the straps are connected to eyebolts in the segment. Each strap contains several eyelets to increase the flexibility of the solution. In order to suit all cavity sizes, several different sizes (3 to 5) of the bag should be made.

Discussion:
This solution is tested on one segment size, while also larger cavities are to be equipped with plants. It is not yet exactly clear how many different sizes would be necessary for the entire design.
The performance of the bags in this way has not yet been tested over a long period of time. This might reveal weak points in the design that should be improved upon.

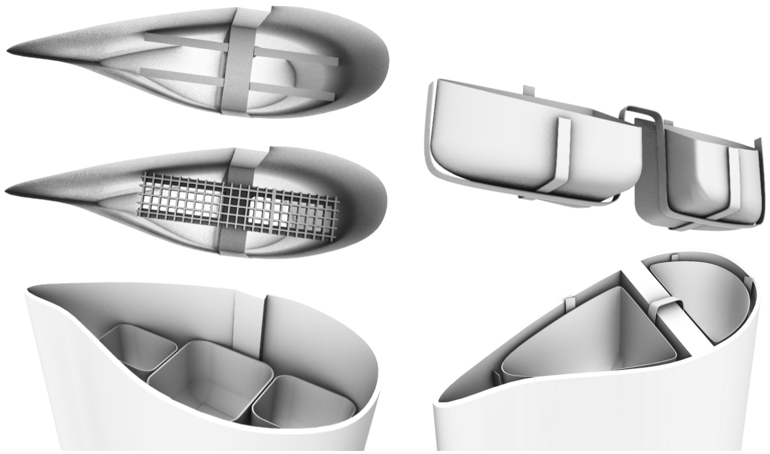


Figure K.6: Two options for plant placement

Figure K.7: Final vegetation bag prototype

Figure K.8: Installed vegetation bag

Appendix L - Additional testing

To complement the previously covered development steps, two tests were performed. The effect of the elements on exposed edges is evaluated, and the concept for plant placement is validated in terms of material strength.

The tests will assist in iterating the design and formulating a well-grounded plan for the production of the Blade Barrier.

Exposure to the elements
For a period of four months (mid-October until mid-February), the segment was left outside on a grassy field. The purpose was to see if and how the untreated brims of the blade would deteriorate. The segment contains a foam material for the sandwich structure, as opposed to the frequently used balsa wood.
The material showed little deterioration after this period. The most significant change is the connection between the foam and the GFRP next to it in the structure. This connection started to wither. Research mentions that balsa wood deteriorates much more rapidly when exposed to moisture.

The conclusion is that it is essential to process all edges in the construction to block moisture from entering the internal structure.

Strength validation test
It was found to be most convenient to use geotextile bags for the vegetation, that would be connected to the brim of the segments (see appendix K).
The following test was performed to validate the suitability of this concept in terms of strength, and to evaluate the design of the vegetation bag.

A low fidelity prototype of the vegetation bag was made using a woven PP shopping bag and two polyester straps. The ends of the straps are bolted to the inside of the segment, 3cm underneath the brim of the cut edge. This test was done using a segment with an unfinished brim.

Stone tiles of an average of 12kg each were placed into the bag to simulate the weight of the plants and (wet) soil. In total, the bag managed to safely carry 120kg, which is 30kg more than the expected maximum weight to be carried in this scenario.
The holes for the bolts were photographed before and after the test, and no discernible damage or wear could be observed in this area. It was also concluded that the weight of the tiles was mostly carried by the transverse strap. This was due to imperfections in the prototype, and the fact that large solid weights were used instead of soil.

This further confirms the strength and quality of the blade material, as the weight in the actual scenario would be more evenly distributed over all connection points.

The design of the bag concept is considered valid. However, to further ensure proper performance over long periods of time, reinforcing straps of 5 cm in width are selected for the final design.

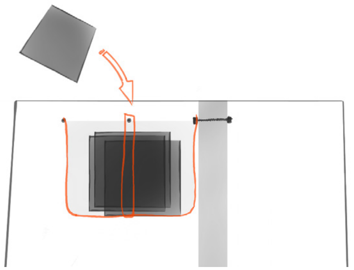


Figure L.1: Schematic overview of test set-up


Figure L.2: Connection of the bag to the segment


Figure L.3: Low fidelity vegetation bag


Figure L.4: Prototype carrying 120 kg worth of tiles

Appendix M - Acoustic simulations

The following is an overview of the setup and results from the performed acoustic simulations.

Simulation plan

"How does the Blade Barrier design perform compared to its generic counterparts?"

Software used:
- Rhinoceros 7
- Grasshopper
- Pachyderm (grasshopper plug-in)

Set up:
Sound source as a line
- Height: 2 metres
- Road material: asphalt
- Traffic speed: 120 km/h
- Cars / hour: 1500
- Medium trucks / hour: 500
- Heavy trucks / hour: 300
- Buses / hour: 200
- Motorcycles / hour: 50

Gap between two large surfaces to place barrier designs into.
- Width: 20 metres.

Observer points at close, average and far distances

Barrier types: no barrier, 5m barrier, 6m barrier, Blade Barrier

Simulations:
No barrier
- Close (2 m)
- Average (5 m)
- Far (30 m)

Generic barrier 5m
- Close (2 m)
- Average (5 m)
- Far (30 m)

Generic barrier 6m
- Close (2 m)
- Average (5 m)
- Far (30 m)

Blade Barrier
- Close (2 m)
- Average (5 m)
- Far (30 m)

Results:
Sound Pressure Levels for each simulation. Divided by 8 frequency groups, and A-weighted average SPL in decibels.

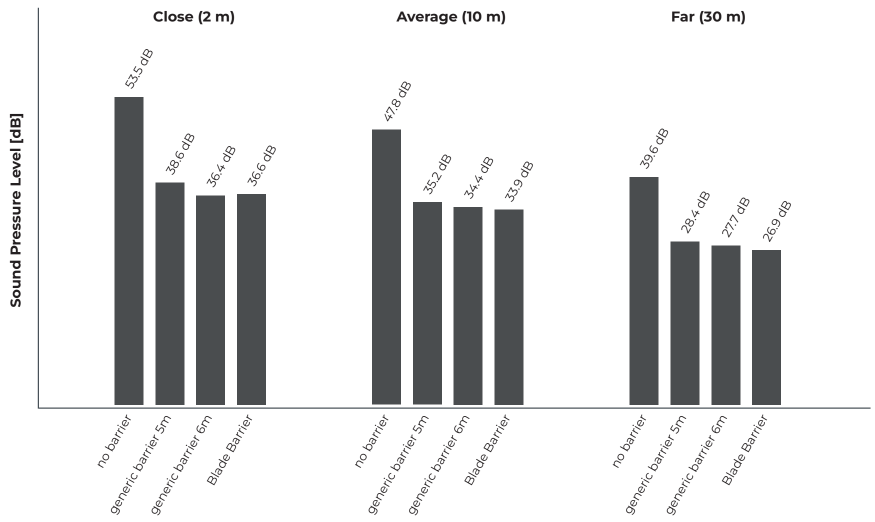


Figure M.1: simulation results averages

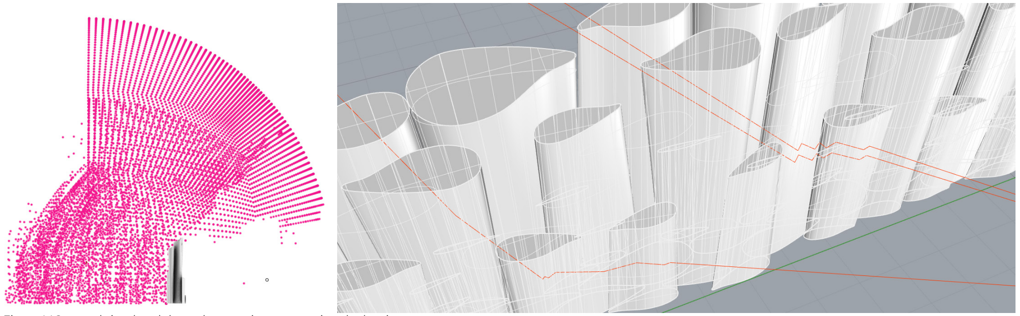


Figure M.2: sound simulated through raytracing penetrating the barrier

No barrier	Close (2m)	Mid (10m)	Far (30m)
0 (low freq.)	54.9	49.5	41.2
1	52.3	46.7	38.6
2	51.2	45.6	37.5
3	50.2	44.7	36.6
4	49.6	43.8	35.5
5	45.6	39.7	31.7
6	39.5	34.2	25.8
7 (high freq.)	34.2	28.8	20.3
Average SPL [dB]	53.5	47.8	39.6

Generic barrier 6m	Close (2m)	Mid (10m)	Far (30m)
0 (low freq.)	43.4	41.2	34.2
1	39.4	37.3	30.5
2	36.8	34.8	28.0
3	34.4	32.4	25.7
4	31.7	29.7	23.0
5	26.4	24.4	17.7
6	19.1	17.1	10.3
7 (high freq.)	12.3	10.3	3.3
Average SPL [dB]	36.4	34.4	27.7

Generic barrier 5m	Close (2m)	Mid (10m)	Far (30m)
0 (low freq.)	44.6	41.8	34.6
1	40.6	38.0	31.0
2	38.0	35.5	28.7
3	35.6	33.2	26.4
4	32.9	30.5	23.7
5	32.4	25.2	18.4
6	20.2	17.9	11.0
7 (high freq.)	13.5	11.0	4.0
Average SPL [dB]	38.6	35.2	28.4

Blade Barrier	Close (2m)	Mid (10m)	Far (30m)
0 (low freq.)	42.2	40.5	33.4
1	38.3	36.6	29.8
2	35.7	35.2	27.2
3	33.4	31.7	24.8
4	33.4	29.0	22.2
5	25.4	23.9	16.9
6	18.2	16.5	9.6
7 (high freq.)	17.3	9.6	2.5
Average SPL [dB]	36.6	33.9	26.9

Figure M.3: simulation results

Appendix N - A20 Blade Barrier proposal impressions

Following are a number of additional impressions for the A20 Blade Barrier proposal that are not found in the main body of the report.


Figure N.1: birds-eye perspective


Figure N.1: Blade Bridge connecting existing routes to the *green corridor*


Figure N.3: Blade Made furniture and curvilinear path


Figure N.4: Blade Barrier integrated with pre-existing bridge structure


Figure N.5: perspective from the high-way

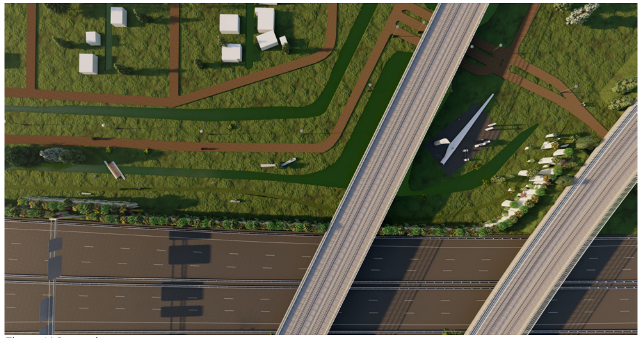


Figure N.6: top view

Appendix O - Insights from WindEurope 2022 event

In April 2022, Blade Made was represented at the WindEurope conference in Bilbao. The main purpose for Blade Made was to strengthen its connections within the industry, and develop new opportunities for Blade Made projects.
Existing constructions were presented as a way of showing what the company has built so far, and to show proof that repurposing is a worthwhile solution. Concepts for new projects were shown to spark the interest of potential clients.

The Blade Barrier was presented as well to communicate the goal to scale up to larger - and more impactful - constructions. Connections were made with companies that own wind farms, and therefore know firsthand about the overarching issue of blade EoL. Conversations with these parties yielded various valuable insights that are relevant for the Blade Barrier project.

These insights are listed here:

- Blade Made's business model is to not process the blades themselves, but rather to connect relevant parties to set up projects. Blade Made mainly provides knowledge and designs. It is therefore possible to set up projects worldwide. This is what sets it apart from similar companies such as , who reprocess the blades in-house.

- In South America, no reprocessing infrastructure (such as the cement kiln route in Europe) is in place. In the coming five years, a great number of turbines will be decommissioned. Responsible parties there are concerned with the blade EoL, and look for sustainable solutions such as the Blade Barrier to deal with the blade waste stream.

- In order to create enough support to set up a large scalable Blade Made project, it is necessary to convince many stakeholders of the feasibility and desirability of such a construction. Also, local societal acceptance is desired to gain enough confidence that a project will be a success. Therefore, most parties see value in smaller objects (such as furniture and playgrounds) as a first step, after which the door will be opened for more ambitious projects.

- Conversations are in line with earlier findings that usually, available blades will manifest as an influx of identical blades, as individual wind farms are decommissioned in one go. This means that it is likely that for scalable projects, designs will need to be made using identical blades.

- As a Blade Barrier could potentially be realised in any country dealing with EoL blades, it is advisable to keep the production process as simple as possible. This way, local contractors can be employed for cutting, reprocessing and installation. The decommissioning parties should ideally be involved in the project early on, so as to streamline the entire logistical process.

- Blade Made projects could enhance the general acceptance and enthusiasm regarding wind energy among local communities.

Figure O.1: Blade Made at the WindEurope 2022 conference