From Blade to Barrier

The embodiment design of a noise barrier from horizontally oriented, decommissioned wind turbine blades.

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Author: S.M.O. Ornstein 4885139

Chair: Ir. J.J. Joustra

Mentor: Ir. G. Nijenhuis

Company: Heijmans Infra B.V.

Supervisor: ing. M.J.A. van Amstel - Projectmanager

Preface & Acknowledgements

This thesis marks the final project of my studies at Industrial Design Engineering in Delft. It has been an amazing journey, and I have learned a lot during my time here. As a designer, I have always been interested by the reuse of products and materials, and this project has been a great source of inspiration.

Working on the noise barrier from blades has taught me not only about engineering and design, but also about myself and the role I want to take in future projects: turning ideas into reality. During these last five months, I realized how my ambitious ideas underestimated the amount of work the project required. If it were up to me, the real satisfaction would come when the entire barrier is built in real life. Still, with this challenge I have proven to myself that designing is where I belong.

Exploring the reuse of wind turbine blade material has both been fun and inspiring. It showed me how to design for a more sustainable future, and I hope this thesis will inspire others as well. I can sense a growing awareness around me of the importance of blade material reuse, and I would be proud to be among those who lead the way.

I would first like to thank my supervisors, Jelle Joustra and Gerard Nijenhuis, for guiding me through this project, even during the lonely summer months. Your trust gave me the confidence to rely on my own judgment and grow into a stronger designer. Israel Carrete, thank you for the advice and help during the start of the project, and Gerard, thank you especially for the many WhatsApp voice messages and conversations when my head was overflowing with ideas.

At Heijmans, I am grateful to Edwin van Osch and Mark van Amstel for offering me the chance to continue my project in Rosmalen with the support of the Geluidsbeheersing team. A special thanks goes to Erik Nouwen and Johan Grevelink, who were always interested in my progress and helped me with all my questions along the way.

Lastly, I want to thank my girlfriend, housemates, friends, and parents for their positive energy, support, dinners, feedback, and brainstorming sessions. Cas, thank you for taking the time to help me with rendering the final visuals. I’m looking forward to sharing my presentation with you all and discovering what the world has in store for me and my future profession.

Executive Summary

This thesis explores the potential of repurposing decommissioned wind turbine blades (WTBs) into structural elements for highway noise barriers. While wind energy continues to expand, the retirement of older turbines is generating a growing stream of composite blade waste. It is a material that is difficult to recycle and often disposed through environmentally harmful methods such as landfilling or incineration. The blades possess valuable mechanical properties, making them suitable for reuse, but significant challenges remain. Their varied dimensions, curvature, and composition complicate design integration, and the emerging supply of blade for structural reuse is entering uncharted territory with little proven large-scale experience. This master thesis aims to provide a viable, practical solution for integrating WTB reuse into infrastructure, demonstrating the capabilities of wind turbine blades as a noise barrier.

The blade barrier in a nutshell
The blade is cut into 12-meter segments. Depending on the required height, one barrier design uses a sequence of identical 12-meter pieces (Chapter 8.1). Each segment is placed horizontally in U-shaped frames, creating a serrated top edge. This approach keeps the frames and foundation simple and straightforward (Chapter 8.4, 8.9).

The road-facing surface follows the blade's natural curve, tilted 10–20° backwards to deflect sound upward into the sky (8.2). Both ends of the segments are capped to protect the open edges, and the front surface is treated with an anti-graffiti coating (Chapter 8.8).

Assembly is efficient: segments are easily positioned in the frames, holes are drilled, and the segment is secured with plugs (9.6, 9.2). Between the segments, a cover strip placed against the caps, provides an acoustic seal (9.3). After every 32 segments, and emergency exit is placed in between (9.5). Additional safety measures against fire, vehicle impact, and water drainage are also integrated into the design (8.8, 9.4). Figure 1 shows the result.

Outcome
The developed blade barrier concept has proven to be a feasible, scalable, and practical solution for reusing decommissioned wind turbine blades. While challenges in logistics, acceptance and cost still need attention, the design shows strong potential. The reuse of blades adds clear sustainability value, addressing the growing waste problem while offering a good alternative to traditional noise barriers.

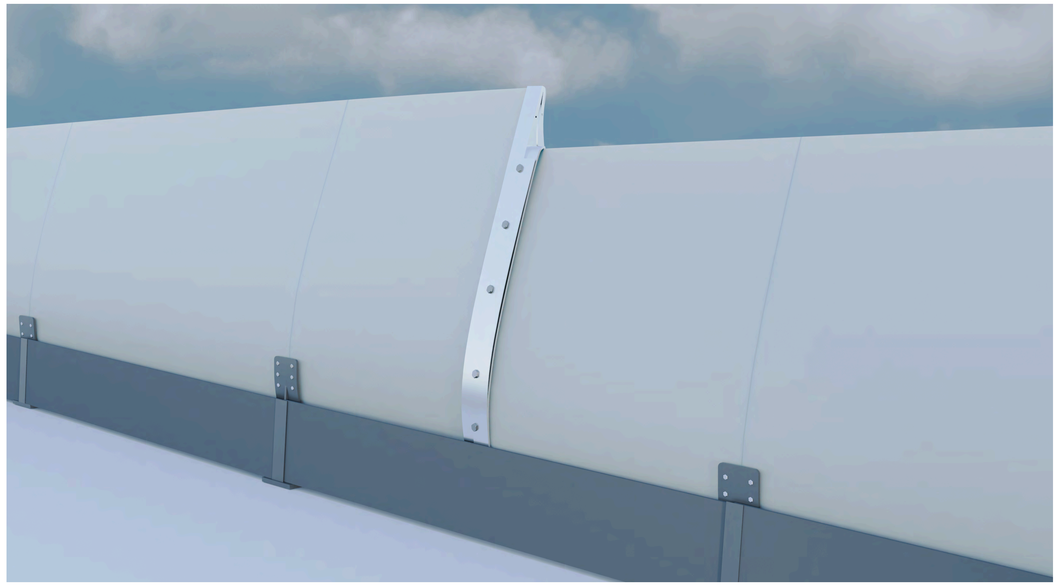


Figure 1: Sneak peak of the final design - Co-creation with Cas van den Eertwegh.

Abbreviations

CFRP	Carbon fiber reinforced polymer
EOL	End of life
FRP	Fiber reinforced polymer
GCW	Richtlijnen Geluidbeperkende Constructies langs Wegen
GFRP	Glass fiber reinforced polymer
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LE	Leading Edge
MKI	Milieu Kosten Indicator
MGS	Modulair Geluidsscherm
MW	Mega Watt
PC	Personal Communication (in sources only)
TE	Trailing Edge
TL	Transmission Loss
TRL	Technology readiness level
WSM	Where Segments Meet
WTB	Wind turbine blade

Sectioning terms
Terminology shown in Figure 2.
Blade: one full (decommissioned) wind turbine blade
Segment: a large cross-section cut from the blade
Panel: a plate of material cut from a segment

Root: the cylindrical stem of the blade that transitions to the midspan
Midspan: the airfoil shaped middle section of the blade
Tip: the thin end section of the blade

Figures that are not captioned or indicated with A to Z are authors own.

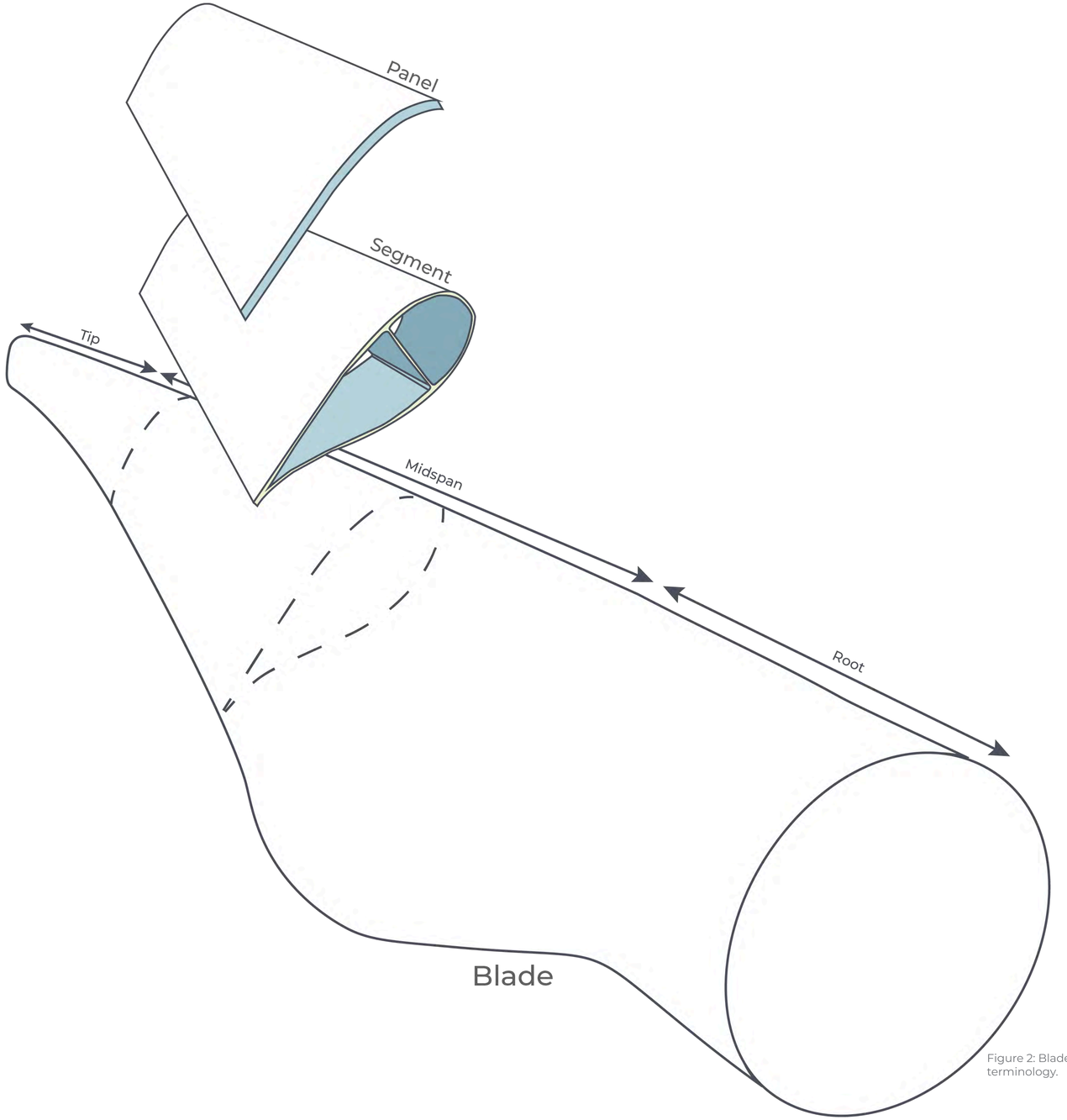


Figure 2: Blade terminology.

Table of contents

Preface & Acknowledgements 3
Executive summary 4
Abbreviations 5
Table of contents 6

Chapter 1: Introduction 7
1.1 Problem definition 8
1.2 Research questions 9
1.3 Approach 10
1.4 Scope & vision 11
1.5 Reading guide 13

Chapter 2: Wind turbines & Blade material 15
2.1 The evolution of blades & Turbines 16
2.2 The material composition of WTBs 23
2.3 The mechanical properties of WTBs 26
2.4 Recycling WTB material 29
2.5 Logistics 35
Chapter takeaways 43

Chapter 3: Noise barriers 45
3.1 What is a noise barrier? 46
3.2 Structural & Environmental stresses 47
3.3 Noise barrier construction visit 49
3.4 Safety standards 50
3.5 Aesthetic experience 51
3.6 (Dis)assembly processes 52
3.7 Maintenance 53
3.8 Business and sustainability implications 54
Chapter takeaways 55

Chapter 4: Acoustics 56
4.1 The acoustic properties of WTBs 57
4.2 Noise barrier acoustics 59
Chapter takeaways 63

Chapter 5: List of criteria & Requirements 64
5.1 Mapping context to criteria 65
5.2 Criteria and Requirements 66

Chapter 6: Ideation 68
6.1 The 7 key focus areas 69
6.2 Morphological chart 77

Chapter 7: Conceptualization 78
7.1 Concept 1: Combined Cassettes 79
7.2 Concept 2: Jagged Jaws 81
7.3 Concept 3: Bolted Balancer 83
7.4 Implications 85
7.5 Evaluation 87

Chapter 8: Concept iteration 89
8.1 Use of similar segments 90
8.2 Acoustics of road-facing curvature 91
8.3 Wind on the barrier: Forces modeling 92
8.4 The U-frame & Foundation 94
8.5 Fixing the Segment in place 99
8.6 Shear web location 101
8.7 Connecting segments, soundproofing and closing 102
8.8 Protection 104
8.9 Placement & Aesthetics 106
Chapter takeaways 107

Chapter 9: Embodiment & Visualization 109
9.1 The U-frame 110
9.2 Fixing solutions 111
9.3 Closing & Soundproofing 112
9.4 Koios Plinth 114
9.5 Emergency exits 116
9.6 The assembly 117
9.7 Roadside aesthetics 120

Chapter 10: Prototyping & Evaluation 122
10.1 Material & Restrictions 123
10.2 The Alu-frame setup 124
10.3 Acoustic tests 125
10.4 Manufactured components pricing 126
10.5 Processing guide from blade to barrier 127
10.6 What happens to blade material that is left unused? 128
10.7 Life cycle assessment 129

Discussion 130
Conclusion 131
Recommendations 132
Personal note 133
References 134
Appendices A–K 137-145

1.
Introduction

Wind turbines have become an unmistakable feature of our landscapes over the last decades. The number of turbines will grow and so will their size. In the next 5 years, WindEurope is expecting to install 187 GW of new wind power, 80% of which are offshore turbines, quadrupling the current numbers (Costanzo et al., 2025). While the new arrival of the next generation turbines supplies us with green energy, the old generations are reaching the end of their service life. After 20 to 25 years, wind turbines are decommissioned, often more from an economic perspective rather than the degradation of the material of the blade (Tazi et al., 2019).

Currently, around 85–90% of a wind turbine's total mass can be recycled using established processes. However, recycling the blades remains a major challenge due to the complex composite materials they are made from (LM Wind, 2024). Old blades often end up buried in landfills or burned, which is not only bad for the environment but also a waste of the valuable materials they are made from (Chen et al., 2019). In 2025, the waste of composite material in the Europe measures 60.000 tonnes, which will increase to over 800.000 tonnes in 2050 (TNO, 2022). Although several technologies exist to recycle these composites, they are still in early stages of development and not yet viable at industrial scale. This is either due to cost, efficiency, or limited availability (Chen et al., 2019).

The combination of materials used in wind turbine blades (WTBs) results in a unique set of valuable properties, including high stiffness, resistance to buckling, and low density (Buckney et al., 2013). These characteristics make decommissioned blades well-suited for structural reuse in applications where their mechanical performance can still be effectively utilized (Joustra et al., 2021a). This reuse strategy tries to resource the material efficiently and focuses on environmental protection, leading to better recycling methods and less virgin material use. A noise barrier will exist next to the road for a long time, storing blade material for an extended life and further reuse.

TU Delft is part of the LICHEN-BLADES research consortium, which focuses on understanding wind turbine blade material and developing new ways to use its potential. One of the consortium partners is Heijmans, a construction and engineering company with a strong focus on sustainability. Within this consortium, Heijmans gave me the opportunity to explore the reuse of WTB material in a highway noise barrier. The decommissioned blades can be cut into segments and applied as standardized barrier elements. By giving blades a second life and combining them with a modular design, the barrier offers both a practical reuse solution and a contribution to a more sustainable future.

1.1
Problem definition

Repurposing decommissioned wind turbine blades (WTBs) for structural applications present several challeges. The composite material cannot be reshaped and every blade differs, not just between types and manufacturers, but also along the length of a single blade. This variation in shape, curvature, and dimensions makes it difficult to create consistent, continuous structures from reused blade material.

In the case of a horizontal noise barrier, these challenges become very clear. Combining segments with different geometries can quickly lead to misalignments, creating gaps that reduce the acoustic performance of the barrier. To be effective, the design must deal with these tolerances while still being simple enough to build at scale.

The challenges go beyond design issues. The supply chain of incoming blades ready for structural blade reuse is still very new and unexplored. In this field, there is little real-world experience or proven business models to rely on. Decommissioning, processing, storage, and transportation all need to be organized in a way that matches the growing flow of blades reaching end of life. Meanwhile, current disposal methods are outdated and options such as landfilling is even already banned in many countries. While the volume of blade waste will be rising fast, the urgency to solve the problem will too.
At the same time, the reuse of WTBs faces strong competition from conventional noise barrier materials that are already trusted by industry. To gain the confidence of the industry as well, blade reuse needs to show that it is not just technically possible, but also cost-effective, environmentally beneficial, and scalable. Only then can WTB reuse position itself as a credible and trustworthy alternative for future infrastructure projects.

1.2
Research questions

The assignment of this thesis is to develop a detailed design for a scalable noise barrier made from horizontally oriented WTB material. Since both the material and the application were already determined, the research could be focused and structured. The process began with exploring the blade material and noise barrier design challenges, followed by concept development, and finally refining and detailing the key aspects in the embodiment design phase.

To guide this process, four key research questions were formulated, each addressing knowledge gaps and project goals:

Key research questions:

1. How can decommissioned wind turbine blades be reused efficiently in modular and scalable noise barrier applications?
2. What design and construction strategies can ensure a seamless horizontal arrangement of WTB segments in a noise barrier, minimizing sound leakage and misalignment, maximizing ease of installation and viability?
3. What are the logistical and technical challenges in the current supply chain for decommissioned WTBs, regarding processing locations, storage, and noise barrier assembly?
4. How to ensure the added value of using WTBs as building material gains the trust of the current competitive market?

1.3
Approach

This project is structured according to the double diamond design framework developed by the Design Council (2019), consisting of four stages: Discover, Define, Develop, and Deliver. These phases form the backbone of the design process and guide the transition from the research phase (Discover & Define) to the design phase (Develop & Deliver), as shown in the Figure 3.

Personal approach
The approach taken in this project was to act like a sponge, absorbing as much information as possible by studying previous work on noise barriers, talking with experts, and discussing with peers. During the research, curiosity continuously raised questions, new areas were explored, and ideas were captured through sketches and prototypes.
One personal challenge in this process was the impulse to explore too much, drifting away from the scope and making decision-making more difficult. This is why a clear approach, structured planning, and concrete project framing were essential to keep me focused and moving forward.

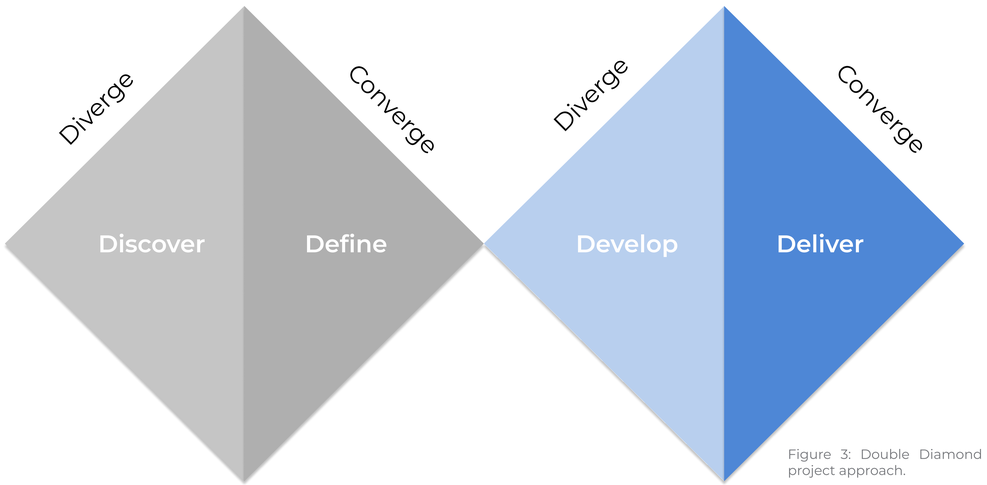


Figure 3: Double Diamond project approach.

Goals
Each phase has its own objectives and goals, structured as follows:

Discover
This phase focuses on understanding the context of reusing wind turbine blades as highway noise barriers. The goal is to obtain as much information as possible by researching material composition and structural properties of WTBs, decommissioning forecasts and blade availability, challenges in recycling and reuse, existing noise barrier standards and acoustic requirements, and practical design “rules.” This phase also included sparring sessions with experts and site visits.

Define
In the next phase, research findings and key insights were translated into technical requirements, forming the basis for the scope of further concept development. The goal is to create a frame to work with, without letting too many factors distract the desired outcome, as the research questions direct towards.

Develop
This phase is all about generating, iterating, and testing design ideas. The goal is to use creative sessions, material tinkering, prototyping, and expert feedback to choose a concept and start detailing it until the project is ready for the final stage.

Deliver
In the final phase, the selected concept is developed into a detailed embodiment design. The goal, apart from a significant prototype, is to deliver a detailed construction and assembly plan, next to an implementation strategy. This includes assessing the logistical feasibility from decommissioned material supply to processing, manufacturing components, and building the barrier. Considerations that fell outside the scope are presented as recommendations for further development.

1.4
Scope & Vision

During the course of this project, through research, sparring sessions with experts, and collecting insights, new ideas and questions automatically came to the surface. The use of WTB material and the horizontal orientation was fixed, but the way the blades were cut and the segments used was still open. After evaluating the choice between using panels or segments (Appendix C), it was ultimately decided to continue the design phase of the project with blade segments as the main noise barrier elements.

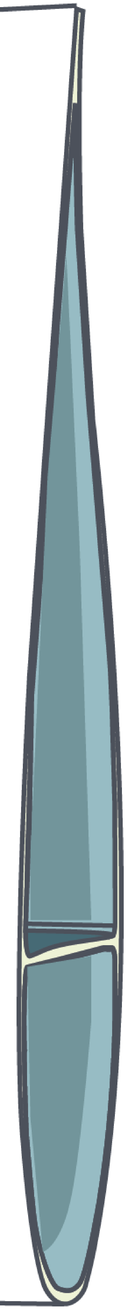
The project vision is to develop a blade barrier that is close to real-life execution. A modular barrier, effective in reducing noise, visually appreciated by its users, and helping to preserve the value of the material down the path of lifecycles. The embodiment of a feasible and scalable solution for the structural reuse of WTBs.

The scope of the next project phase is:

1. Efficient reuse of decommissioned blades in modular, noise barriers.
2. Design and construction strategies for minimizing sound leakage.
3. Logistical and technical challenges in processing, storage, and assembly.
4. Building market trust in the added value of WTB-based materials.

The Frame defines the playing field with the following boundaries:

- The barrier is realized from hole segments, not from panels.
- The barrier's orientation is horizontal, alongside the highway.
- The segments' connections seal the barrier to a degree of sufficient noise attenuation, but is not the primary focus.
- It is ok to reuse less than 80% of an entire WTB.



My personal vision is creating a solution to deal with composite blades ending up as waste. Realizing a noise barrier together with Heijmans is a perfect opportunity to give decommissioned blades a new purpose. Instead of incineration or shredding, I see a growing number of initiatives that reuse the blades in structural applications (Appendix F BladeMade, Re-wind, 2025), which seems like a good start.

However, these are often not scalable solutions for the waste problem we are about to face. And because of the complex nature of composites sandwich structures, there has not been a proper solution to reuse the material itself, like steel.

A madman would say that a wind turbine blade is the perfect solution for making a noise barrier. It's complex shape, size and material properties make it inefficient in space-use, and barely absorb sound.

I'm not trying to build the perfect noise barrier using traditional methods, but rather to give large amounts of blade material the opportunity to be reused and preserved. The balance lies in both storing the material along the road and creating a functional and scalable noise barrier, while we wait for future applications and technologies that can reuse WTB material to it's full potential.

1.5
Reading guide

After the previous introduction with problem definition, research questions and approach, this thesis is built up of nine more chapters, a **discussion**, **conclusion** and **recommendations**.

Phase one: Discover and Define

Chapter 2 **Wind turbines & Blade material:** Dives into the world of wind turbines, blade shapes and sizes, material composition, blade recycling methods, and a processing time-line from decommissioning to reuse.

Chapter 3 **Noise barriers:** Dives into the world of noise barriers, what they are, how they work, environmental stresses, safety standards, aesthetics, (dis)assembly process, maintenance, and sustainability implications.

Chapter 4 **Acoustics:** Gives a combined view on the acoustics of both blade material and noise barriers, and regulations that come with it.

Chapter 5 **List of criteria & requirements:** Takes all these findings and translates them into criteria, requirements, kick starting the next phase.

Phase two: Develop

Chapter 6 **Ideation:** Starts to define seven key focus areas and generate concepts with the help of a morphological chart.

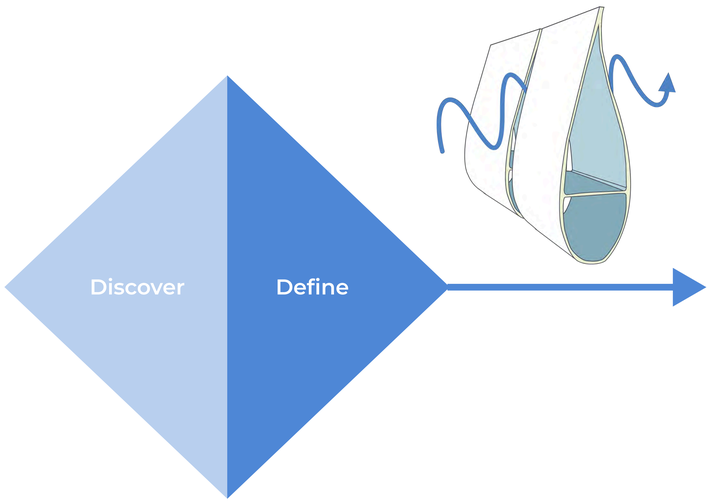
Chapter 7 **Conceptualization:** Further iterates on concepts, reflects, evaluates and chooses the final concept with methods.

Chapter 8 **Concept Iteration:** Iterates further on the chosen concept and addresses, in addition to segment orientation and real-world wind forces, the design challenges from all the previous chapters, including frame, foundation, fixing, soundproofing, and safety.

Phase three: Deliver

Chapter 9 **Embodiment & Visualization:** Finalizing the design by detailing all components, and visualization of the assembly and road-side aesthetics.

Chapter 10 **Prototyping & Evaluation:** Evaluates on the previous chapters with prototypes, acoustics, cost, processing and sustainability topics.


Discover
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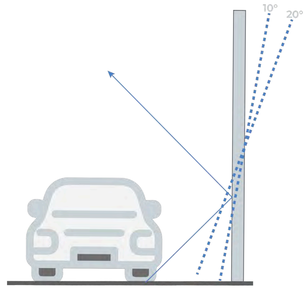
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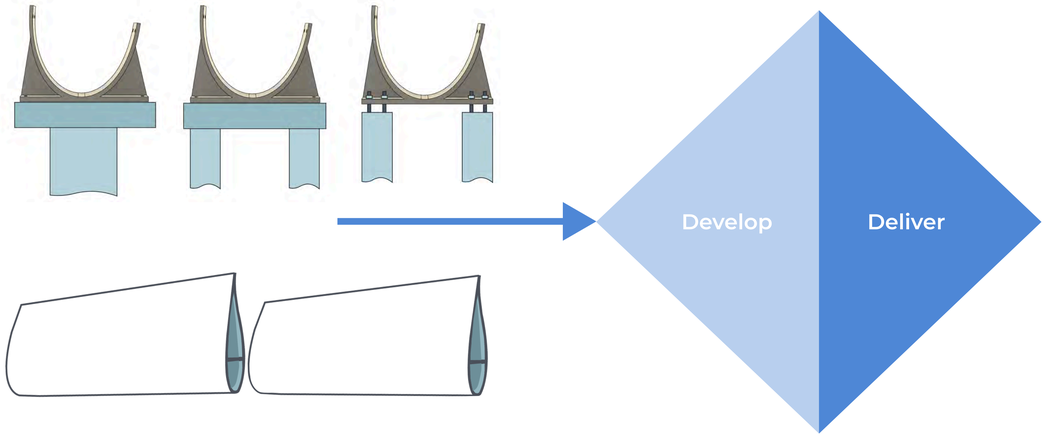
Develop
Deliver

Information
storm ahead...

2.
Wind turbines & Blade material

For centuries, wind has been used as an important energy source. The iconic wooden mill from Holland evolved into a more powerful turbine made from aluminium and steel. The modern wind turbine that stands tall in the Dutch landscape, began to take shape in the late 20th century. A shift in the industry, transitioning to fiber-reinforced composites in the 1980s, enabled the production of longer, lighter, and more durable blades (Leadvent Group, 2024). With thousands of blades worldwide reaching the end of their operational lives, we are challenged to unlock effective strategies for reusing these large and complex composite structures.

This chapter takes you through the following topics:

2.1 The evolution of blades & Turbines
Growth, shape & return of material

2.2 The material composition of WTBs
Overview of material

2.3 The mechanical properties of WTBs
Why it is a suitable building material

2.4 Recycling WTB material
Methods, initiatives & challenges

2.5 Logistics
From wind turbine to blade segments

2.1
The evolution of blades & Turbines

2.1.1 The terminology of a turbine
2.1.2 The shape of a blade
2.1.3 Growth in number and wind parks
2.1.4 Return flow of composite materials
2.1.5 First blades that will be decommissioned
2.1.6 Pressure and suction side
2.1.7 Retrieving data of different WTB shapes
2.1.8 Methods to find applications and shapes

2.1 The evolution of blades & turbines
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From wind turbine to blade segments

2.1
The evolution of blades & Turbines

Wind turbines have made an extraordinary transformation since their earliest versions in the late 19th century, when the first electricity generating wind turbines were developed. These early turbines were about 10–15 meters tall and only produced a few kilowatts (Gipe & Möllerström, 2022)(Figure 4). Today, modern wind turbines have grown to enormous machines, especially offshore. The 90 meter tall NREL 5MW turbine (National Renewable Energy Laboratory, 2009), which is used in this thesis as standard reference model, is dwarfed by new giants like GE's Haliade-X (14–18 MW class), which stands over 260 meters tall. A single machine of this caliber can power up to 16,000 households per year (Rodriguez, 2024).
The shape and structure of wind turbine blades varies per model, as each manufacturer designs them differently based on their own standards and technologies. This lack of standardization complicates reuse and recycling (Schmid et al., 2020).

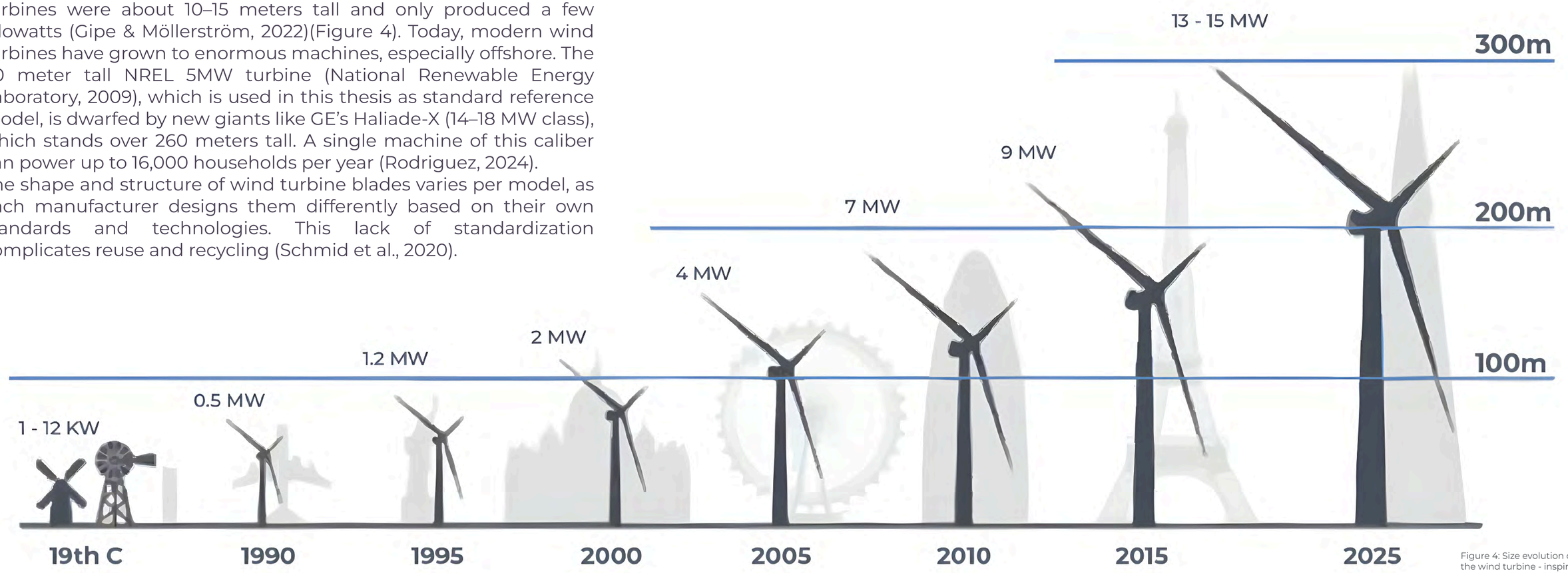


Figure 4: Size evolution of the wind turbine - inspired on image (Brunel, 2021)

2.1.1 The terminology of a turbine

Before diving into the shape of wind turbine blades and following chapters, it is useful to cover the main terms within the wind turbine terminology (Figure 5).

Nacelle
The nacelle is the ‘head’ at the top of the tower that houses internal components such as the gearbox, generator, and control systems. It protects these elements from weather and may be equipped with lighting for air traffic visibility (Iberdrola, n.d.).

Hub
The hub connects the three rotating blades to the main shaft and transfers the mechanical energy generated by wind to the gearbox inside the nacelle.

Tower
The tower is the tall, tapered structure that supports the nacelle. It can reach up to 170 m in height and carry loads of up to 260 tonnes. Steel is the most common material used for the tower, although concrete and hybrid towers are increasingly used as well (Iberdrola, n.d.).

Roughly 96 percent of a wind turbine, excluding the blades, can be recycled by mass (Eneco, 2025). This value can vary slightly depending on the size and type of the turbine. In addition to the steel towers and reinforced foundations, the generators and other metals of internal components are also suitable for reuse.

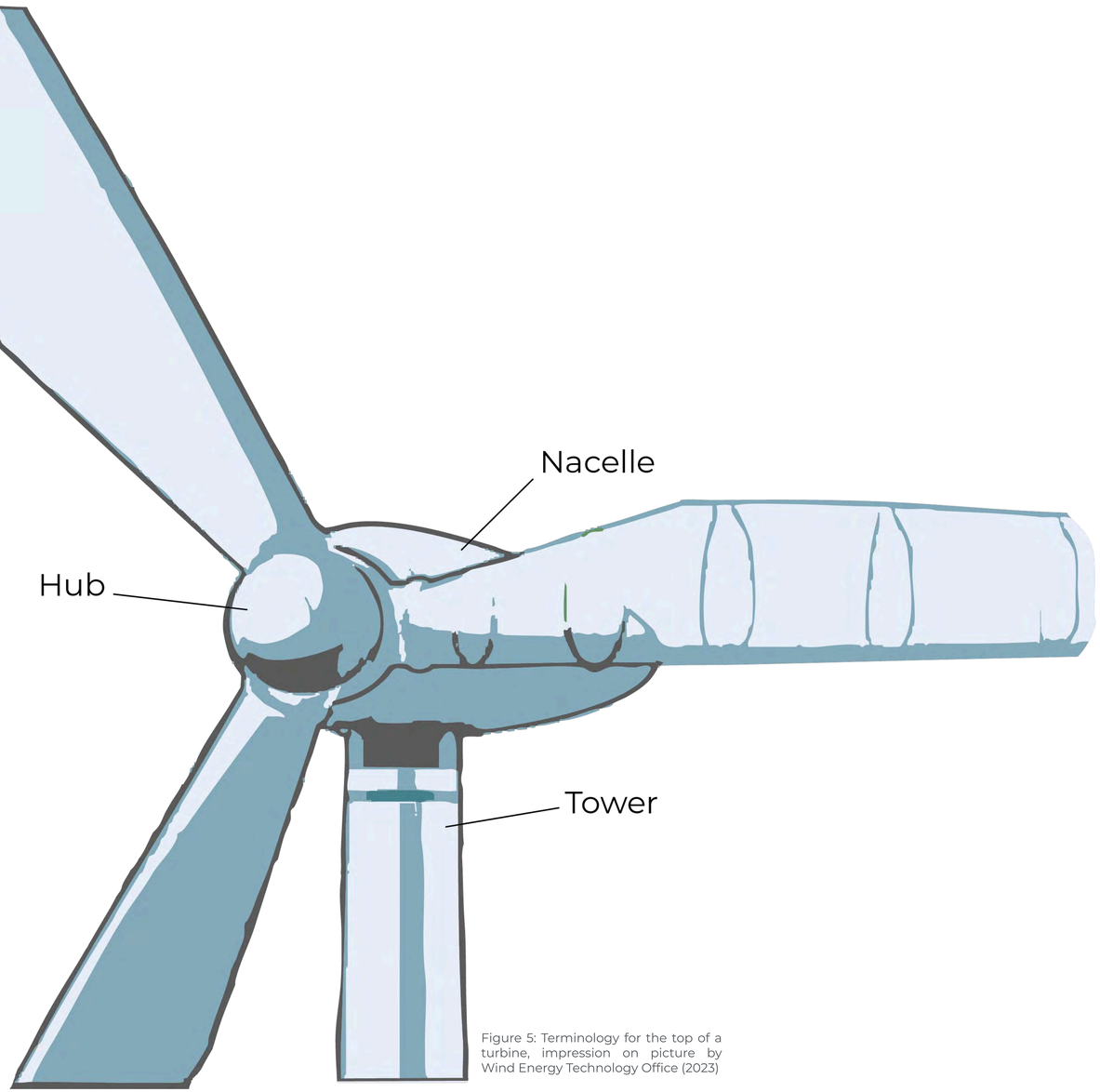


Figure 5: Terminology for the top of a turbine, impression on picture by Wind Energy Technology Office (2023)

2.1.2 The shape of a blade

While wind turbine blades may look similar, their shape varies significantly depending on the turbine model. The geometry of a blade is defined by an airfoil like shape, that plays a critical role in determining a blade's aerodynamic performance, including lift and drag, as well as its structural strength (Wind Energy Technology Office, 2023).

A blade can generally be divided into three sections: the inboard, midspan, and outboard (Figure 6).

- The inboard section, which is often referred to as the root, is largely cylindrical. This shape is more for structural support rather than aerodynamic efficiency.
- The midspan transitions into a more aerodynamic shape, and becomes slimmer as it tapers towards the tip. The five numbered shapes are part of DU (Delft University) systematic airfoil series.
- The outboard section, or blade tip, is a flat airfoil shape, optimized for speed, and is often curved outward to prevent a collision with the tower when the blade bends under high loads (Joustra et al., 2021b).

The earlier mentioned NREL blade is a model used for research purposes and is used for reference in this thesis because its data on research and specifications of shape are publicly available, which is often not the case for commercial blade models. Next to that, the ~60m long blade was designed for a 5MW turbine, which is found both onshore and offshore, making it a good representative for current turbines that will be decommissioned.

Since wind turbine blades are manufactured using thermoset composite materials, their shape is permanent. This has implications for reuse: the cylindrical inboard section is not ideal for applications that require flat, straight panels, such as noise barriers. The midspan and outboard sections offer more regular, flatter surfaces, making them more suitable.

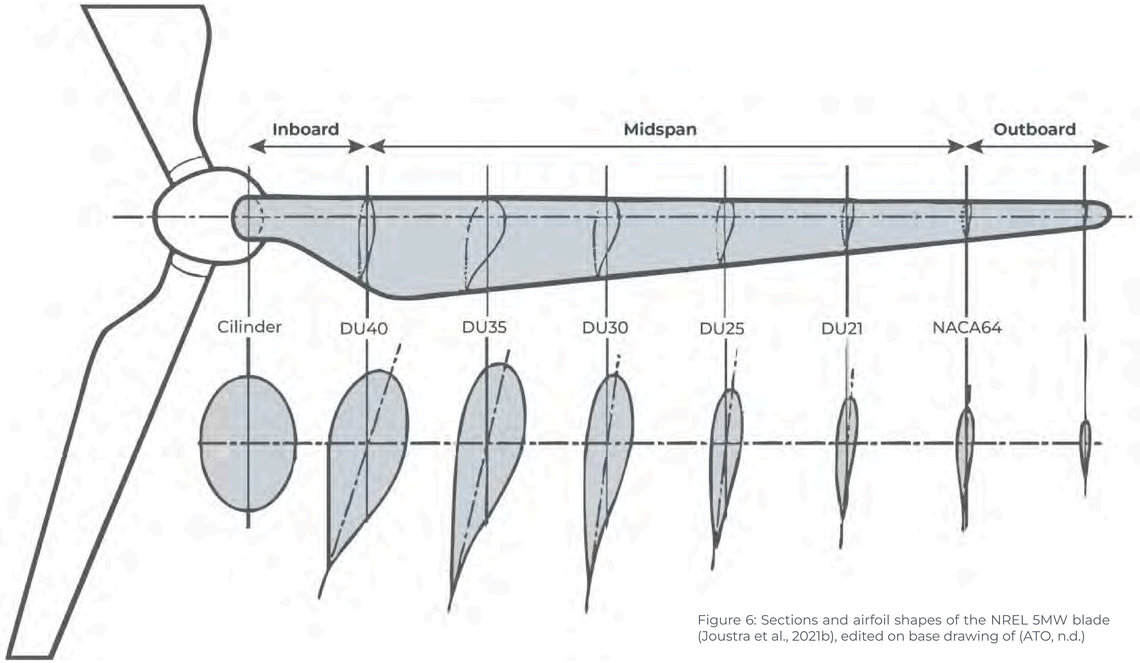


Figure 6: Sections and airfoil shapes of the NREL 5MW blade (Joustra et al., 2021b), edited on base drawing of (ATO, n.d.)

2.1.3 Growth in numbers and wind parks

Apart from their size, the number of turbines has been growing rapidly. In The Netherlands, the offshore wind sector has grown significantly in recent years. At the end of 2023, approximately 4.7 gigawatts (GW) of offshore wind capacity was installed, a bit more than the 4.5 GW target (Lankhorst, 2023)(RVO, 2024a). Looking ahead, the Dutch government aims to increase offshore wind capacity to 21 GW by the end of 2032. The planned expansion includes new wind farm zones like IJmuiden Ver and Nederwiek (Noordzeeloket, 2024)(Figure 7).
Besides the growth in the dutch wind energy sector, we can expect that over the next 20 to 25 years, a large number of wind turbines will reach the end of their operational life. Starting with older parks, the Princess Amalia Wind Farm and the Egmond aan Zee Offshore Wind Farm (OWEZ) are scheduled for decommissioning within a few years (Offshore Energy Association AYOP, 2025).

One thing is for sure: soon, a steady return flow of decommissioned blade material will begin, and grow for at least another 100 years.

2.1.4 Return flow of composite materials

As the numbers and size of blades increase, so does the volume of composite waste. According to a report published by WindEurope (Schmid et al., 2020), by 2050, Europe could face around 60,000 tonnes of blade waste each year. A significant portion of this will come from the large offshore installations near the Dutch coast.

However, there is little to no experience worldwide when it comes to decommissioning offshore wind farms (AYOP, 2025). Essentially, decommissioning these wind farms relies on the same principles as installation, but then reversed. However, a detailed action plan requires more research and innovation. Energy transition companies e.g. ECHT and TKI Offshore Energy, are currently busy on this topic. The chapter Logistics (2.5) will give a more in-depth explanation on the steps and possible solutions that are implemented to develop an efficient process.

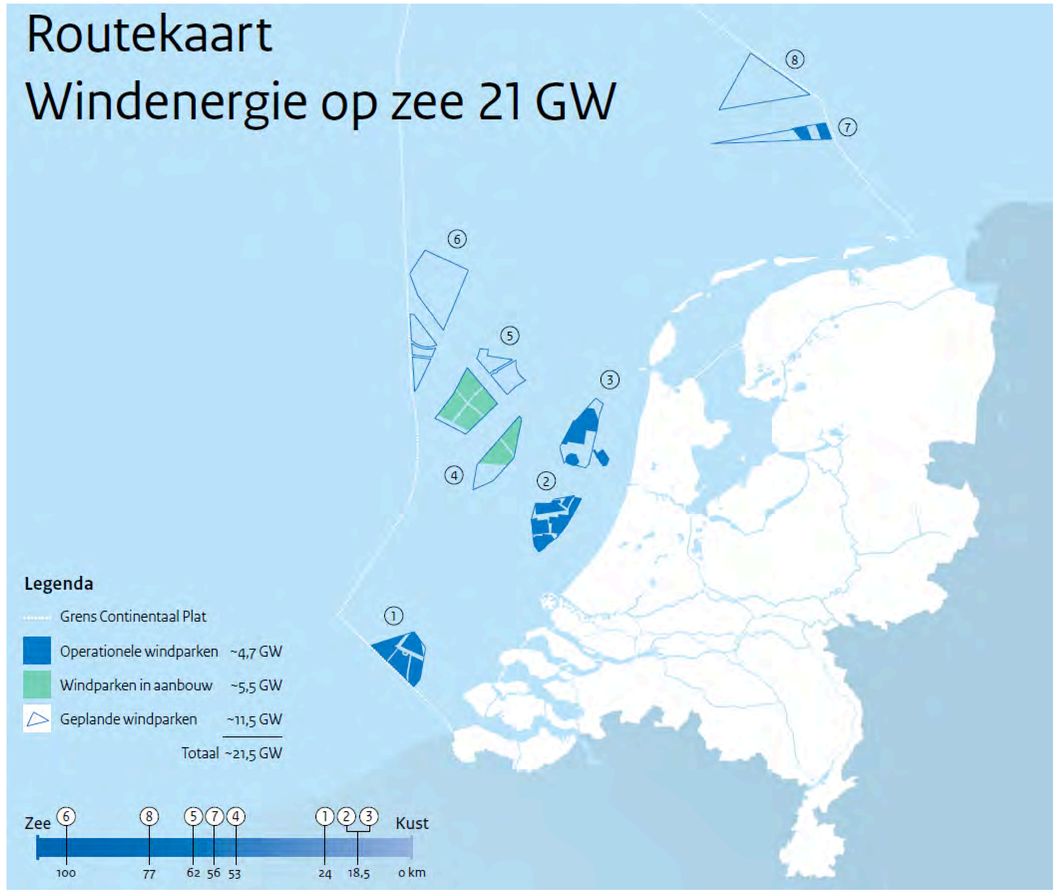


Figure 7: Roadmap of Dutch offshore wind parks (Noordzeeloket, 2025).

2.1.5 Pressure and suction side

A wind turbine blades cross-section is shaped like an airfoil, similar to an airplane wing. The distance between the nose and tail is called the chord of the blade (Figure 8). The pressure side is the surface facing the incoming wind, where the airflow slows and pressure increases. The suction side is the surface on the opposite side, where the airflow accelerates and pressure drops. This pressure difference creates lift, which produces torque to turn the hub ot the turbine. The distribution of curvature, thickness, and twist along the blade is designed so each section works efficiently across different wind speeds (Burton et al., 2001).

2.1.6 First blades that will be decommissioned

As mentioned before, the Egmond aan Zee Offshore Wind Farm (OWEZ) and Prinses Amalia Wind Farm are among the first scheduled for decommissioning, in 2027 and 2028 (Jurrius & Van Hoof, 2024). The types and sizes of these turbines according to RVO (2024b) are:

Vestas V80 2MW - Prinses Amalia (2008).
Vestas V90 3MW - OWEZ (2007).

Both have blades of around 40 to 45 meters and a max chord length of about 3.5 to 3.9 meters (GlobalSpec, n.d.). Chord length is the distance from LE to TE (Figure X). Although these blades are shorter, the NREL 5MW has in 30m midspan an average chord length of 3.5m (Jonkman & Musial, 2010), which makes their chord lengths very comparable.

It can be concluded that with the use of a NREL 5MW blade model, a suitable solution for soon to be decommissioned blades can be realized. This conclusion will be important in the later stages of the design process.

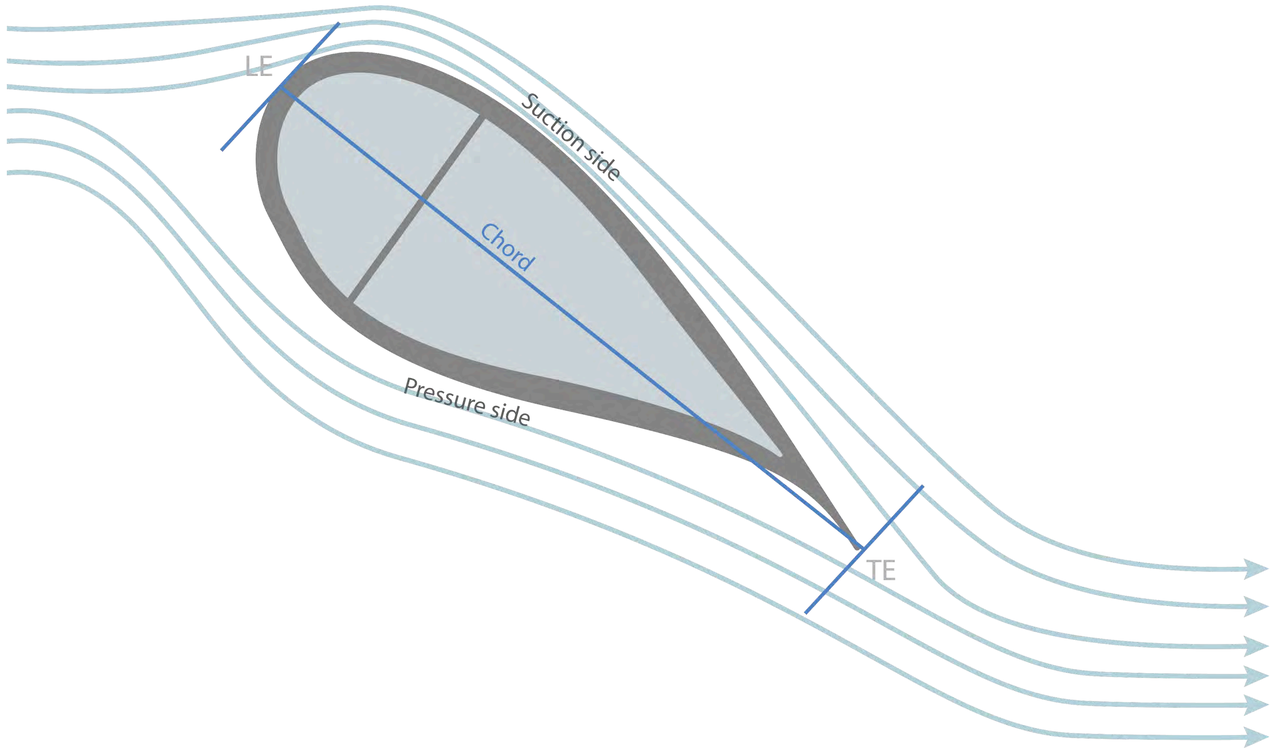


Figure 8: Suction and pressure side of a blade's cross-section.

2.1.7 Retrieving data of different WTB shapes

It is difficult to collect reliable blade data, because commercial blade manufacturers do not share as much information about their secret blade formula. This is nothing out of the ordinary, but quite inconvenient for research and development of subsequent reuse project that involve blades.
E.g. to know the exact blade dimensions and obtain 3D models. BladeMade, a company focused on upcycling discarded WTBs into various products like urban furniture, playgrounds, and other architectural elements, expressed their struggles with obtaining blade data as well (De Laive, PC, 2025).

Currently, for some applications, blades are being measured manually, at intervals of 10 cm along the curve and 1 meter along the length of the blade. These highpoint dots create a map that a computer can turn into a surface model (De Bruijcker, PC, may 2025).

Alternatively, more recent scanning technology allowed researchers at the TU to create a 3D scan of a blade or segment. A side note here is that because the surface is very smooth and large, tape or markings should be added to prevent the scanner from getting confused (Joustra, PC, may 2025).

We can conclude that an extensive database with blade types, brands, measurements, 3D models and structural performance data is highly desirable, if not needed to be able to make designing for subsequent reuse scalable. How exactly this should be realized is out of the scope of this project.

2.1.8 Methods to find applications and shapes

Carrete et al. (2023) developed the Circular Applications Through Selection Strategies (CATSS) methodology, which supports identifying suitable applications for materials by understanding them at multiple levels. One of the tools within this approach is the creation of a “piece map”, a visual diagram similar to a butcher’s cow poster, that illustrates which parts of a wind turbine blade are usable for which types of applications. This helps guide segmentation and reuse by aligning specific blade sections with their most promising second-life functions.

Gabriëls (2025) has initiated the development of a parametric segmentation model at Heijmans to efficiently cut a large blade into manageable panels. Its goal is to find patterns that limit cutting losses and reduce material waste. It is also important that such a model is able to adapt to different sizes and shapes of WTBs that become available.

Both these strategies to select the best suitable parts of the blade can be used to determinate exactly which part of the midspan can be cut into noise barrier segment best.

2.2
The material composition of WTBs

2.2.1 What are wind turbine blades made of?
2.2.2 Leading Edge Erosion (LEE)

2.1 The evolution of blades & turbines
Growth, shape & return of material

2.2 The material composition of WTBs
Overview of material

2.3 The mechanical properties of WTBs
Why it is a suitable building material

2.4 Recycling WTB material
Methods, initiatives & challenges

2.5 Logistics
From wind turbine to blade segments

2.2
The material composition of WTBs

Wind turbine blades (WTBs) are structures designed to withstand significant aerodynamic and structural loads over their long service lives. The material composition of the blade plays an important role in optimizing its performance while balancing weight, cost, and durability (Cooperman et al., 2021). In the context of circularity and reuse in applications such as noise barriers, it is essential to understand what these blades are made of, how they behave mechanically, and how they can be recycled keeping high value.

2.2.1 What are wind turbine blades made of?

The material composition of wind turbine blades is highly specialized and varies along all directions. Typically, modern WTBs are composed of glass fiber-reinforced polymer (GFRP) composites, optimized for stiffness, strength, and low density. These materials are layered and combined in a sandwich structure with a layer of balsa wood or foam in between (A). Different regions of the blade have different structural functions (figure 9).

The root of the blade is a solid GFRP cylinder, designed for secure mounting to the hub. The materials used in the blade taper towards the tip, getting thinner to reduce weight while maintaining strength. The cross-section on the next page explains the other structural components in the blade.

(a)

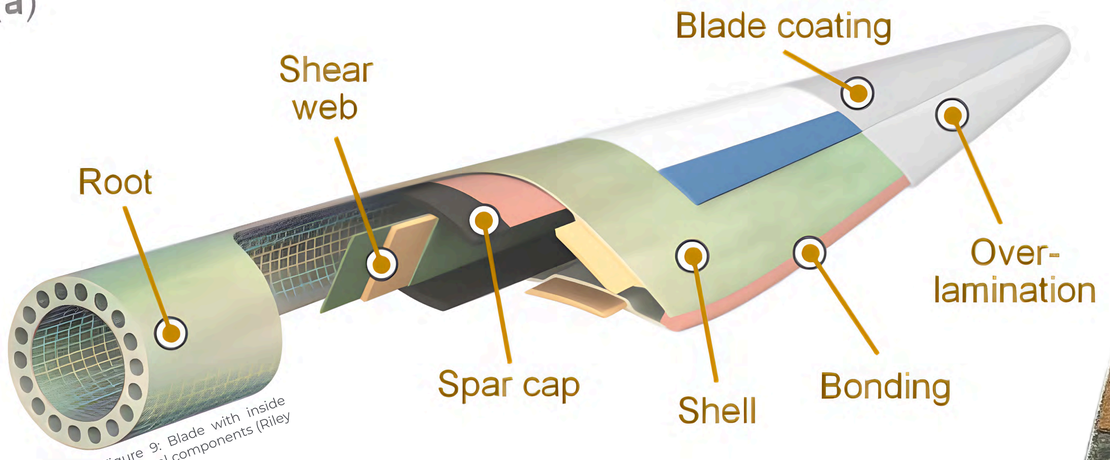
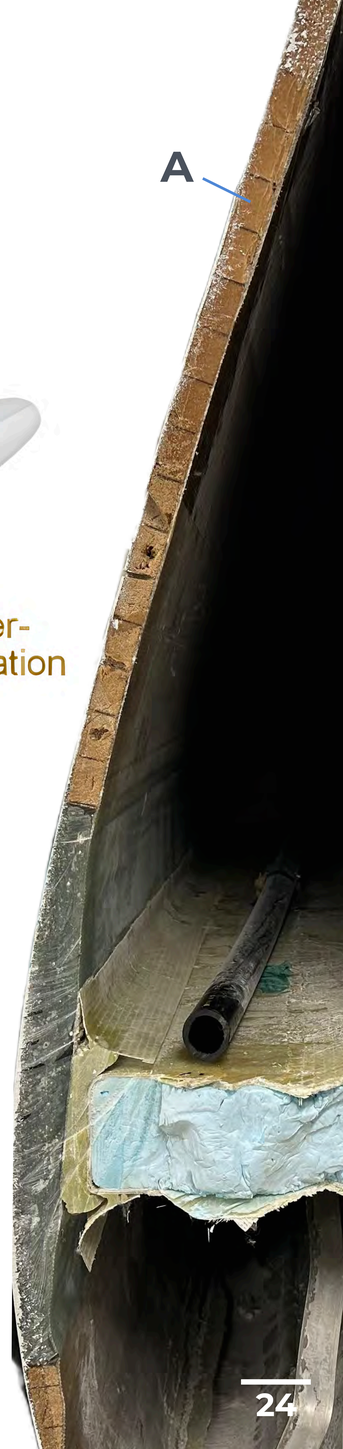


Figure 9: Blade with inside structural components (Riley et al., 2025).

A



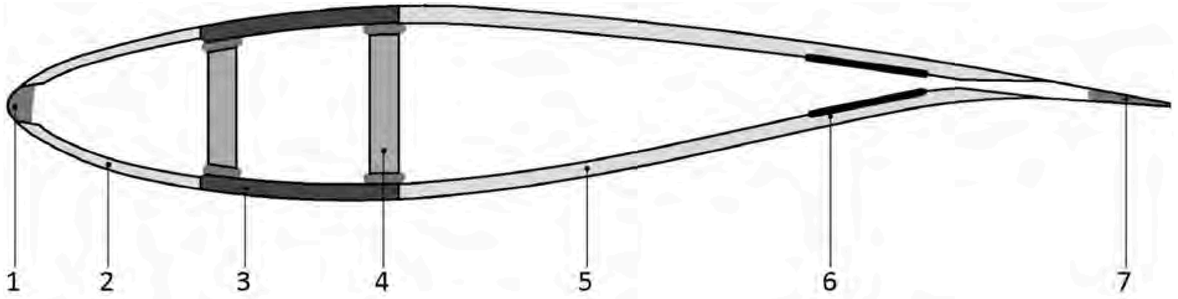


Figure 10: Picture and points (Joustra et al., 2021b)

1&2. Leading Edge (LE)
The front edge of the blade that cuts through the wind, is often made of glass fiber-reinforced polymer (GFRP) sandwich structure. The absolute tip and tail of the droplet shape are where the two halves are glued together with structural adhesive (1&7).

3. Spar caps
These form the structural backbone of the blade together with the shear webs and are from thick, prepreg GFRP, or sometimes carbon fiber-reinforced polymer (CFRP).

4. Shear webs
Connecting the upper and lower blade shells, and are typically GFRP-foam sandwich panels. They provide the structural rigidity with the spar caps from root to tip.

5&6. Trailing Edge (TE)
The rear part of the blade, also from GFRP-balsa wood sandwich structures. These regions are wider and straighter, making them potentially useful for cutting large panels.

Shells and coatings
The outer shell includes protective coatings for UV resistance and moisture protection, in addition to structural laminates.

2.2.2 Leading Edge Erosion (LEE)

As previously described, the leading edge of the blade cuts through the wind as it rotates. Over its lifetime, high-speed impacts with rain and hail gradually erode the blade's outer shell. This erosion reduces its aerodynamic efficiency and in turn the annual energy production (Duvelle, 2021). The issue is more significant offshore, where larger blades endure higher wind speeds. Because there is an increasing number of wind turbines built offshore, the industry identifies LEE as a serious concern.

For the barrier design, some assumptions were made regarding LEE:

- Apply a quick fix with a new coating if only surface is damaged (Figure 11).
- Discard the blade if cracks or holes expose the balsa core, as this goes beyond repair.
- Take no action if the design covers the leading edge from direct exposure, for example by orienting it downward or other components shielding it.

Figure 11: LEE on a blade (Duvelle, 2021).

2.3
The mechanical properties of WTBs

2.1 The evolution of blades & turbines
Growth, shape & return of material

2.2 The material composition of WTBs
Overview of material

2.3 The mechanical properties of WTBs
Why it is a suitable building material

2.4 Recycling WTB material
Methods, initiatives & challenges

2.5 Logistics
From wind turbine to blade segments

2.3

The mechanical properties of WTBs

Wind turbine blades are engineered to be lightweight, extremely strong, and capable of withstanding decades of loads in harsh environmental conditions. Although they appear thin and flexible, and might bend in strong winds, they are designed with composite materials that ensure minimal degradation over a 20-25 year lifespan and are driven by mechanical performance:

- **High stiffness-to-weight ratio**
  This enables blades to resist bending and buckling under wind loads, particularly important in the spar caps and leading edge.

- **Low density**
  Composite sandwich structures (GFRP with balsa or foam) help reduce overall blade weight, which improves efficiency, lowers material use and transport costs.

- **Fatigue resistance**
  Blades must endure hundreds of millions of loading cycles throughout their lifespan. FRP composites offer excellent fatigue performance.

Fibers adding strength
Fiber reinforced polymer offer a high strength-to-weight ratio. The mechanical behavior of these composites is determined by the fiber type (typically glass or carbon), the resin (usually thermoset epoxy), and the fiber orientation. Variations such as uni-directional (UD), bi-directional (BD), and triaxial (Triax) lay-ups allow tailoring of stiffness and strength to local load conditions in the blade (Joustra et al., 2021b). UD fibers provide high tensile stiffness and are used along the blade's length to withstand bending. BD and Triax lay-ups distribute strength in multiple directions, making them suitable for areas experiencing complex load patterns like the root or trailing edge.

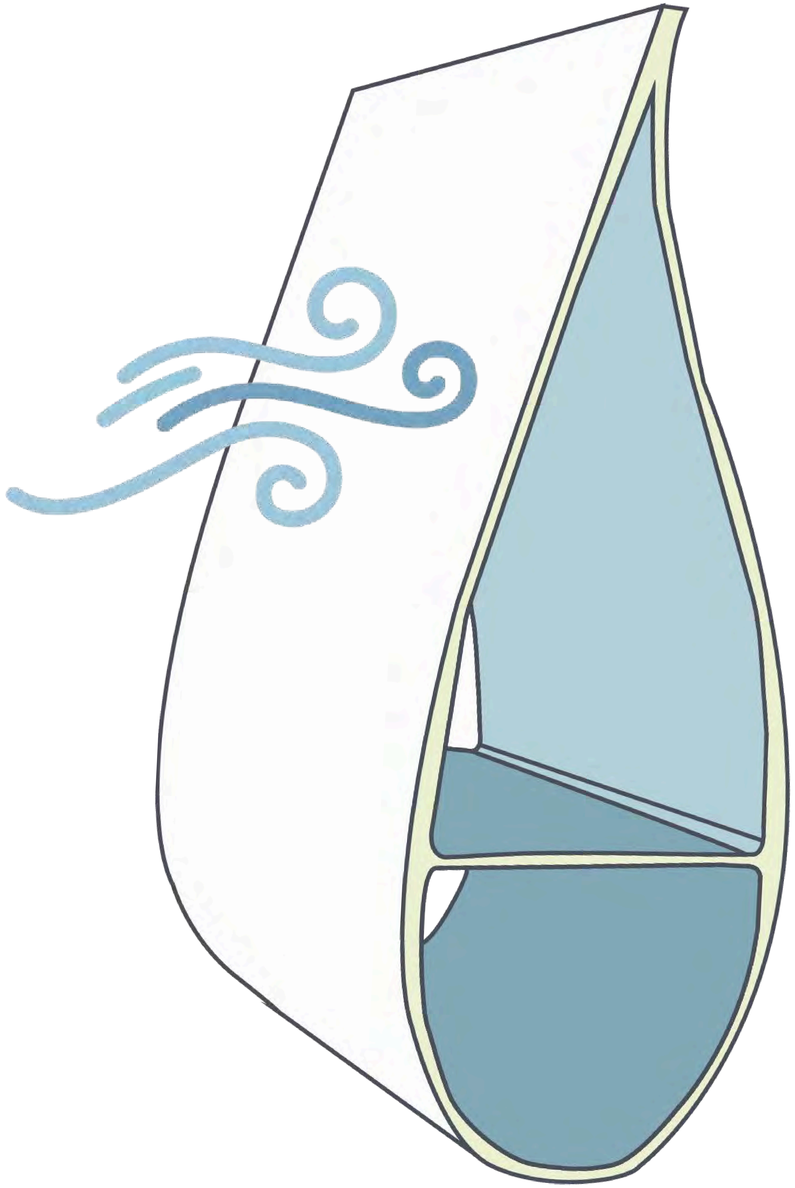
Low density
In sandwich structures, low-density core materials such as end-grain balsa (approx. 150 kg/m^3) or various structural foams (e.g. PVC, PET) are used to resist local buckling and add stiffness without excessive weight (Stoll, 2014). Balsa is especially relevant for reuse in noise barriers due to its higher density, which can enhance acoustic performance. A disadvantage is its sensitivity to moisture which may reduce long-term durability compared to foams.

Residual properties of used blade material
Used wind turbine blades, even after 20+ years of service, often retain their structural integrity. Studies found minimal degradation in stiffness or strength in spar caps from decommissioned blades (Alshannaq et al., 2022). No signs of fiber separation or crack growth in the spar caps were detected, indicating good fatigue resistance and the potential for reuse.

Fatigue
Noise barriers are expected to withstand around 100 million cycles of wind load over a 50 year lifespan (Gabriëls, 2025), which is a lot less than the cycles experienced by WTBs over 20-25 years, which are up to 1 Billion (Ziegler et al., 2017). Given the durability of FRPs observed in retired blades, fatigue performance in a second-life application like a noise barrier is expected to be more than sufficient.

The strength of segments
The study of Joustra et al. (2021b) introduces a segmentation approach that assesses the blade's shape and structure, to identify suitable segments for reuse. This method helps find parts that keep sufficient structural strength after the blade is cut into segments.
Joustra's research provides evidence that segmenting wind turbine blades is a viable strategy for structural reuse and highlights that blade segments, particularly those with favorable geometries and material properties, can be repurposed without much loss of strength.

Deflection
Gabriëls (2025) and Broniewicz et al. (2024) conducted multiple digital model analysis on verification of load-bearing capacities and deflection. Both concluded that larger panels of sandwich and solid GFRP are strong enough to withstand the respected loads. When considering to keep the segments of blades intact, their structural composition will definitely pass the test.



2.4
Recycling WTB material

2.4.1 Current recovery
2.4.2 Emerging methods
2.4.3 Blade reuse initiatives

2.1 The evolution of blades & turbines
Growth, shape & return of material

2.2 The material composition of WTBs
Overview of material

2.3 The mechanical properties of WTBs
Why it is a suitable building material

2.4 Recycling WTB material
Methods, initiatives & challenges

2.5 Logistics
From wind turbine to blade segments

2.4

Recycling WTB material

Before covering current and emerging recycling methods of WTB material, lets look into the material life journey to get an idea of the possibilities of recovery between blade and waste.

Material life journey
For any large scale product or material that is approaching the end of its service life, it is desirable to look into the most valuable way of repurpousing the material. As for WTBs, it should be of great interest to retain its value as long as possible, since the material still has potential for large scale reuse applications. The material can pass through multiple lifecycles before its value is considered nothing more than waste, and ends up at the bottom of the waste hierarchy pyramid (Figure 12)(Joustra, 2025)(Nagle et al., 2020).

- **Prevention**, designing changes to lengthen the service life of WTBs.
- **Life extension**, taking care of the blade by cleaning and repairing it.
- **Repurpose**, decommissioned blades are repurposed in their entirety, e.g., in architectural or infrastructure projects.
- **Structural reuse**, whole components or large sections are given new functions, such as noise barriers, bridges, or shelters.
- **Recycling**, at material-level, like mechanical shredding or pyrolysis to reclaim fibers and use in other applications.
- **Recovery**, using the material as fuel and burning it for energy.
- **Disposal**, landfilling or burning without recovery.

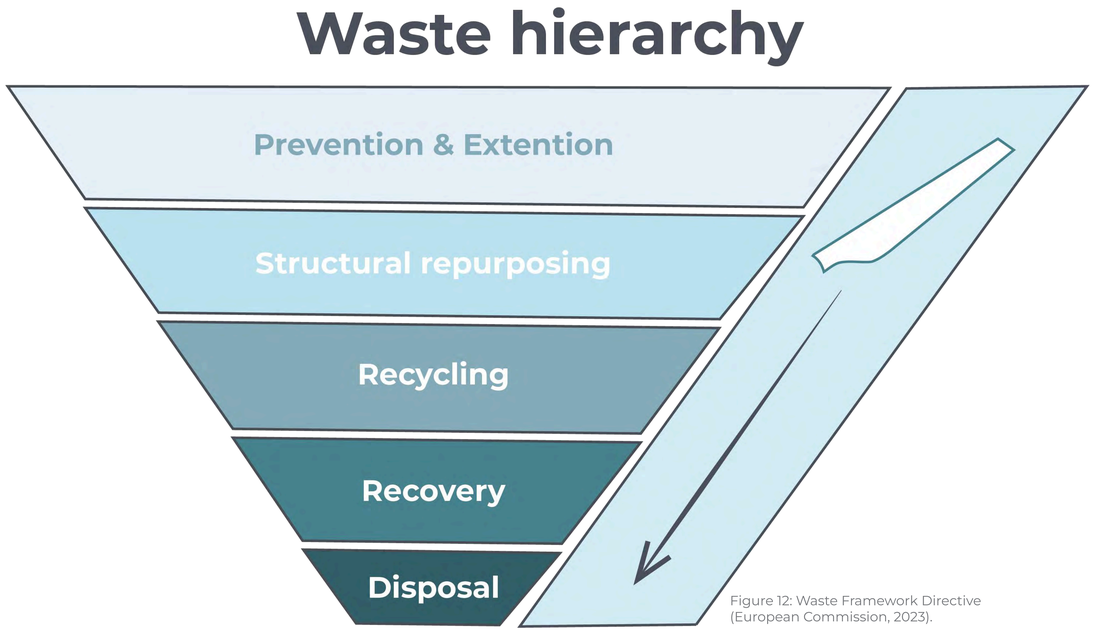


Figure 12: Waste Framework Directive (European Commission, 2023).

2.4.1 Current recovery

Recycling wind turbine blade material is known to be difficult due to the thermoset nature of the polymers used. Unlike thermoplastics, thermoset composites cannot be melted and reshaped, as they are chemically cross-linked during curing (Chen et al., 2019), (Joustra, 2025). When looking at traditional methods for handling decommissioned WTBs, they are limited, far from ideal and increasingly problematic.

Landfilling is still the most widely used method globally, in the US for example (Figure 13). In Europe however, the Landfill Directive has introduced strict operational requirements for landfill sites. Their objective is to protect both human health and the environment. Additionally, in supporting the EU's transition to a circular economy, the Landfill Directive introduced restrictions on landfilling of all waste that is suitable for recycling, used as other material or for energy recovery from 2030 (European Commission, 2025).

Incineration can be done to recover some energy from resins and fibers, but emits toxic fumes and does not recover any materials.

Mechanical recycling Involves shredding blades into granulate or fibers, which are then used as filler in materials like concrete or thermoset composites (Van Osch, PC, 2025). While mechanical processes are better than disposal or incineration because they prevent combustion, thereby significantly lowering emissions (Royer, 2025), the irreversible process of shredding significantly downgrades the material's structural potential.

Figure 13: Landfill of blades in Wyoming, by: Benjamin Rasmussen (2020).

2.4.2 Emerging methods

Continuing up the ladder of retaining the value of WTB material are some emerging recycling methods aiming to improve circularity, e.g. chemically or mechanically separating the material, or reshaping it.

Pyrolysis involves heating composite materials in the absence of oxygen to decompose the resin matrix, recovering the fibers. The RE_SORT project by Fraunhofer WKI is developing pyrolysis technologies, such as quasi-continuous batch and microwave pyrolysis with radiation, to make recycling of thick-walled composite structures a more economically viable process (Fraunhofer, 2023). However, challenges remain, such as degradation of fiber quality at high temperatures and the energy-intensive nature of the process (Rathore & Panwar, 2022).

Chemical recycling, such as **solvolysis**, uses solvents to break down the resin matrix, enabling the recovery of both fibers and resin monomers (Sobek et al., 2024). The ZEBRA project from LM Wind Power and Arkema has demonstrated the feasibility of recycling wind turbine blades made from the thermoplastic resin Elium®, achieving a complete recycling cycle (ZEBRA consortium, 2024).

Reusing shreds

As mentioned before, blade material can be mechanically separated and the shredded fibers reused. A few examples of emerging technologies that use shreds are:

- The integration of recycled short fibers into 3D printing filaments (De Bruijcker, 2025)(Polyproducts).
- Cold-pressing the fibers into 100% circular building material, in the shape of planks and beams (KoiosTitan, 2025)(Figure 14).
- Shredding discarded composite products to manufacture insulating noise barriers (Miljøskærm, 2025)(Figure 15).

These emerging recycling methods are the foundation of more sustainable wind energy products, and address the challenges of the end-of-life management of turbine blades.

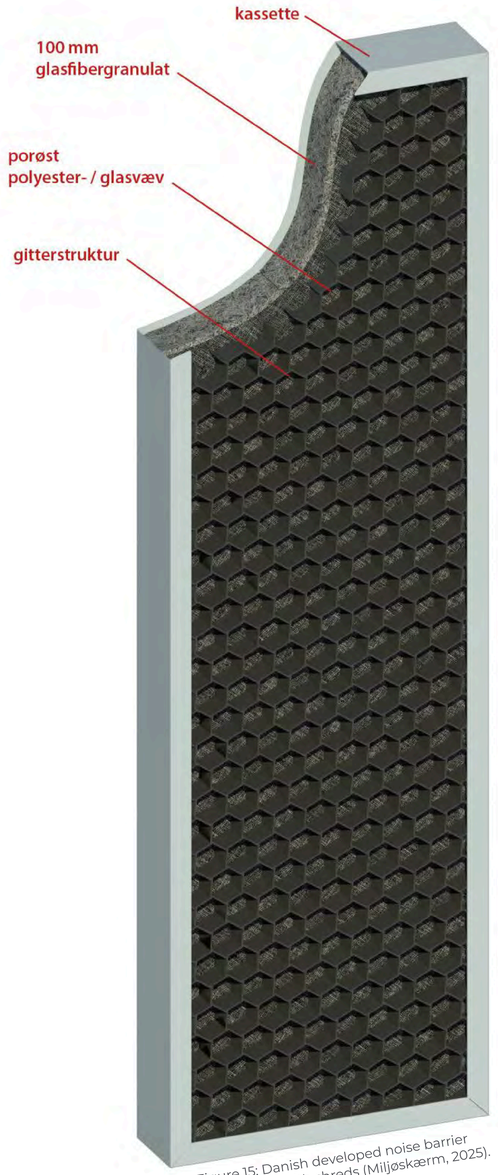


Figure 15: Danish developed noise barrier screen filled with shreds (Miljøskærm, 2025).

Figure 14: Picture taken of compressiet plank material (KoiosTitan).

2.4.3 Blade reuse initiatives

Further up the ladder, some recent developments have been focusing on the structural reuse of blades or blade segments.

Blade-Made has built a noise barrier of full blades, along the dutch innovation strip along the A58 Oirschot (Figure 16). Their unique selling points are: full blades for optimal material use and minimal processing, less steel for foundation needed.

Figure 16: BladeMade barrier from full blades (Rijkswaterstaat et al., 2025)

Poly Products has built a pedestrian bridge as well, with a blade segment as structural beam component (Figure 17). The additional highlight from this design is the composite filament used for the deck and rails, that is tailored on the curvature of the blade. This 3D printed structure shows promise in the reuse of WTB shreds as well.

Re-wind USA and **GeorgiaTech** have built a pedestrian walking bridge in the forest with the use of a large 15m segment (Figure 18). Their calculations confirmed that the blade had the structural load capacity (Ackall et al., 2025).

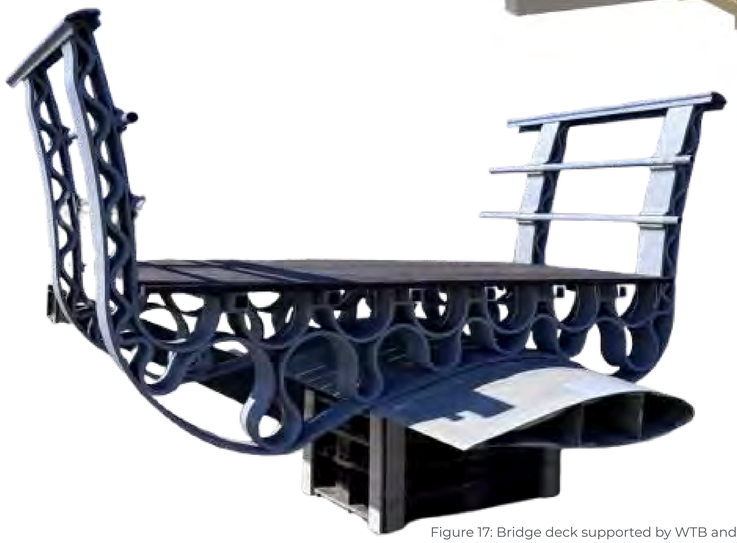


Figure 17: Bridge deck supported by WTB and printed with composited (Poly Products, 2025).

Figure 18: Bridge deck with long segment as structural component (Ackall et al., 2025).

Challenges
Repurposing wind turbine blades will become a growing global issue that demands local solutions, as the volume of decommissioned blades increases across different regions (Joustra, 2025).

- **Distributed stock:** Blades are decommissioned at wind farms often located in remote or offshore areas, making collection and transport to central processing locations costly and logistically complex.

- **Economic viability:** The costs of logistics, disassembly, processing, and adaptation has to compete with the low market price of virgin materials. Without consistent demand for repurposed blade products, economic incentives might remain limited.

- **Long lifespan, slow turnover:** Wind turbines are built to last, which means blade decommissioning does not happen every day. This slow turnover complicates planning for steady supply and investment in infrastructure or business models that rely on blade reuse.

- **Risk of acceptance:** The public and governmental regulations might have difficulties accepting repurposed materials, especially in structural or visible applications like infrastructure or noise barriers. Concerns around safety, aesthetics, or durability need to be addressed through certification and clear communication.

Implications
Deeney et al. (2023) highlighted the challenges to the recommended strategies for processing end-of-life (EOL) wind turbine blades, as outlined in the Material life journey. Most recent research focuses on recycling, which is only the fifth preferred option.

Obstacles for the more valuable methods may include:
- Lack of financial rewards discourages manufacturers from producing more durable or reusable blades.
- Limited access to blade composition and design data makes repurposing and recycling more challenging.
- There is a lack of financial motivation to prioritize the more valuable methods over simple disposal.

To address these challenges, the following solutions are proposed:
- Applying payment structures for ownership that reward blade durability and longevity.
- A centralized data-bank or information sharing system to support second-hand markets, repurposing, and recycling.
- Using compliance bonds to give companies a financial push to handle EOL processing in a sustainable way.

Conclusion and project goals
The goal of this thesis is to translate structural reuse of WTBs into using large segments. Although this approach reduces the value more compared to full-blade reuse, the project aims to offer a more realistic, economically viable, and scalable solution. A more segmented approach allows for large volumes of blade material to be reused effectively in new applications, while still keeping large portions intact, valuable for later lifecycles.

2.5
Logistics: from wind turbine to blade segments

2.5.1 Decommissioning
2.5.2 Processing the blades into segments
2.5.3 Industrial cutting techniques
2.5.4 Cutting for small-scale prototyping
2.5.5 The trade-off between waterjet and circular saw cutting
2.5.6 Visualization of the setup

2.1 The evolution of blades & Turbines
Growth, shape & return of material

2.2 The material composition of WTBs
Overview of material

2.3 The mechanical properties of WTBs
Why it is a suitable building material

2.4 Recycling WTB material
Methods, initiatives & challenges

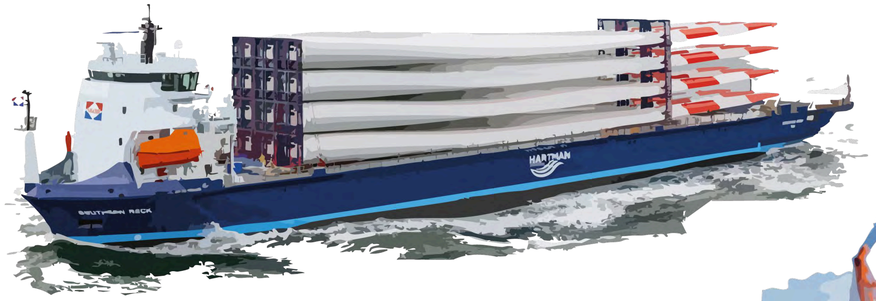
2.5 Logistics
From wind turbine to blade segments

2.5

Logistics: from wind turbine to blade segments

When it is concluded that a wind turbine has reached the end of its service life, the logistics of decommissioning and recovering its materials for reuse must be addressed. As mentioned before, the tower and electrical components of a turbine is made from steel or other metals that can easily be recycled (CAPE Holland, 2023).

As addressed many times by now, recycling the blades proves a lot more difficult. This chapter describes the process timeline from decommissioning the wind turbine, transporting, and processing the blades into segments and panels.



2.5.1 Decommissioning

Depending on whether the wind turbine is offshore or onshore, a detailed plan and quota must be realized. The decommissioning process typically involves multiple stakeholders. Offshore handling and vessels are roughly twice as costly to operate as land-based operations (J. Stokman, PC, 2025). Just like during installation, dismantling an offshore turbine requires a large stabilized vessel or jack-up ship equipped with a crane. These operations involve heavy lifting and precise manoeuvring, which require high safety standards. The turbine axis is locked to prevent any rotation while removing the blades. A rack on the ship's deck is used to temporarily store the blades. Removing blades from a rack is easier than placing them in, which means slow operation to avoid accidental damage is necessary (Seaway7, PC, 2025).

Once the blades are harvested, they are unloaded at a nearby harbor, enabling ships to shuttle back and forth to the decommissioning site. Ideally, the blades are processed right after unloading them on the docs to minimize additional transport and handling.

Cutting blades while still onboard is generally avoided. It is too complex, poses stability challenges, and risks polluting the ocean with glass fiber dust. Onshore decommissioning follows a similar plan: blades should be processed as quickly as possible. Since blades are high in volume but relatively light in weight, transporting them in smaller sections improves logistics, reduces costs, and simplifies compact storage later in the process.

Promising location for processing

As covered previously in chapter 2.1.3, the Dutch wind farms Egmond aan Zee and Prinses Amalia are approaching their retirement. The Offshore Energy Association AYOP (2025) has pointed out the Noordzeekanaalgebied, including the Port of Amsterdam, to be the perfect location for processing decommissioned wind turbine components from both offshore and onshore parks. Although the province of Zuid-Holland might appoint the Port of Rotterdam as most suitable, for the sake of this example and the locations of the Egmond and Amalia farms being closer to IJmuiden, AYOP will be set as processing base.

There are several strong reasons for this:

- Strategic Location & Logistics: The region is easily accessible by sea through IJmuiden, making it suitable for large-scale transport. Transporting dismantled turbine components over water is more efficient, less disruptive, and cheaper than over land, especially for massive blades and towers.

- Existing Infrastructure: The Port of Amsterdam is a bulk port with space for handling large projects. Companies like TMA Logistics have already demonstrated their capability by handling logistics for Windplanblauw and the decommissioning of Vattenfall’s Eemmeerdijk park.

- Experienced Network: The AYOP network (Amsterdam IJmuiden Offshore Ports) provides a strong local ecosystem of experienced companies specializing in dismantling, recycling, and logistics. This makes the region well prepared to process EOL turbines sustainably and efficiently.

- Onshore and Nearshore Capacity: Apart from offshore, the region also has the facilities to manage material from onshore and nearshore wind parks, further increasing its promise as a decommissioning hub.

2.5.2 Processing the blades into segments

Once the blades have been offloaded at the harbor, the next step is to process them into manageable segments. This chapter outlines the challenges involved in cutting the blades and highlights the necessary safety measures. Based on research and expert consultation, the three most viable cutting techniques for large-scale blade processing are compared, and an outline for a scalable processing strategy is presented.

Cutting challenges

Wind turbine blade material (GFRP) is an extremely tough material. Cutting into it results in rapid tool wear and dulling, increasing operational costs and tool maintenance. Industrial grade tooling is necessary to have large scale processing locations. Next to that, the cutting process produces fine glass dust and potentially toxic fumes, especially when friction causes the resin to heat up. These byproducts can cause serious health issues, such as respiratory issues and skin irritation (Pupping, 2025).

Required safety measures

To ensure safe processing of the materials, several precautions must be taken:

- Dust Extraction: Cutting should be done in a closed, ventilated space with vacuum systems attached directly to tools. These systems should be equipped with Type 2 HEPA filters to capture fine particles.
- Personal Protective Equipment (PPE): Workers must wear full-body protective suits, including goggles, gloves and respiratory masks fitted with FP3 filters to prevent inhaling micro-glass particles (Figure 19). Extra hearing protection in a small space is desirable.
- Fume Control: When cutting large or dense blade sections (such as spar caps), friction can release toxic fumes from the resin. In such cases, additional gas filters must be used in respiratory equipment (Pupping, 2025)

Figure 19: PPE for cutting segment with jigsaw (Neuman, 2024)

2.5.3 Industrial cutting techniques

Processing wind turbine blades at large-scale requires the use of industrial-grade cutting tools that can handle the tough, layered structure of GFRP composites. Each method presents trade-offs in terms of cost, safety, speed, and feasibility. The three most viable techniques currently used in the industry are outlined below, based on expert interviews and research.

A. Diamond-tipped wire saw

This method is widely used for making full cross-sectional cuts (Figure 20).

- Advantages:
  - Delivers clean, straight cuts.
  - Water-cooled operation helps minimize dust and prevents overheating.

- Disadvantages:
  - Still generates fine dust.
  - The wire wears quickly and is expensive to replace.
    - costs are often charged per meter of usage.
  - Requires constant tensioning and a stable setup.
  - During cutting, the wire can begin to oscillate or "wiggle," reducing cut accuracy (BladeMade, PC, 2025).

B. Large circular saw (diamond-edged)

Typically mounted on heavy machinery such as excavators (Figure 21), this method is used for in the field cutting of large components.

- Advantages:
  - Offers more flexibility for cutting irregular shapes.
  - With the correct setup, precision cutting is achievable.

- Disadvantages:
  - High dust output and significant tool wear due to the abrasive nature of the GFRP material.
  - Requires diamond or ceramic blades without teeth to avoid damaging the material via chipping or delamination (separation of fiber layers).

Figure 20: Diamond wire saw (Huada Superabrasive Tool Technology Co., Ltd., 2023)

Figure 21: cutting wind turbines with circular saw (Gallery - Echidna Rock Saws - Fiberglass, n.d.)

C. Water jet cutting
A high-pressure stream of water is used to cut without mechanical contact (Figure 22). This method is best suited for dense areas such as spar caps, where other tools may struggle.

- Advantages:
  - No tool degradation, as there's no mechanical abrasion.
  - Dust is contained in the water and can be filtered, improving worker safety.
  - Produces highly precise and clean cuts.

- Disadvantages:
  - Slow and inefficient for cutting large, curved blade surfaces.
  - The focus of the jet worsens the thicker or more irregular the material composition is.
  - Advanced multi-axial machines capable of handling complex blade geometries are not yet readily available, making operations largely manual and time-consuming (Joustra, PC, 2025).
  - Risk of internal water ingress in sandwich structures.
  - High water consumption requires proper filtration and management systems.

2.5.4 Cutting for small-scale prototyping
For educational or prototyping purposes, simpler tools can be used:
- Manual or handheld tools: handsaws, tile cutters, jigsaws, or angle grinders (Carrete, PC, 2025).
- Small-scale water jet systems can also be used.

However, these methods require the person to be close to the material, making the earlier discussed protective equipment essential.

With large-scale cutting, the factor of health hazards is relatively small because the operator is working with large (automated) machines that increase the distance to the material enough to worry less about the dust and fumes. It has to be noted that safety precautions are still advised at all times.

Figure 22: Waterjet cutting TNO (2022).

Challenges
At the IDE Faculty (TU Delft), large-scale cutting is currently not feasible due to a lack of appropriate equipment and a ventilated workspace. InHolland University of Applied Sciences operates a small composites lab nearby in Delft, where limited-scale prototyping is possible. Expanding these operations to accommodate full blade segments would require detailed logistical planning, if the team at Heijmans is ready.

Each cutting method presents pros & cons of precision, speed, safety, and operational cost. Due to the variation in blade structure, ranging from hollow airfoil shapes to dense spar caps, a combination of techniques may be required for efficient processing. The next chapter will cover the preferred cutting-method when it comes down to large scale segmentation.

2.5.5 The trade-off between waterjet and circular saw cutting

When it comes to segmenting the wind turbine blades, different facilities make different choices depending on their available equipment, project scale, and desired outcomes. For instance, the circular demolition company Vlasman does not recommend waterjet cutting for this purpose. As noted during the interview:

“We’d use a lot of water, and that has to go somewhere. If we collect it in a reservoir, it ends up contaminated with glass fibers. I’d rather use that water for concrete.”

In contrast, Van Nobelen Delft does use a large flatbed CNC waterjet cutter. Their facility is set up to filter runoff water, capturing glass fibers together with abrasive residues from cutting. In that setting, waterjet cutting becomes a workable solution.

This difference highlights a broader trade-off. On one hand, waterjet cutting offers the ability to produce relatively clean cuts, saves tool degradation and better dust collection. On the other hand, it comes with challenges: high water consumption, contamination risks, difficulties in precisely following curved contours, and inconsistent cut quality.
Sawing, in contrast, can be logistically simpler, the technology is currently ready and has a much lower environmental impact (Royer, 2025). However, it may be more limited to cut complex geometries, makes tools dull and creates more dust.

Ultimately, the choice depends on several factors:

- Geometry of the blade sections available for cutting
- Machines on hand for both processing and logistics
- Duration of the project and whether investment in new setups (such as a custom waterjet bed) is justified
- Future scale of operations, whether one-off projects or recurring, large-volume processing is expected

While waterjet technology holds promise and could become a viable solution in the future, it is not yet optimized for large-scale processing of wind turbine blades. The environmental drawbacks, technical limitations, and logistical complexity currently outweigh its benefits. For now, circular saw setups provide the most reliable and streamlined processing line, making them the preferred choice for handling large blade volumes.

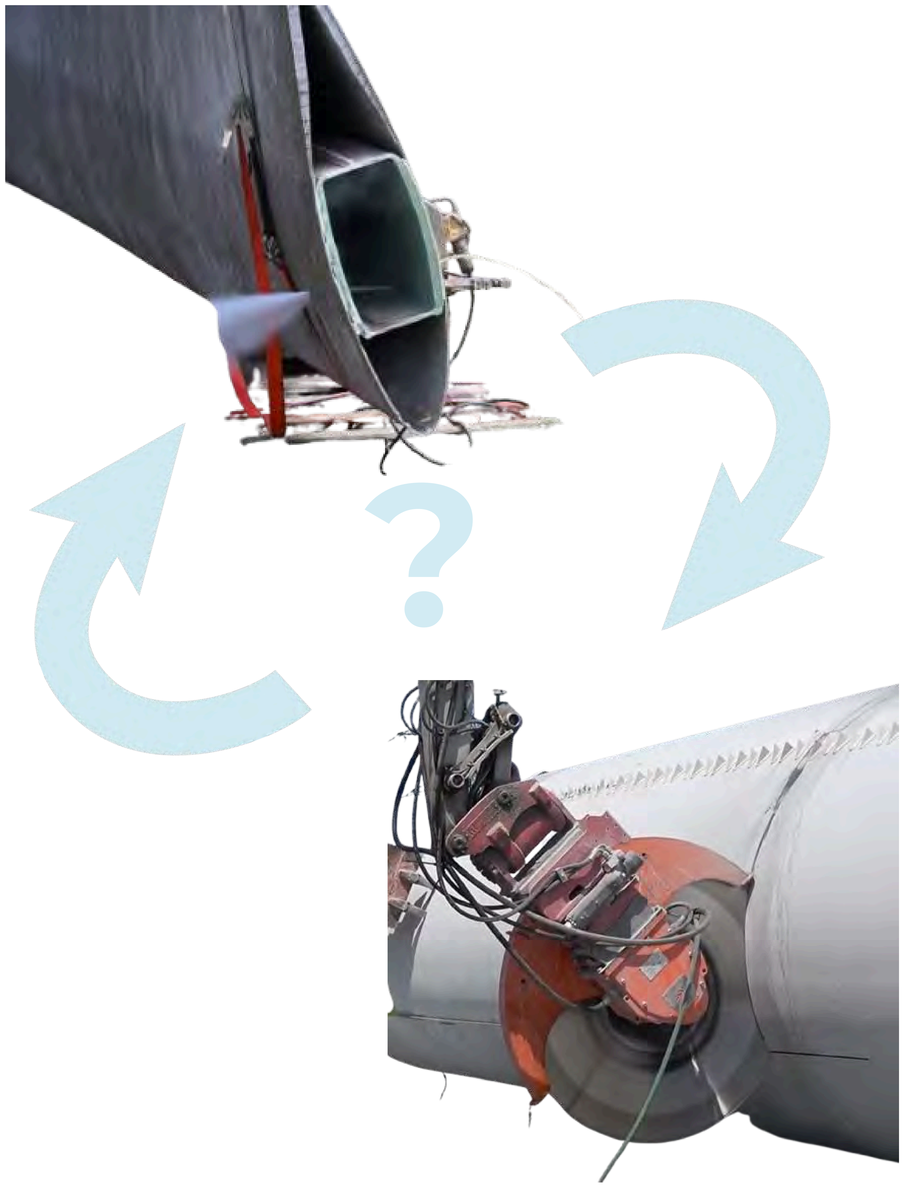


Figure 23: Trade-off between waterjet cutting and sawing (Echidna Rock Saws & TNO, 2022).

2.5.6 Visualization of the setup

After consulting some more with Vlasman, a segmentation strategy has been proposed to streamline the processing of large volumes of the same wind turbine blades. The goal is to automate and scale the cutting process by establishing a compact "cutting factory" near the blade collection point, which for now will be inside a port in AYOP territory. Setting up the cutting factory in the port minimizes transport and allows for immediate processing into manageable segments, which can be transported further.

The process setup would include a long flat frame where each blade can be positioned securely with the leading edge aligned for straight 90° angled cuts. A large diamond-ceramic miter saw, similar to an oversized chop saw (Figure 24), would slice the blade into segments along its length. The saw should be able to adjust the cuts according to any required segment length. These segments are then removed using a forklift and placed on pallets or loaded directly onto trucks for further transport. A crane system would reload a new blade into the jig to keep the process continuous and efficient.
Although the saw is watercooled which helps to reduce flying dust, for extra environmental safety and dust control, a retractable tent structure could be used to cover the cutting area, reducing exposure to airborne fibers and protecting workers (J. Stokman, PC, May 9, 2025).

Once blades are segmented, post-processing steps are required. This includes sanding the edges to remove sharp glass fibers and applying a protective coating or paint to prevent moisture infiltration, especially in blades with foam or balsa cores (Joustra et al., 2021a).

Figure 24: Impression of cutting station - made partially using AI.

Chapter 2

Takeaways

- Wind turbines have been growing in size rapidly over the past decades.
- The NREL 5MW blade is used as standard reference model
- The dutch government is aiming to increase the offshore capacity rapidly.
- The Princess Amalia and the Egmond aan Zee Offshore Wind Farm (OWEZ) are scheduled for decommissioning within a few years.
  - These Vestas V80 and V90 turbines are smaller than the reference blade but are still applicable to later design choices.
- A steady return-flow of blade material is evident.
- So far it has been difficult realizing a public dataset with blade dimensions, 3D models and structural performance.
  - Part of incentives to create higher reuse numbers.

Structural properties

- Blades are mainly made from glass fiber-reinforced polymer (GFRP), with foam or balsa cores.
- GFRP retains structural strength even after 20–25 years, and research proves WTB material to be suitable for structural reuse (Joustra et al., 2021b)(Broniewicz et al., 2024).
- The cross-sectional profile of the blade tapers towards the tip, the trailing edge region has potential for large panel extraction, the spar caps and shear webs are more suitable for structural components.
- Leading Edge Erosion (LEE) needs to be inspected, and actions to decide if the blade is still reusable will follow.

Recycling

- Material value hierarchy: prevent > extend life > recover product > reuse > recycle > recover energy > dispose.
- Recycling WTBs is difficult due to thermoset polymers.
  - Landfilling and incineration are undesirable and restricted in the EU.
  - Mechanical recycling downgrades material quality.
- Emerging methods include:
  - Pyrolysis (recovers fibers but is energy-intensive).
  - Solvolysis (breaks resin chemically).
  - Reusing shredded material to make new products.
- Multiple recent projects show promise in using large blade segments in structural reuse implication.
- Challenges of repurposing are:
  - Distributed stock: The remote and offshore locations of wind farms make transporting and processing decommissioned blades logistically difficult and expensive.
  - Economic viability: High processing costs and low demand for repurposed products limit the financial attractiveness compared to virgin materials.
  - Long lifespan, slow turnover: The infrequent decommissioning of blades makes it hard to establish a consistent supply chain or investing.
  - Risk of acceptance: Public and regulatory skepticism around safety and aesthetics can hinder the adoption of repurposed blade materials in visible or structural applications.
- Creating more incentives for applying reuse methods higher in the waste hierarchy are also challenging.
  - solutions might include: implementing reward strategies, open source data banks or compliance bonds.

Logistics

- Offshore handling and vessels are up to 2-3 times more expensive to operate than land-based logistics.
  - because of specialized jack-up vessels, heavy-lift ships, and weather sensitive planning.
- The perfect candidate for a decommissioning hub are the harbors in the Noordzeekanaalgebied.
  - Transport of blades over water is cheaper than over land.

Processing blades

- Cutting challenges include: The toughness of GFRP results in toolware, operational cost, industrial grade machines.
  - Health wise, glass-dust and possible toxic fumes are involved.
- Safety measures for cutting blade material are:
  - Dust extraction system, fume control and personal protective equipment (PPE).

Cutting techniques and preferred method

- Diamond-tipped wire saw: clean straight cuts, water-cooled, but requires constant tensioning and is expensive.
- Large circular saw: more flexibility, percision cuts, but more dust genreation and toolwear.
- Waterjet cutting: no tool degradation, good dust collection, precise cuts, but slow and possibly damaging to the interal layers of the material.

- Preferred method and setup: processing location near the harbor with a large overhead circular saw cuts the blades into segments. A blade frame, crane, forklift and cover tent are involved in the process.

3.
Noise barriers

Noise barriers, also known as sound or acoustic barriers, are structures designed to reduce unwanted traffic noise from roads or railways for nearby environments. This chapter covers how a noise barrier holds up against environmental stresses, important safety and aesthetic considerations, assembly processes and maintenance. The requirements and design guidelines for Dutch noise barriers were taken from the noise barrier “bible”: Richtlijnen geluidbeperkende constructies langs wegen (GCW) (CROW, 2012). With the support of the Geluidsbeheersing team at Heijmans, who specialize in designing noise barriers and infrastructure projects, these topics were critically investigated and assembled into key takeaways, covered at the end of this chapter.

This chapter takes you through the following topics:

3.1 What is a noise barrier?

3.2 Structural & Environmental stresses
Wind load, foundation & water management

3.3 Noise barrier construction visit

3.4 Safety standards

3.5 Aesthetic experience

3.6 (Dis)assembly processes

3.7 Maintenance

3.8 Business and sustainability implications

3.1
What is a noise barrier?

Noise barriers are structures designed to protect nearby communities from road and railway noise. In The Netherlands, a road network of roughly 3,500 km stretches the country. Traffic noise near major highways frequently reaches 70 to 80 dB at a distance of 50 meters, which is comparable to the sound level of a vacuum cleaner. According to the European Environment Agency, noise levels above 55 dB affect over 120 million Europeans and are linked to stress, sleep disturbances, hypertension, and other health issues (EEA, 2016).
In a dense populated country as The Netherlands, it is evident that noise barriers are an essential part of the roadside.

Shape, size, and placement
Standard noise barrier units are typically 6 meters long, with heights ranging from 2 to 5 meters depending on local noise reduction needs. In more special cases, noise mitigating structures can be much taller, but for the sake of a blade with a chord length of around 2 to 5 meters, the standard noise barrier is considered.

At Heijmans, 6-meter wide segments are preferred, as even shorter panels require more foundations and significantly increase costs (Van Osch, PC, 2025). While longer segments are technically feasible, they are usually avoided due to higher material costs and the need for stronger foundations to withstand greater wind loads.

Noise barriers are commonly placed along highways, railways, and bridges, especially near sensitive areas like residential zones. Space is often limited in such regions, which restricts design freedom. Because the design regulations differ between road and rail applications (CROW, 2012), this project focuses primarily on highway applications, ideally in non-residential zones where there may be more space to accommodate a wider or off-shaped blade barrier.

Most barriers are made from concrete, metal, wood, or transparent panels, often in modular prefabricated forms. Lemmens et al. (2023) renewed the MGS (Modulair geluidsscherm) manual, a helpful tool for definitions of modular systems and guidelines when designing a noise barrier.

An important implication throughout this thesis is that a barrier made from wind turbine blades does not fit within the conventional typologies of MGS and GCW. The blade material is neither homogeneous nor virgin: it consists of layered composites with varying compositions, and its previous use means there is limited knowledge about its remaining lifetime and acoustic performance. Consequently, standard design requirements such as minimum service life, durability, and noise reduction cannot simply be applied. Instead, they must be carefully reconsidered and adapted, requiring flexibility in both the interpretation and implementation of existing regulations.

3.2
Structural & Environmental stresses

The most important loads that a noise barrier construction has to face are the deformation and fatigue against wind, rather than the weight of the structure. In order to determine the appropriate structural rigidity, rules apply for calculation:

- The norms (NEN-EN 1991-1-4) and guidelines for calculating wind load on large structures can be found on p.57 of CROW (2012).
- The barrier is divided into sections A,B,C,D, because the loads differ towards the end of the barrier (Figure 25).
- Section D is considered the largest section as it resembles all of the middle. A barrier of 4 meters high will have an A,B,C of 16 meters at its end and beginning.
- The Netherlands has three wind-regions with different norms and guidelines, the first region experiences the most wind (Figure 26).
- There maximal deflection, which happens at the top-middle is set at 50mm (CROW, 2012)(Figure 27).

The calculation of wind forces on the blade barrier will be covered later, in Chapter 8.3.

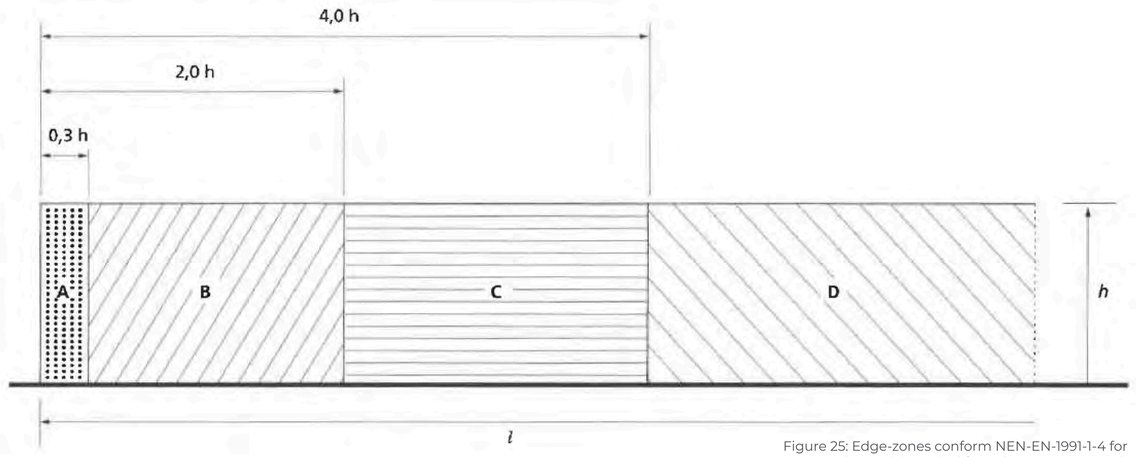


Figure 25: Edge-zones conform NEN-EN-1991-1-4 for determining wind force (CROW, p.58, 2012).

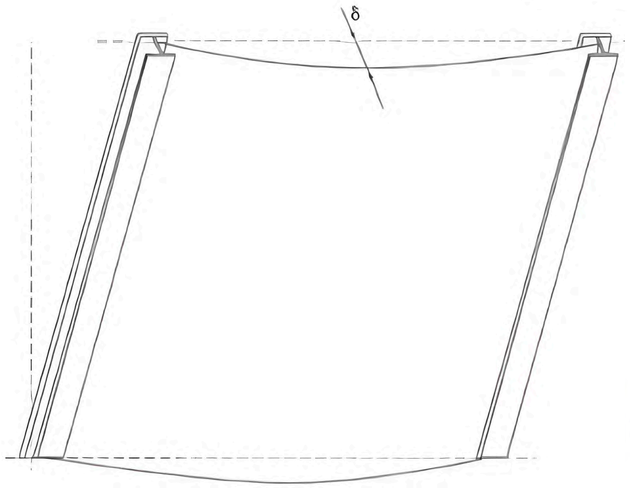


Figure 27: Max. deflection at the top (CROW, 2012, p. 66).

Figure 26: Wind-regions of The Netherlands inspired on (Cameramasten, n.d.).

The foundation
The foundation differs along the entire length of noise barrier. Heijmans takes soil inspections and does measurements, at the construction site before the barrier will be installed. The collected data is put in an excel, which data is filled in by Dynamo into Revit, the 3D software with all the needed components (Alwan, PC, 2025). This software creates the whole assembly of the barrier with heights, placement and the depth of the foundation at each 6-meter frame (Figure 28). Every pole has its own XYZ-Coordinates (Van Amstel, PC, 2025).

The foundation is highly dependent on the design of the barrier and the soil composition it is placed on. Determining the foundations happens at a later stage of the project, and thus will be out of scope. However, the frames or connections that place the noise barrier on the foundation will have to be able to connect with existing foundation setups. The next chapter *site visit,* will give some visual context.

Corrosion
Steel foundations and frames are prone to corrosion. To make sure the structural integrity remains safe, the steel components could be a bit thicker than the required minimum, or protected with a special paint coating (CROW, 2012). To save weight and material, a coating seems more suitable for the blade barrier design.

Water management
A barrier needs proper water management to prevent damage and erosion. A good method is adding drainage slits under the noise barrier that elevate it about 5 to 8 cm off the ground (Figure 29). These are implemented to prevent water accumulation (pooling) and make a wildlife passage underneath. Furthermore, the design is required to prevent damage from animals (nesting birds) and have proper drainage for everything that is able to collect water.
Although a plus to drainage slits are reduced maintenance needs, because the blade material is not touching the ground. These gaps are only acceptable if they don't significantly affect acoustic performance. More recent regulations do not allow a slit over the full length in densely populated areas, but only openings at intervals (Grevelink, PC, 2025). Lastly, erosion control is especially important near elevated roads and taluds (sloping embankments), as they slowly sink and the drainage gap gets bigger (CROW, 2012, p. 69).

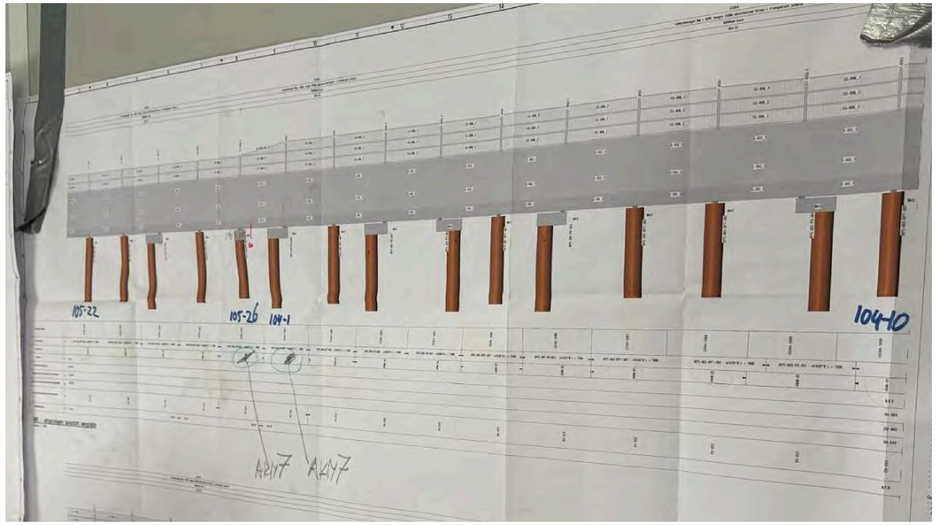


Figure 28: A9 Amstelveen project Heijmans overview of foundations, on the wall in 'keet'.

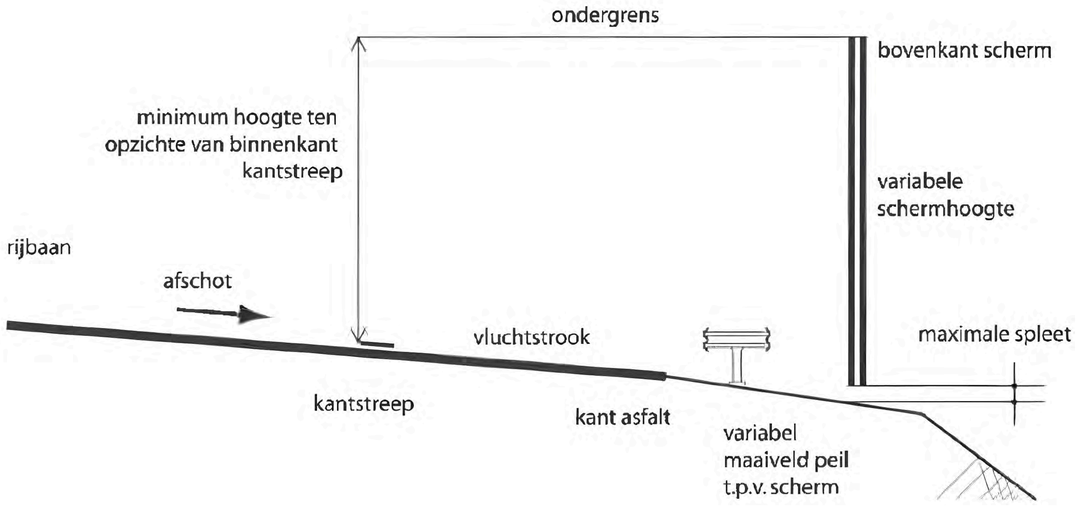


Figure 29: Drainage slit (CROW 2012)

3.3
Noise barrier construction visit

Heijmans is currently working on a large noise barrier project along the A9 in Amstelveen, until 2027. They are placing acoustic barriers of seven meters high along the highway, and I had the opportunity to experience first hand how building a noise barrier takes place.
More pictures can be viewed in Appendix J.

How barriers are built
First of all, a lot of planning is involved. In this case, the full road was newly laid, conveniently leaving a large operational strip (A).
As mentioned previously, the foundation is different along the barrier. It was clearly visible that there were two main types: a regular pole (B) and a block of concrete (C). They do this because sometimes the 6 meter distance between frames aligns with old foundations in the ground, causing the new pole to be moved next to it. Because 6m needs to be 6m, the threaded bolts are now encased in iron bar reinforced blocks of concrete (C&D).
Lastly, it was clear how the frames tapered to a larger footprint, fastened by big M48 bolts for the tensile loads of this large moment arm (B). The gray coating of the frames is the perfect example for corrosion prevention.

3.4
Safety standards

Since roads often carry large volumes of fast-moving traffic, and noise barriers are sometimes placed close to the roadside, the relevance of safety considerations is high. A safe noise barrier needs critical attention to minimize risks of collision, fire hazards and safe fleeing-options. The three key aspects of safety are as following:

Traffic-safe placement
Along highways, an obstacle-free zone is mandatory, which size is dependent on the speed of the traffic. Noise barriers without the ability to guide or take the impact of a vehicle collision placed in this zone, must have a guiderail in front (Figure 30)(CROW, 2012, p. 48).
If the barrier includes an overhanging profile, it cannot extend into the zone, further than the guiderail. It is assumed that the WTB noise barrier will be placed behind a guiderail for safety. However, even with this protection, it is recommended to design the road-facing side of the barrier with a smooth or flat surface to reduce the risk of injury or escalation in the event of a collision (CROW, 2012).

Lastly, an extra buffer zone between the barrier and the road is desirable. This improves visibility for drivers and doesn't cause nervous driving when changing lanes, being afraid to hit the barrier. Additionally, more space allows for better construction and maintenance logistics, such as storing panels or mowing the grass (Van Beurden, PC, 2025). However, in many cases, space is limited.

Emergency exits
Emergency exits must be installed at intervals of no more than 400 meters, though their exact placement depends on the road context and location. Additionally, the escape doors should not compromise the acoustic performance of the barrier (CROW, 2012).

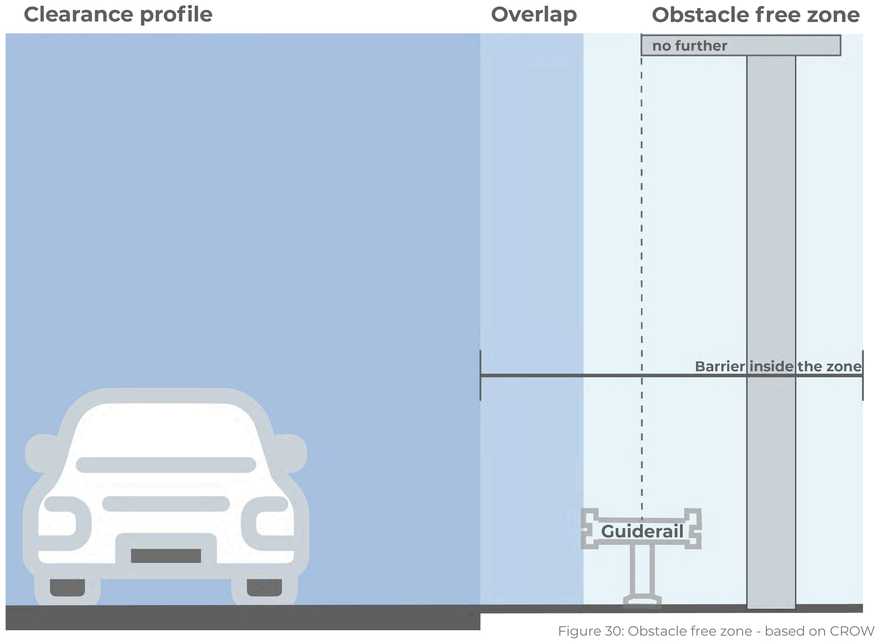


Figure 30: Obstacle free zone - based on CROW information (2012), inspired by Gabriëls (2025).

Fire safety
Fires may occur near barriers due to wildfires, vehicle accidents, or engine malfunctions. Noise barriers should help prevent the spread of fire and not produce toxic smoke when burning. Normally, non-combustible and low-emission materials are selected for a barrier. However, in recent study by Wang et al. (2024), WTB material came out classified as not fire-resistant. It showed to be ignitable by lightning or developed nacelle fires, and once the blades caught fire, they would deform, disintegrate and emit toxic smoke.

Because of this, extra measures are necessary to keep the fire under control. These may include adding fire-resistant strips at fixed intervals or applying fire-retardant coatings. Next to that, reserving extra space between the road/guiderail and the barrier is advisable, and maintaining vegetation around the barrier helps lower fire risks (CROW, 2012, p. 54).

3.5
Aesthetic experience

When designing a noise barrier, it is important to consider the perspectives of both residents and road users. Since these groups experience the barrier from different sides, they require different points of attention. The design should integrate into its surroundings as a coherent whole, blending in smoothly. Key aspects to consider for both groups include style, form, and color. All relevant aspects of environmental experience are discussed in detail in CROW (2012), pages 31–38, for those seeking further explanation.

The manual for modular noise barriers (MNB) by Lemmens et al. (2023), or MGS in Dutch, highlights the key aspects of designing for aesthetics:

- The MNB should contribute to a calm and continuous road appearance.
- The MNB should still enable the recognizability of location, route, and direction.
- The MNB should promote consistency in, avoiding random styles.
- The MNB should give equal attention to the road-facing and the environment-facing side.
- The MNB should be easy to maintain and keep their (spatial) quality throughout their lifespan.

Resident side
The residents living close to the barrier are considered the most important group of users. Although the barrier helps with reducing road noise, it also contributes to a loss of their view. Important aspects for acceptance of the barrier by residents are:

- Style: the close-up scale is experienced much different compared to the road side. Acceptance of the barrier will come when its tailored towards the residential area.
- Color: the barrier should have colors that fit the surroundings. Lighter colors towards the top might help with reducing the feeling of its overwhelming size.
- Expression: the barrier could be merged with its surrounding environment by taking on a similar appearance.

Road side
The most important aspect for the road user, who is experiencing the barriers appearance at high speeds, is that their driving performance is not influenced. The barrier design can neither de distracting with too many random shapes, nor can it be boring, with no changes at all.
Some varieties in the design should help to keep the attention of the driver, although sometimes local changes such as emergency doors, a bridge or a road sign create enough variation already.

Additionally, a drivers orientation on the road is important. As mentioned in safety, an extra buffer zone improves visibility for drivers to orient their location with buildings or trees behind the barrier. The barrier itself can also be used as a new orientation point by adding art. To limit the perception of confining high walls, the barrier can be angled backwards, colored or vegetation can be added. This improves driving comfort and decreases road nervousness.

3.6
(Dis)assembly processes

As mentioned before, the whole site undergoes soil inspections and preparations before the construction starts. This includes leveling the soil, managing water flow to divert rainwater away from the foundation and marking possible obstructions underground such as cables (Build It, 2025).

According to the plan made with the help of computer aided software, the holes are drilled for the hollow steel foundation piles, and the concrete foundation is poured inside. After the foundation is hardened, the frames are placed on the bolts that stick out of the concrete top, which is reinforced with a frame of steel bar (Figure X).

Afterwards, vehicles transporting material, and a crane to lift segments start assembly of the barrier. Because (part of) the highway needs to be closed to bring the supply, work will be done mostly at night to minimize traffic and hindrance for commuters.
Making use of Prefab parts is desirable for smooth and fast assembly. Leaving room between the road and the barrier helps to keep the roadworks on the side and can be used to temporarily store building materials (Van Beurden, PC, 2025).

For disassembly, a few important criteria need to be considered (CROW, p.81):

- Disassembling parts on location need to be done without destructive methods as sawing or breaking.
- These parts are easy to handle and transportable.
- The process does not release harmful substances or leave behind any contaminating residues in the surrounding environment.
- The barrier remains stable and does not collapse, even during temporary phases of structural instability.

3.7
Maintenance

Keeping the noise barrier in good condition is essential for ensuring a long service life. Common factors that affect this include the quality of the materials used, exposure to environmental conditions, and corrosion of supporting frames. In addition to structural durability, maintaining the visual appearance of the barrier is important for both road users and nearby residents. Because graffiti is often sprayed on barriers, a large white blade surface will definitely attract attention to painters. To prevent this, anti-graffiti coatings could be applied. Other approaches include: artworks, planned graffiti, or growing vegetation in front of the barrier. Regular cleaning to remove graffiti, dirt, moss, or bird droppings will help preserve the barrier's appearance and contributes to a longer life.

Growing vegetation can be aesthetically pleasing and help noise reduction. However, the additional loads from plants and the maintenance they require must be taken into account. The material also needs to withstand a humid climate when covered in plants. Adding soil and regular pruning are necessary (CROW, 2012, p. 84). Van Osch (PC, 2025) noted concerns about large overgrown plants potentially catching wind and collapsing onto the roadway. The smooth surface of the segments may lead to poor growth or detachment because plants have trouble sticking to it. In that case, the implementation of plant supporting cables or frameworks are necessary, which asks for additional maintenance. For these reasons, a clean, plant-free barrier design is likely more practical and reliable.

As during installation, a maintenance strip alongside the barrier is advisable to allow access for vehicles to clean, prune, mow and repair. To safe time and cost, the repair of broken segments or frames should be modular and fast, disassembling only what needs to be replaced.

3.8
Business and sustainability implications

The way to participate or execute projects, companies often apply for a tender. The market is highly competitive, and to get selected to build a noise barrier is not an easy task. Competing with traditional prices, methods and materials is difficult, especially if you have none of these. WTBs might be a new sustainable solution, in most cases the market remains skeptical towards the scalability (Zuur, PC, 2025).

This is where the MKI score (Milieu Kosten Index) comes in. Companies that value an environmental friendly design, award points for certain criteria. These points can vary from 6 to 20 or even 50 euro per MKI point and give a fictive discount on the cost price. This means that if a proposed solution is a bit more expensive but ticks all the boxes of the criteria set, it is still very much able to compete (Keetels, PC, 2025).

For the Life Cycle Assessment (LCA) of the noise barrier, Heijmans will not be looking into the decommissioning, as the supplier involved will count this in their process. Furthermore, they account for zero material waste, 80% should be reused and 20% will be granulated for other purposes (Van Osch, PC, 2025). The decommissioning process of the blades and shredding the material into fibers are two processes with a significant impact in the LCA that have to be taken into account. Positively, while WTB material performs similarly to wood and concrete on MKI indicators, its greenhouse gas emissions are reduced by more than 16% compared to alternative materials (Royer, 2025). These results show potential in material recovery from WTBs. More on LCA in chapter 10.7 of evaluation.

Chapter 3

Takeaways

Standard noise barrier segments are 6 meters wide; shorter ones require more foundation and become too costly, longer ones are possible but need additional calculations (Van Osch, 2025).

Structural and environmental stresses

- Design must resist wind deformation (NEN-EN 1991-1-4).
- The top middle deflection guideline is 50mm max.
- Soil inspections guide barrier foundation design (via Revit).
- Foundation is tailored per location; addressed later in the project.
- For corrosion, special paint coats the steel components.
- Erosion control is an important factor when the barrier is built on elevated banks of sand.
- 5-8 cm elevation allows for drainage, and protects material from water and dirt. However, gaps must not compromise noise reduction.
- When foundation is placed, moving it sideways to avoid old foundation is normal.

Traffic and fire safety

- Barriers close to roads need guide rails.
- Buffer zone preferred for visibility and logistics.
- Emergency exits, required every 400 meters, should not reduce acoustic performance.
- Barriers should not spread fire or emit toxic smoke.
- WTBs are not fire-resistant; add fire-resistant coatings/strips.
- Extra space and cleared vegetation reduce fire risk.

Aesthetic experience

- Residents and drivers experience the barrier differently; both sides matter.
- Design should blend with surroundings and promote road clarity.
- Calm, consistent appearance, continuity
- Clear spatial awareness of road user
- Acceptance of the residents by incorporating color and purpose.

(Dis)assembly

- Construction prep includes soil leveling, drainage, and marking utilities.
- Poles placed in holes and foundations poured.
- Assembly uses prefabricated parts, cranes, night work to reduce traffic disruption. Extra space near road helps with constructing and logistics.
- Disassembly has to be: non-destructive, non-contaminating and easy to handle and transport.

Maintenance

- By cleaning and maintaining the barrier, its service-life increases.
- Vegetation adds beauty and sound absorption but needs pruning, soil, and moisture-resistant materials. A vegetation-free barrier is preferred.
- Overgrown plants can fall in high wind, point of attention.
- Graffiti risk is high: use anti-stick coatings, vegetation, or approved artworks.
- Leave maintenance strip for vehicle access.
- Repairs should be modular, replacing only damaged parts.

Business and sustainability

- Competing on price alone is hard; MKI score helps via sustainability points.
- MKI points can lower the bid price by €6–€50 per point.
- Heijmans doesn't include decommissioning in LCA, the supplier does.
- Waste guideline Heijmans: 80% recycled, 20% granulated.
- Highest LCA impacts: blade decommissioning and fiber shredding.

4.

Acoustics

After diving into the world of wind turbine blades and noise barriers, it is important to understand the acoustic principles of sound waves interacting with its surroundings. This chapter covers the theory behind the noise interaction of a WTB segment and its sandwich material with the road noise, and what acoustic requirements influence the design and placement of the blade barrier.

This chapter takes you through the following topics:

4.1 The acoustic properties of WTBs
Theory & test results

4.2 Noise barrier acoustics
Requirements & design choices

4.1
The acoustic properties of WTBs

Firstly, sound can interact with a material in four different ways.
These main interactions are illustrated in Figure 31 with a segment as reference:

- **Reflection**: the sound reflects off the material in the sky or back to the road, depending on the angle of the source's sound waves and barrier surface.
- **Absorption**: the sound is absorbed in the material. Good absorption is often correlated to porous surfaces and objects with large mass, like stone walls.
- **Transmission**: the sound is transmitted as energy waves that vibrate through the material. Transmission loss can be increased by thickening the barrier (Laxmi et al., 2021).
- **Diffraction**: the sound bends over the top of the barrier. This phenomena occurs more intensely on sharper edges. Thickening the edge or incorporating an extra overhang (T-top) helps to lower the effect (D. Ragni, PC, 2025).

Road traffic noise mainly falls between 100 Hz and 1000 Hz, with most energy around 250–800 Hz (Rochat & Reiter, 2016). This range includes engine and tire noise, and should be the focus for effective noise barrier design.

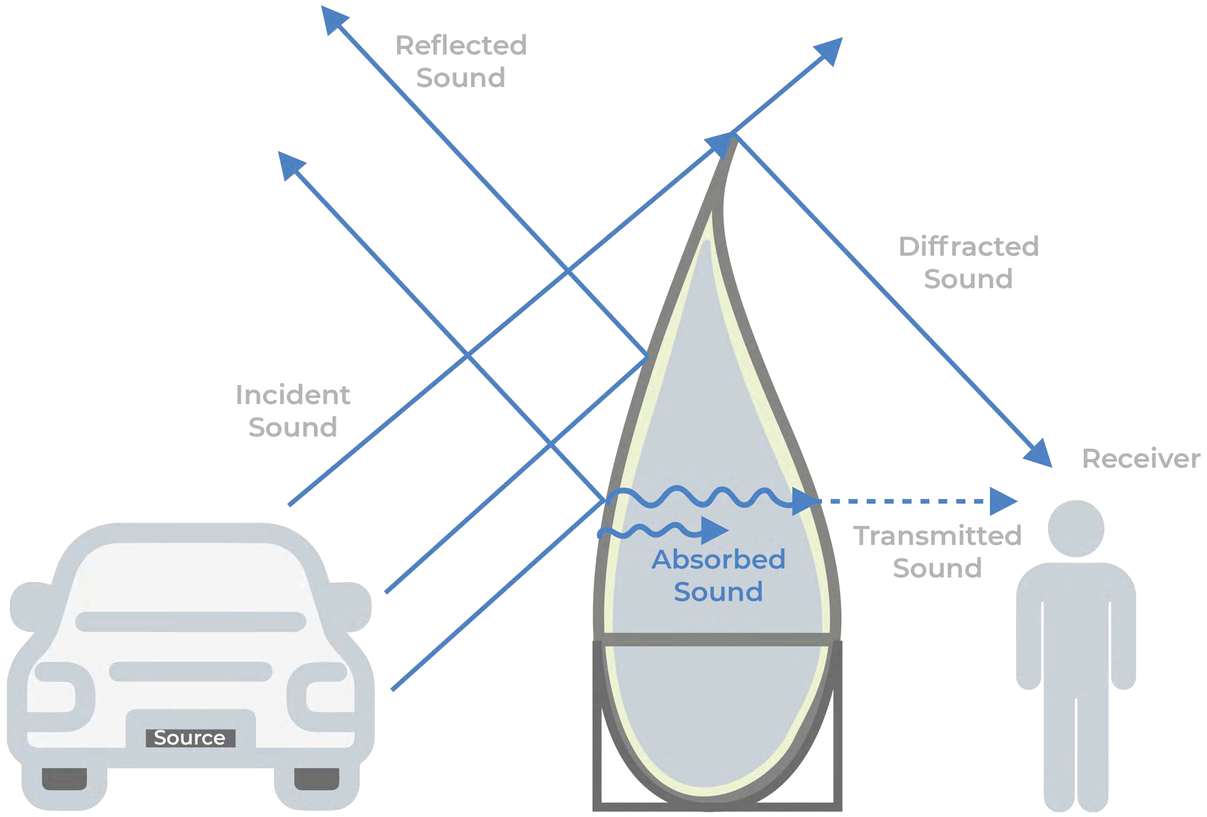


Figure 31: The four sound interactions.

4.1.1 Acoustic performance of WTB material

Neuman (2024) conducted a series of acoustic tests on a panel of blade material in an anechoic chamber at TU Delft, measuring both sound absorption and transmission loss.

Absorption

The single-layer panel showed absorption coefficients consistently below 0.2 across all tested frequencies (Figure 32). To put this into perspective: an absorption coefficient of 0.2 means that about 20% of the incident sound energy is absorbed, while 80% is reflected or transmitted. At 0.1, only 10% is absorbed and 90% is not. This is very low compared to specialized absorptive materials such as rockwool or foams, which can reach coefficients of 0.7 to 0.9 at certain frequencies. The results therefore indicate that WTB material acts primarily as a reflective surface rather than an absorber.

Transmission loss (TL)

For transmission loss, the blade panel performed ok, considering its relatively low density. Between 570 and 1000 Hz, TL values ranged from 5 to 13 dB (Figure 33). This means that sound energy passing directly through the panel was reduced by that amount. For context, effective noise barriers typically aim for at least 25 dB TL (CROW, 2012). At higher frequencies, the material performed somewhat better, likely due to its porous core and layered composite structure, as also noted by Broniewicz et al. (2024). As a last note, at lower frequencies, additional testing should be done to check whether resonance effects will occur.

Implications

Neuman's results make it clear that a single WTB panel is insufficient for effective noise barrier construction, falling roughly 15 dB short of the desired performance. The low absorption and inconsistent TL suggest design requirements such as using a double-layer configuration, integrating absorptive materials, or adding mass to increase acoustic insulation.

Conclusion

While WTB material is not effective as an absorber, it can still serve as a suitable and effective base material for roadside noise barriers. Its strength lies in reflection rather than absorption, meaning it can contribute to blocking the road noise, especially when combined with additional acoustic design strategies.

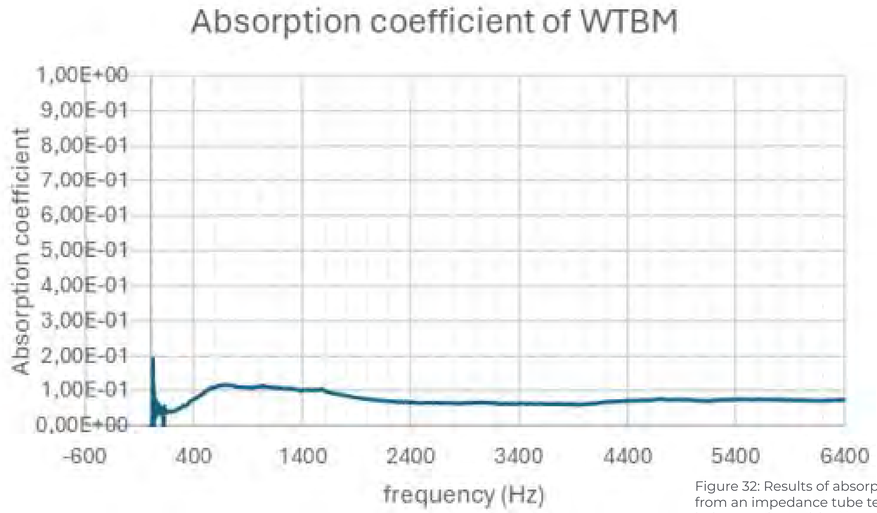


Figure 32: Results of absorption coefficient from an impedance tube test on GFRP - balsa wood panel, by Neuman (2024).

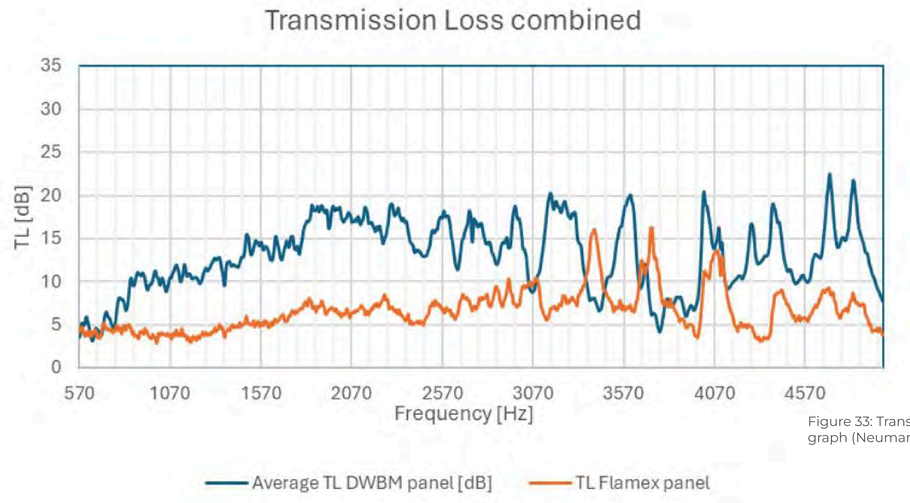


Figure 33: Transmission loss graph (Neuman, 2024).

4.2
Noise barrier acoustics

After gaining knowledge on WTB acoustics, this chapter covers the more technical ‘rules’ for acoustic barriers according to CROW (2012).
The primary objective of a noise-reducing structure along the road, is to limit noise disturbance for nearby environments. The effectiveness of such a noise barrier depends on several factors. These include its placement in the road cross-section, as well as its height, length, and the distance between the noise source (the road) and the receiver (the buildings, or in this case the person, to be protected) (Figure 34). Additionally, the design and acoustic properties of the barrier play a critical role in its effectiveness to function as noise reducer.

Three of the four sound phenomena can cause noise to reach the areas behind the barrier:

- Transmission, where sound travels through the barrier material
- Diffraction, where sound waves bend over the top of the barrier
- Reflection, where sound bounces off and travels over the barrier on the opposite side of the road.

The extent to which each of these effects occur is determined by the barrier’s geometry, weight and acoustic characteristics, such as absorption. To assess the barrier’s performance, European norm NEN-EN-1793-2 is used. This standard expresses the noise reduction capabilities of a barrier in decibels (dB). A sound insulation (DLr) of around 25 dB is the norm for a noise barrier of the WTBs caliber (CROW, 2012, p. 14). There is a formula and some extra factors involved, but these will not be covered in this thesis. Gabriëls (2025), does have a more detailed description on this topic, may it be of further relevance.

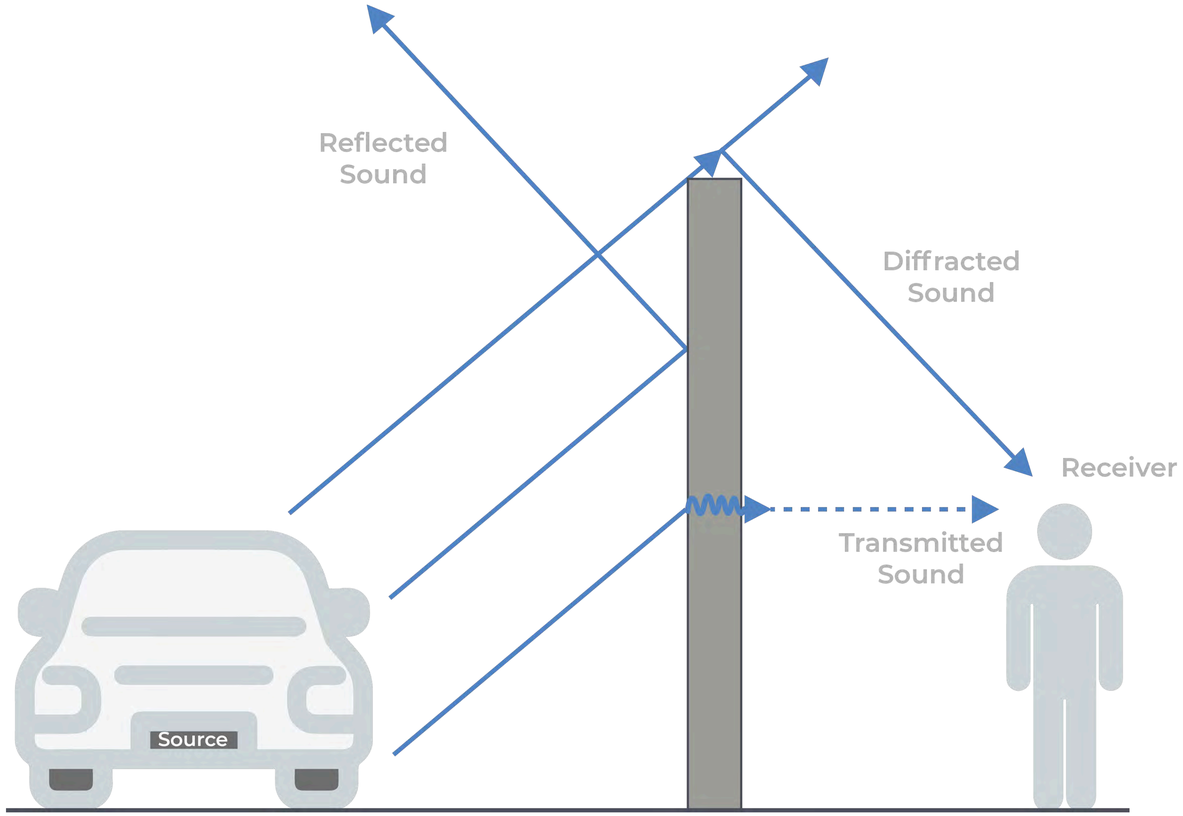


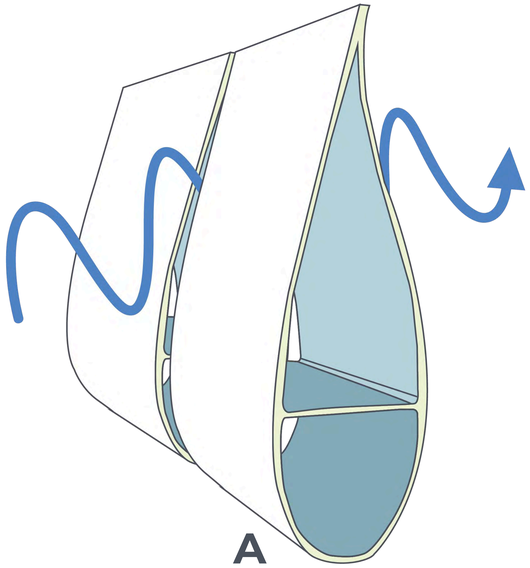
Figure 34: Sound interacting with the noise barrier.

4.2.1 Transmission

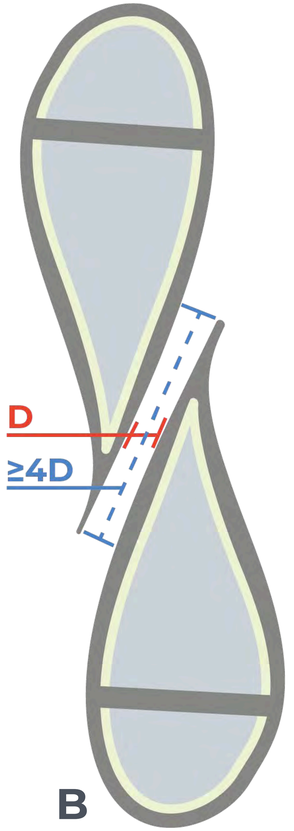
To meet the required noise reduction levels, sound transmission through the barrier can be neglected. The assumption is made that transmission through the material is negligible, when the DLr is 10dB higher than the barriers effectiveness (CROW, 2012). Noise-reducing structures must be constructed to be acoustically sealed. Openings, gaps, and poorly sealed joints significantly reduce the sound insulation performance and result in increased noise levels behind the barrier. Even small air leaks can compromise the effectiveness of the entire structure (A).

Consequently, the blade segments should connect tightly together, avoiding any air gaps that could allow noise to pass through.
When intentional openings are introduced for drainage or ventilation, they must be carefully designed to minimize sound transmission. A commonly applied rule is the 4xD principle: any opening with a diameter or width of D must be overlapped by surrounding acoustic material extending at least 4×D (B). For example, a 10 cm gap requires a 40 cm overlap on all sides to maintain noise reduction performance. The drainage slit poses less of a problem usually, because the ground and grass close to it have high absorbing qualities (Grevelink, PC, 2025).

An effective method to reduce transmission **through** the material instead of the barrier's possible air gaps is by increasing the mass of the segments. This can be done by filling them with materials such as sand or shredded fibers (Van Beurden, PC, 2025).
As discussed earlier, based on research by Neuman (2024), a double layer of wind turbine blade material may be necessary to sufficiently reduce transmission (C). Considering the use of full segments, which are automatically double layered, the fear of transmission is no longer an issue.



A



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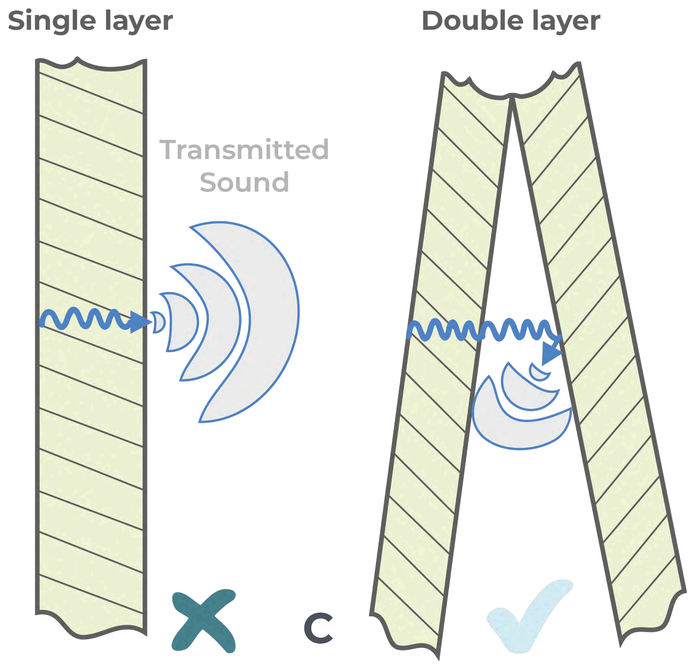


C

4.2.2 Diffraction

Diffraction occurs when sound waves bend over the top of a noise barrier, continuing into the area behind it. A distinction is often made between barriers with a sharp edge, such as transparent sound screens, and those with a rounded or blunt top, like concrete walls. The edge shape plays a significant role in how much sound is diffracted. That is because the frequency of the sound waves is in direct correlation to the amount of diffraction (Barba & Martinez-Orozco, 2022). As shown in Figure 35, the high-frequencies are diffracting less than the low-frequencies, which because of their longer wavelength, bend more around the top into the shadow zone.

Since the top edge of a wind turbine blade segment is relatively sharp, it may cause more sound to bend over the barrier. This effect can be mitigated by rounding the top edge or adding a feature near the upper edge, which helps scatter and diffuse the sound waves. A T-top extension (A) or the WHIS®top (4silence, 2025)(Figure 36) are measures that improve the acoustic performance by reducing the impact of diffracted noise (CROW, 2012, p. 15).

Lastly, some future blades that have designs like a flat-top trailing edge or one with spikes, might enhance the edges against diffracting and are highlighted in Appendix H.

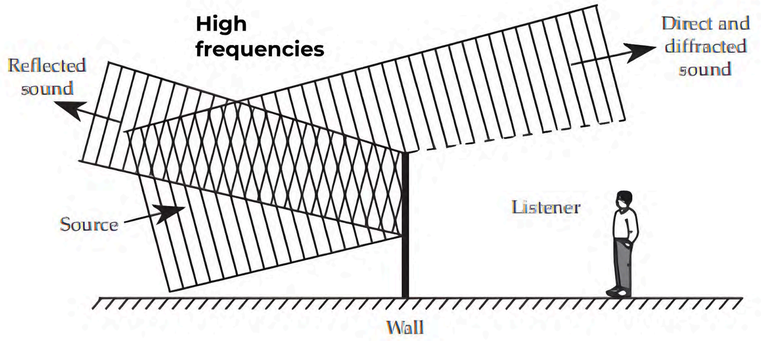


Figure 35: Diffraction at different frequencies (Admin, 2018)

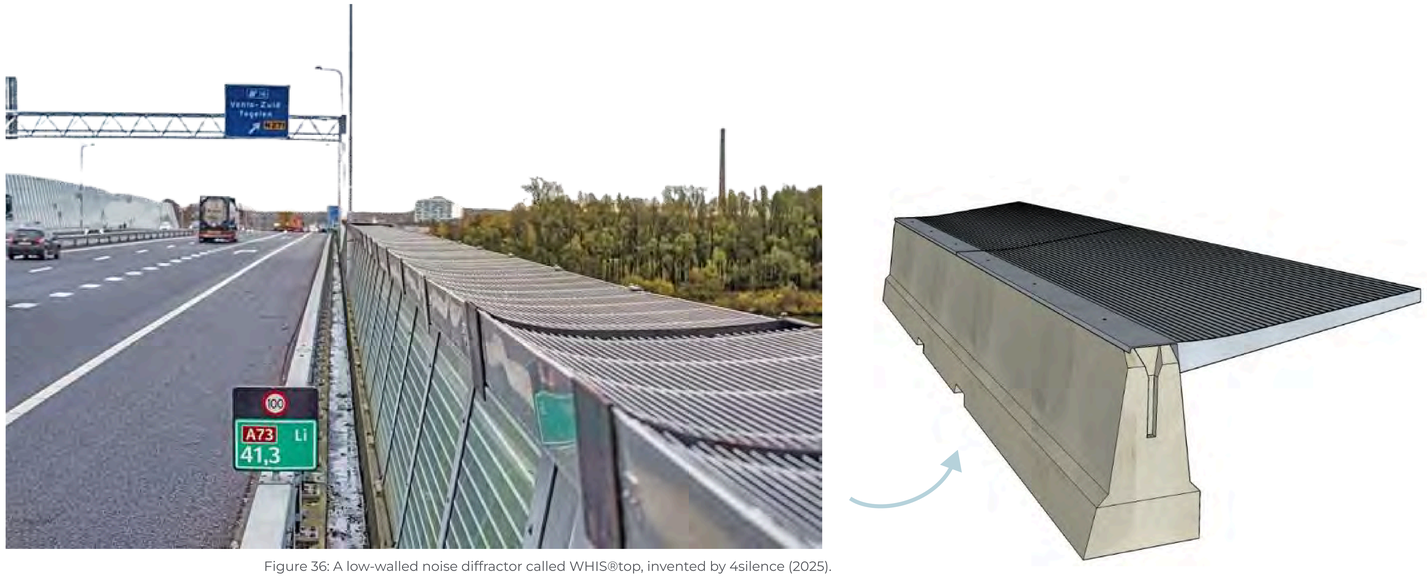


Figure 36: A low-walled noise diffractor called WHIS®top, invented by 4silence (2025).

4.2.3 Reflection

The reflection of sound waves by a noise barrier can contribute to increased noise levels along the road, especially when hard, reflective materials are used. This effect can normally be reduced by using sound-absorbing materials and finishes. However, since the composite outer shells of WTBs is a highly reflective material (Neuman, 2024), reducing noise with absorption is not feasible.

Consequently, the shape and angle of the barrier become the critical for reflecting the noise. Angled and curved surfaces can redirect sound waves away to areas where they pose less of a problem, which is a good alternative for barriers that do not have absorptive qualities (CROW, 2012). Research suggests that tilting blade segments at an angle of 10 to 20° from vertical as shown in Figure 37, is an effective strategy to reflect sound waves into the sky, thereby reducing the impact on nearby receivers (Gabriëls, 2025). An angle exceeding 20° requires additional structural research, which is why the segment will stay within the 10 to 20° margin (CROW, 2012). In chapter 8.2, the tilt and orientation of the barrier will be discussed, after the chosen concept design.

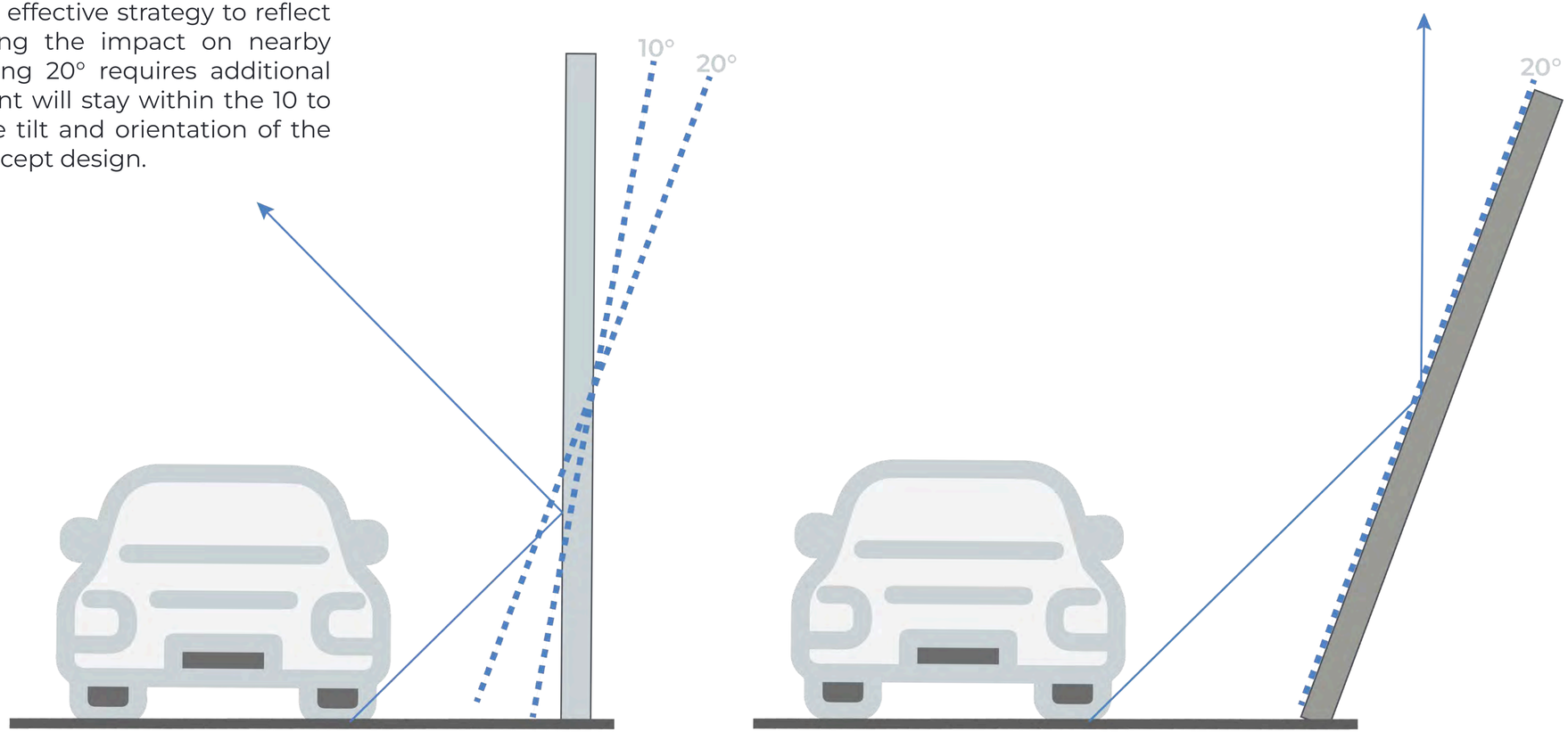


Figure 37: Reflection of sound on an angled noise barrier.

Chapter 3

Takeaways

WTB acoustics

- Sound can interact in four ways: Reflection, Absorption, Transmission and Diffraction.
- Road traffic noise is between 100 Hz and 1000 Hz.
- Neuman's research (2024) shows poor sound absorption and a Transmission loss (TL) value between 570 and 1000 Hz measured from 5 to 13 dB. This is not the desired 25dB (CROW, 2012).
- The results suggest design directions such as a double-layer configuration, integrating absorbing materials or adding mass.

Barrier acoustics

- Main goal: reduce noise that can reach the receiver.
- Key factors: placement, height, shape, and distance from road to buildings.

Transmission, diffraction and reflection

- Barriers must be airtight; even small air leaks reduce performance.
- Openings must follow the 4×D rule.
- The assumption of mass is made that makes the Transmission Loss (TL) negligible.
- Diffraction; sound bends over barriers top.
  - Worse at low-frequencies than high-frequencies
  - worse with sharp edges. Rounded tops, special deflectors or T-tops reduce this effect.
- WTB shells are highly reflective; absorption not feasible.
- Use angled/curved blade surfaces (10–20° tilt) to deflect noise upward.

5.
List of criteria & Requirements

In this chapter, all the gathered insights and key takeaways of chapters two, three and four are mapped and reformulated into criteria and design requirements for the next phase of the project. The scope, frame and vision that have already been covered in chapter 1.4, which have been formulated at this stage in the project.

This chapter takes you through the following topics:

5.1 Mapping context to criteria

5.2 Criteria and Requirements

5.1
Mapping context to criteria

As the project title describes, the assignment of this thesis is to realize the embodiment design of a noise barrier made from horizontally oriented, decommissioned wind turbine blades.
Because thousands of WTBs will reach their end-of-life in the next 20–25 years, finding reuse strategies for decommissioned blades is urgent. It is desirable to keep as much value in the material as possible, also in subsequent lifecycles. Translated to this thesis, which focuses on the first reuse cycle of the WTBs, the aim is to maintain the blade material in good condition and utilize the structural integrity of the shape and material (Joustra et al., 2021b).

It has been decided to extract large segments or panels of WTB material for the construction of a noise barrier, within feasible sizes. The edges exposed after cutting have to be minimized, protecting the material from moisture and rot, and thereby prolonging its life. All elements with direct consequences for the qualitative state of the material fall under **Durability** criteria. Processing the material falls under **Safety and Health** criteria.

Next, all the different sizes and shapes of blades that will become available, have to be processed with possibilities to scale up the noise barrier production. To accommodate varying blade geometries, the parametric segmentation model partially developed by Gabriëls (2025) is a promising solution to minimizing waste and mapping blade shapes for design reasons. However, further development of a shared database is out of the scope for this project. The assumption will be made that once a wind park is decommissioned, a large quantity of identical blades will be available for the construction of a specific barrier design, which can then be slightly altered to suit other blade types in the future.

Demonstrating the scalability of a WTB noise barrier is not an easy task. Scalability in terms of readiness level needs to be proven by supply chain planning and costs indicators to make it worth investing in. For now, the barrier design itself should demonstrate scalability by effectively using blade segments to realize a modular noise barrier. Modular barrier units, fast and easy assembly, repair and adaptability of the noise barrier, fall under **Modularity** criteria.

For reducing noise and ensuring airtightness, **Efficiency** criteria are set. The logistical feasibility of decommissioning, construction and cost, as well as the importance of competing with traditional barrier designs, fall under **Viability and Feasibility**.

The barrier’s aesthetic experience along the road, acceptance by residents and road users, and integration in the landscape fall under **Desirability**.

Lastly, the further lifecycles of the barrier, environmental implications (LCA), and ease of dis-assembly for reuse fall under **Sustainability**.

5.2
Criteria & Requirements

Based on the takeaways from the wind turbine blade and noise barrier chapters, all gathered insights were mapped in context, and different focus areas were assembled into a list of criteria. A criterion is defined as an important topic or bar that needs to be reached for success, preferably scoring as high as possible. After the criteria, a list of requirements specifies the mandatory guidelines the noise barrier design must meet. These requirements have to be concrete and rock solid. In the concept development stage, they must be considered in the design to make it acceptable.

5.2.1 List of Criteria

General:
- The blade barrier should accommodate different blade shapes without much alternation of the design.

Modularity:
- The assembly of the (pre-assembled) barrier segments onto the foundation is time, labor and cost efficient.
- The barrier is adaptable to the needs of the landscape (bridge, highway exit, emergency doors).
- Access strips for maintenance vehicles allow for fast modular assembly and repairs.
- The barrier anticipates changes of landscape, safety requirements or aesthetic desires, adapting with its modularity.

Efficiency:
- The barrier has excellent noise mitigation qualities.
- The barriers spatial footprint is as compact as possible.

Durability:
- Processing the blade is done with methods that minimize tool degradation but keep maximum extraction efficiency.
- The barrier design keeps WTB material intact and the construction structurally sound, by protecting it against environmental stresses.
- The barrier uses anti-graffiti solutions, like coatings, accepted art or vegetation.

Desirability:
- The looks of the barrier add value to the landscape, both for the resident and roadside.
- The barrier promotes the feeling of spaciousness and freedom, and does not divert attention or causes collision fright.

Sustainability:
- The blade material during processing is disposed in an environmentally responsible way.
- The barrier minimizes its processes' impact in the LCA.
- The dis-assembly of the barrier is efficient and makes subsequent reuse possible.
- The added sustainable value of the barrier should contribute to the competitiveness.

Viability:
- The costs of realizing the WTB noise barrier makes it competitive against traditional solutions.

5.2.2 List of Requirements

The list of requirements is a living document. Table 1 has been updated at the end of the project. In the Table legend (2), the colors explain the current status of each requirement.

color	explanation
	incorporated/tested - is sufficient
	critical assumptions or calculations - not tested but feasible
	critical assumptions or discussions - not tested, questionable feasibility

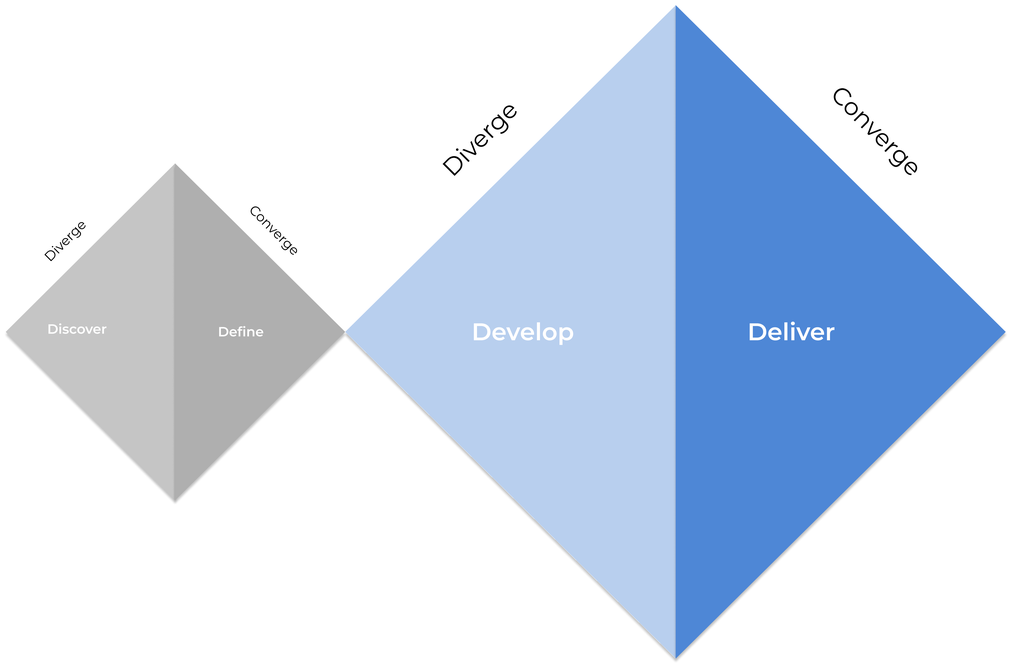
Table 2: Legend for list of requirements.

nr.	Topic	Importance	Requirement	Status	Why?
1.1	General	Must	The barrier needs to have a minimum service life of 30 years.		To be viable as project.
2.1	Modulairity	Should	The barrier's sub-assemblies can individually be repaired or removed.		More efficient repair and or maintenance.
2.2	Modulairity	Could	The barrier is adaptable to the needs of the landscape (bridge,exit, emergency doors).		To be built in the varying landscape.
3.1	Efficiency (acoustic)	Must	Openings, emergency exits, drainage slits, cannot reduce the effectiveness with more than 5dB (CROW,		Compromizing airtightness.
3.2	Efficiency (acoustic)	Must	The noise barrier has to have an effective sound mitigation of at least 25dB (NEN-EN-1793-2).		reduction of noise is sufficient.
3.3	Efficiency (acoustic)	Must	The roadfacing surface is tilted backward between 10–20° .		to deflect sound upward.
4.1	Durability	Must	The barrier has to withstand at least 5 million wind-load cycles (NEN-EN 1991-1-4).		To not fail and fall over.
4.2	Durability	Should	All the WTB material's open edges are sealed or treated.		vulnerable to moisture and rot.
4.3	Durability	Should	The barrier has to be elevated 5-8 cm above ground level for a drainage slit.		to prevent water pooling.
5.1	Safety	Must	The barrier has to be protected with a guard rail and buffer zone.		against colliding vehicles and for maintenance.
5.2	Safety	Must	Emergency doors have to be located every 400 meters (CROW, 2012, p.52).		Road safety.
5.3	Safety	Should	Protective measures have to reduce firespreading by double the time than without.		Against the spreading of fire.
5.4	Safety	Could	Maintenance, pathway mowing and cleaning has to be done once a year.		fire, blocking of exits and aesthetics.
6.1	Health	Must	Cutting WTB material has to be done with minimum: FP3 filter mask, gloves, glasses.		Safety equipment against dust irritation.
6.2	Health	Should	Cutting is done with the circular saw and sufficient dust collection systems.		to prevent airborne dust particles.
7.1	Desirability	Could	The barrier is visually accepted by 80% of users from both the road and residential side.		Fitting in the surrounding landscape.
8.1	Sustainability	Should	The barrier keeps the WTB material intact, even after its end of life.		for subsequent reuse.
8.2	Sustainability	Could	80% of the blade's volume can be structurally recycled.		for efficient reuse
8.3	Sustainability	Could	The above ground structure has a lower impact (LCA) than traditional barrier designs.		competitiveness.
9.1	Viability	Could	Offshore decommissioned blades should be cut in segments within 1 day as they arrive on land.		Processing speed.
9.2	Viability	Should	The logistics chain of decommissioning to assembly should cost a minimum of €400/m^2 barrier.		cost-effective.
9.3	Viability	Should	The construction and assembly should take a maximum of 100m in 4 weeks.		streamlined and time efficient.
10.1	Feasibility	Could	Transport, storage and assembly of the barrier have similair cost and effort to traditional barriers.		No excessive cost or effort.
10.2	Feasibility	Should	The barrier can be assembled with a crane, forklift and less than 10 onsite construction workers.		No excessive cost or effort.

Table 1: List of requirements.

6.
Ideation

In this chapter, the start of the second diamond has begun: the development phase. The iterative process of idea generation, collaborative brainstorming sessions, expert talks and more, led to the **7 key focus areas.** With the use of design methods, three concepts were created and further developed in the next conceptualization chapter.



The 7 key focus areas:

1. Segment length	**2. Orientation**	**3. Inter-segment connection**	**4. Frames & Foundations**
5. Soundproofing	**6. Closing off the sides**	**7. Segment to frame connection**	**6.2 Morphological chart**

6.1
The 7 key focus areas

After defining the focus and frame of the project, some initial ideas were formulated into possible design directions:

- Combining smaller, tip-side segments, to a single prefab-unit for the barrier, with similar height as single larger segments.
- Looking into upcoming supply of decommissioned WTB material, sizes and models.
- determining the geometry of blades, and the segments that can be extracted from it.
- Making sure a concept can handle shape differences.
- Optimizing the spatial footprint to reduce the barrier's width.
- Looking into aesthetic cohesion and user acceptance.

The ideation started with obtaining scale models of blades, to get a physical feeling of shape. The first iteration here was from vacuum formed plastic. The NREL 5MW blade was on scale 1:50 but the post-processing was a lot more work than expected. That is why 3D printing segments in the same scale was done, and immediately resulted in much more precise shaped segments.
With a lot of brainstorming, sketching, printing small tests and talking with experts at Heijmans, a lot of ideas came to the table (appendix A).

To give some more direction into all the scattered ideas, the seven most important aspects of the barrier design were set up. Each category was brainstormed about with small models, and were compiled into a morphological chart of sub-solutions. The next chapter will cover all seven areas with their sub-solutions and implications.

Focus area 1

Segment length

The first focus area is the length of segments used in the design.
There are three lengths considered;

6 meters, which is the standardized barrier width of MGS (Lemmens et al., 2023).
12 meters, which is double the length and requires less sawing.
24 meters, to keep the blade even more intact, while staying within the boundaries of regular truck transport.

Above the 24 meters, an exceptional convoy is necessary to transport the blades to the construction site. Although below 6 meters can be much more compactly transported, these dimensions require more poles and/or frames to support the barrier than longer blade segments. Next to that, additional cutting is required.

The weight of segments varies on the size of the initial blade.
A large segment of 12 meters is approximately 2-5 tonnes (Appendix B)(Malone, 2025). Although it is much lighter than concrete or steel equivalent surfaces, large segments with irregular shapes and awkward center of mass are more challenging to handle during construction.
Another con concerning the shape of longer segments is that the blade tapers to the tip, about 75cm per 12 meters. With 24 meter segments, which taper from a 4.5-meter to a 3-meter effective height, this would conclude in a large portion below the minimal acoustic barrier height, or exceeding above. In both cases the efficiency of material use and or effective height is limited.

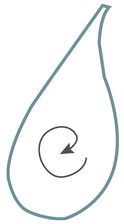
Choice to continue
Considering all the pros and cons previously mentioned, 12 meter segments Allow a more sustainable solution by keeping more material intact, while remaining effective for modular solutions and handling. That is why from this point in the process, all three concepts will be considering 12 meter segments into their designs.

Note: For future designs a length of exactly 12m is not necessary, but rather a range between 8-16 meters is advised, depending on the length of the full blade and the way it can be cut in the most effective way. For the NREL 5MW blade of ~60m, the first 12m of the root and last 12m of the tip are not suitable for use, the three segments in the middle are (Figure 38).

Figure 38: prototypes of vacuum formed and 3D printed NREL blade, scale 1:50. Below shows three usable segments, the tip is not present in this picture.

Focus area 2

Orientation



The second focus area is the orientation of the segment.
There are four different orientations considered;

Point-up, with the sharp TE on top and the centre of mass down (A).
Pros: Stable, reliable, easy placement.
Cons: Diffraction edge, wide base.

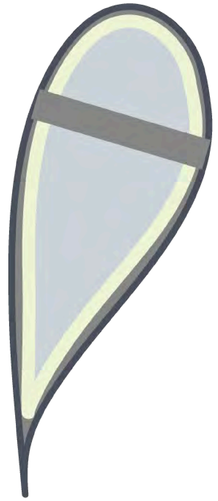
Point-down, with the LE on top and the point of mass up (B).
Pros: Leaves room for a frame, wider top, less diffraction.
Cons: Less stable, awkward placement.

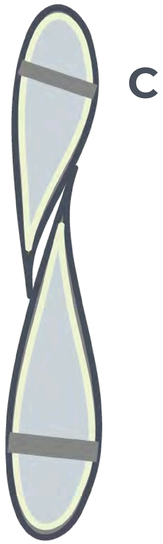
Both, the overlap of two more narrow pieces that together create a flatter and higher barrier segment (C).
Pros: Saves space, efficient blade use.
Cons: More fastening required, curvature must fit.

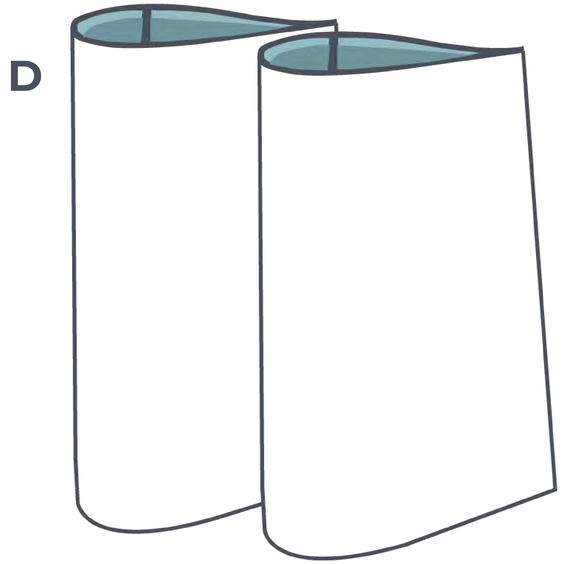
Vertical, where segments stand up straight with a little overlap (D)
Pros: Can go high.
Cons: less efficient in covering long distances, much more foundation poles.

Angled
The barrier will always chase the 10-20° angle sweet spot as this creates the most optimal deflection up into the sky of sound waves (Chapter 4.2.3).

Note: Horizontal top or bottom is dependent on different concept designs. Keep in mind the effective barrier height and drainage slit.

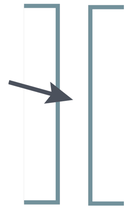






Focus area 3

Inter-segment connection



The third focus area is how segments are connected to each other. A connection is especially important for the acoustic seal, but also for the strength of the barrier. Because soundproofing and closing the ends are among the next focus areas that aim for noise reduction, inter-segment connection purely focuses on the structural connection between segments.

Thermal expansion
One of the main concerns when connecting large composite segments is thermal expansion. Wind turbine blades are made of glass fiber reinforced polymer (GFRP), which has a relatively low coefficient of thermal expansion (CTE).
For a segment of 12 meters and a temperature change of 40°C it will be about 1cm of expansion or contraction, which is relatively little (Appendix B).

Tolerances in geometry and alignment
In addition to thermal behavior, geometric tolerances of segments are an important consideration:

- **Saw cuts are not precise**: Based on visual inspection of collected segments and real world scenario thinking, the possibility of imprecise cut ends are high.
- **Profile mismatch**: Blades have a continuously varying profile, which means that if segments are cut from different locations, their outer geometry will not align. This became evident after playing around with 3D printed scale models.
- **Road geometry:** Highways are not perfectly straight or level, requiring barriers to be built along gradual curves and elevation changes.

Based on practical advice from Grevelink (PC, 2025), a tolerance of about 5cm between segments is recommended to allow for manageable assembly and misalignment.

Risks of a Fully Fixed Structure
Another reason to avoid rigid connections is related to structural safety and wind behavior. In a scenario where segments are rigidly fixed to one another, the entire barrier could behave as a single mass. If one segment fails under extreme wind loading, there's a domino effect: the connected segments may be pulled down with it (Grevelink, PC, 2025).

Rigid structures amplify stress concentrations. A system with built-in freedom of movement is far more forgiving and robust under realistic environmental conditions.

Conclusion: Segments are not rigidly connected.
Due to the combination of:

- Minimal thermal expansion
- Real-world cutting tolerances
- Varying blade geometry
- Irregular road alignment
- Structural safety concerns

Instead, segments should be mounted independently, with a small slit of about 4-6 cm between them. This gap provides freedom for movement and misalignment without transmitting stress or failure between elements. The acoustic sealing of this slit will be solved by the focus areas soundproofing and capping.

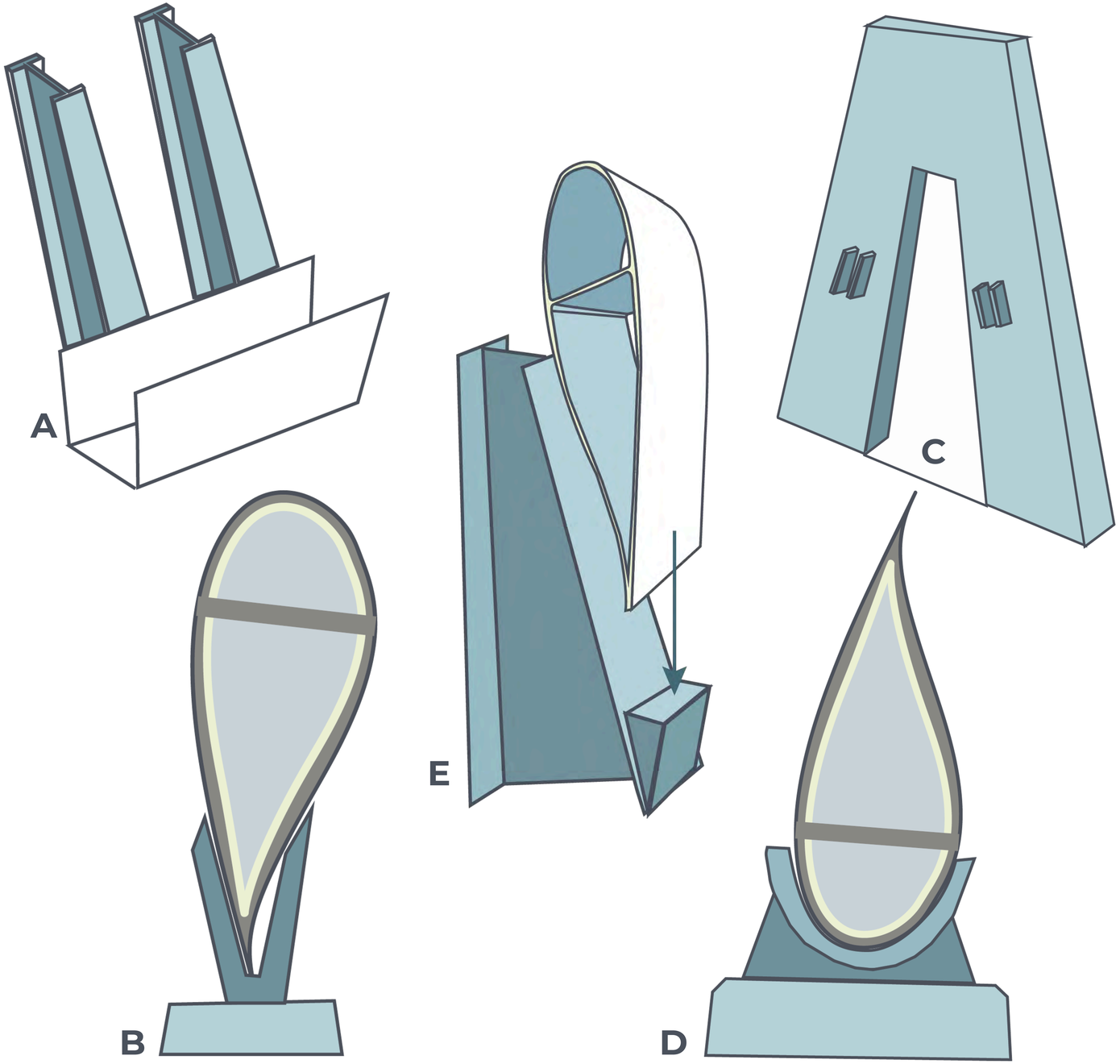
Focus area 4

Frames & Foundation

The frames and foundation are the most important structural contributors of the barrier. Without them, there would not be a barrier able to stand. Since wind is the biggest factor of load, and 12 meters make the surface twice as big as usual 6-meter designs, a good construction is needed.

Foundation itself is highly dependent on the location of the barrier, both wind region and soil conditions. These are out of scope. What will be considered is the amount of foundation and frames needed in terms of sustainability, and that the connection of the frame to the foundation are engineered strong enough.

- Concrete gutter with holed I-beams (raadliggers)(A)
- V shape for the blade (B)
- A-frame with movable foot where segments meet (C)
- U-frame every 6 meters (D)
- Big A-frame clamping the shear webs or spar caps (E)



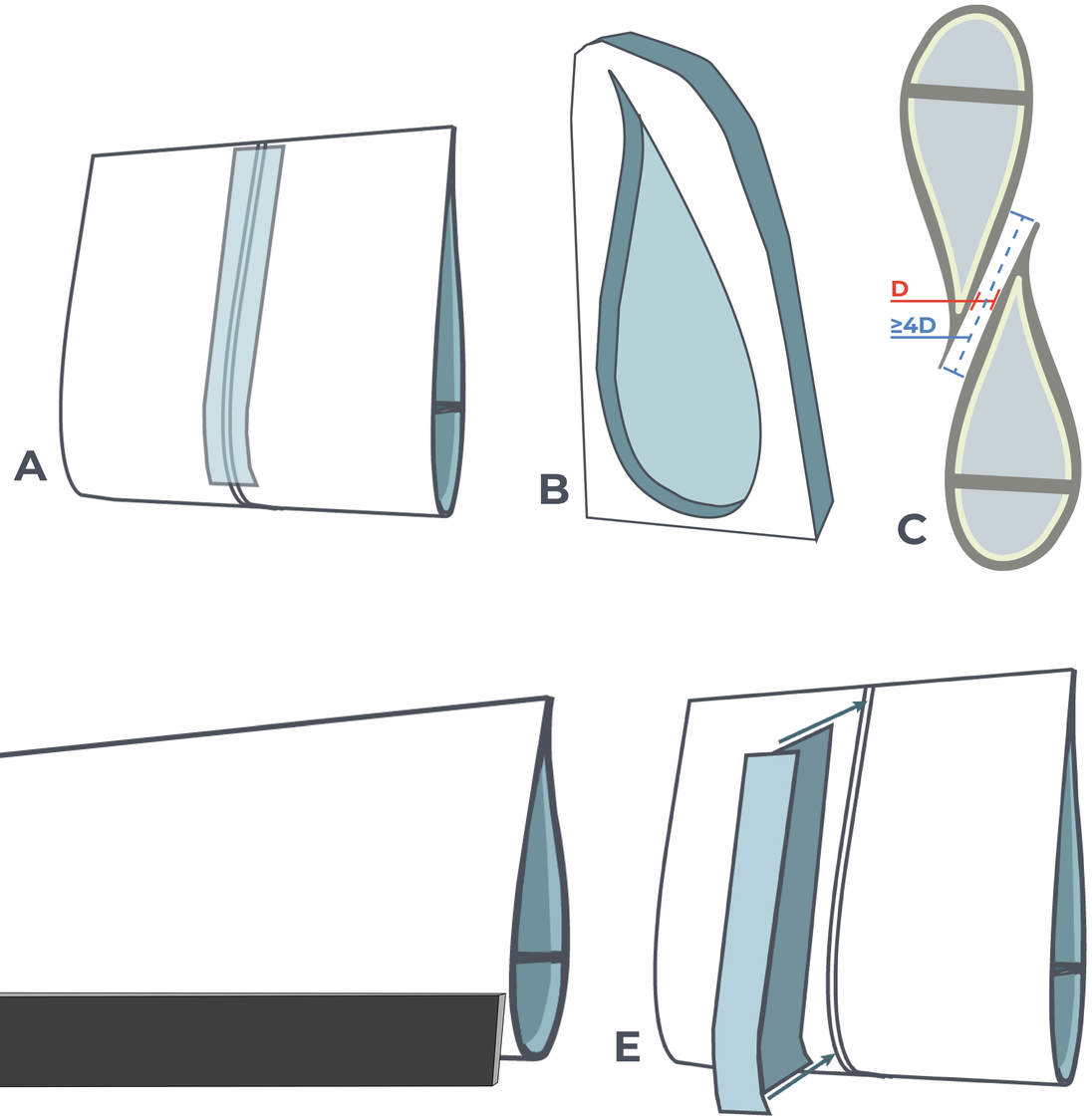
Focus area 5

Soundproofing

Soundproofing is making sure gaps and slits are sealed to prevent noise leaking through. The main areas of attention are where segments meet (WSM), and underneath the barrier. Mostly in current solutions a cover plate of steel or rubber is screwed onto the slits. There is also a drainage slit, but whether or not this is needed depends on the orientation of the segment, the placement and how big the slit is. Because the material is maybe prone to big mowers passing through every once in a while mowing the roadside vegetation, often a concrete plinth is there to protect the barrier.
The koios titan compressiet plates could be used here instead.

- Cover plate, glued or screwed (A)
- Cassettes 3D printed (B)
- Overlap 4XD (C)
- The Koios plinth (D)
- T-insert, rubber (E)

To reduce diffraction over the edge of the barrier, a T-top or some kind of extra could be incorporated. The focus does not lie with this extra component.

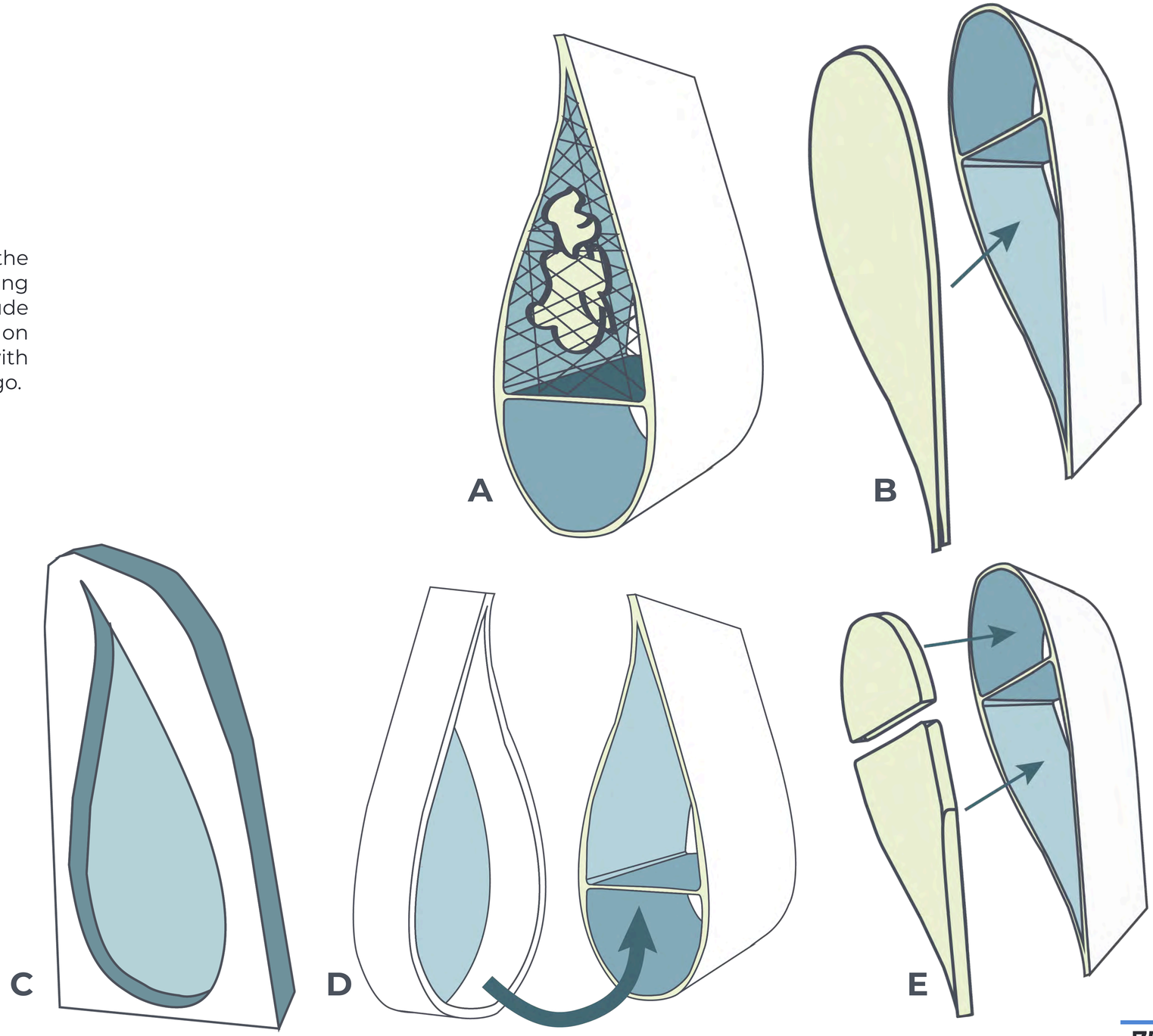


Focus area 6

Closing off the sides

Capping the ends is important for protecting the open edges of the segment against moisture ingress and unwanted animals crawling inside. For acoustic reasons, a resonance test should conclude whether closing the segment has a negative or positive effect on noise reduction (chapter 10.3). maybe filling it with shreds helps with sound absorption, but workers installing inside a segment is a no-go.

- Mesh and foam spray or coating (A)
- Glue a plate (B)
- Cassettes 3D (C)
- custom cap (D)
- Rubber inserts or half planks (E)



Focus area 7

Segment to frame connection

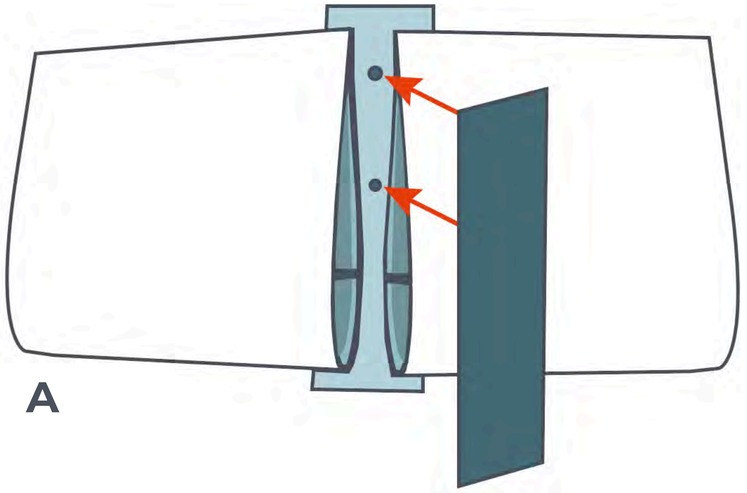
The segment has to be fixed to the frame, otherwise it would fall over by a strong gust of wind. Although keeping the segment untouched is desirable to not damage the laminates for subsequent lifecycles, it requires more investment to go for non invasive fastening methods.

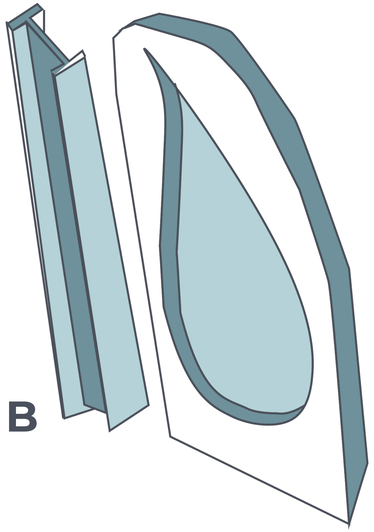
- Bolting clamping plates WSM into threaded tube (A)
- Bolting the cassette to a frame (B)
- Modular pin board that holds shape in place (C)
- 3D printed plate from the front in shape (D)
- Bolting through the back of the segment (E)

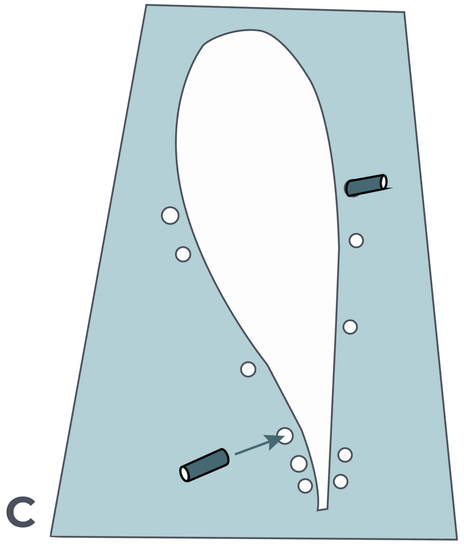
Drilling holes in the material comes at a risk of delamination, weakening the fibers in the material and compromising on blade intactness.

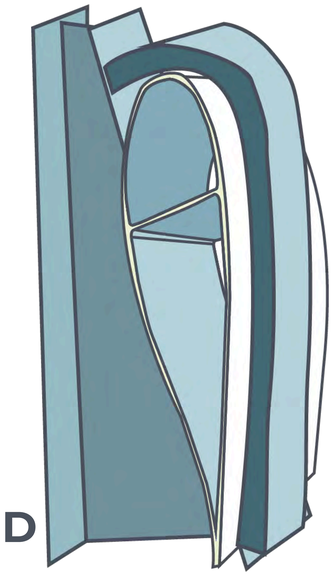
After seeking advice from experts, drilling a hole is not as big of a problem as it might seem. Increasing the contact area to enhance load distribution with a plate, or strengthening the hole with a bushing insert set with epoxy, the fixation in holes is sufficient (Grevelink, PC, 2025).

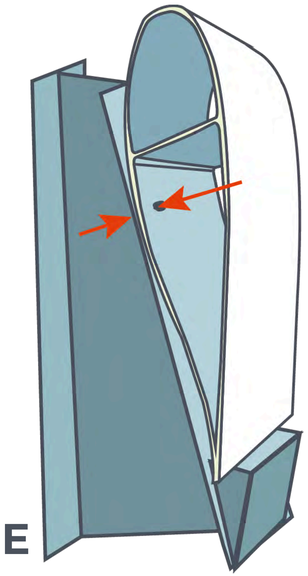
As for the intactness of the material, it is a balance between cost and simplicity of the construction VS non-invasive fastening designs. Every individual that got asked the question how significant 4 small holes in a 48m2 surface really are, said: not at all. If purely for aesthetic reasons they are easy to fill/cover up with epoxy.
Whether the holes pose a threat in jeopardizing the structural reuse of the entire segment is something that should be researched in later projects.











6.2
Morphological chart

Finally, after defining all the sub-functions of the barrier design into the seven key features, they were compiled into a morphological chart. This is a method from the Delft Design Guide (2013) used to find many solutions to a defined problem by deconstructing it into sub-functions.

The chart in Figure 39 shows the combinations:

- Combined Cassettes
- Shark teeth
- Bolted Balancer

More combinations with other sub-solutions were done in the iterative process, but these three concepts showed the most promising design directions. The upcoming chapter will explain the three in more detail.

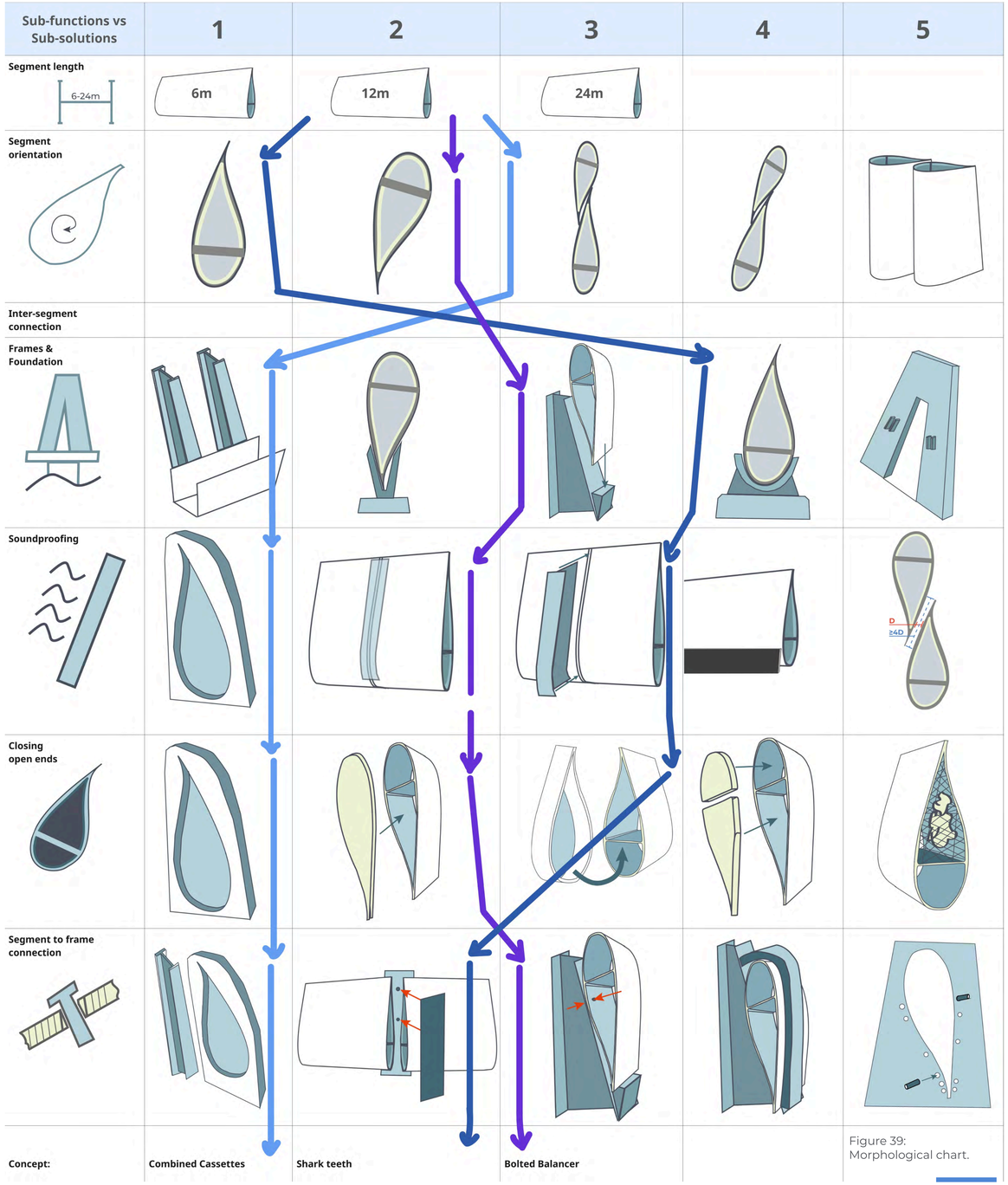


Figure 39: Morphological chart.

7.
Conceptualization

In this chapter, the three concepts that came out of the morphological chart are further developed. With their Pros & Cons and important implications, the most important criteria helped select which concept is most promising, and taken to the embodiment phase.

This chapter takes you through the following concepts:

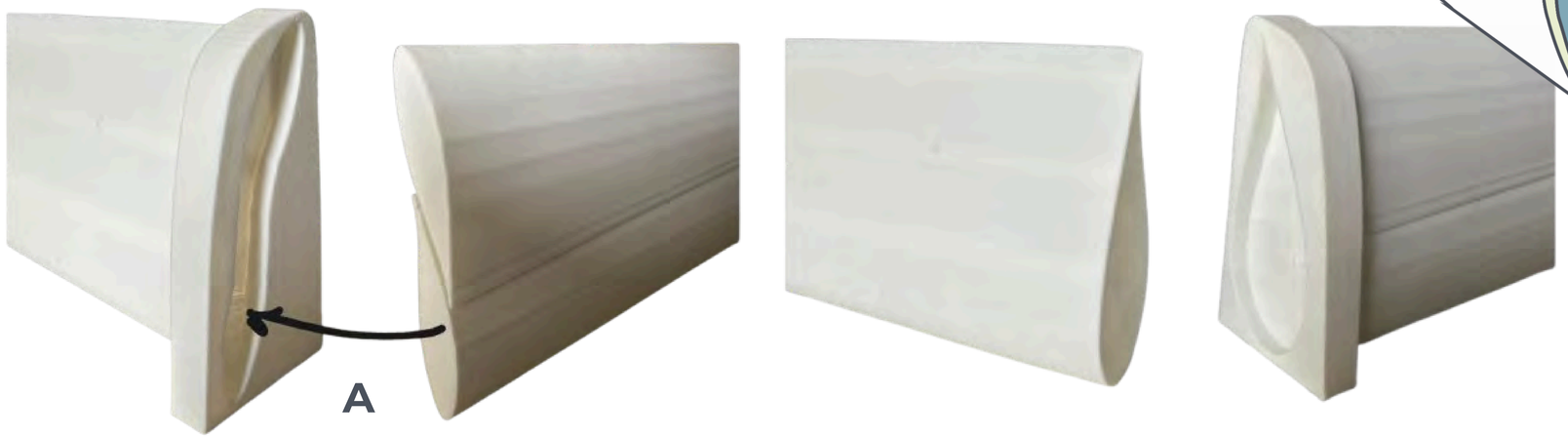
7.1 Combined Cassettes	**7.2 Jagged Jaws**	**7.3 Bolted Balancer**	**7.4 Implications**	**7.5 Evaluation**

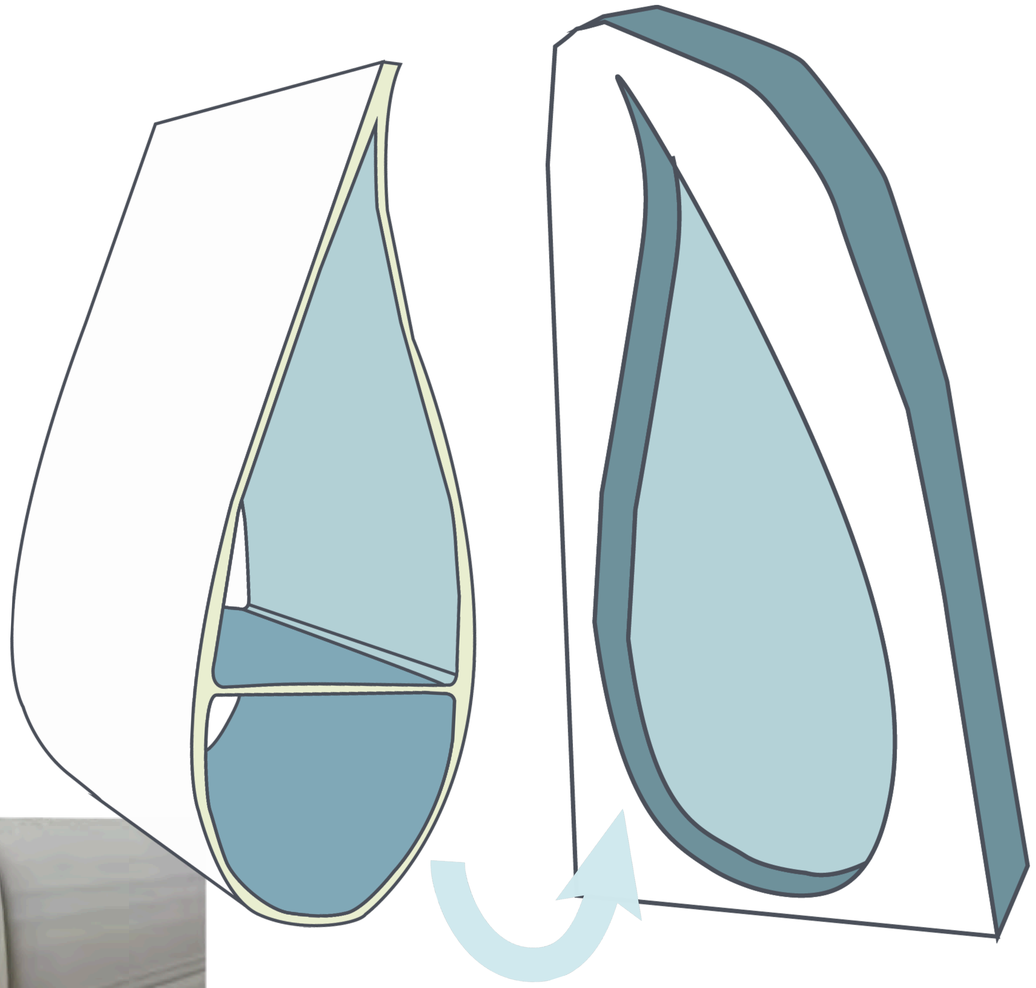
7.1

Concept 1: Combined Cassettes

Combined Cassettes features custom 3D printed frames from recycled WTB shreds. The cassette is tailored to the cross-section of the segment on both sides. Additionally, the cassette can be printed to accommodate a double blade configuration (A). The concept creates a ‘middle piece’ that gives the fitting of different segment profiles a more continuous appearance. The cassette is one unit with different insert in both sides. Such a shape is difficult but printable in large scale, the exact model needs more developing and the price depends on how thick it needs to be for strength (De Bruijcker, 2025)(Polyproducts). An alternative is to split the cassette into two simpler ones.

The segments and cassettes can be assembled at the blade processing location in order to make prefab units, that can be installed immediately. The Cassette is glued to the segment, making it a perfect capping solution to preserve and protect the blade material.



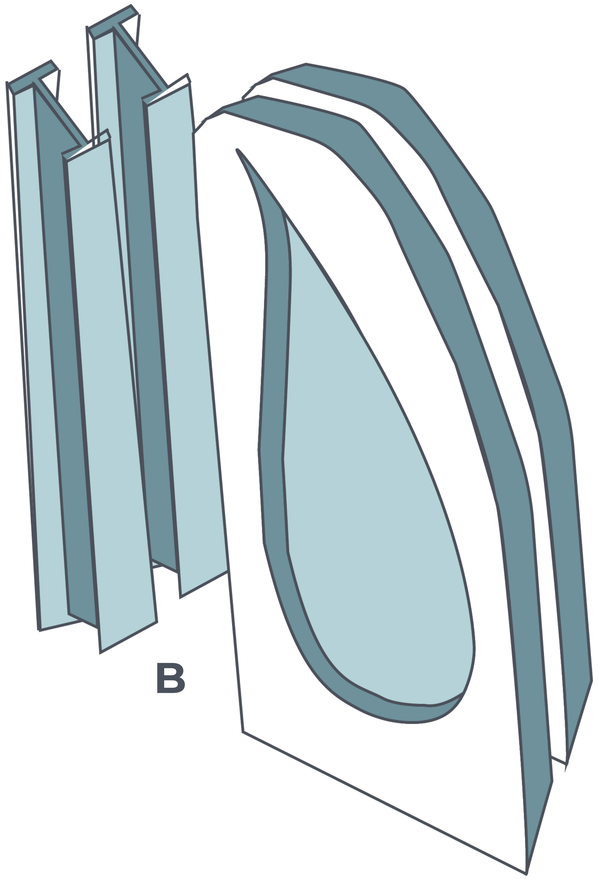


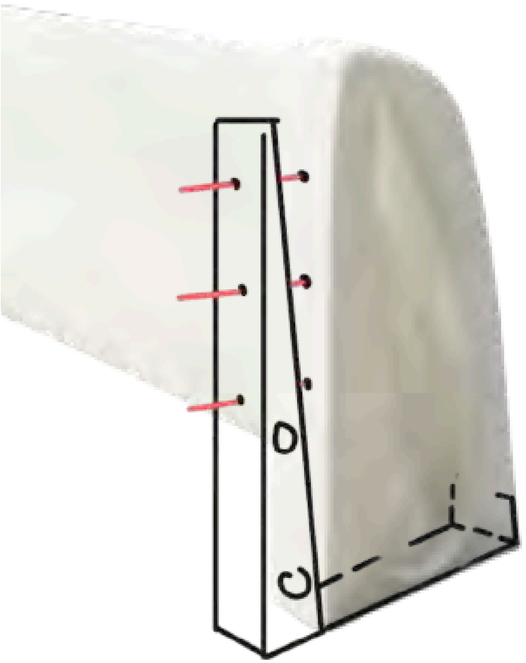
Frame and fastening
Because the exact stress tolerances of a 3D printed cassette are unknown and difficult to measure without a 1:1 prototype, a steel I-beam is added to the construction. Because a 12-meter segment fixed only at the ends with a relatively small overlap has to endure massive stresses (Nouwen, PC, 2025), the Cassette will be bolted on these steel pillars from the back (B).

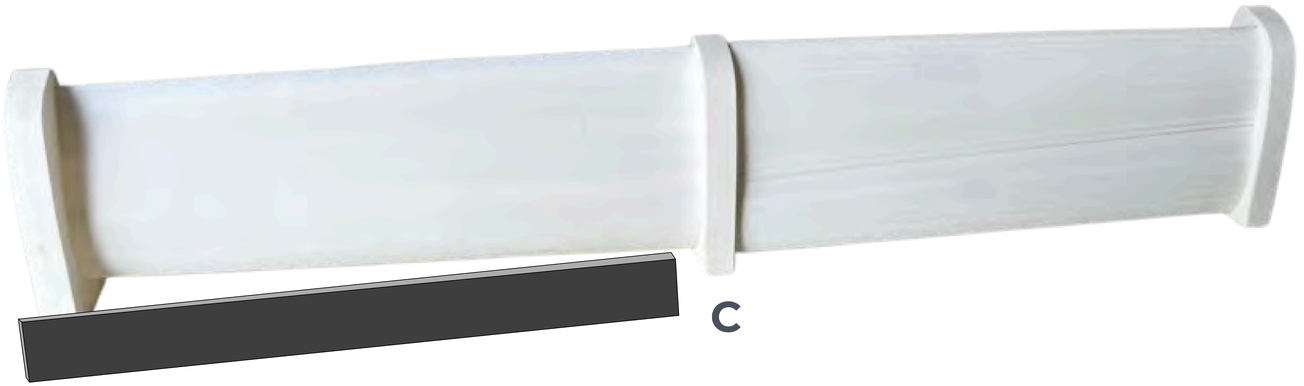
For acoustic protection, the slit between cassettes needs to be covered with one of the sub-solutions (cover plate or T-flap), and a plinth can be added to protect the underside against noise leakage (C). This plinth might need extra ribs or supports as a 12-meter span causes it to bend under its own weight.

Pros:
- Cassette is multi-functional: capping sides, protecting edges.
- Recycled material in cassettes and plinth.
- Horizontal top (height optimization).
- High wall with two smaller blade segments.
- Keeping blade material fully intact.
- Good blade to barrier ratio.

Cons:
- Since the connection of composite cassette to foundation might break, additional construction beams make the barrier wider.
- Tight tolerances of blades inserted in cassettes.
- Little freedom of movement if the road is not straight.
- Difficult to assemble the single cassette on site: shoving large blades sideways and lowering them is a puzzle.
- The overlap of the two smaller blades will not be possible with blades more curved towards the end.
- A double sided insert in the cassette will be difficult to print.
- Need for bespoke modeling, new technologies (expensive).
- The downside to the split cassette is that more different shapes need to be printed.





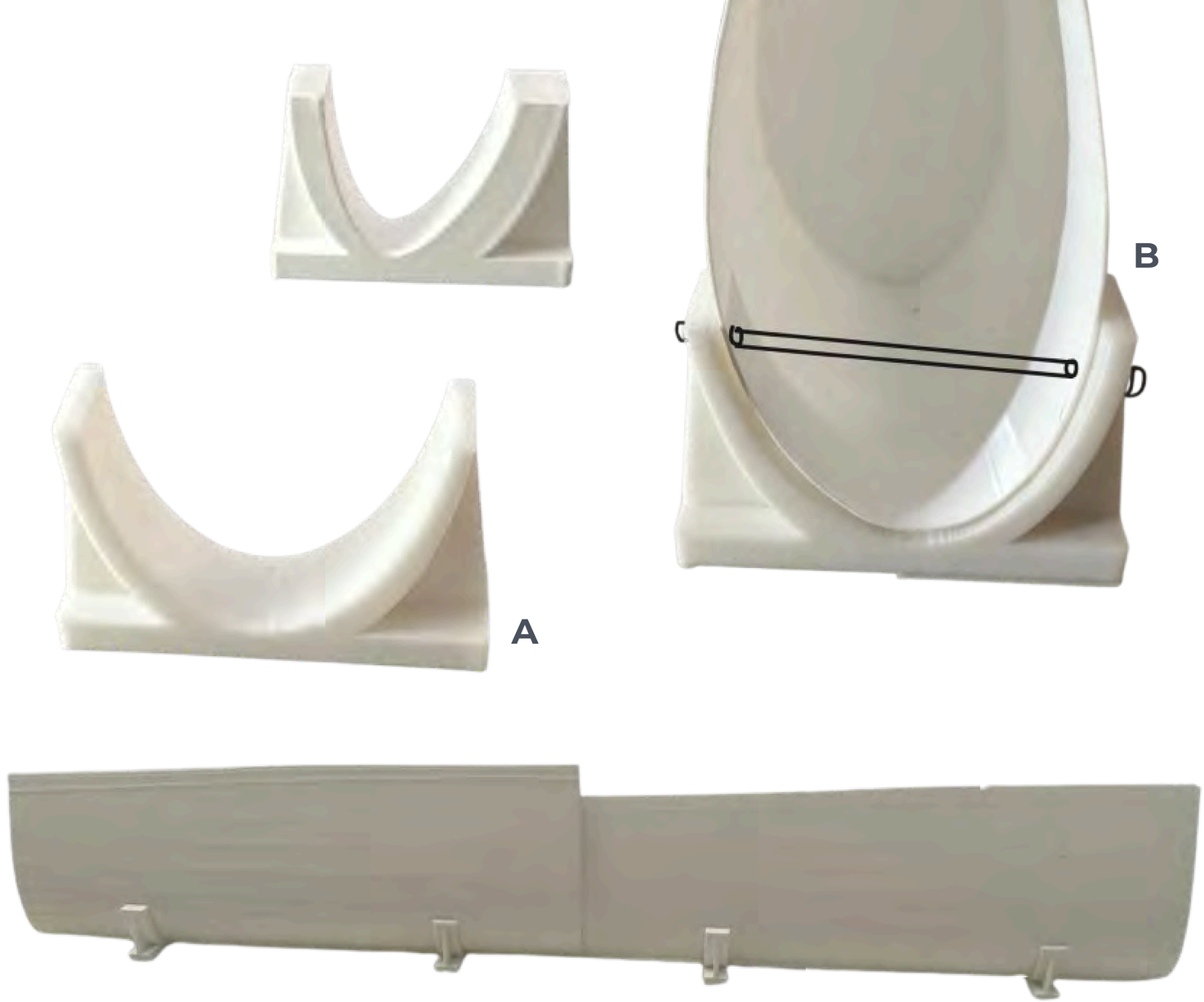


7.2
Concept 2: Jagged Jaws

The name comes from the jagged edge aesthetic that the top of the barrier gives when multiple segments are placed in a row. Jaws is for the shark and the frames. The segments rest with their LE horizontally on two U-shaped frames that are tailored for the blades cross-section (A). The frames stand 6 meters apart and accommodate a blade of 12 meters, to have equal spacing throughout a chain of segments.

Frame & Fixing
The frame has a bottom plate for stability which is bolted onto the foundation, a U-shaped plate profile for the blade, and two vertical ribs between the plates to make the whole frame more rigid. The blade is fixed in place with a through-all long bolt, through the spar caps (B).

With this design the spatial footprint of the barrier is significantly reduced, making it only a bit wider than the actual segment dimensions.

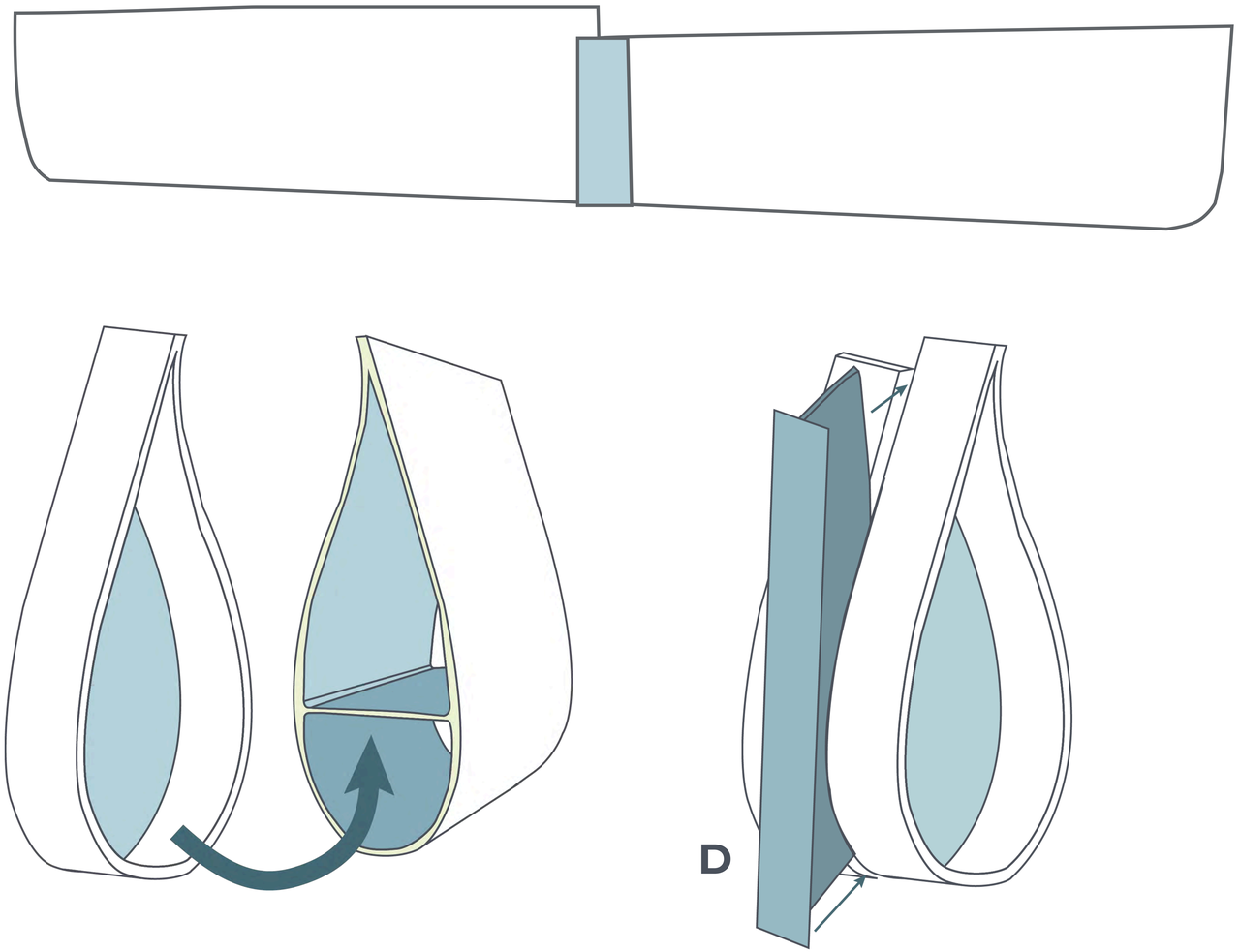


Acoustic sealing
The ends of the segments are covered with a lid in the shape of the cross-section (C). The slit in between the segments is acoustically sealed with a rubber T-shaped beam that fits in (D). This is screwed into the lids, to minimize damaging the blade with screws.

Pros:
- Relatively easy to place segment into frames.
- Efficient spatial footprint.
- Directly considered manufacturable (Grevelink, PC, 2025).
- Modular: 6 frames and 3 segment sizes make different barrier heights.
- A lot more freedom in tolerances.
- Can go through gradual corners, up or down hill.

Cons:
- Excess material due to minimal barrier height.
- Jagged look could be disturbing the road-users at high speeds.
  - (but it gives the effect that you can still see it were old blades).
- Invasive holes in material.
- Less efficient full blade use for one barrier, more efficient for different height barriers.
- Sensitive to diffraction.

Extras:
- An additional plinth of compressiet similar to concept one.
- A rubber slab in the frame for grip, material protection and tolerances.
- Pre-installed through-all long bolt to save assembly time.

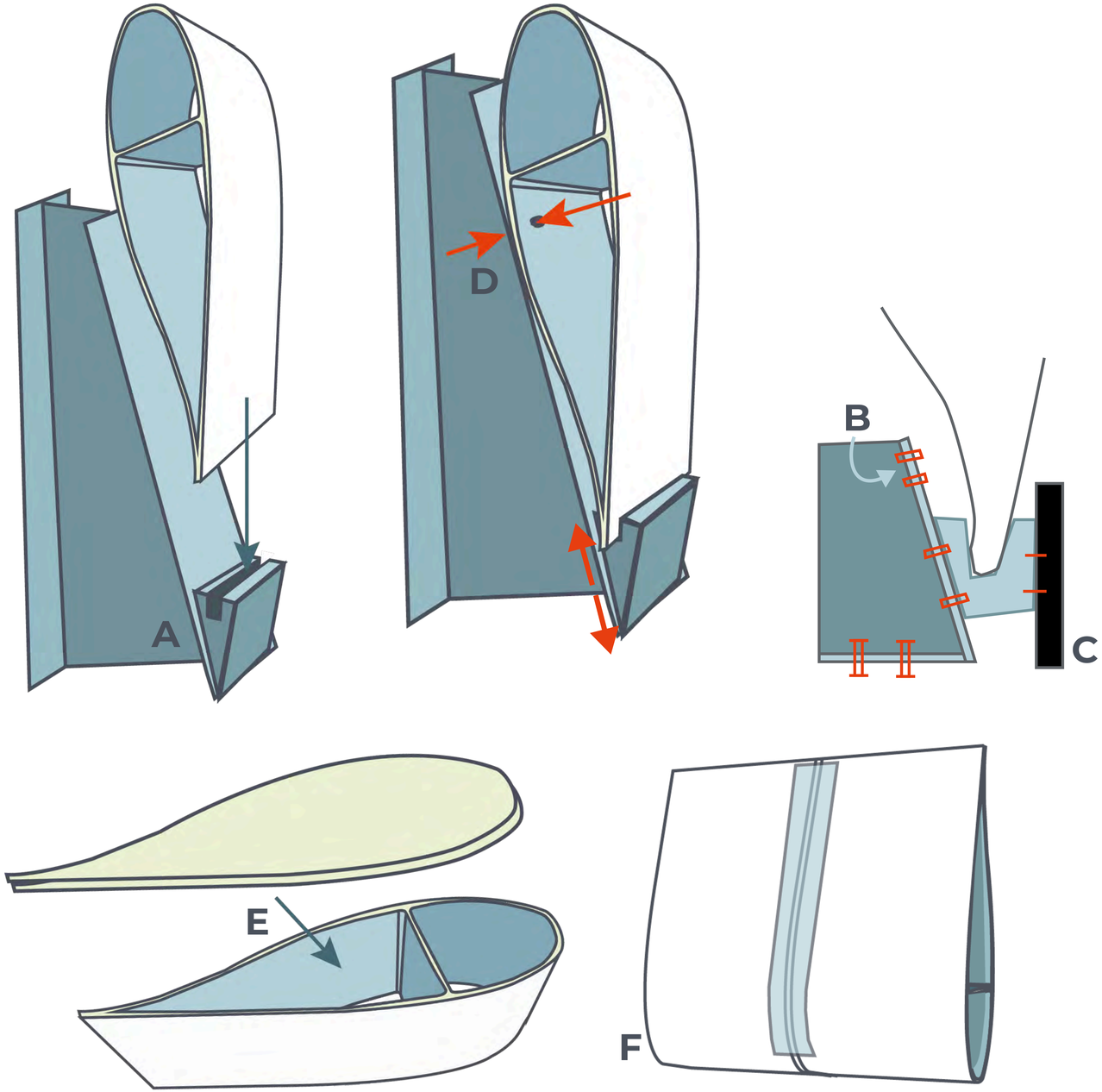


7.3

Concept 3: Bolted Balancer

In this concept, the segment is placed with its TE down in an adjustable block, to orient top of the barrier horizontally. The idea behind this orientation is to enable more space for the placement of frames (A). The A-frame's wider base makes it stronger and is fixed to the foundation. The adjustable support block is bolted on the A-frame, which has extra holes to accommodate different blade heights (B). The slot to insert the TE provides rubber for protection. The majority of the construction is made from steel parts.
The compressiet plinth is bolted onto the support block (C).

Fastening & soundproofing
The blades are secured with bolts from the back to the frame (D). These bolts need big washers to spread forces, which are pre-installed before covering the ends with glued cover plates to protect the edges (E). These plates are shaped as the cross-section of the ends and could possibly be pressed from compressiet as well. The acoustic seal where segments meet is a cover-strip (F), that can be fastened in the sides of the cover plate.



When adding the double blade segment, An extra frame component is needed to align them with the top and the road-facing surface of the barrier (F). The smaller blades are bolted on a separate component, which is fixed to the frame (G).

Pros:

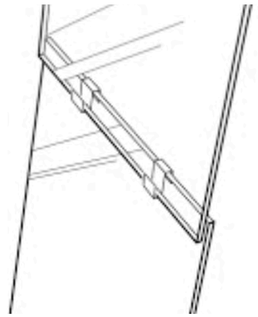
- Efficient space use and spatial footprint.
- Recycled composite material in caps and plinth.
- One base A-frame, with modular options (no custom frames).
- High wall with two smaller blade segments.
- Good blade to barrier ratio.

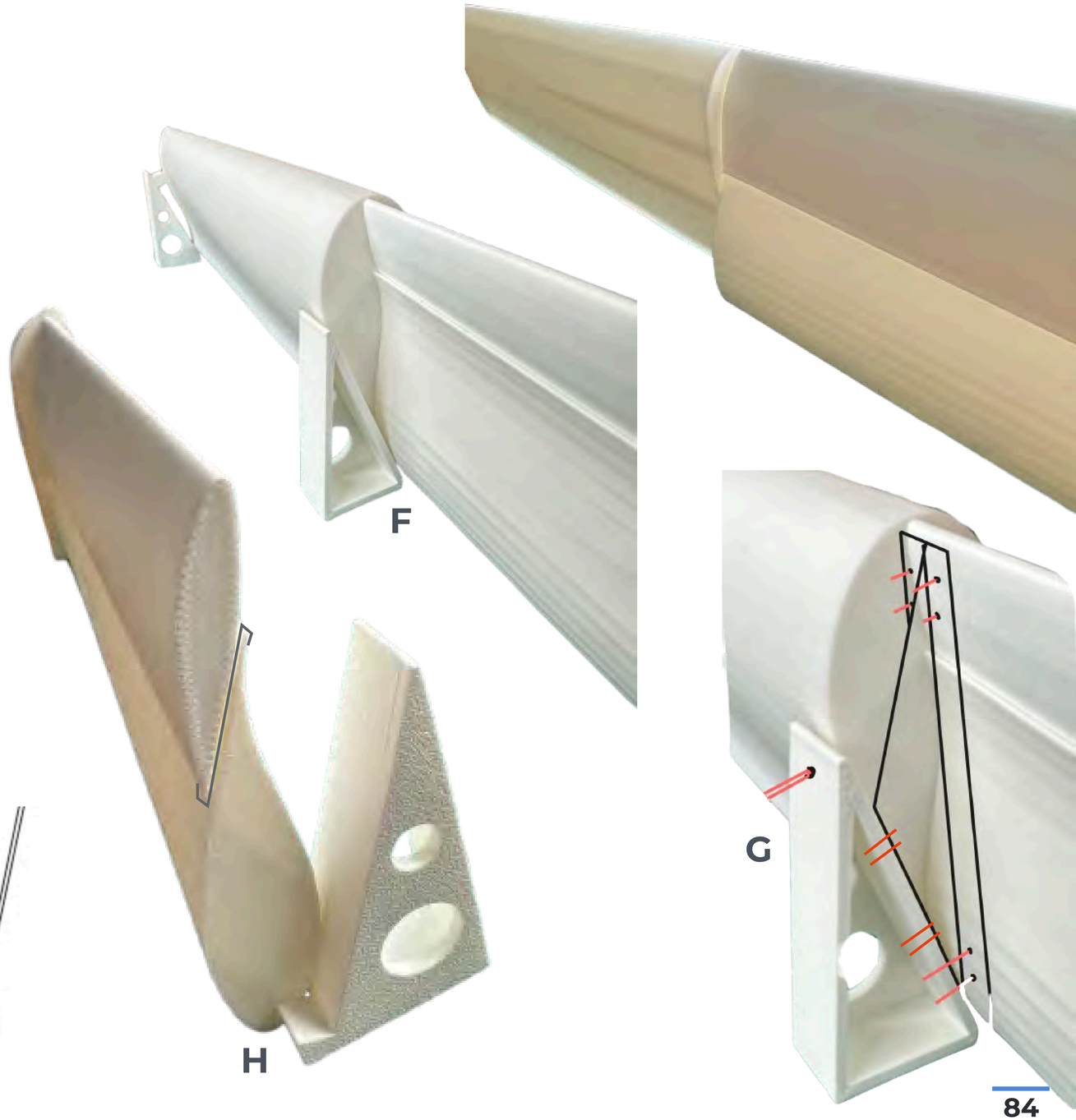
Cons:

- Relatively high number of components.
  - Higher costs, manufacturing steps and assembly time.
- Complicated multi-shaped construction where ends meet.
- Invasive holes at ends for bolt securing.
- Questionable structural reliability of bolts.
- Odd center of mass for placing and balancing on frame.

Extra:

- Additional hooks could be placed between two smaller blade segments to distribute their weight on both the fasteners and the lower segment (H).





7.4
Implications

After prototyping and iterating on all three designs, some of the pros and cons raised questions about their feasibility and started important discussions with experts. These are the biggest design concerns:

- After reviewing the profiles of the end of the segments, which are supposed to connect as seamlessly as possible, big differences in the models were evident, especially ones with a double smaller-blade configuration (See F on previous page). The thickness of the barrier would jump from close to 2 meters to about 50 cm. These differences result in difficult frame setups, in order to keep the front of the barrier a continuous surface.

- Although some of the frame concepts did account for this difference, constructors at Heijmans discourage a situation where a frame is multi-complex because it houses different sizes. It is extremely costly to make and horrible to set up: “I can guarantee you will run into problems if you don’t work with tolerances. For placement, badly cut edges and thermal expansion” (Grevelink, PC, 2025).

- Especially for the third concept, difficulties with hoisting the segment with its sharp edge down seemed like a challenge. In comparison to placing a blade with the LE down, where the center of mass is stable and can be craned with two bands and a ‘lifting equator’ (Figure 40), the LE down creates a shape that cannot be craned the same way. The center of mass wants to fall over and the sharp edge balances on the bands, that even might break. Vugts (PC, 2025), confirmed it would be possible to construct a ‘lifting frame’ for the shape, but this would add cost and complexity to installment. Another way was to use a big gripper or clamp (B) but it was unsure how much it would be able to lift. To conclude, placing the segment TE down is possible but both the sub-solutions named need extra effort to realize.

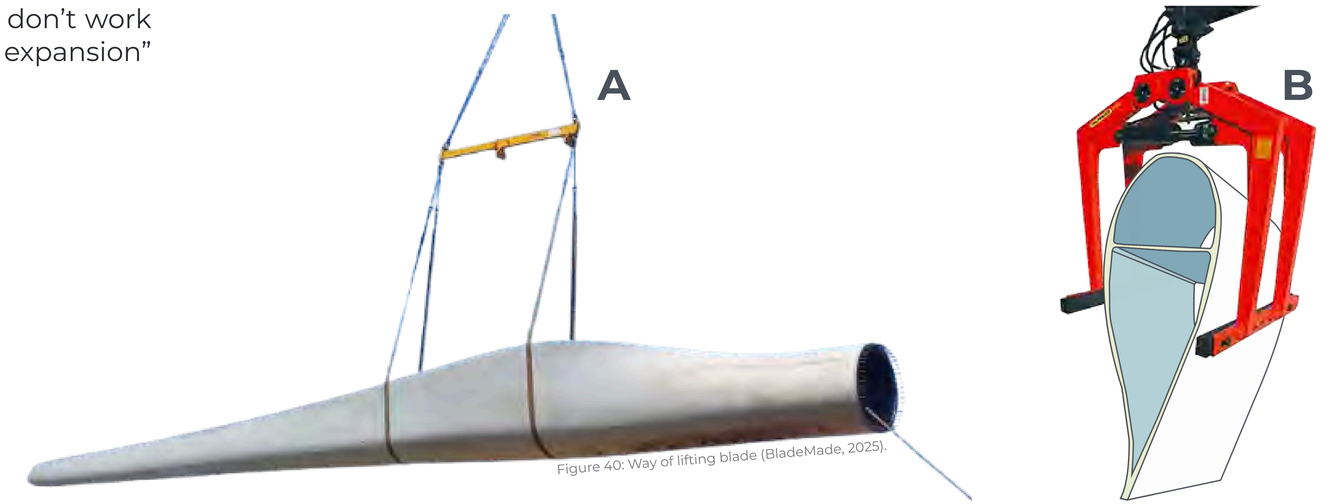


Figure 40: Way of lifting blade (BladeMade, 2025).

- Drilling holes in composite is another attention point. This will require special tooling and has risk of damaging material by delamination (Chapter 2.5.3). Next to that, how much forces are applied on the material through bolt anchoring and will it withstand the wind force? Van der Vinne (2024) Did a test to see how many people could hang on a bolt through a plate of WTB material and it could carry 2.7kN (275kg)(Figure 41). Later bolt calculations are done in Chapter 8.3.

- Another concern regarding structural load bearing was gluing the end caps together. The stresses on these bonds are very complex to calculate and therefore unreliable (Nouwen, PC, 2025). Assuming the glued end caps can carry the weight of a segment is questionable, let alone withstand strong winds. Gluing is not impossible, but since no reliable numerical values can be assigned to adhesive bonds, they may not meet the required standards. Bolted connections on the other hand, can be calculated and verified without complications, which is why they are preferred. In addition, permanent glued connections are not desirable for subsequent reuse, while bolts can be undone more easily.

- Lastly, engineers at Heijmans expressed their doubts about the fatigue strength of composite products like the 3D printed cassettes. With the endless load cycles of wind, is difficult to predict how a shape holds up. Another concern is placing the foundation 12 meters apart. It is 6 meters for a reason, such a large surface needs a lot of foundation and huge frames to stay upright and remain within the 50 mm top-middle deflection limit (Nouwen, PC, 2025).

Figure 41: Hang test on WTB material plate (van der Vinne, 2024).

7.5
Evaluation

Keeping the implications in mind, the three concepts were evaluated using a weighted criteria method. In combination with the MoSCoW method to determine the priority, they were ranked based on their performance on 8 criteria.

What is the MoSCoW Method?
The MoSCoW method is a prioritization tool used to categorize project requirements into four levels of importance:
Must-haves, Should-haves, Could-haves, and **Won't-haves** (Vpadmin, 2023). This is where the acronym stands for.

Must-haves are essential for the project to succeed. Without them, the project would fail or be incomplete.
Should-haves are important but not vital. They add significant value, but the project can still function without them in the short term.
Could-haves are nice to include if resources and time permit. They enhance the result but are not necessary.
Won't-haves are agreed to be out of scope for now, either because they aren't needed or because they don't fit within current constraints.
This method helps align priorities and make informed trade-offs during development.

The criteria in Table 3 are ranked as following:

- **Must:** structural reliance: It cannot fail and fall.
- **Should:** Pre-processing & Manufacturing: It has to be somewhat viable, otherwise it won't even be built.
- **Should:** Assembly time: It has to be easy and fast to install, time and workforce costs money.
- **Should:** efficient sound reduction: It has to be good at mitigating noise.
- **Could:** Keeping material integrity: It keeps the WTBM intact for subsequent lifecycles.
- **Could:** Efficient space use: It is efficient in claiming space alongside the road when it is placed.
- **Won't:** Blade to barrier ratio: A lot of a single blade can be turned into usable noise barrier.
- **Won't:** Modularity: The design is modular and can be applicable for more than one project.

Outcome

Surprisingly, the jagged jaws concept ended up with the highest score in the assessment. Although the 3D-printed cassettes were a personal favorite, the concept's complexity and uncertain structural reliability made it too difficult to pursue. While the level of detail for each concept was limited due to time constraints, a choice had to be made. The jagged jaws concept appears to be the simplest and most reliable option and will therefore be developed further in this thesis.

Criteria	Description	Combined Cassettes (1-10)	Shark teeth (1-10)	Bolted Balancer (1-10)	Weight (0 to 1)	Weighted Score (Cassettes)	Description	Weighted Score (Jaws)	Description	Weighted Score (Balancer)	Description
Criteria	Description	Combined Cassettes (1-10)	Shark teeth (1-10)	Bolted Balancer (1-10)	Weight (0 to 1)	Weighted Score (Cassettes)	Description	Weighted Score (Jaws)	Description	Weighted Score (Balancer)	Description
Structural reliance	Reliability of frames and fasteners on many load cycles.	7	8	6	0.2	1.4	little known on 3D printed composites.	1.6	Steel is good, but design needs to be run by expert. friction	1.2	Bolts through blade material can fail
Pre-processing & Manufacturing	Special parts and frames (cost related)	6	8	6	0.15	0.9	Custom printed cassettes, two types and standard beams	1.2	Two types of frame, drill holes, make a cap lid.	0.9	specialized A-frame with moving foot, attachment hole
Assembly time	sub-assembly steps, ease of construction	8	7	6	0.15	1.2	Scanning ends, Printing and capping, hoisting in place	1.05	capping, placing,drilling on location and fastening	0.9	capping, more difficult crane work, fastening, adjusting
Efficient sound reduction	Soundrecutive messures	8	7	9	0.15	1.2	Good seal all around	1.05	more smooth surface, but diffraction	1.35	round top more effective than sharp
Keeping material integrity	Need for invasive fasteners, open edge protection	10	6	7	0.1	1	no need for invasive connections in blade material	0.6	need for few holes in 12m segment, glued lid	0.7	2 or more bolt holes
Efficient space use	Spacial footprint of barrier	6	9	10	0.1	0.6	With additional beams behind	0.9	only a bit wider than segment	1	Very efficient
Blade to barrier ratio	Efficient use of one blade	9	6	9	0.075	0.675	3/4 of blade, 25m of barrier	0.45	depends on hight needed	0.675	3/4 of blade, 25m of barrier
Modularity	Freedom in roadside placement	5	9	6	0.075	0.375	low, rigid configuration, small tolerances	0.675	6 claws 3 semgent highly modular in height and movable	0.45	Adjustable but bad with unexpected tolerances
			Total		100%	7.35/10		7.53/10		7.18/10	

Table 3: Weighted criteria to determine which concept is best, with the help of MOSCOW method.

8.
Concept iteration

In this chapter, Jagged Jaws goes through another iteration where many topics are highlighted and explained in more detail. Apart from the seven key focus areas, this chapter includes; The consideration of similar segment use, force calculations, roadside acoustic orientation, the trade-off between barrier execution considering a serrated or horizontal top.

This chapter takes you through the following topics:

8.1 Use of similar segments

8.2 Acoustics of road-facing curvature

8.3 Wind on the barrier: Forces modeling

8.4 The U-Frame & Foundation

8.5 Fixing the Segment in place

8.6 Shear web location

8.7 Connecting segments, soundproofing and closing

8.8 Protection

8.9 Placement & Aesthetics

8.1

Use of Similar segments

A lot of thought went into the connection between segments.
Unless the cutting edge matches, e.g. when the barrier uses the gradual height decrease of a full blade when approaching the end, the airfoil shaped profiles are quite different.
To maintain effective barrier height and group similar profiles, segments of the same group are used for the barrier height most applicable for them.

In other words, a barrier with a required acoustic height of 4 meters will be constructed from segments A, while a barrier of 3 meters will use segments B (Figure 42). For one barrier design, segments A and B will not be adjacent. As discussed earlier in key focus area segment length, the consideration is to use the segments effectively per barrier height, having less material stick out above the minimum.

The reason segments are not mirrored and fit with the same cutting plane is because of the difference in curve. As shown in Figure 43, the trailing edge ends up creating a V-shape opening.

The reason for placing the blade segments with a jagged edge rather than with the top lined up horizontally, is covered later in chapter placement (8.9).

Modularity
The barrier design with U-frames will have 3 different segment sizes, each with two custom U-frames. With these components 3 different heights of barrier can be realized with 6 different frame sizes.

One could argue that this strategy leaves a lot of material untouched, but this will be repurposed in other projects. In the evaluation chapter (10.6), a more detailed description is given what exactly happens to the rest of the blade and what other initiatives there are.

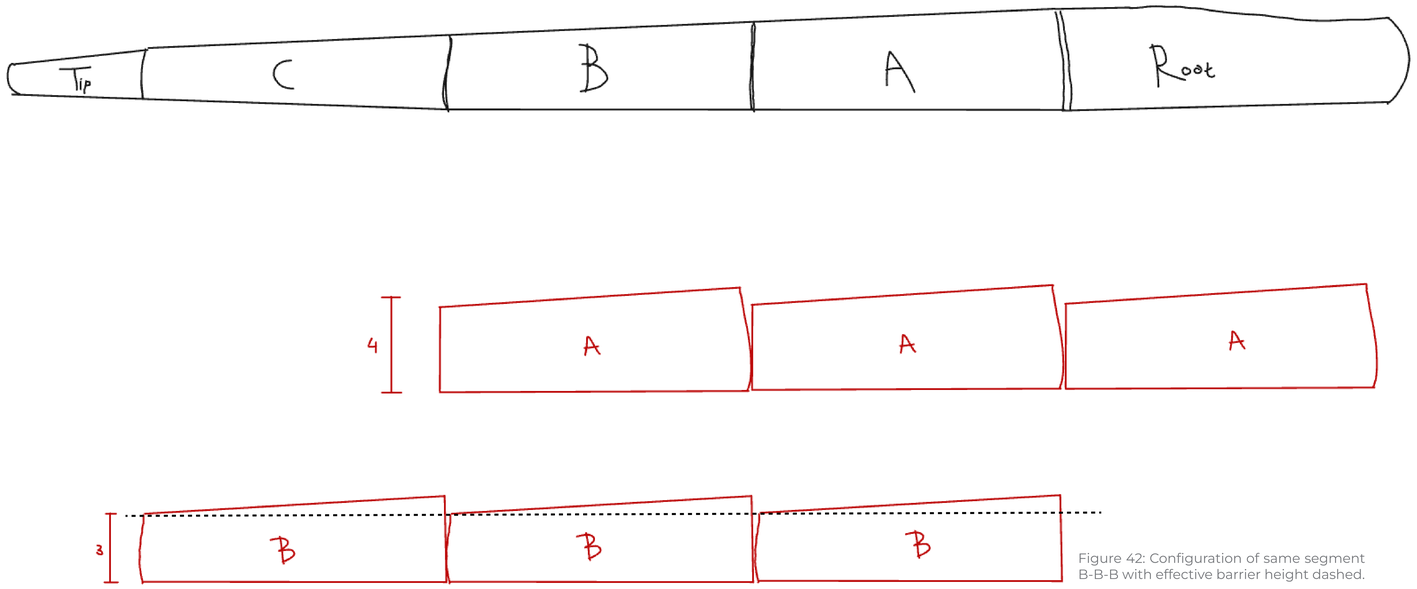


Figure 42: Configuration of same segment B-B-B with effective barrier height dashed.

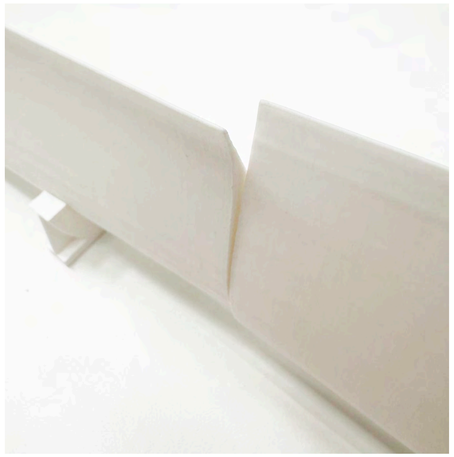


Figure 43: prototypes show V-opening at the top.

8.2

Acoustics of road-facing curvature

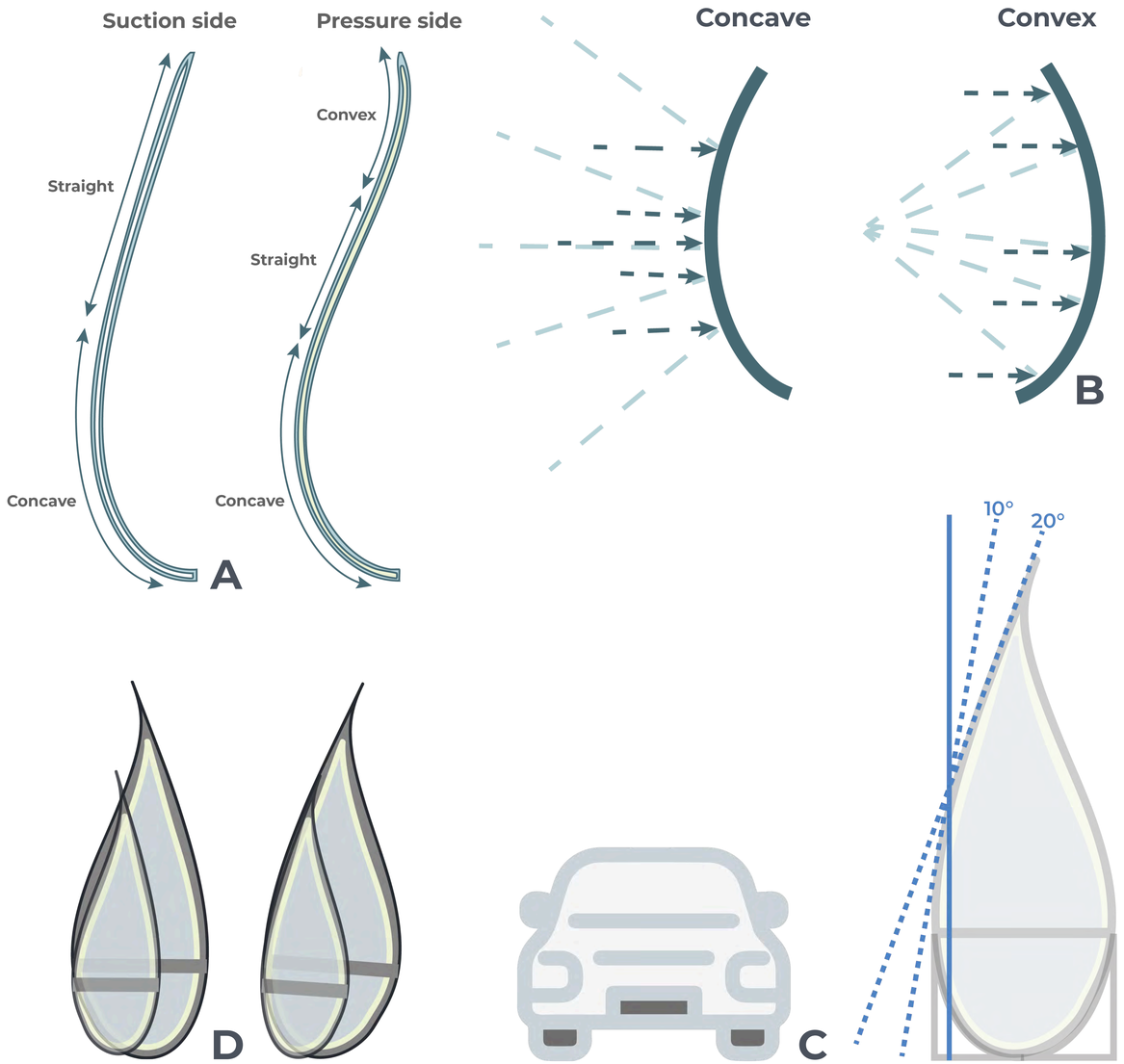
There are two sides of the blade with different curvatures, the pressure side and the suction side (A). Consequently, when placing the segments as noise barrier units with the LE down, there is a side facing the road, and a side facing the resident. A few important factors decide the preferable orientation of the segment, which is the suction side as road side.

Convex & Concave
In principle, a reflecting concave shape redirects sound waves outward, while a convex shape redirects or focuses them inward (B).
Because the pressure side of the blade has a convex on its top, the sound might redirect back towards the road user, while the straight surface of the suction side will always reflect sound upwards.

Next, the concave surface on the bottom of the barrier will reflect the sound down, but this is absorbed by the asphalt or grass, and wont cause any further noise problems. (Van Amstel, PC, 2025). If there will be a plinth placed in front of the barrier, the plank covers the area and creates a flat surface, eliminating this topic all together.

Another notable reason for a preference in the suction side as road side is that after prototyping and evaluation, the shapes of the different cross-sections where segments meet, have a better, more continuous connection (D).

Implications
When a vertical surface is tilted backwards, its height decreases slightly. A 4m high barrier on 20° tilt backwards will loose about 25cm. However, in case of a WTB segment, the TE is pointed straight upward and LE rests in the frame, while the curve of the cross-section creates a naturally angled surface (C). Consequently, the chord length is the same as the acoustically effective barrier height.



8.3
Wind on the barrier: Forces modeling

Assumptions
Before any calculation or engineers advice, some assumptions were done on the structural capabilities of a blade barrier and the U-frames. For example, a WTB flexes in the length but will be super strong in torsion on segment scale (Chapter 2.3). Another assumption was that the Moment-arm would be significantly reduced due to the thickness of the segment. Instead of a pole with base-plate/height ratio of 1 : 10, the U-frame would have a ratio of 1 : 2 to 3 (Figure 44). lastly, a rubber seemed to add extra grip and contact area between the blade and the frame, preventing rotation.

To get an idea of the forces that act on the barrier and the bolts that anchor it, a calculation was done with the help of lead engineer Nouwen (PC, 2025).

Force of the wind
First, the force of the wind was determined (Fw).

- The Netherlands has three wind regions, the first region, northern coastal Holland and islands, has the strongest winds (Figure 45).
- The location was taken in region-1 with flat fields around, without obstructions, e.g. houses or bushes.
- The Fw on the barrier depends on the area and location from the end, in this case middle so zone-D (Figure 46)

These factors lead to a **Fw of 0,76 kN/m²**

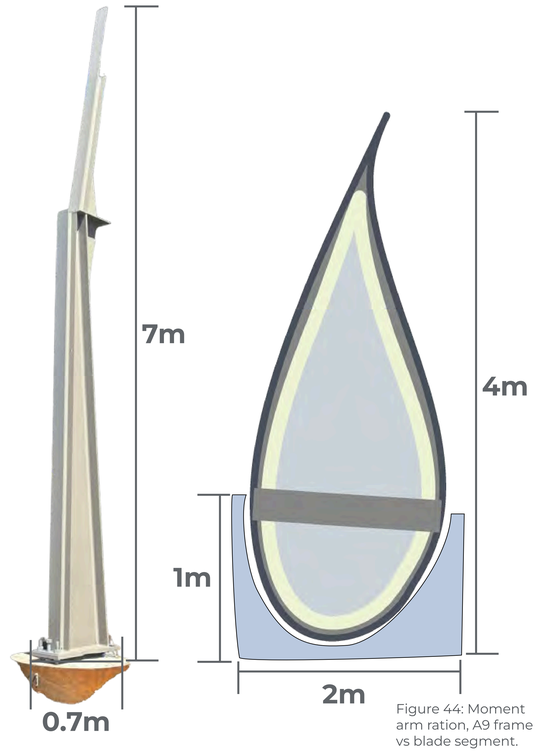


Figure 44: Moment arm ration, A9 frame vs blade segment.

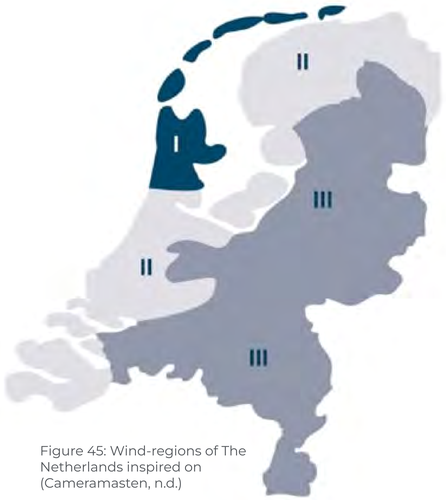


Figure 45: Wind-regions of The Netherlands inspired on (Cameramasten, n.d.)

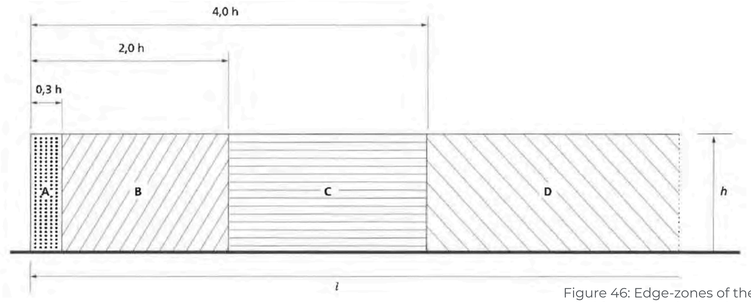


Figure 46: Edge-zones of the wind force on noise barriers (CROW, p.58, 2012).

Forces on frame & bolts
Second, the forces on the frames was calculated with a simplified model.

- For length 12m and height 4m.
- Assuming the vertical load Fz is 0 because the segment rests on the ground.
- Assuming the calculated Fw of 0,76 kN/m²

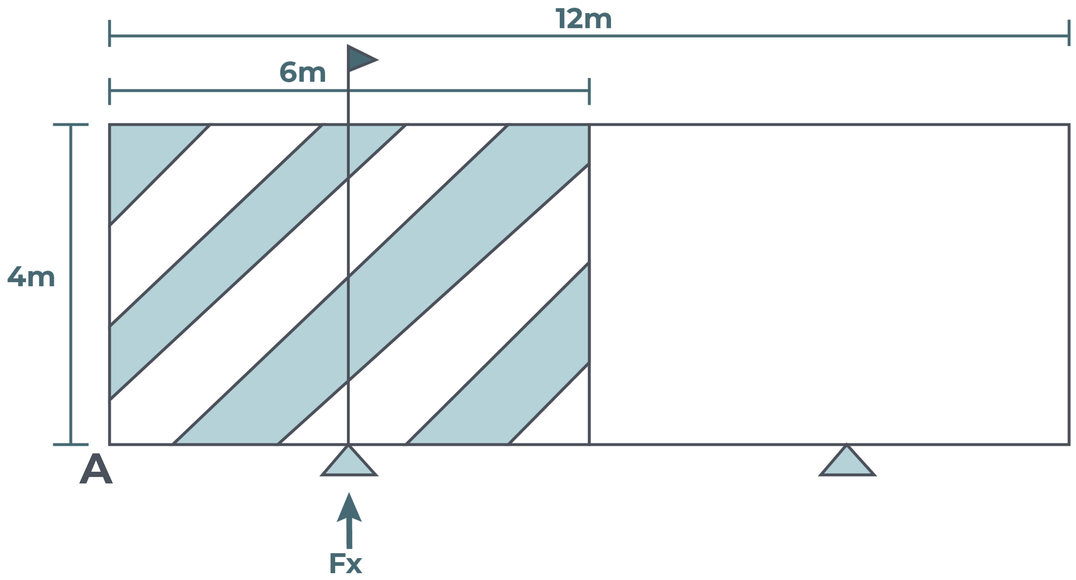
The horizontal load per frame is calculated by wind force times area: Fx = Fw*12*4/2 = 18,2kN (A)

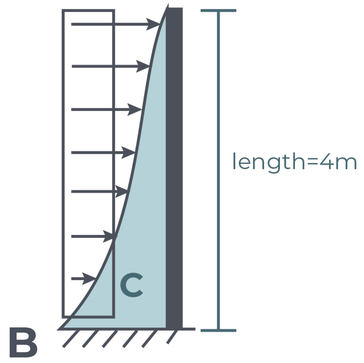
For the maximum bending moment, a section of the panel is taken and simplified to a fixed-end beam with an uniformly distributed load ($C=0.5ql^2$) (B). Here, 0.5 is a constant, q is the length of half the panel and l is the height of the barrier.

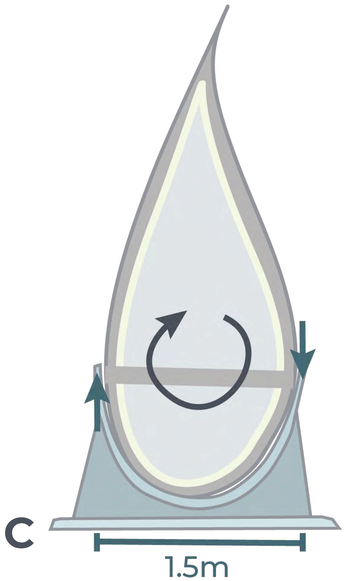
The moment results in: My = 0,5*6*4² = 36,5kNm

Third, the forces on the bolts are calculated by dividing the moment by the arm (C); Fbolts = My/arm = 24,3kN
Usually, a safety factor of 1.5 is added to this, resulting in an ultimate force of **36,5kN per side**.

Nouwen (PC, 2025) emphasized that these forces are not surprising to him, and relatively low, which confirmed one of the initial assumptions. Further design choices based on Fbolts will continue in the next two chapters about frames and fasteners.





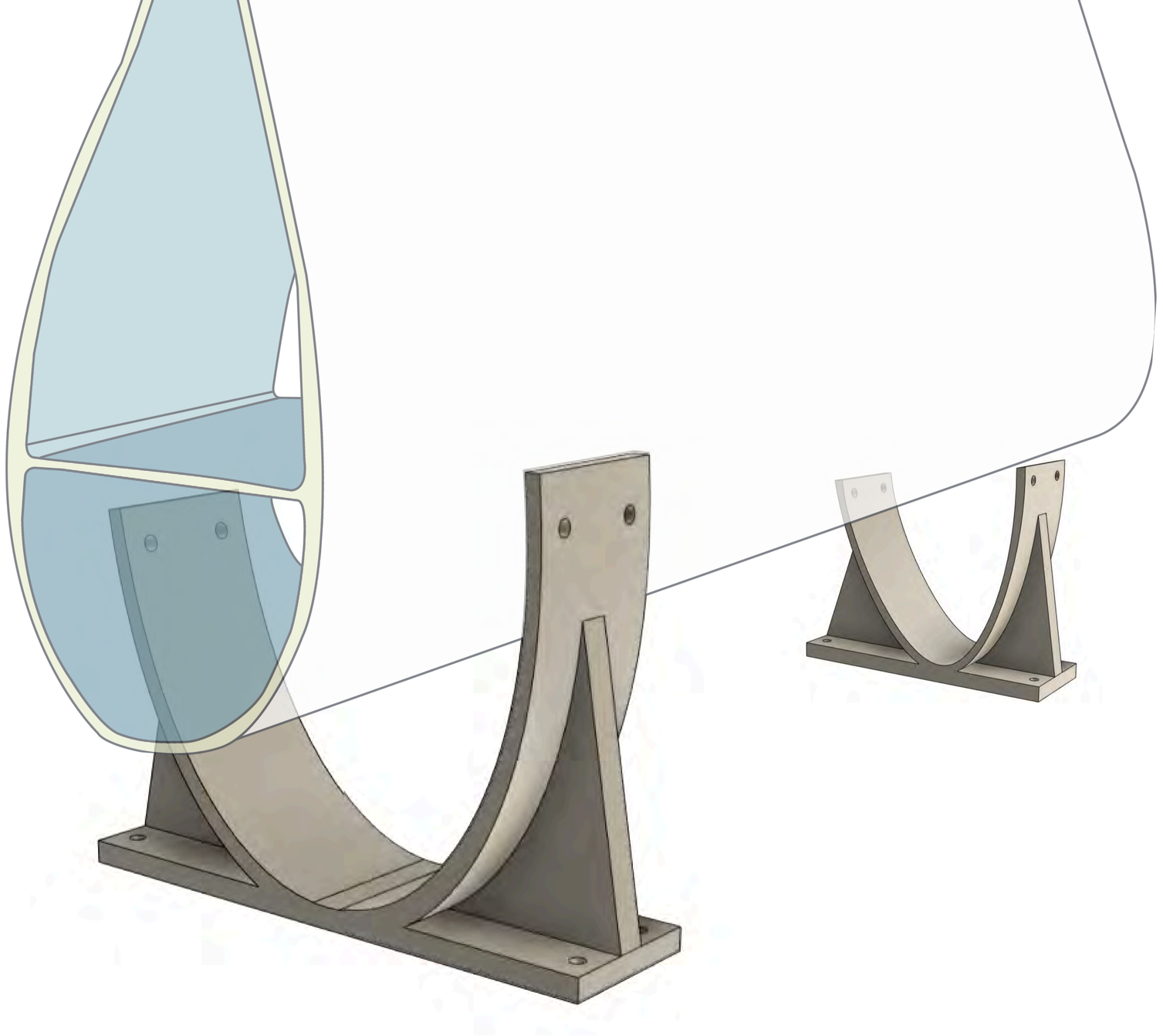


8.4
The U-Frame & Foundation

The previous design of the U-frame followed the exact taper of the blade. due to the added complexity of fabricating such a part, the design was simplified and further iterated on. The new U-frame consist of a steel plate bent around the LE, reaching up to the spar cap areas, a base plate that fixes it to the appropriate foundation, and vertical ribs to increase the rigidity of the frame. The ribs leave the U-plate partially free to accommodate slight bending for tighter segment fixing. This chapter still contains the iterative process, the final frame design, fabrication steps and specs are covered later in embodiment chapter (9.1).

There were four iterations to test a few assumptions:

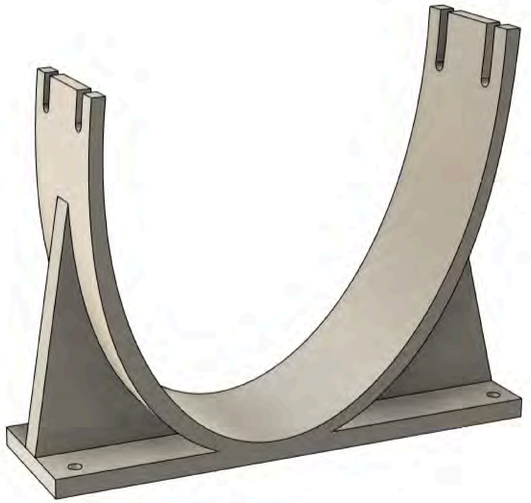
- The height of the frames on the blade surface.
- Holes or slots in the frame for the bolts.
- minimizing material and fabrication steps.
- Going for a more modular approach.



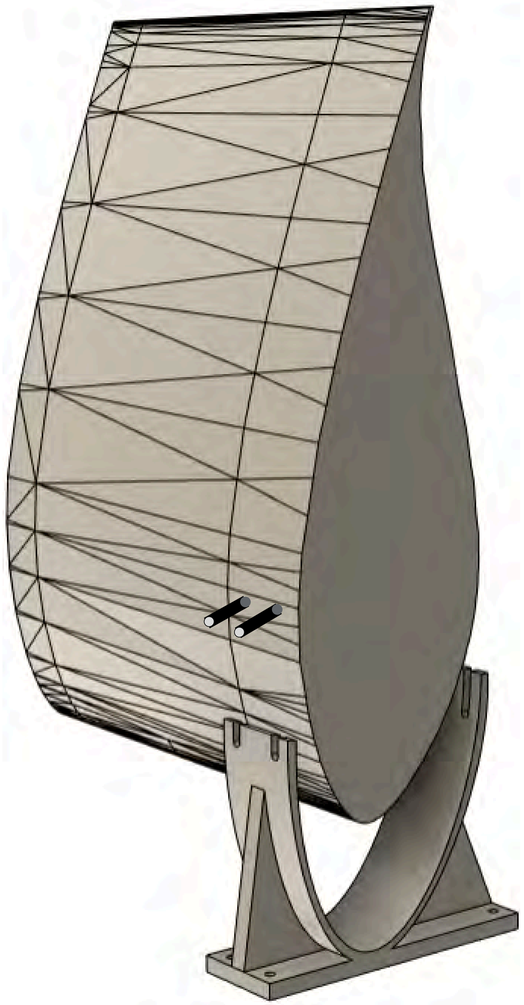
Slots iteration
The open bolt slots iteration (A) was developed to save time with drilling on location because the bolt thread would be inserted prefab. However, this idea would be much weaker compared to closed holes according to Nouwen (PC, 2025), as the bolt would not be kept in place by the surrounding material on the vertical, most crucial load direction. Additionally, The anchors of bolts would be more convenient to drill after the blade segment is placed and angled correctly, avoiding line-up tolerance issues.

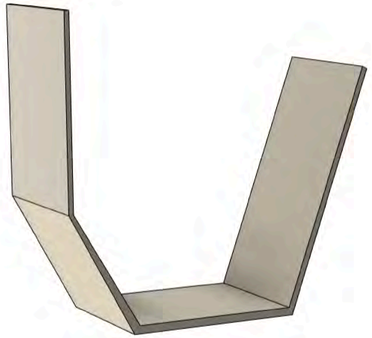
The height of the frame was altered between the original and the slot design, and quickly concluded that the best height of the U-s was until the widest part of the segment, covered later in shear web location (8.6).

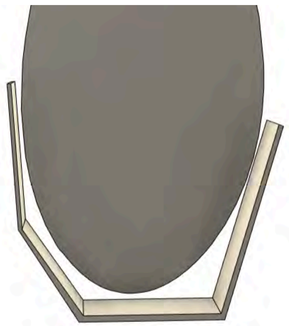
Minimalistic iteration
The second iteration was a folded steel frame with simplified curves (B). Although this design has less contact area, it is much more material efficient. The problem with this design however, was bolting it onto the foundation with a smaller footprint, making it weaker. Although this frame saves virgin material use, it does not make a significant difference in cost with the stronger frame when produced in large quantities (Nouwen, PC, 2025).



A







B

Modular iteration

The third iteration focused on a more modular design, where the U-frame is split into two J-frames (Figure 47). The idea was to make a standard size for all barrier heights, being able to move the J's closer together. Although this simplified the frame even more and is more suitable for mass production, after reviewing the concept together with engineers at Heijmans, some critical design aspects came to light (supported with Figure A to F):

- The bottom would be conflicting when placing it closer together (A).
- Even after simplifying the design (B) the foundation would become complex as to multiple fixing point (C).
- Bolts might conflict on the inside with the segment (D).
- The shape would loose structural rigidity because its no longer attached (E). This also raised questions whether it is still true to assume the weight is resting fully on the ground.
- The size of frames would become inconvenient when scaling down, and the shape of the turbine would never be as flush (F).

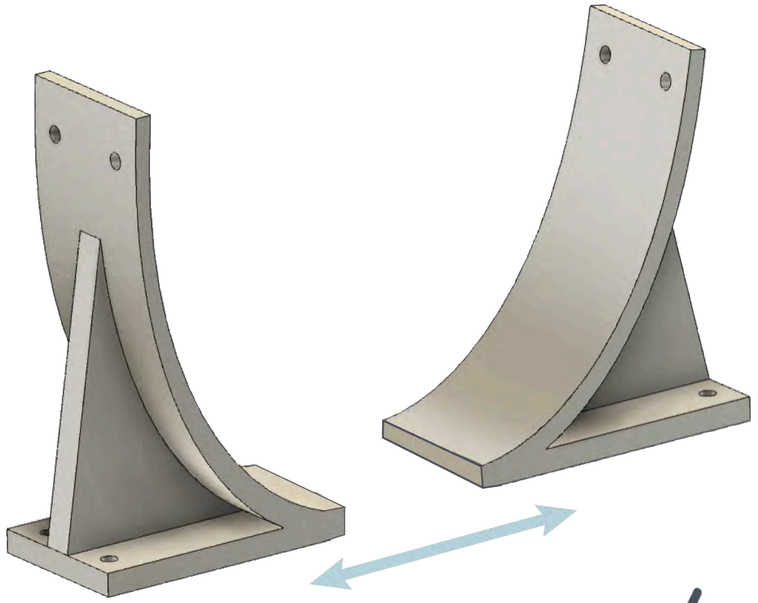
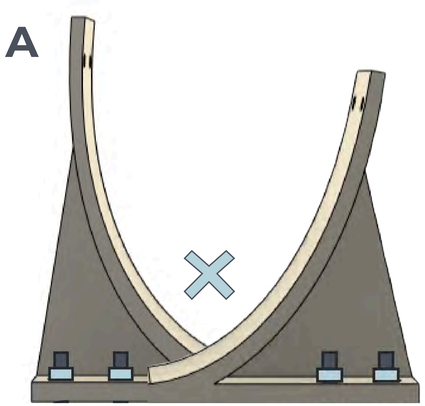
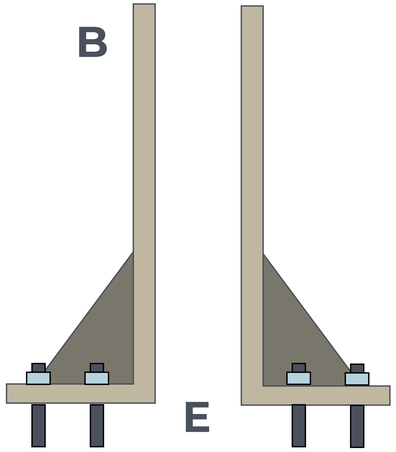
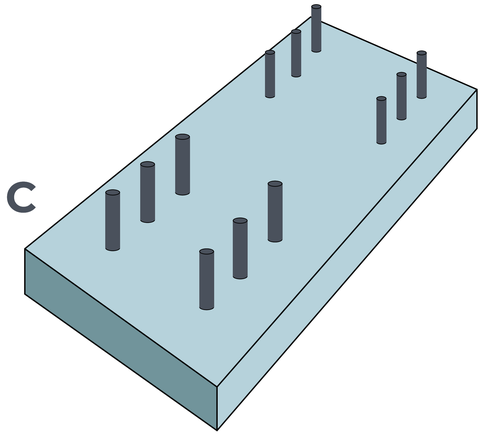
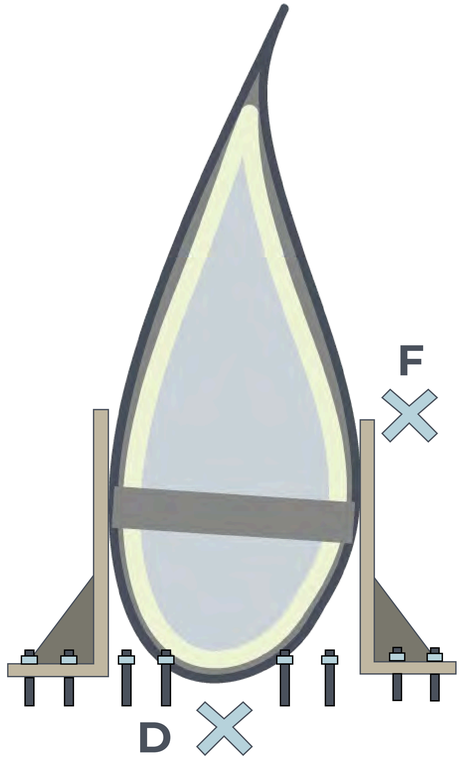


Figure 47: J-frame moves to shape of blade.









Rubber lining sheet

In the U-frame a rubber sheet was added to protect the blade segment (Figure 48). This allows for tolerances in blade and frame dimensions, and adds contact area for a tight alignment. For faster pre-assembly, the lining will be a full sheet of about 3m, preferably already fixed on the U-frame to avoid slipping during placement of the segments. If material has to be minimized, the rubber could be divided in three separate sheets, but extra glue/ processing steps are needed (Figure 49).

Additionally, the rubber sheets seal the freshly drilled holes from any moisture ingress and safe time on additional epoxy treatment.

Lastly, the rubber needs to be covered by the frame, because UV exposed rubber will deteriorate over time. This rules out the design where a rubber flap is added without glue, but hooked on the edges of the frame (Figure 50).

Shear force

At first, the assumption was made that the rubber would increase grip and strengthen the frame against the moment forces. However, after closer inspection, the bolts require as little distance to the material as possible, otherwise the shear causes a moment in the bolt (Figure 51). When it comes to the addition of rubber, the distance it creates between the frame and segment's surface, increases the forces and is not contributing to a stronger bond. Still, a thin layer of about 1-3cm is desired for reasons mentioned above.

Figure 48: Rubber sheet inlay in U-frame.

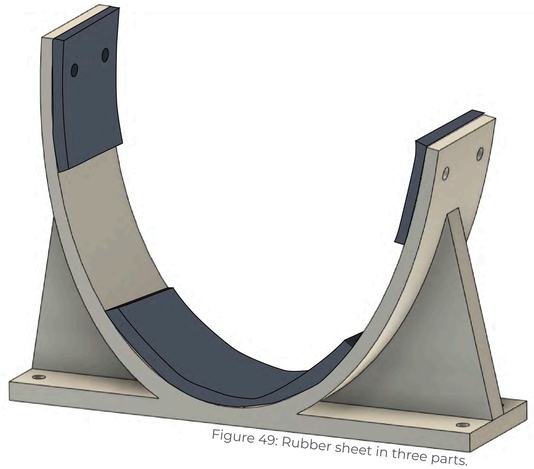


Figure 49: Rubber sheet in three parts.

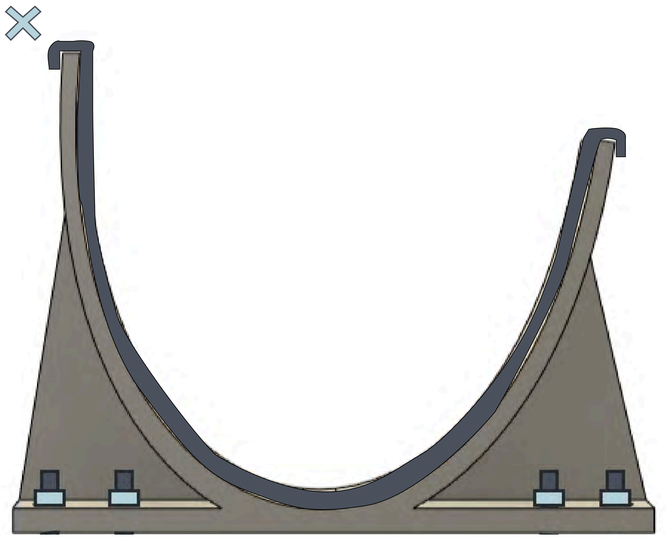


Figure 50: Rubber sheet with edge hooks.

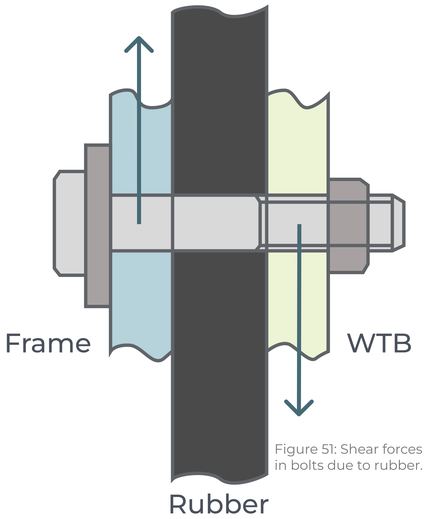


Figure 51: Shear forces in bolts due to rubber.

Frame to Foundation
The U-frame is bolted onto its foundation with 4-8 anchor points.
Washers or plates will need to be placed between the base plate and the nuts, depending on final detailing (Nouwen, PC, 2025). As noted before, the foundation itself will not be elaborated further as the projects scope focuses on the above-ground structure.

Options could include: a large concrete block with one big pole or two smaller poles. Or The frame can be fixed directly onto two smaller poles (Figure 52). Against corrosion and for easier inspection of the bolts, it is best to place the frame on concrete, slightly above ground level. This conveniently adds a few centimeters of height to the barrier.

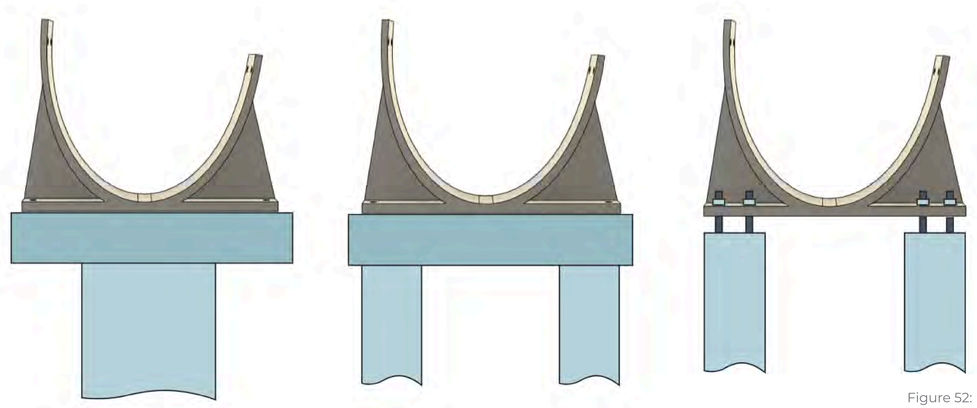


Figure 52: Different kinds of possible foundation.

Frame position
The frames are placed every 6 meters for three reasons:

- The forces will be more evenly distributed by having the frames more in the middle of the segment.
- It allows for better tolerances between segments for various reasons.
- The aesthetic looks like a coherent whole because two blade-ends connect within 6 meters between frames (Figure 53).

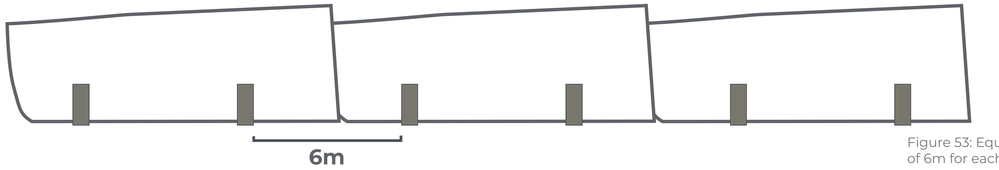


Figure 53: Equal spacing of 6m for each frame.

An important rule of thumb is placing the frames at 1/5 and 4/5 of the length, to cancel out the moment of wind (Figure 54). This would mean about 2.4 meters from the end for the U-frame design, depending on the width of the U-frame. This would mean that the initial 3 meters would be a bit too long.
However, for aesthetic reasons, the frame width, connecting-tolerances and the assumption based on earlier calculations (Chapter 8.3), The frame position will remain in equally spaced distances.

Figure 54: Moment of wind on barrier explained by (E. Nouwen, PC, 2025)

8.5
Fixing the Segment in place

In the initial concept, the segment would be fastened with a long rod with threaded ends through both spar caps, pinched between the frame as it was tightly bolted. Although this is a great solution in terms of strength, in practice it would bring major problems.

- Guiding a 1,5-meter rod through a small hole to the other side will be challenging to say the least.
- The holes are too far from the edge to assist the rod from one of the open sides, and getting someone to crawl inside the segment is for obvious reasons against all rules of safety.

The ‘hollow wall plug’ simplifies the execution of bolting the segment to the frame much easier (Figure 55). First, a hole is drilled after correct placement of the segment, then the plug is inserted and bolted tight. The design of the plug acts like an umbrella, extending its contact area around the hole, making it stronger (A).

The other option is driving a big screw anchor in the shear web (B), on the condition that this has enough thickness. Although even easier to install, this method damages the foam core, and experts expect the anchor bolt to not have enough “flesh” in the core to pull itself tight and achieve sufficient fixation.

Based on previous calculations, each side of the frame needs bolts capable of holding a load of **36,5kN**. According to the Eurocode 3 database on properties for metric hexagonal bolts (EurocodeApplied, 2025), bolt diameters of industrial class 8.8 between M12 - M16 have a shear resistance of **32,4kN - 60,3kN** respectively. In theory, this would mean that a single M16 bolt on each side is enough to hold the segment.

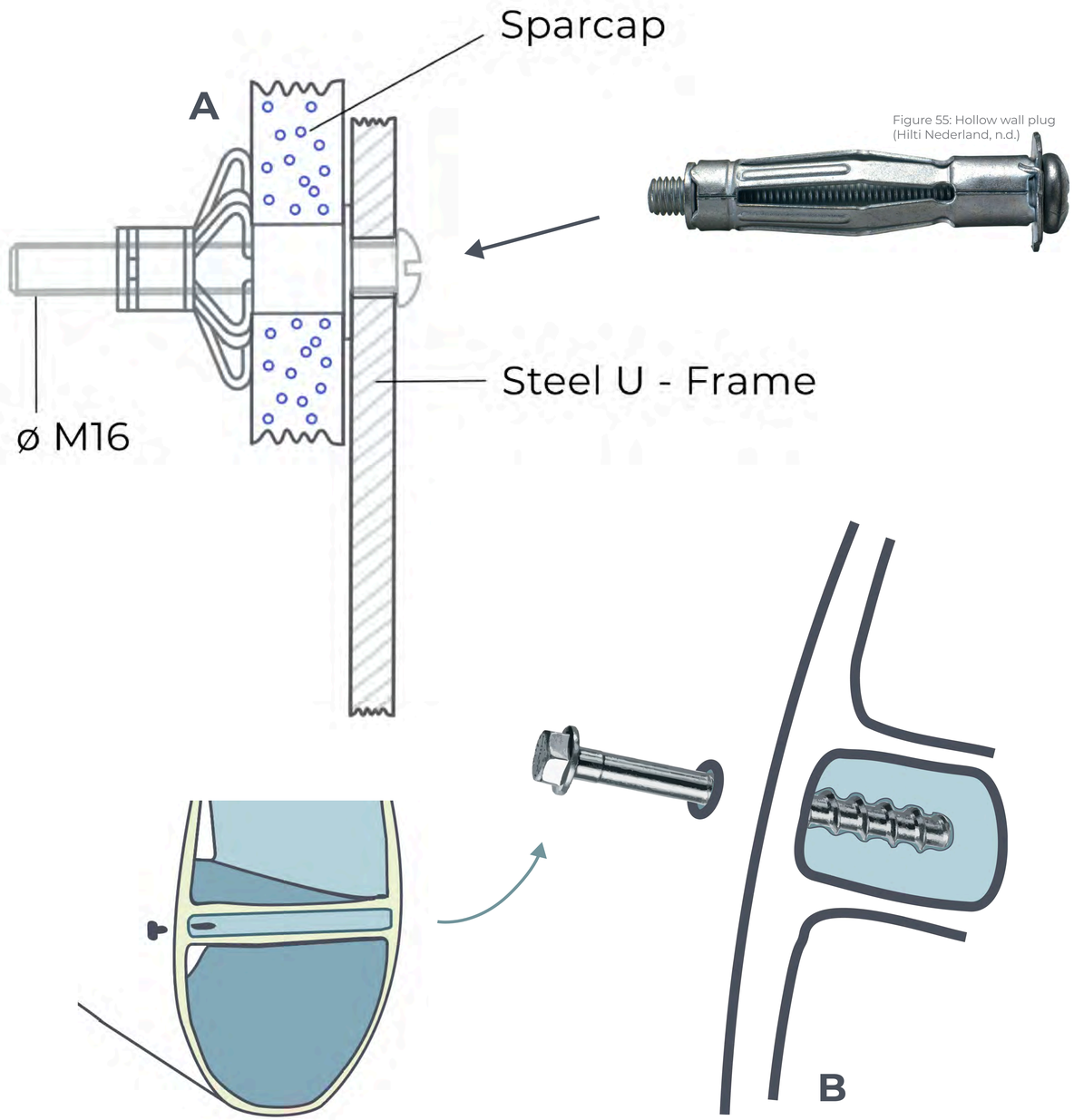


Figure 55: Hollow wall plug (Hilti Nederland, n.d.)

Implications
However, the bolt data is based on perfect conditions and perfect bolts. There are implications that need to be discussed:

- A small moment-arm in the bolt, because of spacing rubber.
- The fatigue cycles of the wind over the barriers lifetime.
- The load-bearing capacity of the WTB sandwich material.
- The shear resistance of the anchors used, are not the same as the bolts.

All these implications are important and would have to be researched once the barrier is ready for production. Hilti, a partner of Heijmans that is able to manufacture the plugs, can advice the best solutions of anchoring (Hilti Nederland, n.d.).
Project executors at Heijmans consider a safety factor on all these liable factors and advise to use **four M16 bolts** on each side of the frame, 16 in total to fix the segment. Although more bolts means more holes and thus damaging the laminates of the WTB material, as mentioned before in key focus area seven, this is not considered problematic.

Figure 56: Sint Sebastiaansbrug - four M16 bolts compared to my hand.

8.6
Shear web location

After examining the shear web locations in multiple wind turbine blades, it is clear that no two are exactly the same. Some blades feature a large box-like web between the spar caps (Figure 57), others have only a single shear web (A), and some even include an additional one near the trailing edge (Figure 58). However, what most have in common is that the shear web is located between the widest part of the airfoil profile. This is a logical structural choice, as it provides the most efficient load transfer between the upper and lower spar caps. For the same reason, the bolts of the U-profile will end up around the same area, to keep the moment-arm as efficient as possible.

By assuming that the shear webs do not significantly deviate over the 12-meter length of a segment, it becomes reasonable to mark their position from the outside: simply observe where the shear web is visible at both open ends of the blade segment and draw a straight line across the surface to connect them. This would be a reliable and accessible method for locating shear webs without the need for scanning equipment or risking a misplaced drill hole.

Since a hollow wall plug cannot settle properly if it aligns with a shear web, it's important to mark the shear web line accurately to avoid drilling into one. To manage the risk of misalignment, two additional holes can be included in the frame design. If two out of **six** holes align with the marked shear web line, the remaining four are still usable for plugs to ensure a secure connection.

As discussed in the frame design chapter, slotted holes are not ideal, especially because the length of the slot would align with the direction of the bending moment on the barrier caused by Fwind. This rules out slotted holes in the frame design to accommodate possible misalignment.

Figure 57: Box-like shear web (Piekut & Bialystok University of Technology, 2024)

Figure 58: Blade segments with shear web in the trailing edge (Eller, 2019).

Closing the sides

Closing the sides of the segments has as main reason to keep the edges dry and keep out animals. The first iteration concept was a segment shaped lid, with a rubber seal inside the edge (A). The Cap posed a good solution, with the extra quality of covering bad cutting edges, a flat surface would have trouble with. However, the cap is a custom made, more high-end solution. That is why other, simpler alternatives, were researched as well.

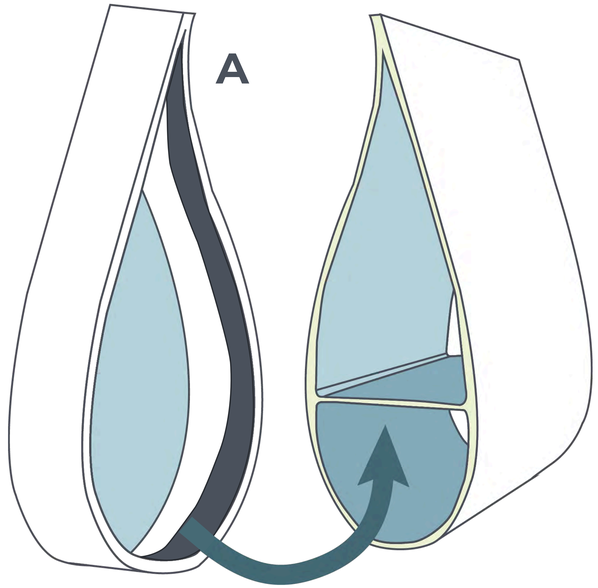
A new stream of ideas, focusing on minimizing material to cap the segments, or leaving them open all together. All came to the conclusion that the cross-sections are so different, that the opening could fit a human (B). Placing a mesh and spraying it with foam is more of a short term solution, and placing a more simple plate shape cover still left openings for birds and smaller animals. Later design decisions will follow in chapter 9.6.

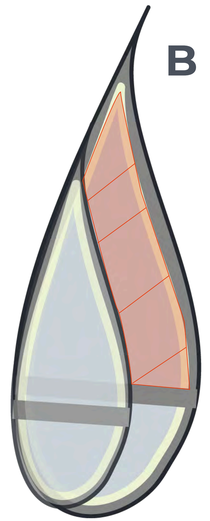
Some important Implications are:

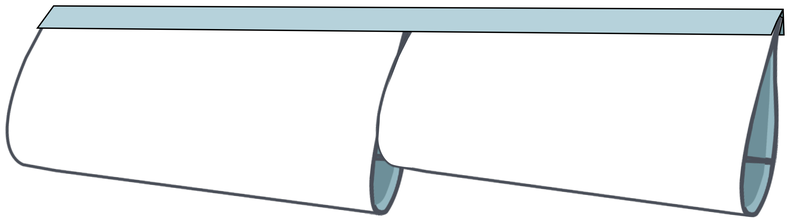
- Whether edge treatment is necessary when caps are involved, and if segments remain (partially) open, how to treat the edges accordingly (appendix G).
- Research should be done on resonance of the segments, and whether covers help or worsen this effect (Chapter 10.1).

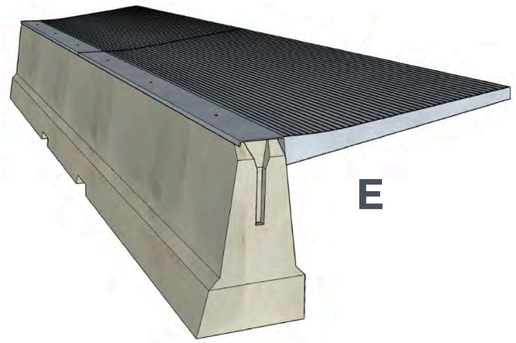
Adding to the top

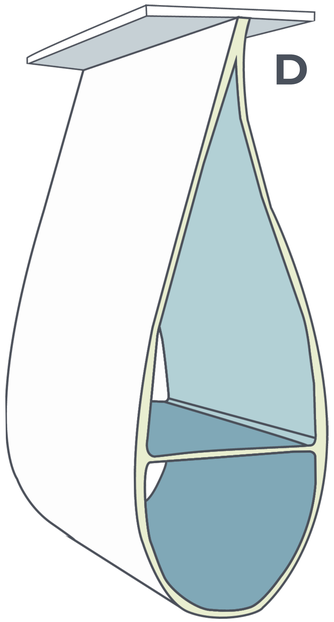
By implementing a cover strip, there is a possibility that filth comes in from the top. To prevent this, a V-top was designed (C). However, this would only work with a horizontal top orientation. This opened new doors: what if this V could be an extra shape against diffraction?
If diffraction turns out to reduce the barriers effectiveness significantly, extra features like a T-top (D) or WHIS®top (E)(4silence, 2025) could be added. In further research, a few WTB designs came up that might also reduce the diffraction edge by their shape alone. Examples include a flat back foil or serrated TE blade (Appendix H). Whether or not extra measures are necessary, depends on acoustic test and will be out of scope for this project.











8.7

Connecting segments, soundproofing and closing

As stated in key focus area three, segments should be mounted independently, with a tolerance of about 4-6 cm between them. This gap provides freedom for movement and misalignment without transmitting stress or failure between elements. The acoustic sealing solutions for the slit will also provide the visual connection between segments, that makes the barrier appear as a whole.
In this chapter, multiple sub-solutions for attenuating noise have been discovered and conceptualized. Later in chapter 9.3, the final version will be explained. Although the two sub-solutions of the first concept iteration were cap and T-flap, the effectiveness and manufacturability of 'the best solution' still needed some thought.

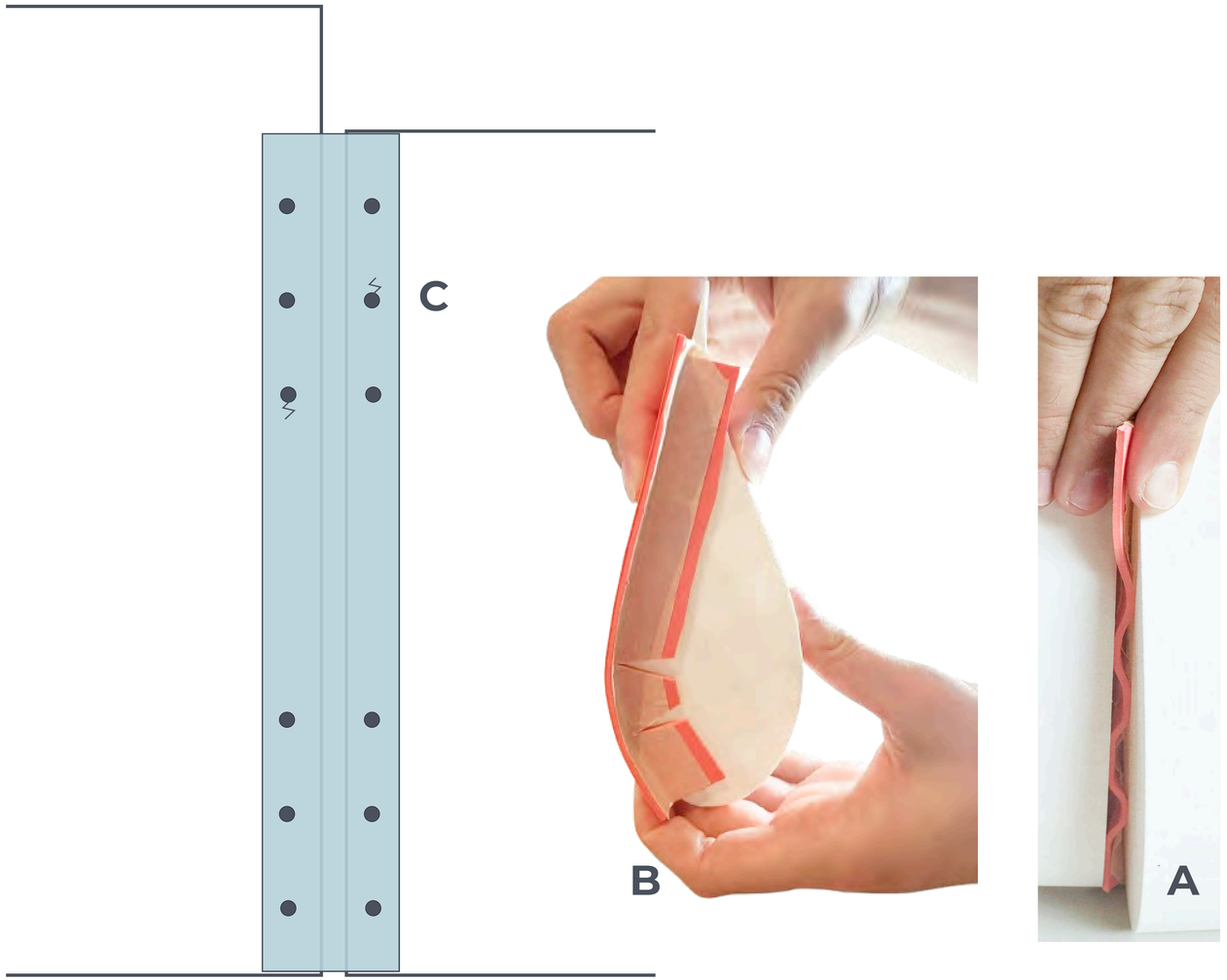
Closing the front
To start, the T-flap was evaluated with a prototype (Appendix D).
The idea behind it was to have a mass produced extrusion profile, to reduce production costs. The main takeaways of the T were:

- It does not bend so easily, and when pressed with force it became wiggly, widening between segment profiles (A).
- To release the unwanted stress in the material, two triangle-shaped cuts were made, making it much easier to bend (B).

Another option to close the slit was a simple cover plate. The plate's material can be a thin strip of steel or aluminium, with a rubber foam behind it for the acoustic seal. Two important implications for this solution are:

- Cover strips mounted with screws on both sides may experience tearing around the fastened holes due to movement of the barrier and stress concentrations (C).
- If the T is from rubber, it will experience degradation from longer UV exposure, becoming brittle, cracked, or discolored over time (Miah, 2021). In general, UV exposed rubber is unadvised (Nouwen, PC, 2025). Making the T from thin steel or aluminium and bending it to shape could also be an option.

Project continuation: The cover strip gives the simplest and best solution.



8.8

Protection

Protection of the barrier can implicate multiple things. This chapter will consider the factors that are most relevant for the barrier design:

- Protection against environmental elements, e.g. rain, corrosion, UV
- Water management, e.g. gutters, sewage or drainage splits
- Protection against sound leaking through.
- Protection against vehicles, vandalism and fire.

Environmental stresses

As mentioned before in chapter 3.2, the barrier has to be corrosion resistant and the blade should be protected against water ingress. The previous chapter about capping addressed the protection of the sides. An important note is the material used for these solutions. Rubber or plastics that are not UV resistant are not suitable for these applications. The frame itself will be coated with corrosion resistant paint as used in other noise barrier projects (Figure 59).

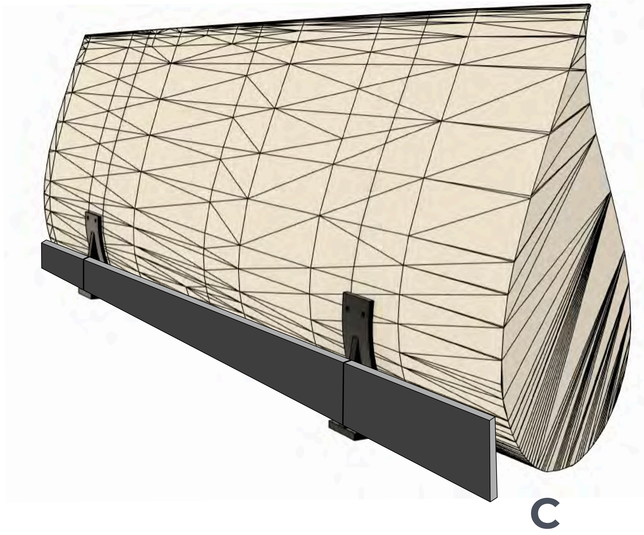
Figure 59: Frame with corrosion paint - A9 Heijmans.

Water and noise management

To prevent water pooling next to the frames, it is important to level the barrier with the ground (A) or optionally raise it on a talud for some extra height (B). The water could disappear in the soil but proper water management is advised to prevent rapid erosion (CROW, 2012).

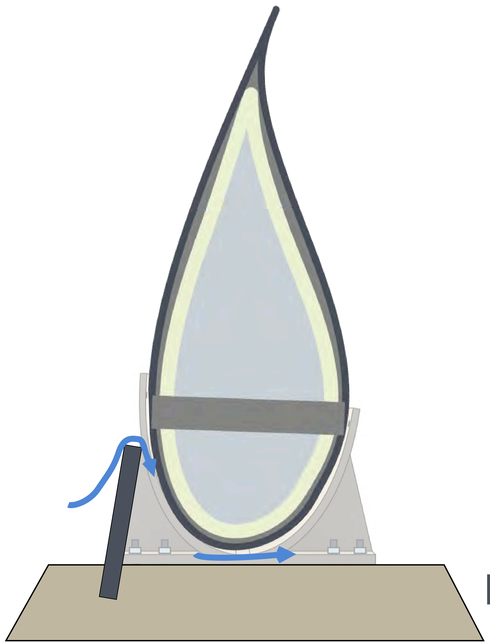
Now, the Koios plinth is introduced (C). When rain is dripping down the barriers surface, the space between the segment and plinth functions as a drainage slit that allows water to flow behind the barrier (B). In case of a flood, the plinth stops water from entering the (residential) area behind the barrier, but does have a overflow function. for better corrosion protection as mentioned earlier, the foundation sticks out slightly above ground level (A). Conveniently, the plinth can rest on the concrete and a drainage slit over the full length is still possible, which would prove most effective. The final plinth design is covered in (Chapter 9.4)

As for stopping noise, the plinth overlaps with the segment and covers the drainage slit, preventing sound from passing under the barrier. Still, wildlife can squeeze underneath.



C

A



B

Vehicles
Maintenance vehicles such as big mowers, cut the grass and might damage the blade material in the process (A). The plinth helps protect that from happening (Van Amstel, PC, 2025). If it breaks, it is a much easier component to replace. How the plinth is exactly installed will become clear in chapter 9.4.
In terms of impact of road vehicles, the barrier does not have to be able to stop them because a guide rail will be placed in front. However, in the unlikely event that a car does hit the barrier, the plinth functions as guiding surface to prevent cars from crashing into a frame.

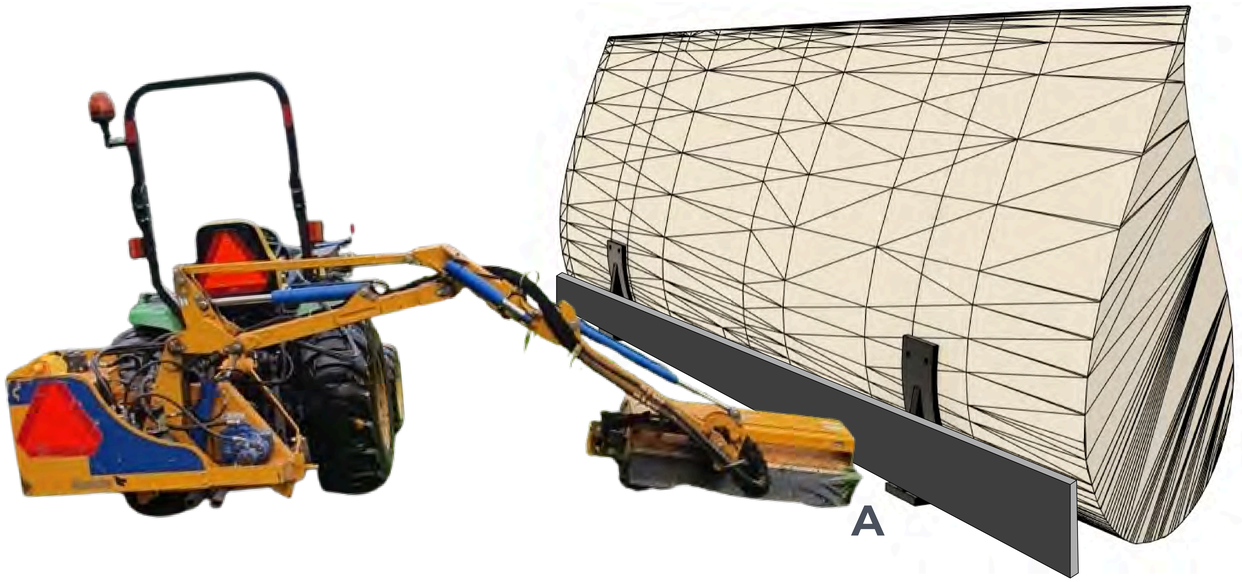
Vandalism
Vandalism is mostly aimed at the prevention of unwanted graffiti. To help this, a protective anti-paint coating will be applied. Art or vegetation is not chosen as it makes the barriers aesthetic too messy, considering most of it has to be covered in order to have effect.

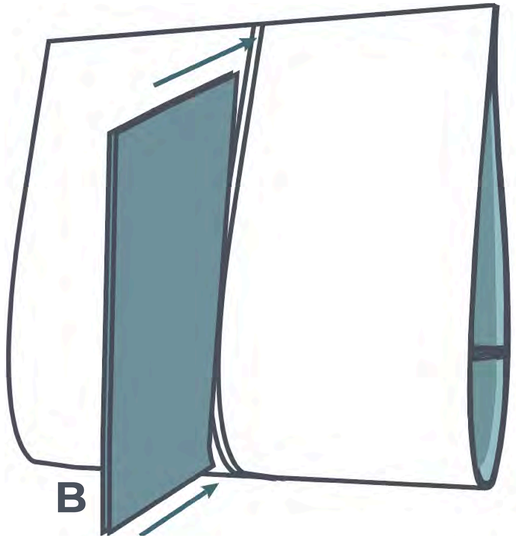
Fire
Another important aspect is fire safety, as covered in chapter 3.4. Next to the measures around the barrier to delay the spreading of fire, such as vegetation maintenance and buffer zones, the barrier itself houses fire retardant measures as well.

Consequently, the sub-solutions named in the previous chapter such as the cap or cover strips, will have to be made from at least a non-flammable, but preferably a fire-resistant material (Euroclass A1 or A2 under EN 13501-1 (Kaukanen, 2024)).

Common materials used in current barrier solutions are:
- Aluminium (with powder coating for corrosion resistance)
- Stainless steel (AISI 304 or 316 for high corrosion resistance)
- Galvanized steel (zinc coating)

As extra measures for increasing fire-proofness, it could be considered to place a board in between segments, such as fiber cement boards or calcium silicate boards (B).



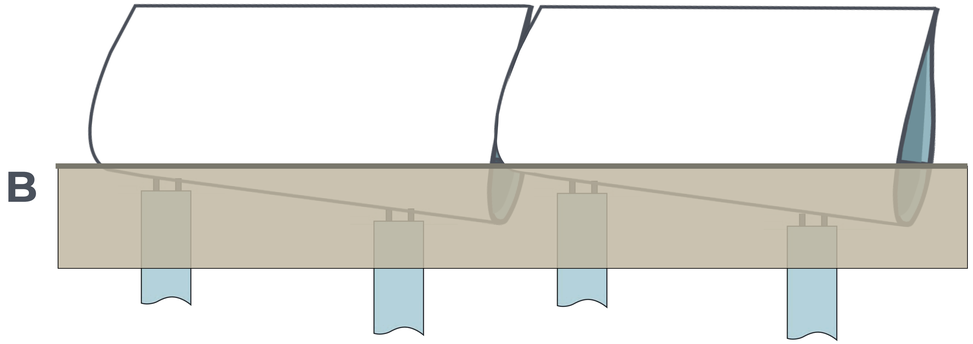


8.9

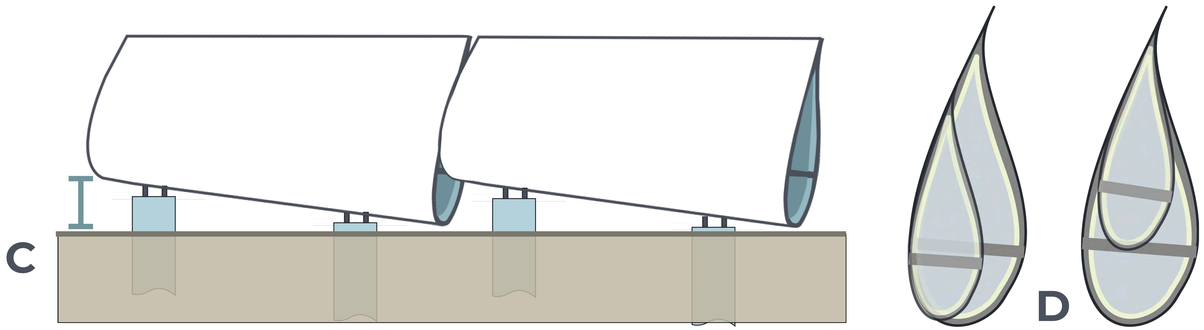
Placement & Aesthetics

Aesthetics
An important factor concerning both the road user and the surrounding neighborhood. This chapter emphasizes primarily on the functional form of the barrier, the perceived look is important but will be secondary.

Shape of the blade
wind turbine blades have an iconic and recognizable shape. To create awareness of the possibilities of blade reuse, a noise barrier that still somewhat resembles a blade or creates curiosity would be a nice added value. However, as described in CROW (2012), the barrier cannot draw attention away from the road. Consequently, the question is raised whether a jagged top is considered visually disturbing at higher speeds (A). Although a barrier with a smooth top would be more calm for the road user, it is still a static object. After rendering the barrier with 3D software and “driving” past it (Chapter 9.7) it can be concluded with certainty that the blade barrier looks cool but will not draw full attention and thus lead to unsafe situations.



Horizontal or Jagged trade-off
As mentioned earlier, the function of the barrier is more important than the aesthetic. After consulting with experts at Heijmans, the execution of placing the foundation to realize a horizontal barrier will be much more complex than for a jagged barrier. In contrast to the horizontal frames and foundation for the Jagged design, the horizontal design will require additional digging and groundwork, and a foundation with altering heights (B). The height difference has to be compensated below ground, as doing it above ground will create a gap between the blade and the soil, causing acoustic problems (C). Lastly, during prototyping, it became clear that the curvature of the segments are better aligned when Leading Edges are collineair, rather than the Trailing Edges (D). Although making the barrier horizontal is possible, it will be more expensive and difficult to realize. With all these factors combined, the choice for this thesis is to continue with the jagged design.



Chapter 8

Takeaways

Orientation
- The barrier design will consist of the same 12 meter segments per blade.
  - there are 3 different barrier height configurations and 6 U-frame shapes.
- The suction side of the segment will face the road, as this surface is more straight towards the top. The acoustic curvature on the top of the pressure side might focus sound waves back to the road user, and is therefore less suitable.
- Lower sound waves that bounce off the bottom of the barrier will be absorbed by grass or asphalt, and the plinth protects sound from passing underneath.

Forces
- The Force of wind on the middle of the barrier in the windiest region will be Fw = 0,76 kN/m².
- After Moment calculations, this comes down to 36,5kN per side of the frame.
  - In context and safety-factors, this will be loaded on 4 M16 bolts per side.

Frames
- The U-frame went through some iterations to test ease of assembly, simplicity and modularity.
  - The slot design featured read-to-go bolt slots and per-installed rods in the segment.
    - however, placing this rod in the segment is difficult and the bolts are less supported.
- The minimalistic iteration featured a folded flat frame, but had a smaller footprint, making it weaker.
- The modular J iteration featured two separate frames that could be moved closer, depending on segment dimensions.
  - However, the design would be conflicting with the bolts in the foundation, and less strong because the frames are not connected.

Rubber
A rubber sheet will be placed in the frame for protection of about 1-3cm thick.
It is one slab, multiple smaller slabs require more processing.
The assumption of extra grip is not true, the shear on the bolts should be minimized, meaning the rubber should not be too thick.

Frame to foundation
- The frames and foundation are placed 6 meters apart because:
  - The forces will be more evenly distributed by having the frames more in the middle of the segment.
  - It allows for better tolerances between segments for various reasons.
  - The aesthetic looks like a coherent whole because two blade-ends connect within 6m between frames.
- An important rule is placing the frames on 1/5 and 4/5, which is closely followed in the design.
- The foundation is dependent on location and soil composition. It could be one big pole, two small poles, with a concrete base for the frame, or directly mounted on a pole.

Fixing the segment
- Bolting the segment to the frame is either through the spar cap with a hollow wall plug, or with a screw anchor in the shear web.
- The fasteners do not have the same properties as calculated bolts, further Implications are:
  - A small moment-arm in the bolt because of spacing rubber increases shear.
  - The fatigue cycles of the wind over the barriers lifetime.
  - The load-bearing capacity of the WTB sandwich material.
- 4x M16 bolts per side of the frame, 16 bolts in total per segment.

Shear web location
- Blades have different shear web designs. It is important to know where the shear webs are located to fasten the frames properly. This can be marked by drawing a straight line from both ends.
- Possible safety-factor: 6 holes in the frame to accommodate miss-alignment of 2.

Soundproofing

- Closing the front with a rubber T-flap is possible when incisions are mare so it can bend.
- A cover strip mounted on both sides might experience stresses at the screws and possibly tare.
  - it is better to connect the cover strip on one side of the segment, and have compressible rubber behind it for the acoustic seal.
  - Rubber deteriorates in direct UV, so using it is only advised when covered by something else.
- Closing the sides is initially done with a cap that is more forgiving for bad cutting edges.
  - Research should be done about the resonance of the segment when closed off.
- Adding extra measures to the top of the barrier to help reduce diffraction can be:
  - A T-top, WHIS®top or V-top, covering the front plates from filth (only on horizontal barrier).
- Choice is made to continue with only a cover strip, extra diffraction measures are out of scope.

Protection

- Environmental stresses
  - Frames get a coating against corrosion.
  - The closing of the sides should also protect the edges against water ingress.
- Water management
  - To prevent pooling, the barrier can be slightly higher.
  - For erosion control, the drainage slit helps.
    - The plinth helps to manage water during floods and heavy rain.
- Vehicles for maintenance or collision
  - The plinth protects the barrier against mowers.
  - The plinth functions as guide rail or crumble zone, with vehicle collision.
- Vandalism, mostly graffiti, should be stopped with a coating.
- Fire protection.
  - Vegetation around the barrier should be maintained
  - Measures to delay a spreading fire are a buffer-zone and making the caps between segments from a fire-resistant material (Aluminium or stainless steel).
  - Or a board of fiber cement or calcium silicate can be placed in between.

Placement & aesthetics

- The functional placement is more important than the visual placement.
- Compared to a horizontal design, the jagged top does not lead to more significant problems for drivers' road attention, and is considered safe.
- The Jagged top is preferred over a horizontal top because of much simpler ground work and lower costs. The horizontal top is still executable.

9.
Embodiment & Visualization

This chapter covers the development of the final design of the blade barrier, by detailing the U-frame, foundation and plinth, realizing the cap and cover strip for soundproofing, walking through an assembly plan, and finally some renders to evaluate the barrier setup at a large scale.

From this point forward, the detailing focuses on scaling up the barrier using a single blade segment type in combination with two U-frames.

This chapter takes you through the following refined key components:

9.1 The U-frame

9.2 Fixing solutions

9.3 Closing & Soundproofing

9.4 Koios Plinth

9.5 Emergency exits

9.6 The assembly

9.7 Roadside aesthetics

9.1
The U-Frame

Final design optimizations
The final frame design shown in Figure 60, is a steel product of 6 parts welded together, consisting of (see Figure 61):

- one base plate that is fixed to the foundation (40mm).
- two bend plates that support the segment and fix it to the frame (25mm).
- tow triangle shaped ribs that connect the bend plates to the base (30mm).
- one thin plate that acts as fixing point of the plinth (8mm).

All these parts are laser cut, including the holes and rounded corners. The bend plates can be rolled by a computer aided machine that knows the exact segment shape (Van Amstel, PC, 2025).
Ultimately splitting the U-plate in two is an optimization to simplify the production and welding of the frame. For the same reason, the edges of the base plate are a bit wider than the ribs, to fit the welds and plinth support (A).
The only implication is that the base plate might have to be a bit thicker.

After welding all parts together, a coatings is applied by hot dip galvanizing the frame to protect the steel against corrosion (NEN-EN-ISO 1461). Afterwards, the frame is painted in a nice gray color.

Dimensions and price
The dimensions of each frame are dependent on the segment used. In the future, this can be determined with a 3D model of the blade. For this thesis, the two frames for the largest blade segment extracted from the NREL model (4m high) were developed, of which the biggest frame dimensions are evaluated on load calculations and production costs (Appendix E). The max frame weight is 750kg, meaning the smaller frames will be cheaper.

Price estimation per pcs: 2 frames € 4132,-
10 frames € 3029,-

Figure 60: Final frame design.

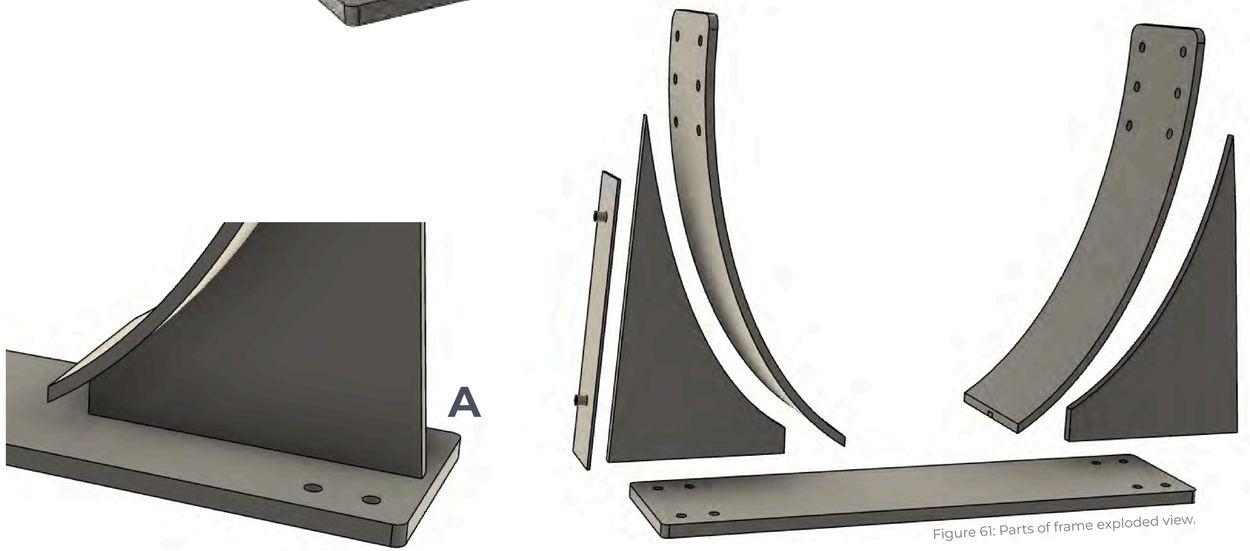


Figure 61: Parts of frame exploded view.

9.2
Fixing solutions

Now that the final frame design is defined, this chapter covers the fixing methods of the frame to the foundation and the segment to the frame.
Note: Throughout the report, the holes in the frames are visually enlarged to make them stand out, in reality they are smaller. The correct dimensions of the frame are covered in Appendix E.

Frame to Foundation
Firstly, the foundation is determined by the location of the barrier and ground composition, which at this time is unknown. The base model used for this design is a concrete slab slightly above ground level. The frame is bolted onto the foundation with four M16 anchoring bolts on both sides (Figure 62). Hot-dip galvanized steel plates are spaced between the base plate and bolts (A).

Segment to Frame
Secondly, The segment is fixed to the frames, each frame with four M16 hollow wall plugs on both sides (Figure 63). Depending on the location of the shear web, only four of the six holes are used. The rubbers used are self sticking 3cm thick EPDM closed cell rubber sheets (Timmermans, PC 2025). To prevent accumulation of drill cuttings and heat generation, the rubbers have bigger holes (B). How exactly the assembly process takes place is covered in chapter 9.6.

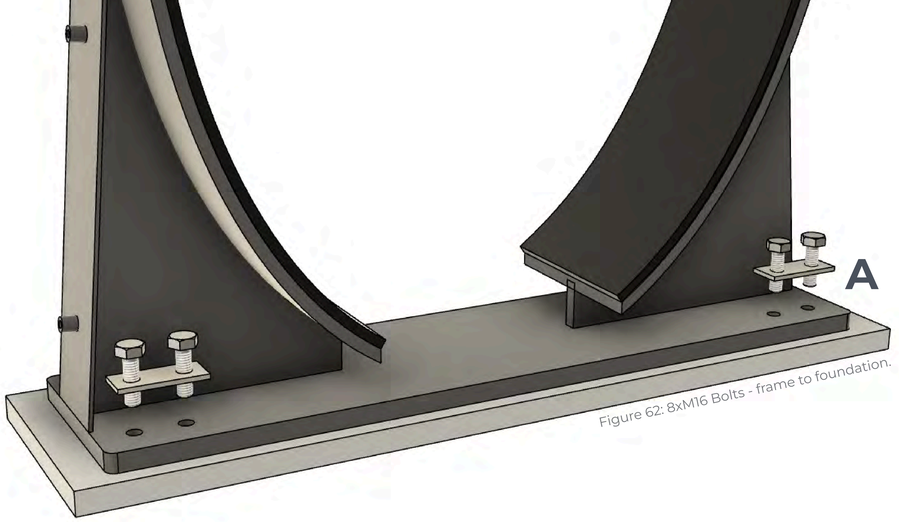


Figure 62: 8xM16 Bolts - frame to foundation.

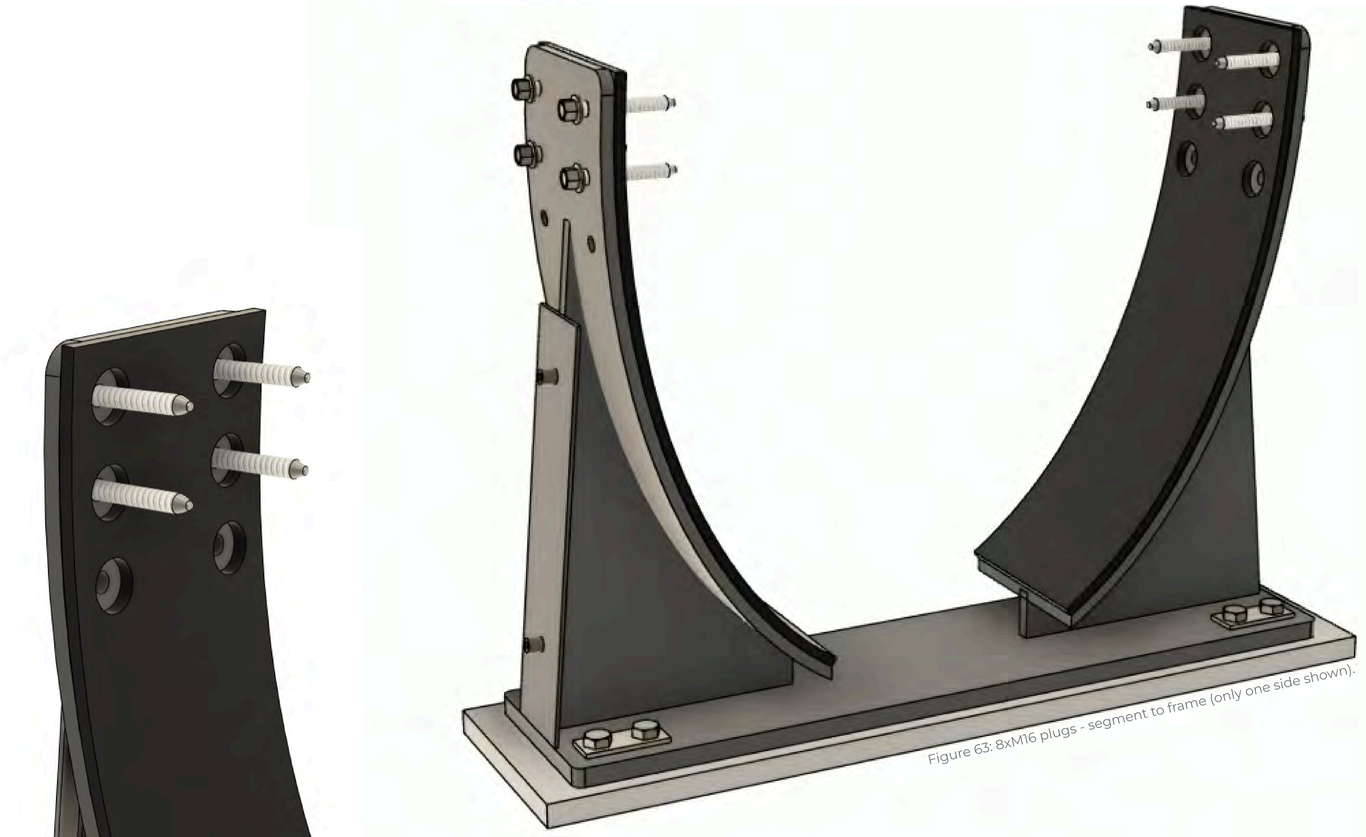


Figure 63: 8xM16 plugs - segment to frame (only one side shown).

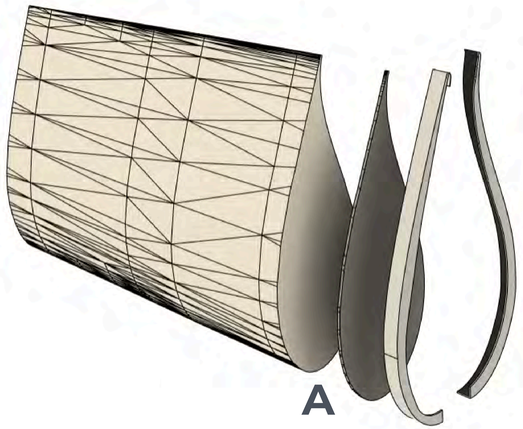
9.3
Closing & Soundproofing

The Caps

The Caps close off the sides of the blade segments and together they form prefab barrier segments, ready for construction. The caps will be made from a 4mm thick stainless steel sheet, with two stainless steel L strips with compriband folding around it (A). Compriband foam-tape is often used in acoustically closing small gaps and slits (B). It is especially useful because it can be compressed and fitted, after which it expands again (Timmermans, PC, 2025). The edge of the segment is overlapped by 15cm, properly sealing the ends, even with rough cutting edges.

A small flap folds over the other profile to protect the top from moisture (C). After placing the strips on both sides against the sheet (D), they are fixed in the balsa wood edge of the segment with special waterproof screws (Figure 64). It is advisable to treat the edges with a bio-based epoxy coating for extra moisture protection (Appendix G).

The stainless steel caps on both sides and the gap in between help to slow down the spreading of flames, in the event of a fire. The small cap has additional threaded fixing points for the cover strip to connect and cover the gap (Figure 65). These are highlighted in more detail in the next chapter.



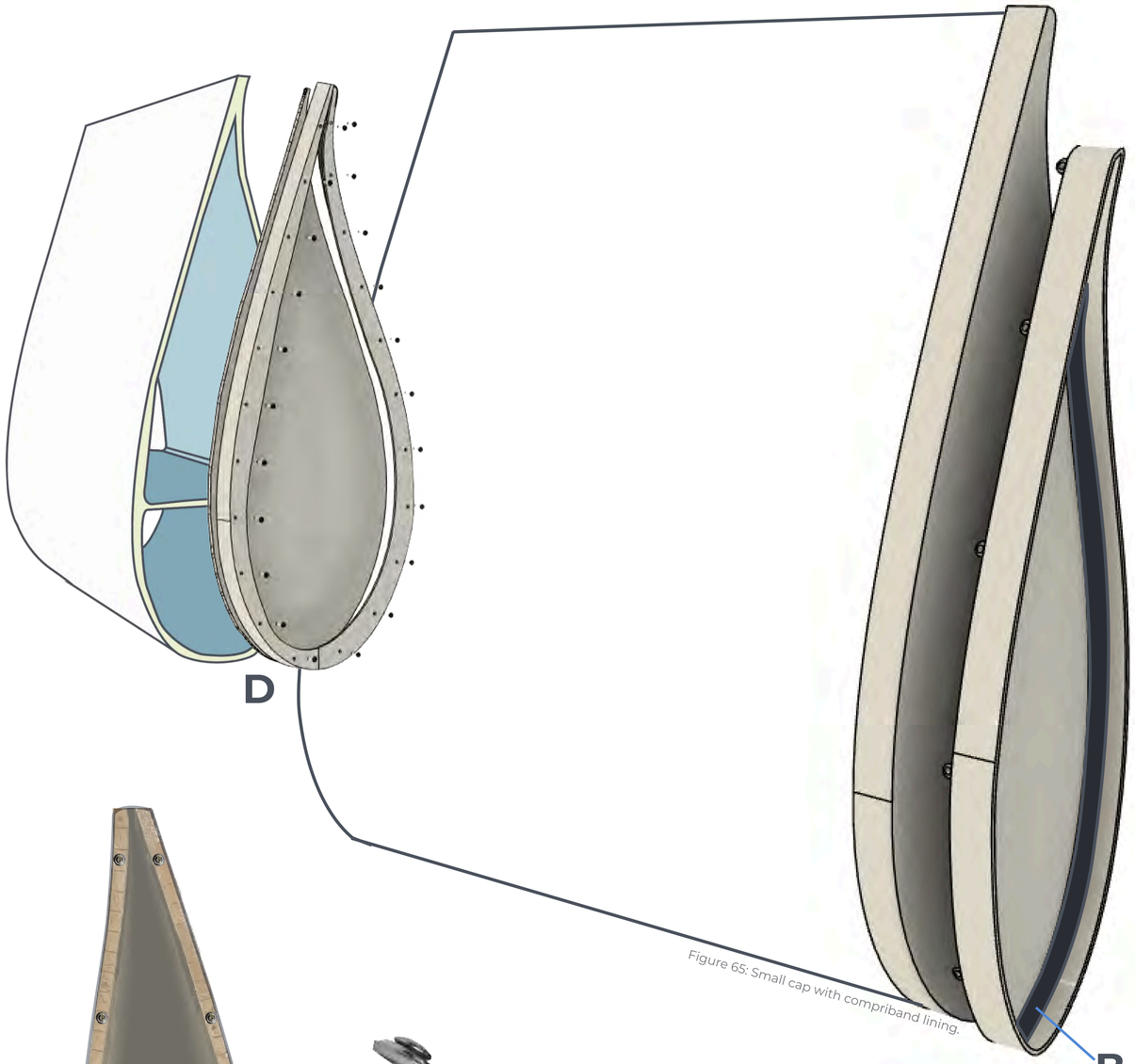


Figure 65: Small cap with compriband lining.

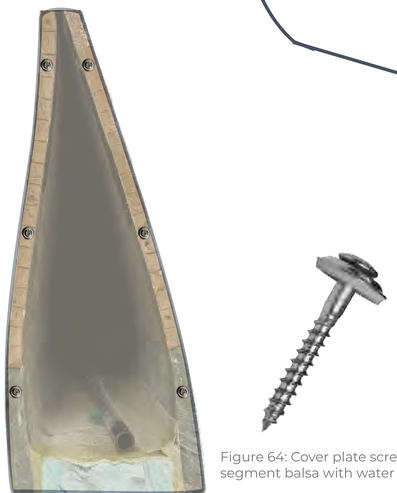
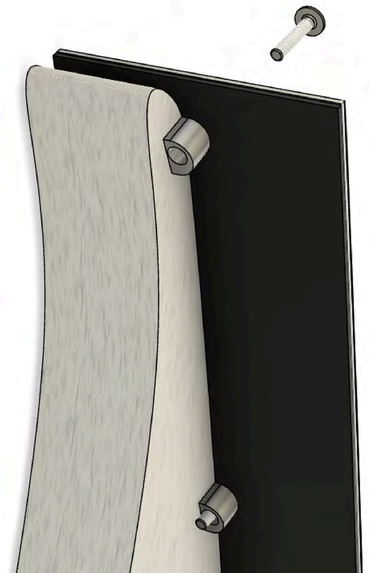


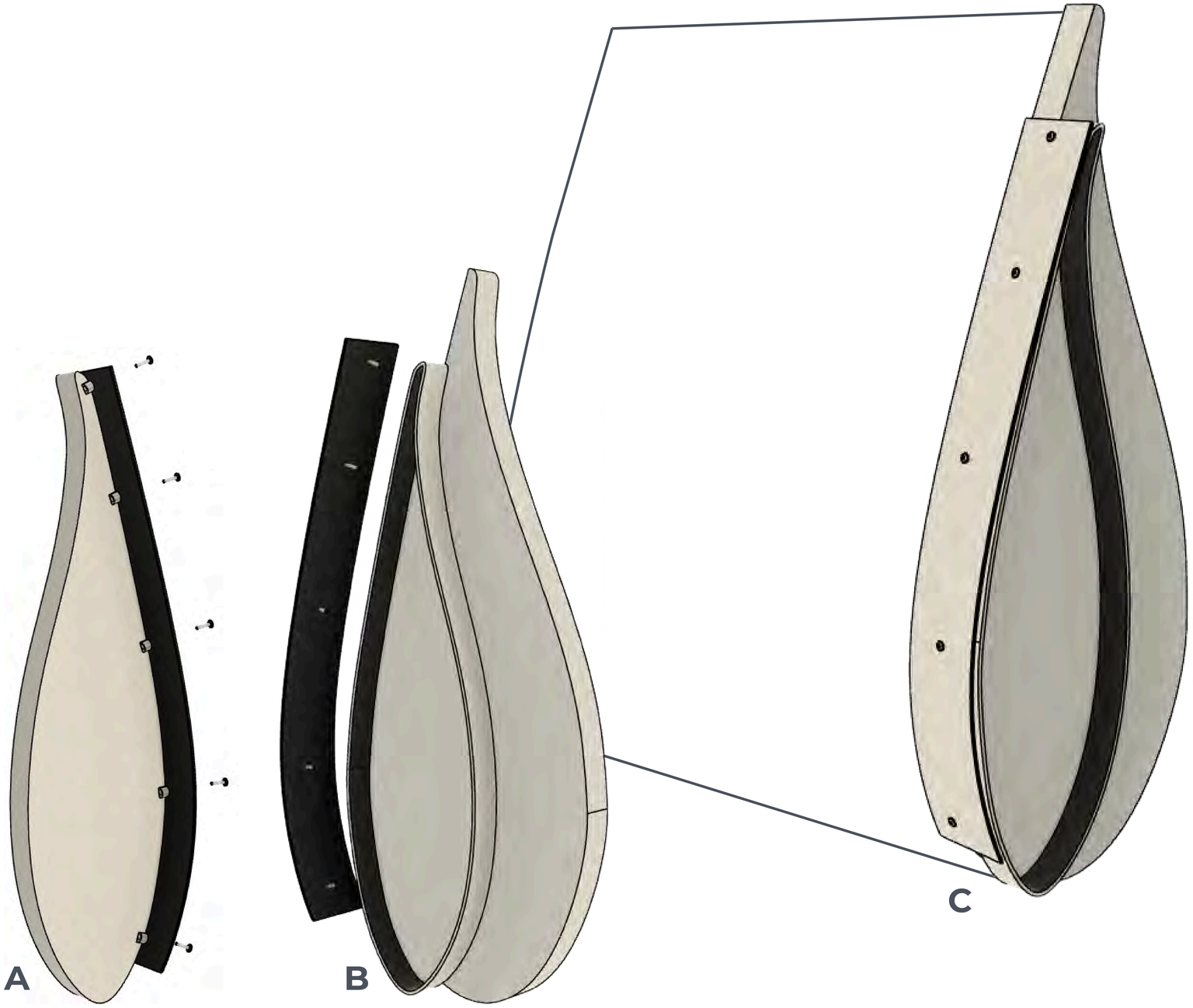
Figure 64: Cover plate screwed in segment balsa with water tight screws.

Cover strip
The cover strip is placed on site, when the caps are already in place. Note: on this page, the cap models has been simplified. The cover strip is a stainless steel strip with five holes, which line up with the threaded bushings on the small cap (A). Similar to the caps, the strip has a layer of compriband that will expand as soon as the cover is screwed in place (B). This will seal the gap between the caps acoustically.

Smart features

- The strip has the same width as the two caps combined (C). Together with the gap tolerances between caps this is about 40cm. Aesthetically, this width is similar to the frames and leaves more than enough overlap for tolerances in case the gap is bigger.
- The screws are not inserted into the blade segment, preserving the material and making watertightness less of an issue.
- Theoretically, the strip does not have to cover the gap behind the plinth (next chapter), but it is advisable to keep some overlap, or even add some extra length to it that can be cut off as excess.





9.4
Koios Plinth

The plinth is made from a mix of shredded blade material and resin, pressed by KoiosTitan to Compressiet©. For every 10kg of Compressiet, 7kg shreds and 3kg resin is used. A plinth of 6m long, 80cm high and 40mm thick is assembled between two frames (Figure 66). This chapter covers the fastening method of the plinth to the frame and the drainage slit configuration. For implications and earlier iterations of the plinth are explained in Appendix F.

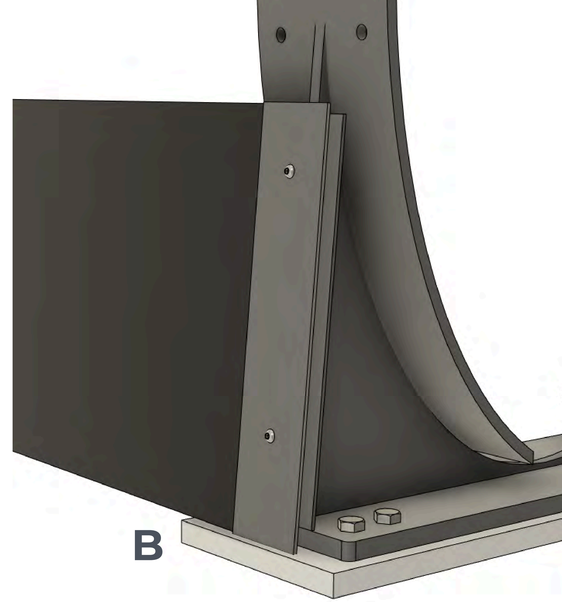
Fastening method

As final fastening method, the plinth is placed on the concrete foundation is leaning against the frame (A). The frame has a plate with two threaded bushings. The plinth is clamped with a cover plate, similar to the acoustic cover strip and fastened with bolts (B). This way of securing the plinth came out on top because it doesn't require additional holes, eliminates the hard to reach problem and accommodates tolerances in length, height and thickness of the plinth. The cover plate is the same height as the plinth for aesthetic reasons, the back plate with bushings doesn't have to be, as long as it supports the plinth during installment.

Thickness and strength

As mentioned in chapter 8.8, the plinth has multiple functions. The primary functions are to seal the underside of the barrier acoustically and protect the segment against mowers, while keeping a small gap for drainage. The secondary function is to prevent vehicles from crashing into the frames, and a nice added bonus is protecting the the bolts of the foundation from road salt, one of the biggest causes for corrosion (Grevelink, PC, 2025).

Because a span of 6m is quite significant, some calculations were done to see whether the plinth would deflect and fail under the mower's impact (Appendix B). Although minimal E-modulus seemed high, one could argue that if a plinth breaks, it fulfilled its purpose in protecting the segment and is easily replaced. For now, a thickness of 40mm is sufficient to hold the accidental impact of the mowers chains. Next to that, since there is little known about the acoustic properties of the material, it is difficult to predict the thickness of the plinth. In any case, the fastening system with cover plate is flexible in adapting to different thicknesses.



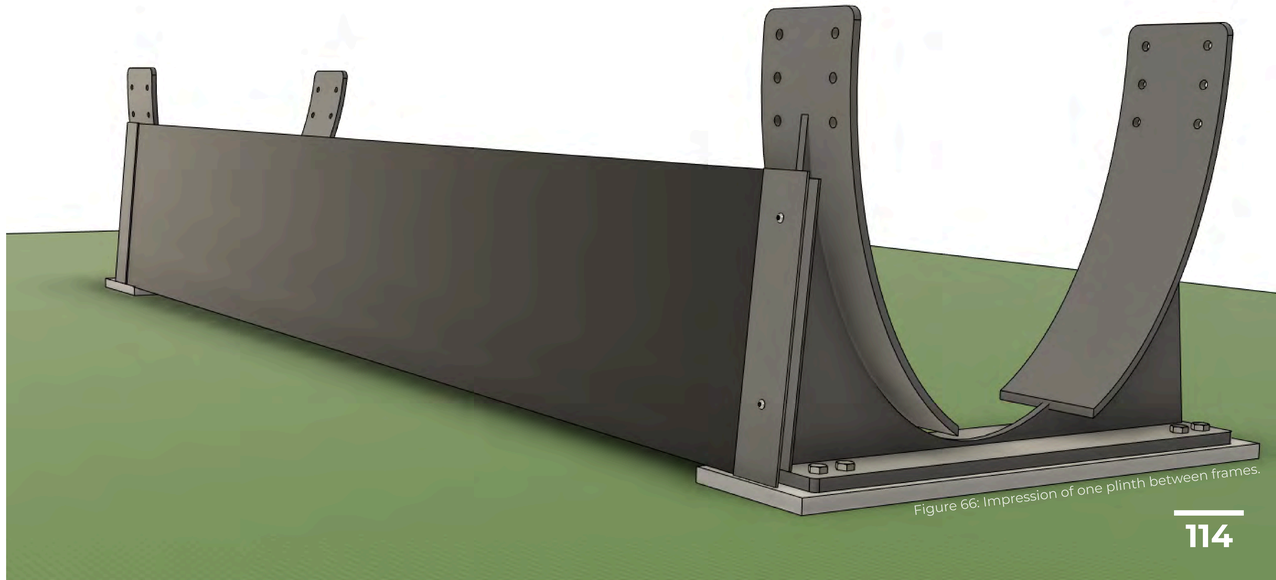


Figure 66: Impression of one plinth between frames.

Drainage slit

Besides protection, the plinth is required to accommodate a drainage slit. In previous chapter 8.8, two types of plinth configurations were discussed. What needs to be addressed is that since CROW (2012), current regulations have become more strict in drainage slits (Grevelink, PC, 2025). In densely populated areas, a slit over the full length is no longer allowed. Consequently, the design with the plinth partially inserted into the ground was developed (Figure 68). This features smaller drainage slits near the foundation of about 40cm and maximum 10cm high (Figure 69). Although this design makes the plinth more rigid, placement time and anchor inspection difficulty is increased. Additionally, when closing the full slit, the plinth becomes the perfect place where trash and leaves can accumulate (A).

When considering the placement of the blade barrier, this will most likely not be in a residential area, simply because of the available space and broader design compared to conventional noise barriers. The preferred design for the blade barrier is therefore the plinth with full drainage slit (Figure 67).

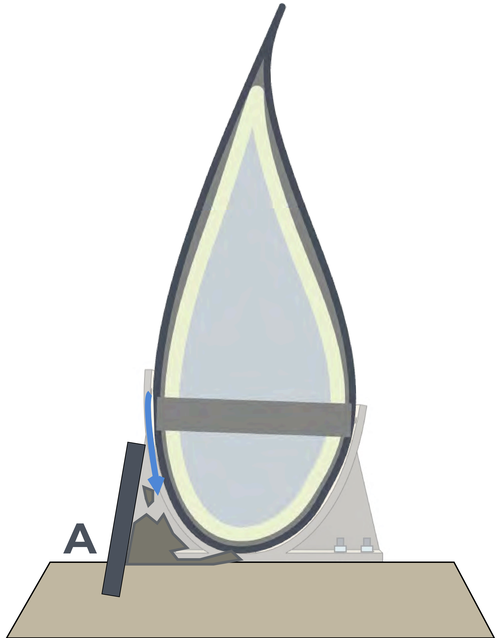


Figure 67: Straight plinth.

Figure 68: Plinth in ground.

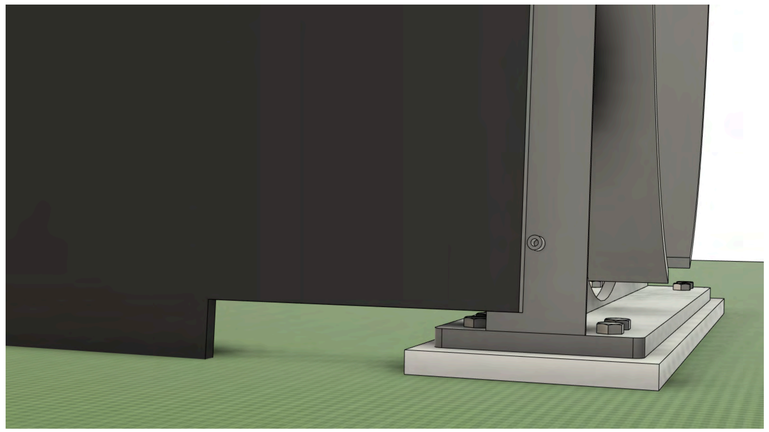


Figure 69: Drainage opening at the foundation side.

9.5

Emergency exits

Safety doors have their own special unit and are placed on a separate foundation. Regulations require an exit every 400 meters, which in this case means after 32 consecutive segments. A door unit of roughly 2 meters is placed between two segments and attached to the caps on both sides to create an acoustic seal (Figure 70). The height aligns with the small end, ensuring the unit meets at least the minimum barrier height. In this setup, the plinth is only 3 meters, ending in two half frames that connect to the exit door's foundation.

Figure 70: Impression of exit door - Co-creation with Cas van den Eertwegh.

9.6
The assembly

Placing the frames
The assembly of the barrier needs to fast and efficient. To execute the barriers installment smoothly, it is desirable to have as little assembly steps on sight as possible, for example, by using prefab elements. This chapter will give a description of the assembly process, starting once the construction site has been controlled, prepared and the appropriate foundation is laid.

First, the frames will be placed on the foundation. These will have markings to indicate which frame goes where. Since the U-frames are not symmetrical, the front, recognizable by the plinth plate, needs to face the road. Once the frames are unloaded from a truck, a forklift is able to deliver the frames to their location. A frame, which varies between 400-700kg (appendix B), can be easily lifted by hooking a band to the bolt holes, and placed on the foundation (Figure 71). At last, they are bolted in place, ready to hold the incoming segments.

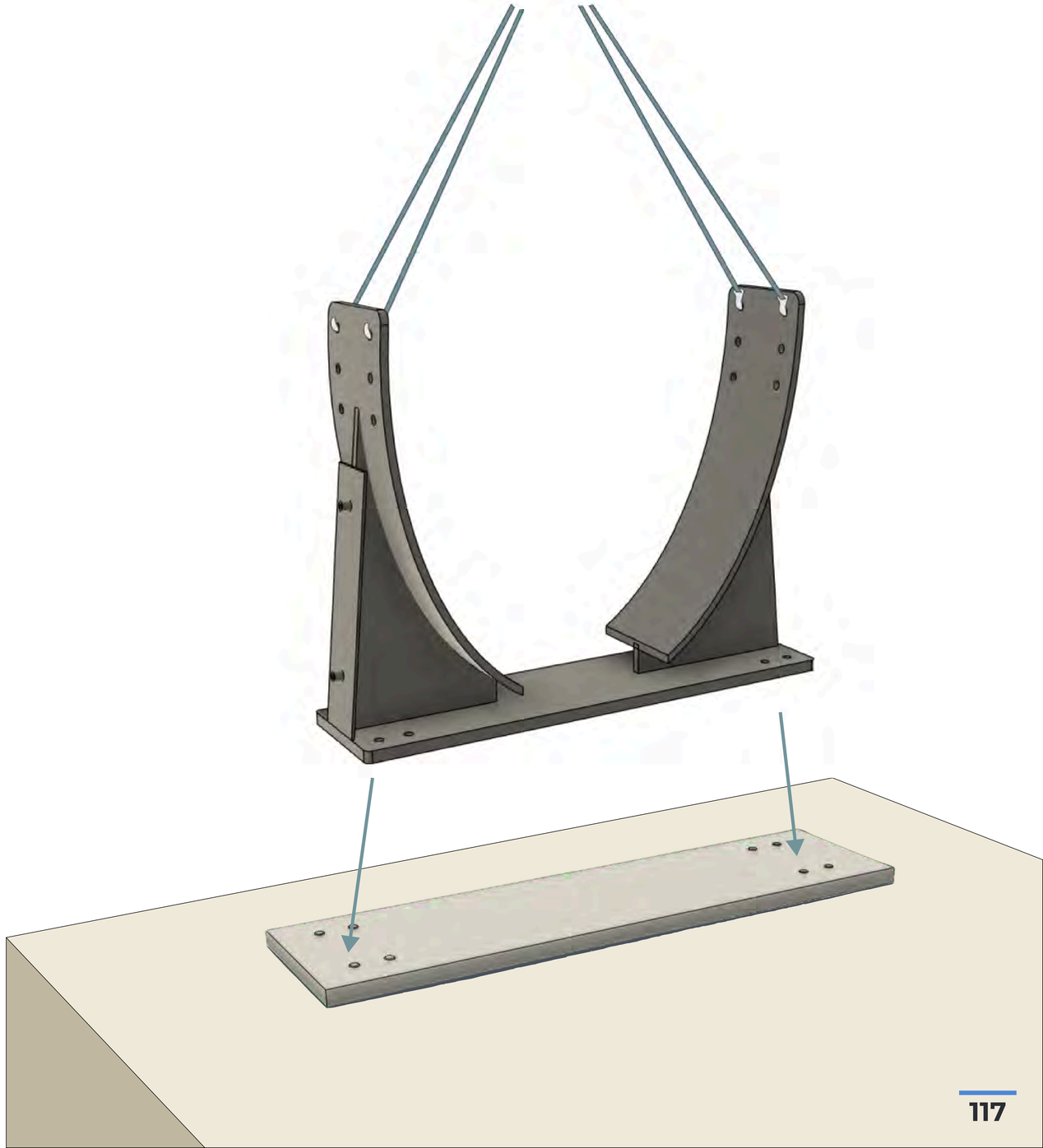


Figure 71: Placing the frame on the concrete foundation.

Placing the segments

Once all the frames are in position, the segments come in by truck. The segments will already have been treated with coating and closed with caps, with their shear web location marked and preferably already equipped with hoisting bands to make hooking tem up to the crane easier.

A crane will lift the segments with hoisting bands and an equator beam into the U-frames (Figure 72). The bands need to be spaced so they do not align with the frames and get stuck. The placing procedure goes slow, in order to align the segment in the correct position, measured by the distance between the ends and the frame. Once the position is established, the segment can be rested fully on the frames. The frames hold the segment steady and in the right angle. The segment is now ready to be fixed in place.

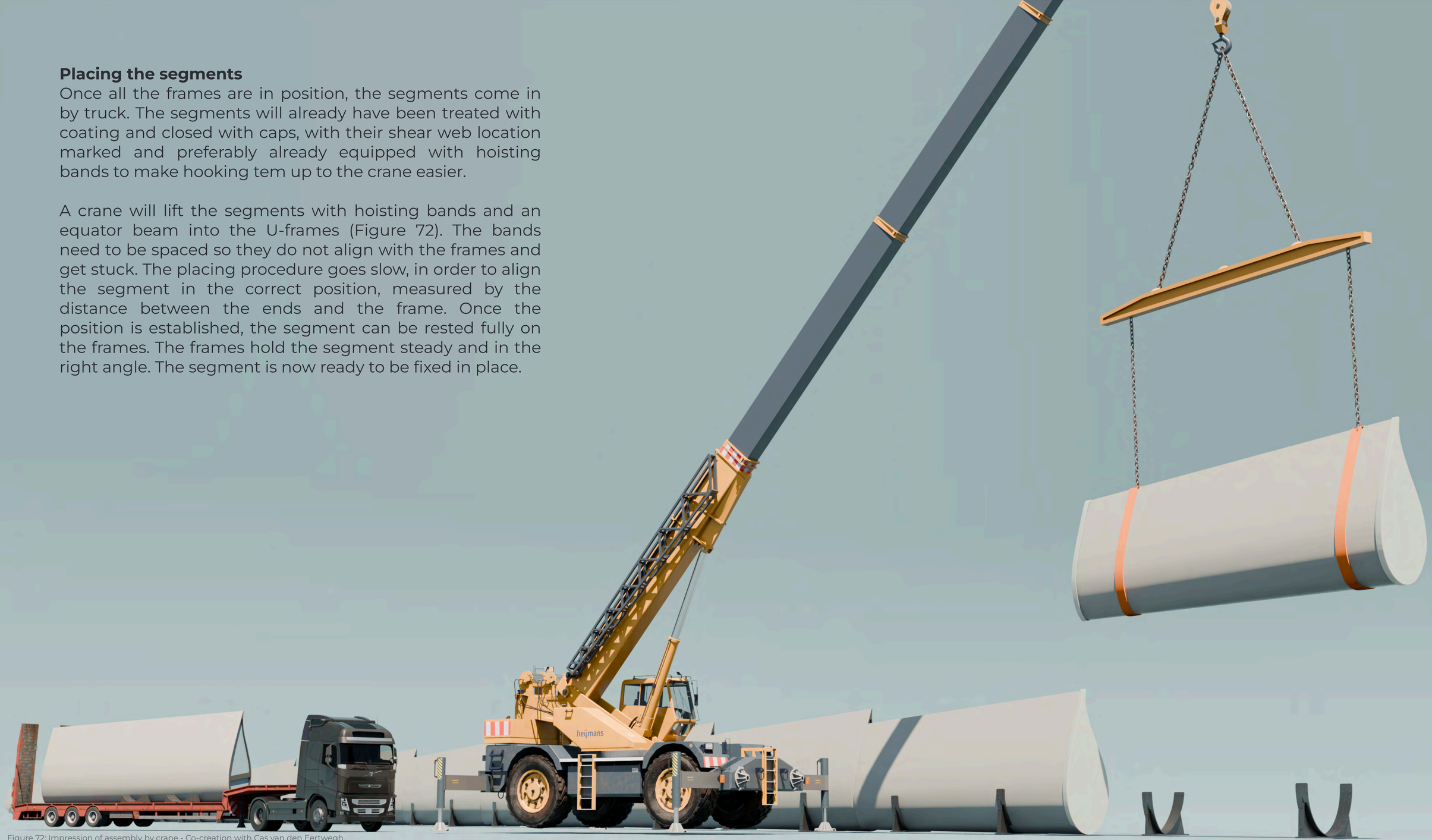


Figure 72: Impression of assembly by crane - Co-creation with Cas van den Eertwegh.

Fixing & Soundproofing

Once the segments are in place, holes are drilled through the spar cap area. The drilling should be done with safety glasses, gloves and a FP3 filter mask, better prepared than the worker in Figure 73. The drill will be fixed to the frame so it aligns perfectly with the holes, making sure the drill bit is not touching the steel. The shear web marking can indicate where or where not to drill. After drilling four correct holes, the segment is fixed in place with the M16 plugs through the spar cap.

Figure 73: Drillig holes in semgent - Co-creation with Cas van den Eertwegh.

Next, the soundproofing cover strips are installed. The holes are lined up with the threaded bushings on the smaller cap and screwed in place (Figure 74). The compriband seals the gap effectively. Finally, the 6m plinths are placed in between each of the frames. The plinth is lifted with a forklift and placed on the concrete foundations, leaning against the frames. When in place, the cover plates are bolted on, securing them tightly (A - Chapter 9.4).

Figure 74: Fixing the cover strip - Co-creation with Cas van den Eertwegh.

9.7 Roadside aesthetics

With all components assembled, the barrier takes its final form (Figure 75).

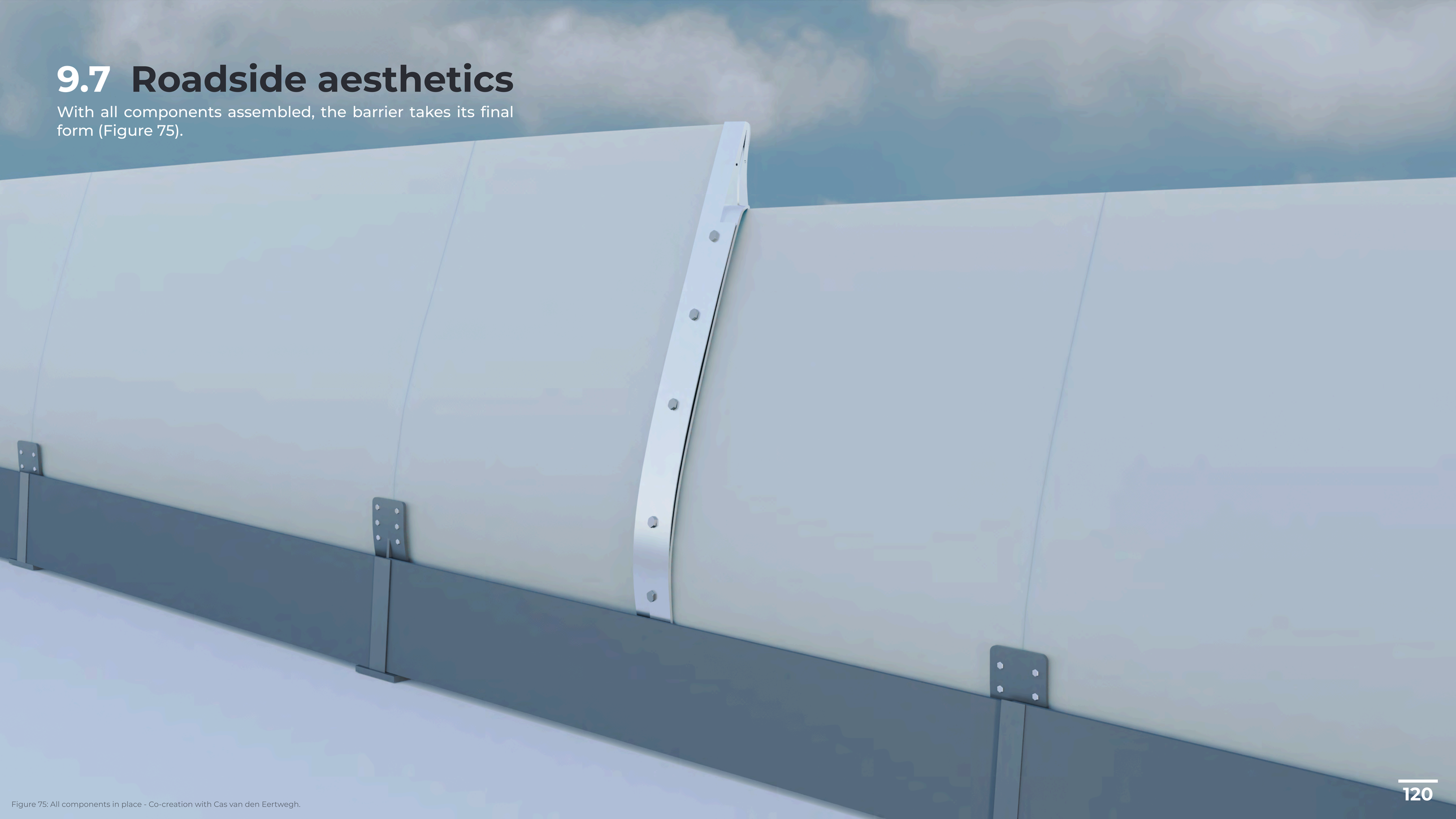


Figure 75: All components in place - Co-creation with Cas van den Eertwegh.

Rendering the final barrier concept next to a road gives a good impression of what it would look like (Figure 76). With an additional test in the rendering software to see how the barrier is perceived from a moving vehicle, it can be concluded that it will not be a problematic attention grabber. The final aesthetic of the barrier is clean, without vegetation or art, treated with anti-graffiti coating. The suction side of the segments faces the road and always tapers in the driving direction.

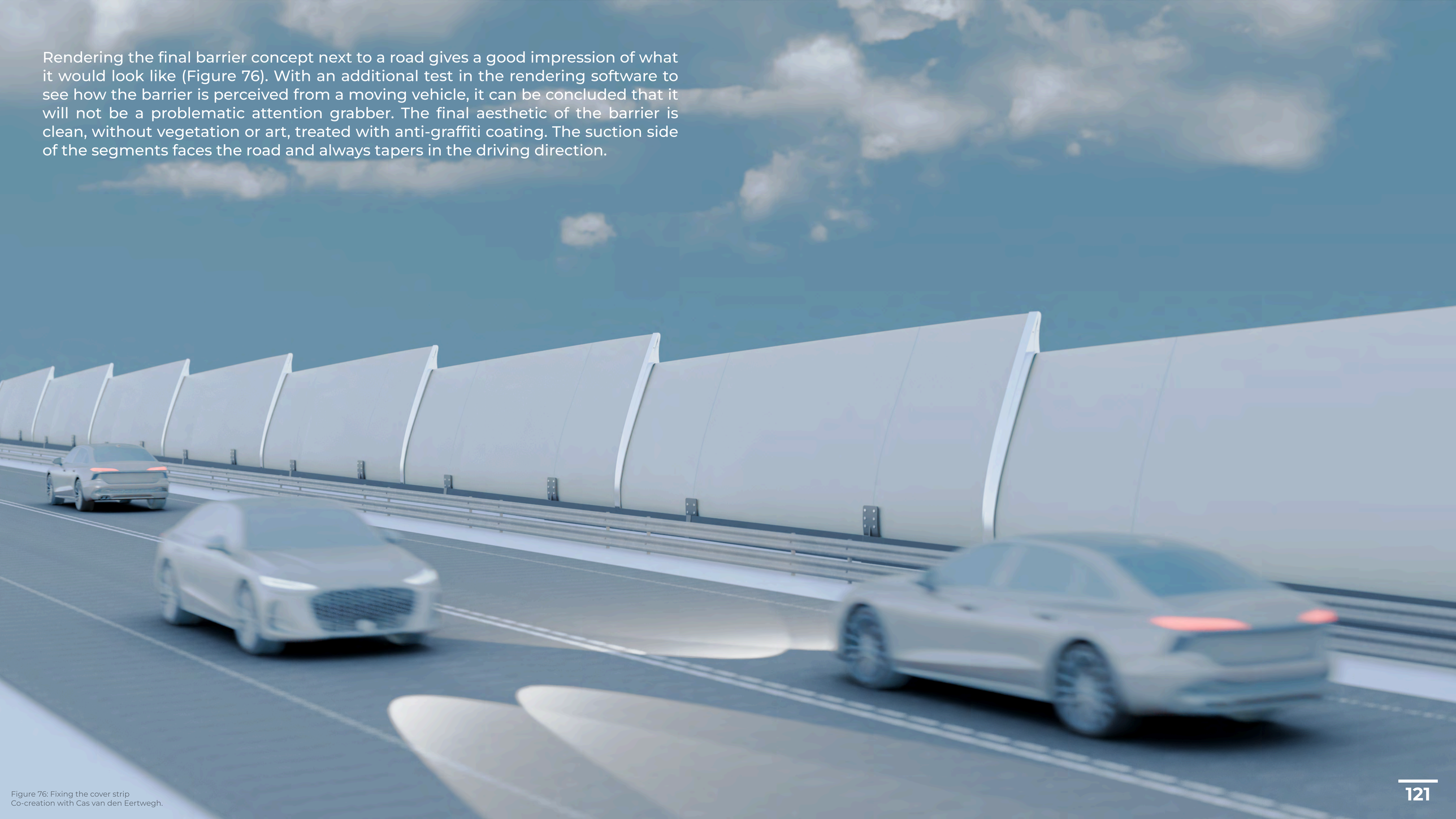


Figure 76: Fixing the cover strip
Co-creation with Cas van den Eertwegh.

10.
Prototyping & Evaluation

Although prototypes supported the design process early on, much of the development after the final concept still took place digitally rather than through physical models. Because it is hard to grasp the true size of the blade segments, building physical prototypes helps to understand their shape, scale, and weight. This chapter highlights key prototyping steps and evaluates the final design in terms of acoustic implications, a component cost estimation, a process walkthrough, what happens to leftover blade material, and a life cycle assessment of the barrier.

This chapter takes you through the following topics:

10.1 Material & Restrictions

10.2 The Alu-frame setup

10.3 Acoustic tests

10.4 Manufactured components pricing

10.5 Processing guide from blade to barrier

10.6 What happens to blade material that is left unused?

10.7 Life cycle assessment

10.1
Material & Restrictions

Blade material
The first steps of beginning to make a large scale prototype is gathering the material. One of the positives was that in the basement of the IDE faculty, profs and former graduates had collected a bunch of blade material from Fraunhofer (Figure 77). One of the pieces that seemed most useful as a segment of about 150cm high, 50cm between spar caps and 210cm from LE to TE (Figure 78).

When taking the blade out of the basement to the workshop area, it became clear that it was extremely heavy to handle without proper lifting equipment, around 300kg. Second of all, if the segment would have been placed upright in a frame, its height would not fit through the doors or in the lift. The only way would be by driving a forklift down into the basement and lifting it upright with a rope or band.

In theory it was possible but extremely limiting (also in prototyping freedom). Luckily a smaller segment which could be handled by two people was available, a good alternative, and still large enough for a significant prototype (next page).

Recycled composite planks
KoiosTitan is a company that makes 100% circular products from shredded composites. Because they also shred WTB material, it felt as the perfect opportunity to ask them for some building material to incorporate in the prototype. In agreement with Heijmans, three planks of 150x30x3,5 were ordered, to use as plinth to block sound for a possible later test. These solid composite planks were heavy as well, about 25kg each.

Restrictions of PMB
The PMB is the IDE workshop where usually all the tools and expertise is available for students to build prototypes. Unfortunately, due to a large renovation the PMB was closed the whole summer and only a handful of tools were still available. This made it extra difficult to build larger load baring structures that would have been needed to support the large blade segment. 3D printing and smaller scale prototyping could still be done smoothly.

Figure 77: basement filled with WTB material.

Figure 78: Discussing the handling of the big segment (Difficult).

10.2
The Alu-frame setup

The applied labs, a technology research lab at the IDE faculty, facilitated aluminium extrusion profiles that were perfect for constructing a custom frame to hold the blade segment in place for the prototype. Building it came with a few small iterative steps (Appendix D) but the final frame did what it was supposed to do:

- Showcasing a larger physical model (A).
- Hold the segment under the appropriate angle (adjustable) (B).
- Making the whole prototype movable by one person with wheels (C).
- Holding the plinth in place (D).
- Supporting the segment with hard foam tiles (E).

This segment functioned as base for testing of the cap and cover strip prototypes, also covered in Appendix D.

10.3
Acoustic tests

Acoustic testing
At first, together with M. van Amstel, a plan for an acoustic test was made to evaluate the acoustic effectiveness of a large blade segment. Planning this together with a company 4Silence, with a sonocat device (A). This device is able to measure the acoustic pressure and the transmission loss from behind the barrier (Figure 79)(Matters Academy, 2022). Doing a test however, was only possible if there would be a proper setup by the end of August. After realizing with PMB staff that making a setup with the initially intended segment proved to be too difficult, another discussion with M. van Amstel was held to re-frame the test and what the desired results were. The conclusion was that a measurement on a panel of 150cm wide from a distance would not have an accurate result, and because Neuman (2024) had some data on the material already, it was decided to not go further into realizing this test.

Recommended future tests
Due to limited time, this thesis has not further investigated the acoustic qualities of the final noise barrier design from WTBs. However, there are still some research areas that could use some attention:

- A Finite element analysis (FEA) should be able to point out whether the barrier segments start resonating with low frequency vibrations of traffic or wind.
- The top edge should be tested on diffraction and based on the outcome, measures have to be taken if necessary, as mentioned in Chapter 8.7.

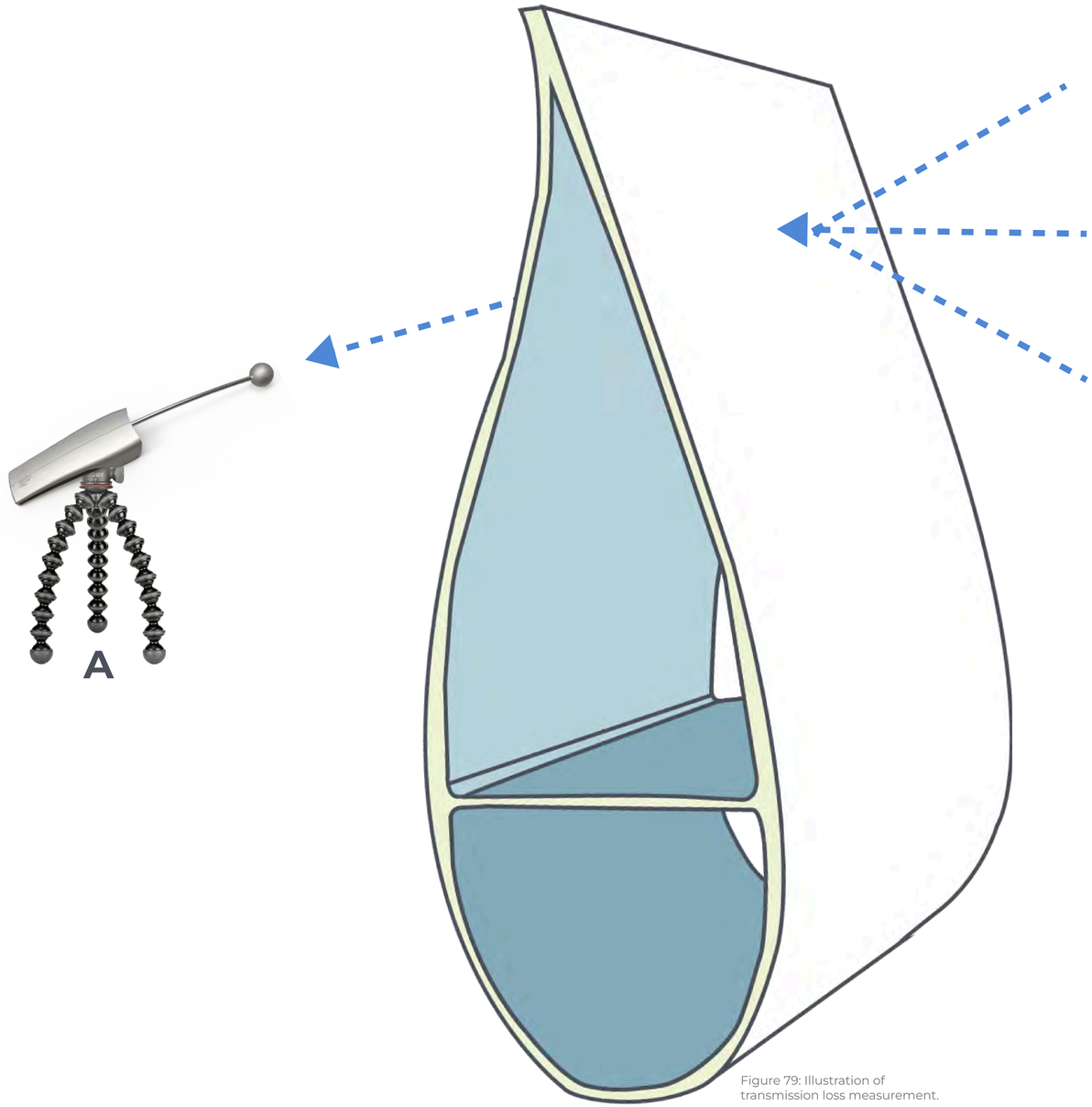


Figure 79: Illustration of transmission loss measurement.

10.4

Manufactured components pricing

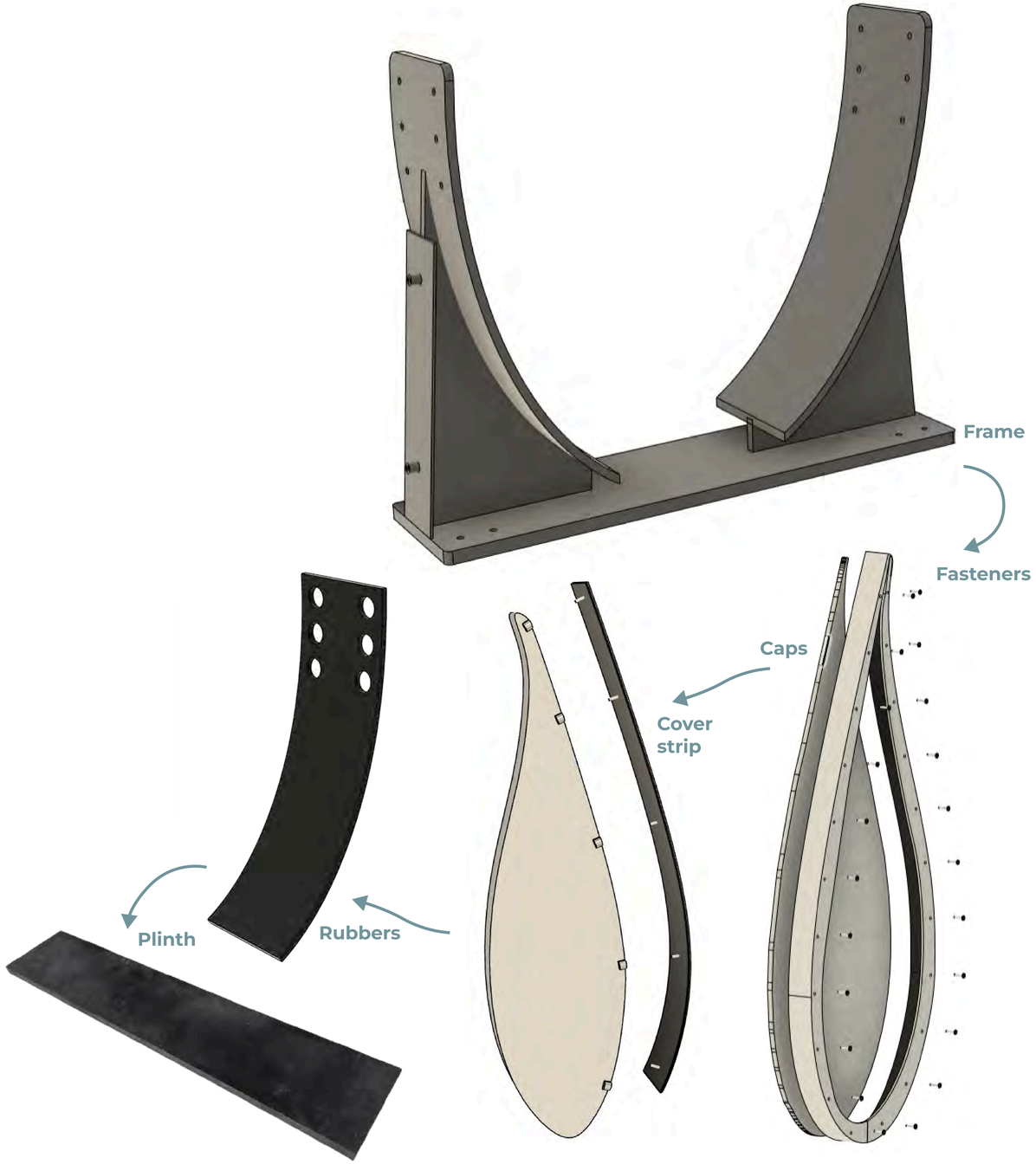
This page gives a rough estimate of the costs of 120 meters of blade barrier, excluding the foundation, labor for assembly, transport and installment. Calculations can be found in appendix B, the frame estimate is covered in Appendix E.

- **The frame:** €2919/pcs, 20 frames are ≈ €58.380
- **The foundation:** Unknown/ out of scope
- **The blade segments:** Unknown/ possibly free
- **The caps:** €780/pcs, 40 caps are ≈ €31.200
- **The Cover strips:** €204/pcs, 10 strips are ≈ 2040
- **The plinth:** €400/pcs, 20 plinths are ≈ €8000
- **All rubbers:** Frame rubbers and all comprimand: €1050
- **All fasteners:** approx. €2000

Total per 120m barrier: ≈ €102.670
Price of barrier per m²: ≈ €214/m²

Conclusion
This outcome is much higher than the initial estimate of €100/m² provided by Van Osch (PC, 2025). The stainless steel caps account for the largest part of the costs, raising questions whether the calculations were accurate. To reduce expenses, alternative materials with sufficient fire resistance and possible to make into caps should be investigated. Another option would be to substitute the airfoil shaped sheet with fiber cement or calcium silicate boards, as mentioned in Chapter 8.8.
Another option would be to leave out the caps entirely and only apply the protective coating to the edges, which would lower the cost to approximately €150/m² which is much closer to the original target.

It should be noted that, apart from the frames, many factors have been excluded from this calculation, such as manufacturing costs, bulk discounts, and that the material prices were not sourced with full reliability. In future research, more detail for the price estimate is required.



10.5

Processing guide from blade to barrier

Preparation: Looking ahead and (dis)assembly and manufacturing
Action: (dis)assembly and manufacturing

Noise barrier project becomes available, suitable for WTB reuse implementation.

- Wind park X is up for decommissioning
- The types of decommissioned blades are determined

Optimal 12m segment cutting model, created with computer software.

- Altering U-frame dimensions to specific segments.
- Altering design of segment caps.

Depending on project and barrier height, the suitable segments are chosen, the fitting U-frame and caps are ready for production.

Decommissioning starts.

- Starting the production of frames and caps.
- Starting prepare and lay the foundation.

- Blades are shipped to processing plant (near harbor).
- Blades are cut and processed.

Segments are treated with coating and pre-assembled with caps.

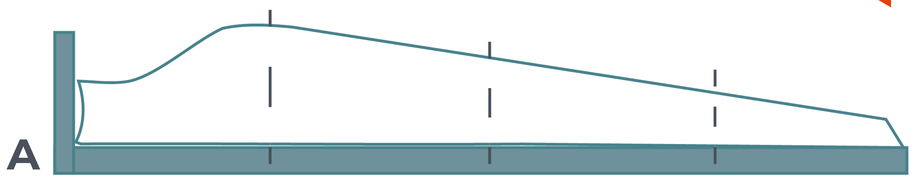
U-frames are ready to be installed.

Installing the blade barrier.

How to cut the blade

- Barrier segments are LE horizontal, meaning the LE has to be placed in a 90° angle with the cutting blade (A).

Explanation



10.6

What happens to blade material that is left unused?

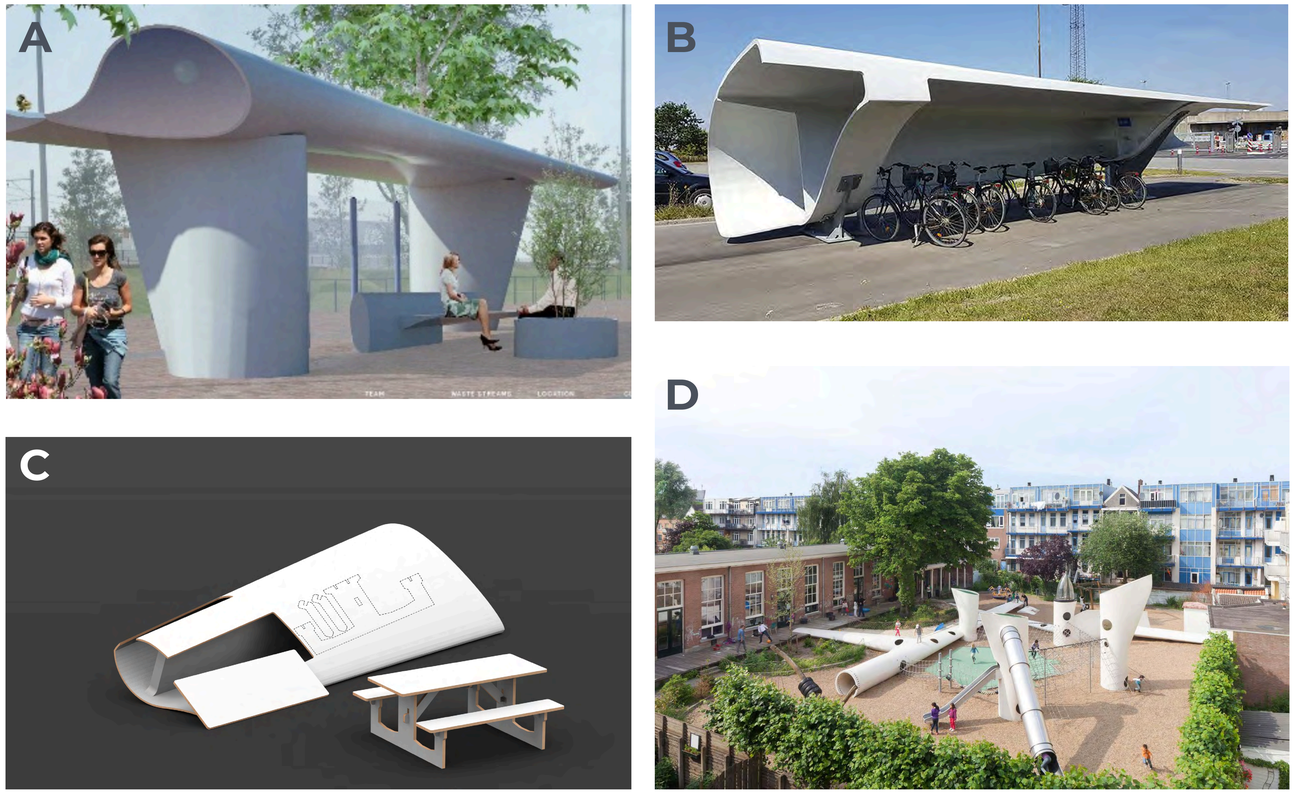
The WTB material that is left unused, whether due to damage, oversupply, or not suitable for the barrier design, depends largely on the condition of the material.

Damaged elements are often unsuitable for direct application and are therefore shredded. Shredded composites can then serve as raw material for innovative products. As mentioned before, Miljøskærm incorporates shredded composites into noise barriers, KoiosTitan applies them in its compressiet© plates, and Poly Products employs the material in composite 3D printing. These Examples demonstrate the potential of applications for shredded material recycling at an industrial scale.

For larger, intact segments of wind turbine blades, a few different options are possible. One option is to store the components for use in later barrier projects, though this is often expensive and logistically challenging. Alternatively, such segments can also be shredded and processed into new materials.

Beyond barriers, smaller-scale projects present further opportunities for reuse. Parts of blades can be adapted for urban infrastructure such as bus shelters (A), bicycle sheds (B), benches (C), or playground equipment (D). On the larger end of the spectrum, blades with insufficient height to serve as barriers may still be structurally suitable for projects such as pedestrian bridges, as demonstrated by Re-wind USA (2025) (Appendix I).

Finally, purposeful landfilling could pose as a different research direction. Wind turbine blades could be repurposed in coastal management, for example, as reinforcement in dikes, water protection works, or even as breakwaters. While still largely experimental, this approach may offer a solution for handling large blade volumes in the future.



(A&D: BladeMade (2021), C: Jelle Joustra (2019), B: The re-wind network (2021)).

10.7
Life Cycle Assessment

Based on the assessment by Royer (2025), this chapter covers the most important factors that influence the environmental impact of using wind turbine blades in noise barriers.

Foundation
Concrete and steel foundations account for over 60% of a barrier's total impact. Longer WTB panels can reduce the number and size of foundations. In theory, a 50% reduction in foundations cuts Global Warming Potential (GWP) and Environmental Impact Indicator (MKI) by about 40%. In practice, however, foundation needs depend heavily on soil conditions, and the actual savings may be smaller than expected.

Although using two frames for a 12m blade segment appears to be a 50% reduction compared to standard 6m modules, the frame spacing remains 6m. Consequently, the actual reduction is only a single frame at each end.

Material comparison
For noise barriers, MKI indicators show the WTB-based option competes closely with wood and concrete, while its GWP is 16% lower than wood and even further reduced compared to concrete and aluminium. This highlights the carbon benefit of reusing decommissioned blades

Virgin resin in plinth
The KoiosTitan plinth, made with virgin resin, contributes significantly to environmental impacts due to fossil-based, energy-intensive production. Switching to bio-resins could cut the MKI by 18%, making this a priority for material optimization.

Cutting methods
Processing methods also matter. Diamond wire sawing has the lowest footprint (3.08 kg CO_2/m^2), followed by circular sawing (5.08 kg CO_2/m^2). Water jet cutting is least favorable (14.39 kg CO_2/m^2) due to high electricity and water use. Given current technology, circular sawing remains the most practical large-scale solution, as proposed in Chapter 2.5.5.

Conclusion
The environmental advantages of WTB barriers are real, but it is closer than expected.

The foundation is so much dependent on the soil composition that claiming anything close to a reduction of foundation size cannot be claimed. Furthermore, two frames per 12 meters of blade sounds like a reduction of half, but effectively this comes down to only two frames less on both ends, compared to a 6m barrier modules setup because they are still 6m apart.

It ultimately comes down to:
- Foundations may be reduced, but only if site conditions allow.
- Lifetime is expected to compete with concrete and far outlast wood.
- Blades provide a low-cost, potentially incentivized material stream.
- While cutting methods can be further optimized, the longer segments already reduce processing needs.
- Switching to bio-based resin for the plinth is essential.

Discussion

This thesis proposed the reuse of decommissioned wind turbine blades in the form of horizontally oriented segments for the construction of a noise barrier. The requirements from Heijmans and the GCW handbook (CROW, 2012) were used as the main drivers for the design, and this discussion reflects on the implications, limitations, and outcomes of the work.

During development, the goal was to meet as many requirements as possible and to bring the barrier concept close to something that could actually be realized. Most requirements were either achieved or show good potential, supported by assumptions, calculations and expert feedback, although not everything could be tested in the time of this project. For the areas where feasibility is still uncertain, this discussion opens up the main points.

Numbers indicated as: (2.3) are requirement from the table (Chapter 5.2.2).

Design feasibility
In terms of design feasibility, the barrier performed well. Technical, structural, and acoustic aspects were taken into account, using expert advice and GCW guidelines. Calculations were made for structural stability, and real-world issues such as drainage, emergency exits, and fire and vandalism protection were considered (4.3-5.4). Processing methods and worker safety were also addressed (6). Assembly (2.1) and disassembly requirements were met (CROW, p.81), meaning the design can be modular and maintain reuse value.

Limitations
At the same time, there are limitations. Acoustic performance, for example, could not be fully tested. The diffraction of sound over the serrated top is unknown, and without testing it is difficult to confirm that the barrier achieves the minimum 25 dB reduction, even though it appears possible in theory (3.2). Another limitation is the uncertainty about the actual lifetime of the barrier (1.1, 8.1). In addition, no quantitative research has been done on how residents and road users would accept its appearance in the landscape (7.1).

Scalability and implementation also raise questions. Supply chain logistics, storage, and construction planning are still largely undiscovered topics. It is not yet clear how long construction would take, or how such a project could be organized in practice (9.1-10.2). Furthermore, Rijkswaterstaat and other regulatory bodies will inevitably influence the process. Since wind turbine blades are not a common building material, regulations still need to be developed for these composites (Van Amstel, PC, 2025). Acceptance of the project is likely, since Rijkswaterstaat already approved BladeMade's project.

Implications
From an environmental point of view, it is clear that the reuse of WTBs avoids a large waste problem and aims for a better circular economy. Still, the LCA did not yet show a strong advantage over conventional noise barriers (8.3). Future improvements could come from a long expected lifetime, bio-based resin plinths, and optimized foundations. Because of these unknowns, it remains difficult to make a fair comparison with existing barrier types in terms of cost, performance, and sustainability.

Positives
There were also positive and somewhat surprising outcomes. The U-frame or "jagged jaws" design came out on top, while 3D-printed cassettes were initially considered more innovative. In the end, the simplicity and reliability of the U-frame proved to be more valuable, and experts confirmed it has real potential in terms of scalability and feasibility (Van Amstel, PC, 2025). Although further development is needed, the principle behind the design is solid and shows real potential for large-scale use.

Conclusion

The overall vision of this thesis was to find a way to reuse blades as noise barriers. It was never expected to be a perfect solution, but rather to make the best of what is feasible now. The idea is to store blades along highways in the form of noise barriers, offering a useful application while waiting for recycling technology to catch up. At that point, the blade material can enter a new phase of reuse.

Looking back at the research questions:

1. **How can decommissioned wind turbine blades be reused efficiently in modular and scalable noise barrier applications?**

This thesis has shown that blade segments can indeed be turned into modular, scalable barriers. Efficiency in terms of material use is not yet ideal and should be improved in the future, but the concept is feasible.

2. **What design and construction strategies can ensure a seamless horizontal arrangement of WTB segments in a noise barrier, minimizing sound leakage and misalignment, maximizing ease of installation and viability?**

The key strategies were the use of caps, cover strips, and a plinth. Aligning segments turned out to be more difficult than expected, which is why large and small blade segments were not combined. The design includes tolerances in multiple areas to allow for misalignment of components while maintaining acoustic sealing (at least on paper). Components were kept simple but still good quality.

3. **What are the logistical and technical challenges in the current supply chain for decommissioned WTBs, regarding processing locations, storage, and noise barrier assembly?**

This question has been present throughout the project but remains only partially answered. Some proposals gave a context, such as processing at an AYOP location with a cutting station, but the broader logistics, assembly methods, and supply chain setup are still uncertain and untested.

4. **How to ensure the added value of using WTBs as building material gains the trust of the current competitive market?**

Royer's (2025) life cycle assessment helped to reflect on this, but concrete answers are still missing. Gaining trust will depend on actually showing the reuse potential with this barrier design and underlining the urgency of the blade waste problem. Hopefully, this thesis can contribute to raising awareness and inspires further innovation in blade reuse.

In short: the blade barrier is not a perfect noise barrier solution, but it is a promising one. With further research and development, it could become a scalable and sustainable option for addressing the upcoming blade waste challenge.

Recommendations

Based on the outcomes of this thesis, a number of areas still need further development in order to bring the blade barrier concept closer to real-world implementation. The following recommendations are grouped into research, knowledge, design, production, and industry. They highlight what actions could make the concept more feasible, affordable, and accepted.

Research gaps
One of the most important gaps is in acoustic research. Large-scale testing on blade segments is still missing, especially regarding resonance effects, diffraction over the top, and reflection off the front surface. These aspects are crucial to confirm the effectiveness of the barrier in practice. The BladeMade A58 project could be a useful reference (BladeMade, 2025).

Another area is user perception. No quantitative research has been done on how residents and road users would experience the aesthetics of the barrier in the landscape. Since public acceptance is essential for infrastructure projects, this should be studied in future work (pages 31–38, CROW, 2012).

Knowledge gaps
Firstly, the type of foundation required will have a strong influence on both cost and environmental performance, and this has not yet been fully determined.

The question of storage and processing also remains open: where will blades be kept before and after they are cut?

Finally, governmental incentives or policies could play an important role in making blade reuse attractive to companies. The presence (or absence) of such support will strongly influence how quickly this type of project can move forward.

Design
The design itself can still be improved in several ways. For example, how the frames are made fitting to given blade dimensions should be further developed, and the steel thickness should be optimized for production, strength and cost.

The components are another important point. The caps and cover strips turned out to be major cost drivers. Alternative materials that are cheaper but still fire-resistant should be explored. More research into the load capacity of the anchors and hollow wall plugs could reduce how many are needed, as the current design probably includes more than necessary (Chapter 8.5).
Now, only 12 meters of a 50-meter blade are being used in the barrier. Although the remains can also be used as lower barriers, finding ways to use more material of each blade for one barrier design would increase the reuse efficiency.

Noise barrier production
For production, it would make sense to focus on Vestas V80 and V90 blades first, since they are expected to become available in 2027 and their dimensions fit the design well.
The logistics of decommissioning, transporting, and processing blades should also be worked out in more detail, including defining which partners would be responsible for which steps.
Furthermore, the material & manufacturing cost calculations and LCA need to be reevaluated once the design, materials, and foundation are finalized, Hopefully getting a more realistic and promising result.

Wind industry
Finally, some recommendations are for the wind industry as a whole. Opening a shared repository with (decommissioned) blade data and CAD models would make it much easier for designers to develop reuse applications .

On the long term, the waste problem should also be addressed at the source. Initiatives such as the ZEBRA consortium (2024), which is working on thermoplastic blades that are much easier to recycle, are an important step in the right direction.

Personal reflection

I would like to end my thesis on a personal note. I have had a great experience working on this project. I got completely swallowed by it, and it feels double to be finishing soon. I have learned a lot about myself and gained the confidence that I have what it takes. It took me many many hours to truly make this project mine, because I think fast but write slow. If I had more time, I would have loved to build a prototype of the frame in steel or even realize a large segment prototype for Heijmans to test. Although it is hard to let go, I feel proud of what I have achieved.

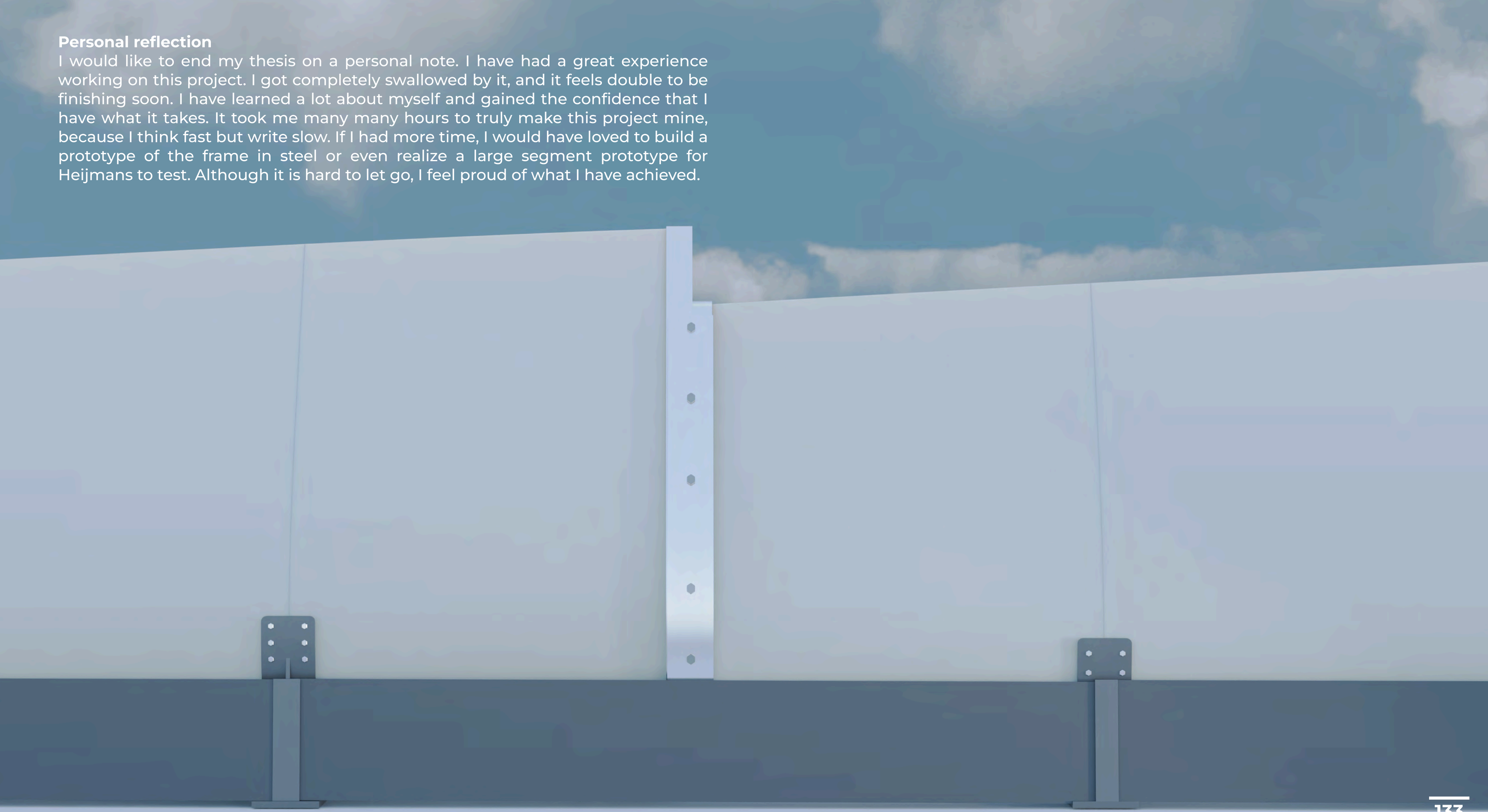


Figure 80: Final barrier close up - Co-creation with Cas van den Eertwegh.

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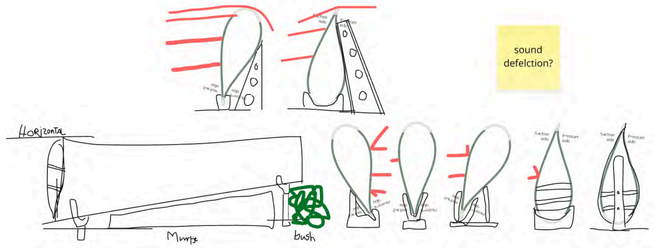
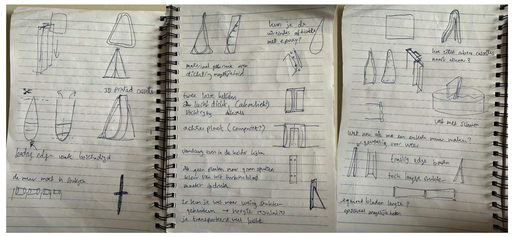
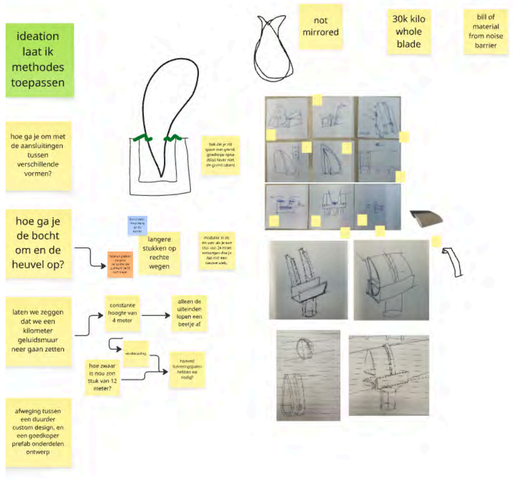
The use of AI

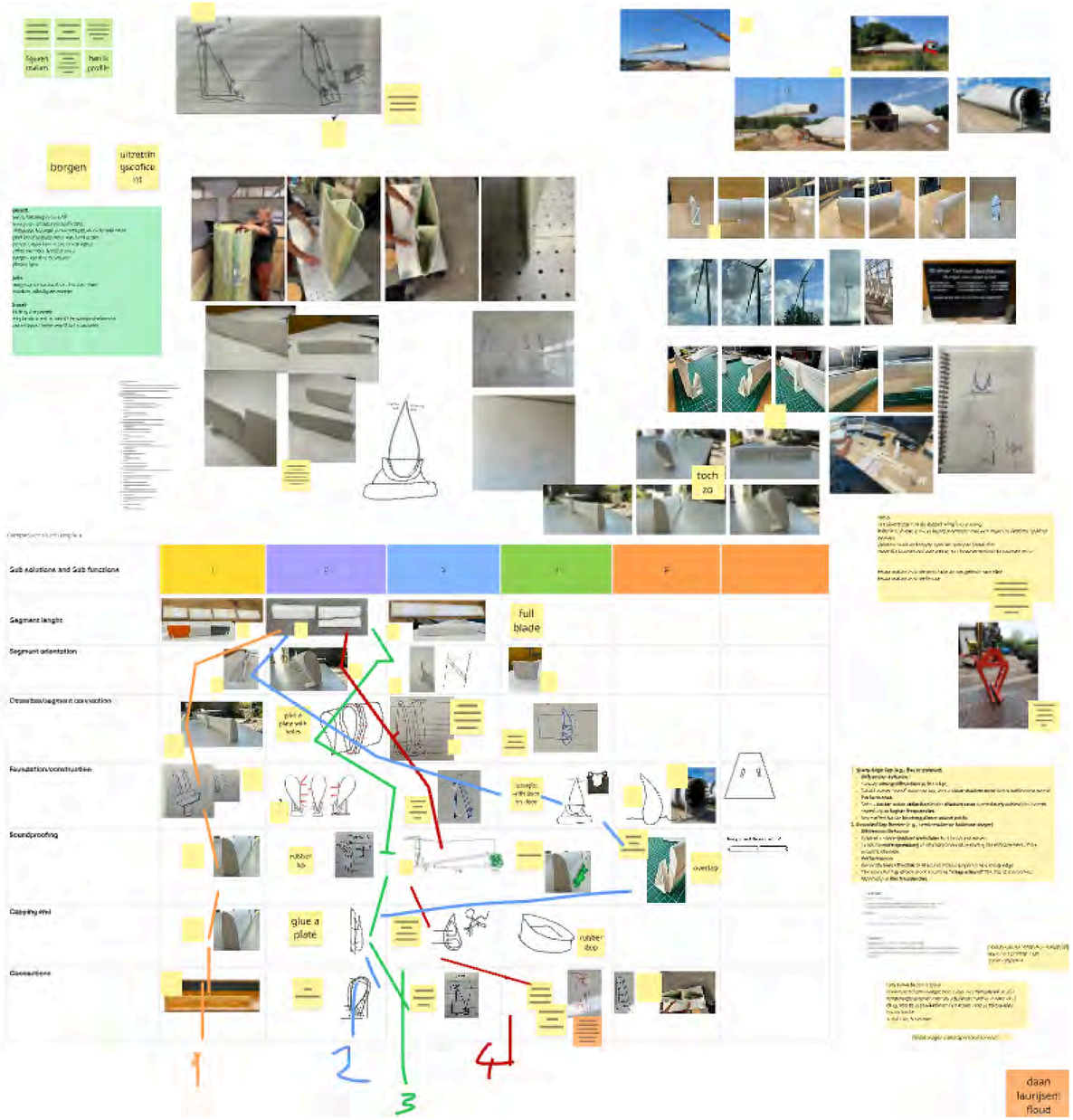
AI, in the form of ChatGPT, was used in this thesis to check written text on spelling, grammar, and clarity. In addition, calculations on material dimensions, costs, and forces were done with AI support. These calculations were discussed and validated by Heijmans engineers, as an additional human check.

Appendix A: Ideation









Appendix B: Calculations

Price calculation per component

Frames
Full cost estimation in Appendix E.
Price for 20 frames is €2919 /pcs

$$P = 3029 + \frac{(20-10)}{(25-10)} \times (2864 - 3029)$$

$$P = 3029 + \frac{10}{15} \times (-165)$$

$$P = 3029 - 110 \approx 2919$$

Foundation
Out of scope

Caps and Cover strip

Step 1: Approximate the area

An airfoil roughly resembles a **trapezoid** for estimation:

- Chord (length) = 4 m
- Maximum width (thickness of shear web) = 1.5 m

Area ≈ $\text{chord} \times \text{average width}$

- Assume average width ≈ 0.75 × maximum width (typical airfoil shape)

$$\text{avg width} \approx 1.5 \times 0.75 = 1.125 \text{ m}$$

$$\text{Area} \approx 4 \times 1.125 = 4.5 \text{ m}^2$$

Step 2: Stainless steel sheet weight

- Thickness = 4 mm = 0.004 m
- Density of stainless steel ≈ 8000 kg/m³

$$\text{Volume} = 4.5 \times 0.004 = 0.018 \text{ m}^3$$

$$\text{Weight} = 0.018 \times 8000 \approx 144 \text{ kg}$$

Step 1: Area of one L-strip

- Long side: 0.15 m × 0.004 m = 0.0006 m²
- Short side: 0.05 m × 0.004 m = 0.0002 m²
- Total cross-sectional area = 0.0006 + 0.0002 = 0.0008 m²

Length = 4 m → volume:

$$0.0008 \times 4 = 0.0032 \text{ m}^3 \text{ per strip}$$

- Two strips → 0.0032 × 2 = 0.0064 m³

Step 2: Weight

$$0.0064 \times 8000 \text{ kg/m}^3 \approx 51.2 \text{ kg total}$$

304 stainless steel sheet: ~€4.0–4.2 per kg (BSSA, 2025).

- SS cover strip 0.004×0.40×4 m → 0.0064 m³ → 51 kg ≈ €204.
- SS airfoil plate → 144 kg component: ≈ €576.
- SS L-strips → 51.2kg ≈ €205

Total: ≈ €985

Rubbers (Source: rubbercal.com)

- Dimensions: 0.40 m × 3.00 m × 0.03 m

$$V = 0.036 \text{ m}^3$$

- Density EPDM closed-cell ≈ 120 kg/m³

$$\text{Weight} = 0.036 \times 120 \approx 4.3 \text{ kg}$$

- Price ~€8–10/kg → ≈ **€35–45 per sheet.**

For L-strips (80 pieces)

- Size each: 2 cm × 15 cm × 400 cm = 0.02 × 0.15 × 4.00 = **0.012 m³**
- Total: 80 × 0.012 = **0.96 m³**

For cover strips (10 pieces)

- Size each: 3 cm × 40 cm × 400 cm = 0.03 × 0.40 × 4.00 = **0.048 m³**
- Total: 10 × 0.048 = **0.48 m³**

Combined volume

0.96 + 0.48 = **1.44 m³**

Weight estimate

Density of compriband (PU/EPDM foam) ≈ 35 kg/m³
→ 1.44 × 35 ≈ **50 kg** total

Cost

Typical ≈ €4–6/kg → ~**€200–300 total**

KoiosTitan plinth

- Bought for the prototype was: 1.5 × 0.3 × 0.035 m → volume = 0.01575 m³ → €50 → price/m³ ≈ 3175 €/m³
- Second plank: 6 × 0.8 × 0.04 m → volume = 0.192 m³ → price = 0.192 × 3175 ≈ €609
- Maybe when ordering in bulk, the price will be lower, lets assume €400

Bolts and screws (Source: Hilti.nl)
Unit prices (approx):

- watertight screws (stainless) ≈ €0.60–1.20 each
- M16 8.8 bolts (steel) ≈ €3–6 each
- M16 hollow wall plug ≈ €3-6 each

- 440 watertight screws → ~€264–528
- 160 M16 8.8 bolts → ~€480–960
- 160 M16 plugs → ~€480–960

≈ €1224–2448 total

Strength of plinth when a mower hits it

With information supplied by KoiosTitan who mentioned the product can be made stronger by adding fibers, and by doing assumptions on loads and max deflection, calculations were done with the help op Erik Nouwen (Heijmans engineer), two mechanical engineer housemates and some ChatGPT.

Materiaal specificatie

Polyester Basis materialen

Treksterkte Ft0 Mpa	Trekstart Ft90 Mpa	Max rek %
60	60	2,0%
60	60	2,0%

Norm: NBN EN B15-211

Buigsterkte Fm0 Mpa	Buigsterkte Fm90 Mpa
38	38
38	38

Norm: EN 196-1

Druksterkte Fc0 Mpa	Druksterkte Fc90 Mpa	Maximum indrukking %
60	60	6,2%
60	60	6,2%

Norm: 196-1

1) Snelle orde-grootte schatting uit je tabel

Je tabel "**Polyester basis materialen**" geeft o.a. **treksterkte ≈ 60 MPa** bij **maximale rek ≈ 2 %**. Als grove benadering kun je hieruit de (secans)-modulus schatten:

$$E \approx \frac{\sigma}{\varepsilon} = \frac{60\ \text{MPa}}{0{,}02} = 3000\ \text{MPa} = 3\ \text{GPa}.$$

Let op: dit is **géén echte initieelastische modulus** (tangent), maar een **ondergrens** op basis van de waarde bij 2 % rek. Het past wel bij een **polyester matrix** zonder vezelversterking (typisch ~2–4 GPa). Voeg je **glasvezel** toe, dan kan de effectieve E naar **~20–50 GPa** (afhankelijk van vezelvolume, oriëntatie en laminaten).

Overspanning		6000	mm	
I =	$1/12bh^3$	2858333	mm4	
U max		50	mm	
F	hor. belasting maaier	10000	kN	<AANNAME>
Emim	FL^3 / 48iu	314869	N/mm2	

The first calculation of Nouwen (2025) resulted in an 314GPa load, which is very high.

Is 10 kN realistic for a flail mower impact?

A klepelmaaier (flail mower) doesn't continuously push with 10 kN; instead, it delivers short, high-energy impacts from the swinging hammers. Literature and practice suggest impact forces of 1–3 kN per hammer are typical. If several hit nearly simultaneously or if something jams, peaks could be higher, but 10 kN seems conservative / possibly too high as a quasi-static design load.

After reevaluating, a few assumptions were changed.

- The plinths are not simply supported but fixed to the frames, making C=196 instead of C=48
- The mower impact of 10kN is high, so 5kN is used instead.
- Making the plinth a bit thicker, from 35mm to 40mm.

Inputs

- $P = 5{,}000\ \text{N}$
- $L = 6.0\ \text{m}$
- $h = 40\ \text{mm} = 0.04\ \text{m}$
- $b = 0.8\ \text{m}$
- $\delta_{\max} = 50\ \text{mm} = 0.05\ \text{m}$
- $C = 196$ (ingeklemd–ingeklemd, puntlast midden)

Calculation

- $I = \frac{bh^3}{12} = \frac{0.8 \times 0.04^3}{12} = 4.2667 \times 10^{-6}\ \text{m}^4.$
- Rearranging $\delta = \frac{PL^3}{CEI}$ gives

$$E = \frac{PL^3}{CI\delta} \approx 2.5829 \times 10^{10}\ \text{Pa} = 25.8\ \text{GPa}.$$

Interpretation

- $E \approx 25.8$ GPa, which is **consistent** with a glass-fibre reinforced polyester composite (typical GFRP range ≈ 20–50 GPa).
- This indicates that, with a 40 mm thickness, the plank would meet the $U_{\max} = 50$ mm requirement under a 5 kN centered point load *given the idealized assumptions* (perfectly clamped supports, static load, no local indentation).

Notes / caveats

- The result is sensitive to assumptions: support conditions, actual load distribution (patch vs point), dynamic impact effects, and real boundary stiffness.
- For a flail mower impact it's advisable to include a safety factor and check local bearing/indentation and fatigue, not only global deflection.

- **25.8 GPa** is the **elastic modulus** E → a measure of stiffness (stress/strain slope).
- **200–400 MPa** is the **strength** (the maximum stress the material can carry before failing).

They're totally different properties. To compare correctly:

Step 1. Compute stress in the plank under 5 kN

For a beam with a midspan point load and clamped–clamped ends:

$$\sigma_{\max} = \frac{M_{\max} \cdot y}{I}$$

- $M_{\max} = \frac{PL}{8}$ (for clamped–clamped, it's actually a bit lower, but this gives an order of magnitude).
- $P = 5000\ \text{N},\ L = 6.0\ \text{m} \rightarrow M \approx 3750\ \text{Nm}.$
- $I = 4.27 \times 10^{-6}\ \text{m}^4$ (from before).
- $y = h/2 = 0.02\ \text{m}.$

$$\sigma_{\max} = \frac{3750 \times 0.02}{4.27 \times 10^{-6}} \approx 17.6\ \text{MPa}.$$

Step 2. Compare with strength

- $17.6\ \text{MPa}$ is the stress in the plank.

With the given values of 60MPa by Koios, this means it is unlikely that the plank would snap in two under a single flail mower strike.
What's more more realistic:

- Local damage: A flail mower hit is not a smooth static point load; it's a short-duration, high-velocity impact. That can cause local crushing, chipping, or delamination at the impact location.
- Repeated hits could fatigue the composite surface.

It can be concluded that the plinth should be thicker at least 40mm thick.
Furthermore, if a plinth breaks, it is not the end of the day, as it can be replaced relatively easily.

Thermal expansion of the segment (Help of Chatgpt)

Formula:

$$\Delta L = \alpha \cdot L \cdot \Delta T$$

where

- α = linear thermal expansion coefficient (1/°C)
- L = original length (m)
- ΔT = temperature change (°C)

Result unit → metres (m).

Using your segment $L = 12\ \text{m}$ and $\Delta T = 40\ ^\circ\text{C}$:

1. With $\alpha = 10 \times 10^{-6}\ /^\circ\text{C}$:
- compute $12 \times 40 = 480$
- multiply: $480 \times 10 \times 10^{-6} = 480 \times 0.00001 = 0.0048\ \text{m}$
- $\Delta L = 0.0048\ \text{m} = 4.8\ \text{mm}$
- relative change = $0.0048/12 = 0.0004 = 0.04\%$
2. With $\alpha = 20 \times 10^{-6}\ /^\circ\text{C}$ (conservative case used previously):
- $12 \times 40 = 480$
- $480 \times 20 \times 10^{-6} = 480 \times 0.00002 = 0.0096\ \text{m}$
- $\Delta L = 0.0096\ \text{m} = 9.6\ \text{mm}$
- relative change = $0.0096/12 = 0.0008 = 0.08\%$

For other typical values:

- $\alpha = 5 \times 10^{-6} \rightarrow \Delta L = 2.4\ \text{mm}$
- $\alpha = 15 \times 10^{-6} \rightarrow \Delta L = 7.2\ \text{mm}$

Takeaway: for a 12-meter blade segment and a 40 °C swing, thermal expansion is **very small** — on the order of **2–10 mm** depending on the chosen α. Even the conservative 9.6 mm is well below typical assembly/tolerance allowances (you mentioned a 4 cm working tolerance earlier), so thermal movement is minor compared with installation tolerances.

This calculation and the 1 cm expansion is low, confirmed and approved by Heijmans engineers **Grevelink** and **Nouwen** personal communication 2025.

Weight of Segment

From GeorgiaTech: The 15-meter blade weighs around 7,000 pounds (Malone, 2025).
7000 pounds = 3175kg 3175/15*12 = 2540kg
NREL is 30 tons for 60m, so on average 500kg per meter so 12m is 6000kg, but the root is by far the heaviest (Joustra, PC, 2025)
Because we dont know the exact dimensions of the georgiatech blade, the estemated weight of a segment will be assumed at 2-5 tonnes

Weight of U-frame (First estimate)(Help of Chatgpt)

lets assume plain carbon steel with density ρ = 7,850 kg/m³
with overall thickness between: 20 mm (0.02 m) and 30 mm (0.03 m).

Plate areas

- Plate A: 2.4 × 0.4 = 0.960 m²
- Plate B: 1.7 × 0.5 = 0.850 m²
- Triangle 1: 0.125 m²
- Triangle 2: 0.125 m²
- Total area = 0.96 + 0.85 + 0.125 + 0.125 = 2.06 m²

Volume = area × thickness

- For 20 mm: V = 2.06 × 0.02 = 0.0412 m³
- For 30 mm: V = 2.06 × 0.03 = 0.0618 m³

Mass = volume × density (ρ = 7,850 kg/m³)

- 20 mm case: mass ≈ 0.0412 × 7,850 = 323.4 kg (≈ 0.323 t)
- 30 mm case: mass ≈ 0.0618 × 7,850 = 485.1 kg (≈ 0.485 t)

Per-piece masses (20 mm / 30 mm)

- Plate A (0.96 m²): 150.7 kg / 226.1 kg
- Plate B (0.85 m²): 133.5 kg / 200.2 kg
- Each triangle (0.125 m²): 19.6 kg / 29.4 kg

Notes

- These figures are for solid flat plates (no cutouts, holes, stiffeners or weld build-up).
- If the plates are galvanized, painted, or have attachment fittings, add a few kg per piece.
- If your frame includes wastage (cutting off corners), fasteners, brackets, welds, or thicker edge reinforcement, the real mass will be higher.

Van Amstel has calculated the large frame to about 750kg, but this is before the optimization.

Appendix C: Continuing with segments

After reviewing the previous noise barrier design by Gabriëls (2025), the choice between a paneled or segmented noise barrier approach raised many concerns:

- Panels include a lot of extra sawing, pre-processing, more tool wear, more post processing, edge treatment, higher risk of material degradation, more assembly steps, higher operational costs.
- The top of the noise barrier has to be covered by an extra component, otherwise water gets in (Nouwen, PC, 2025).
- The filler material (e.g. sand) in between panels, is difficult to add, and not compatible with a drainage slit.
- The assembly has different panels and components, more manufacturing of parts required for prefab-components, longer overall assembly time.
- The logistics of transport and handling in terms of weight and space efficiency, panels score higher for obvious reasons.
- In terms of impact, the extra sawing and processing almost makes up for more compact transport and lighter assembly. However, the additional steps of cutting also require extra lifting and moving segments around.
- The aesthetic appearance of a paneled design might have a slight more coherent look, especially for the road side. That's because for a segment approach, the barrier sub-assemblies can differ between full or double blade.

Based on these critique points, a weighted criteria Table 4 was constructed to see which design would be favorable based on topics perceived more valuable for the current project. From the table below, the noise barrier made from WTB segments concludes more promising.

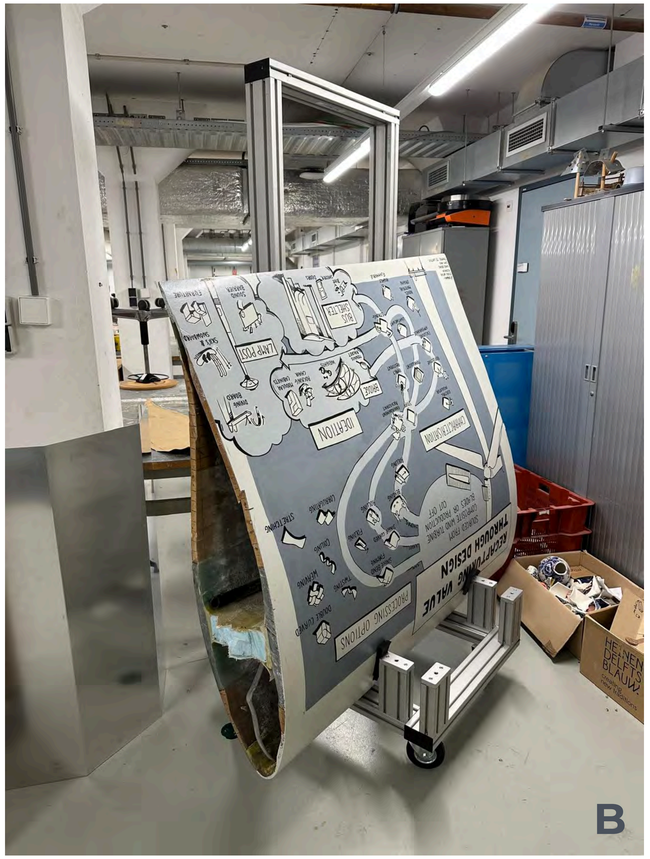
Criteria	Description	Panels (1-5)	Segments (1-5)	Weight (0 to 1)	Weighted Score (Panels)	Weighted Score (Segments)
Processing efficiency	Time, tool wear, amount of cuts, post-processing	2	4	0.30	0.6	1.2
Assembly time	Fewer sub-assembly steps, ease of construction	2	4	0.25	0.5	1.0
Material durability risk	Exposure to moisture, open edges, long-term structural quality	2	4	0.15	0.3	0.6
Manufacturing components	Need for joint parts, additional prefab pieces	2	4	0.10	0.2	0.4
Logistics, transport & handling	Space use, modularity, ease of transport and crane work	4	2	0.10	0.4	0.2
LCA impact processing vs transport	Sawing, edge treatment vs crane lifting and logistics	2	3	0.05	0.1	0.15
Aesthetic acceptance	Visual coherence of the barrier along the road	4	3	0.05	0.2	0.15
			Total	100%	2.3/5	3.7/5

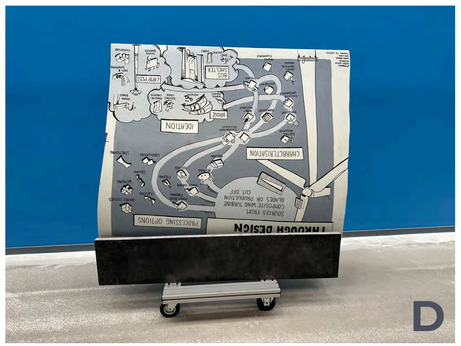
Table 4: Weighted criteria choice for segments.

Appendix D: Prototypes

Alu-frame setup

The first frame was really big, because the assumption was to use the bigger segment (A). It was nice to work with these extrusion profiles, because they could be easily adjusted to the angle the segment needed to be. The outcome of the big frame was not to my liking, the long beam needed to be hidden behind the segment and the extra Alu-beams in the front to hold the plank were too bulky and made the gap between the plinth and segment too wide (B). By tracing the end and cutting a piece of paper, it was easy to set the frame to the 20° angle (C).
After changing all these things, the setup looked much better.
To see whether a horizontal top or leading edge was better, both positions were looked at. Because of the drawing and vertical sides, it looks better resting horizontal on its LE (D).

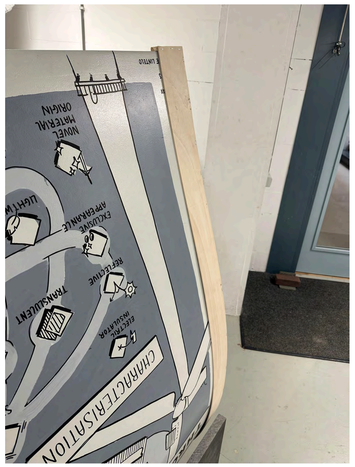




The Cap

To prototype the cap, wood was used.

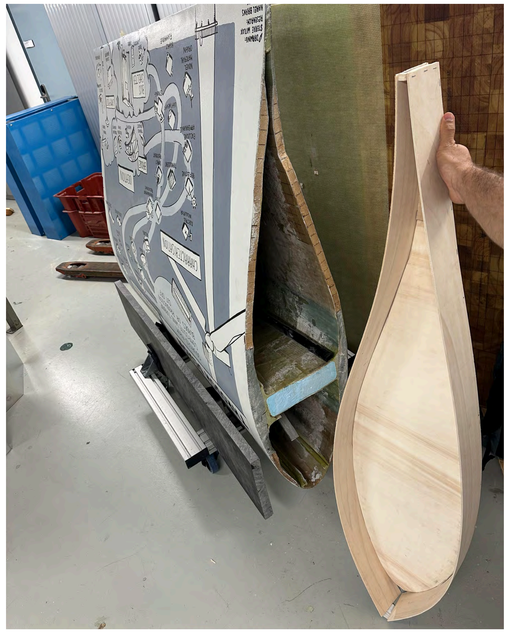
The edges were indeed rough, seen when held against a straight board (A). The idea of making the back square without an edge slipped my mind, as it fits on both sides of the segments' front curvature (D). However, due to the edges, this was quickly thrown away. Two wooden strips were bent and nailed to the traced cover plate (B). The cap works quite well, especially when adding a foam layer I think. When looking from the other side, you can see it closes well (C).

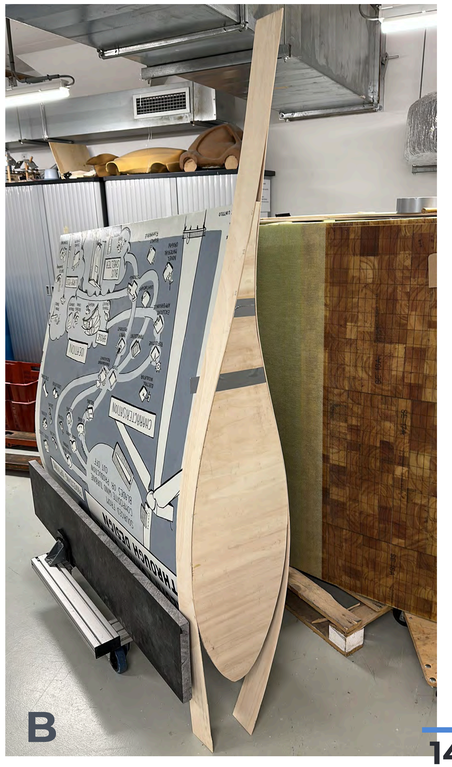


C

A

D





B

The Cover strip
After prototyping the cap, the segment was layered with white paper to cover the drawings (A). Next, the cover strip was prototyped with a sheet of wood, and taped with the right overhang to the short side of the segment, where the other cap would be (B).

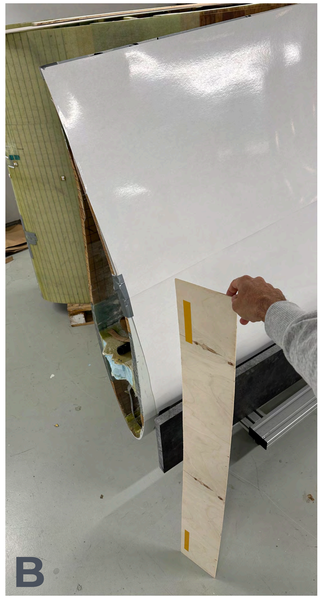
The overhang turns into overlap when the large cap is held against the other end to demonstrate the transition point of two segments (C).

The cover strip and cap align smoothly with each others curve (C2). The reason the cover strip is not the same width of the large cap is because a large chunk of shear web sticks out (B3).

The final prototype is shown in D, where it is safe to say enough overlap is achieved for an acoustic seal, especially when considering the extra compriband and the cover strip being fastened with screws.

A

D


B

B2

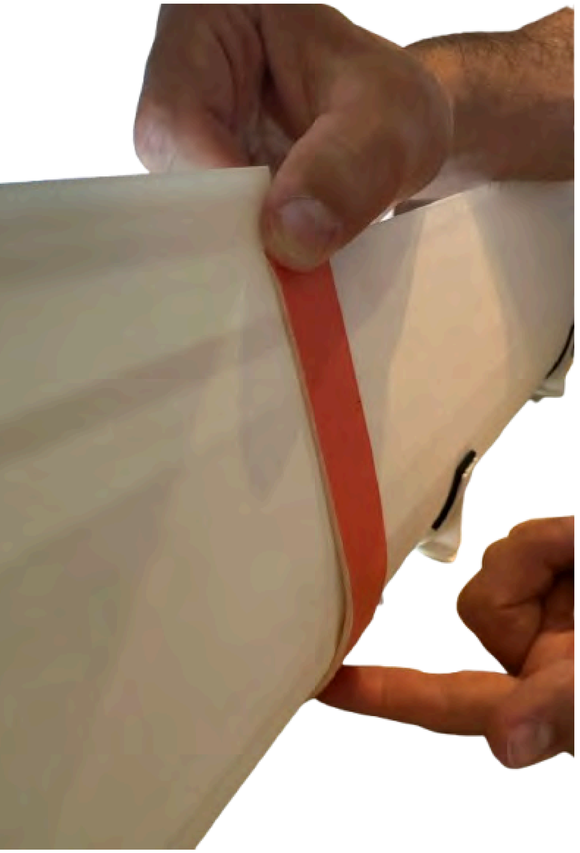
B3

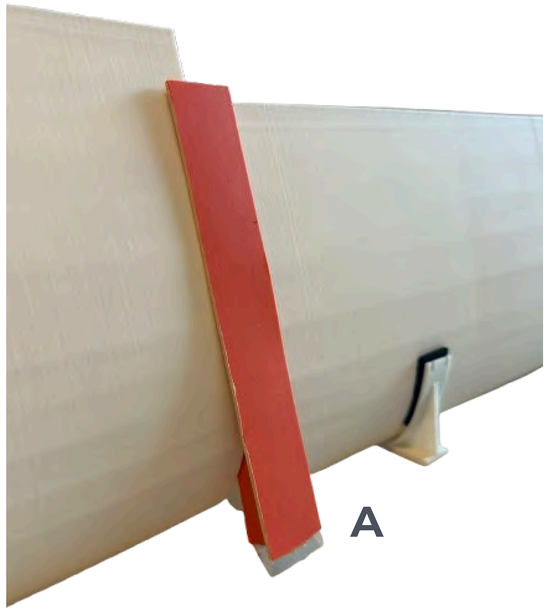
C

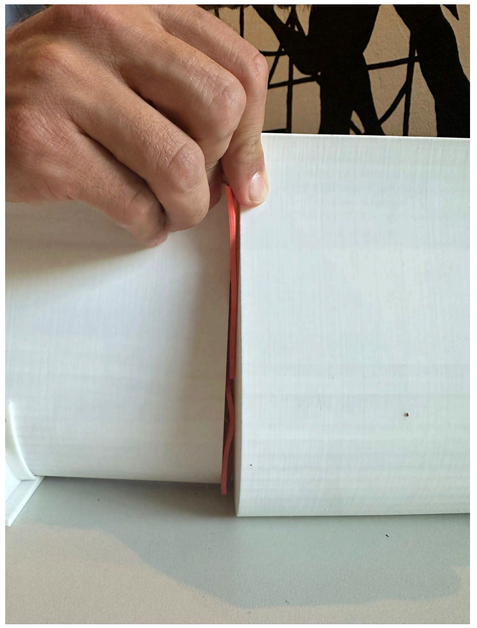
C2

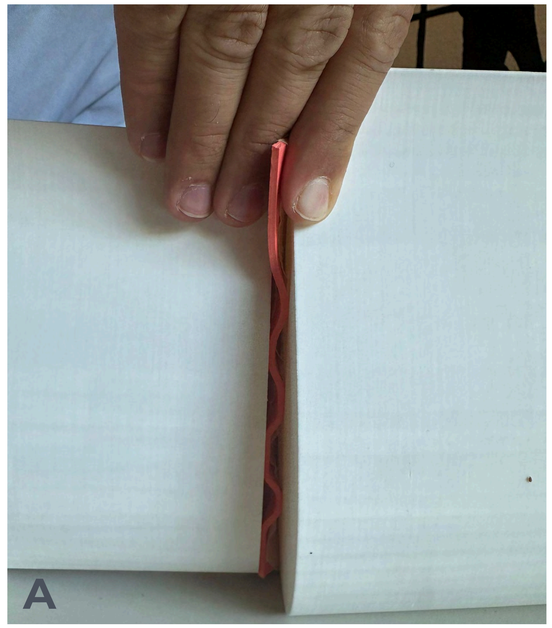
The T-flap

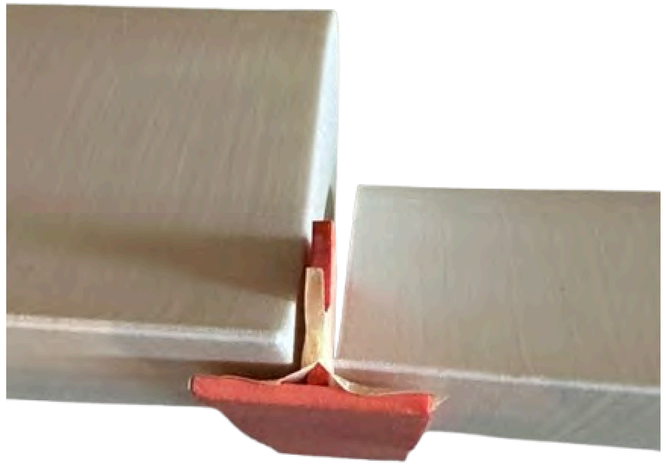
- Straight does not bend, material compresses (A).
- two triangle cuts work well to release stress (B).





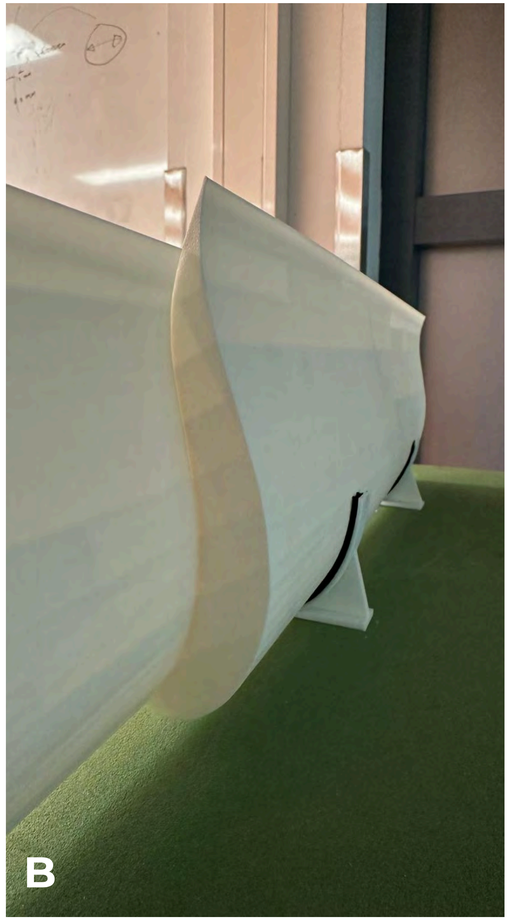






The 3D printed prototype

This prototype was used to get a physical feel of the blade barrier (A) and evaluate its alignment between segments (B). The plinth was also tested on this 3D print (C). For the final presentation, this setup of the final design with three segments will be showcased.

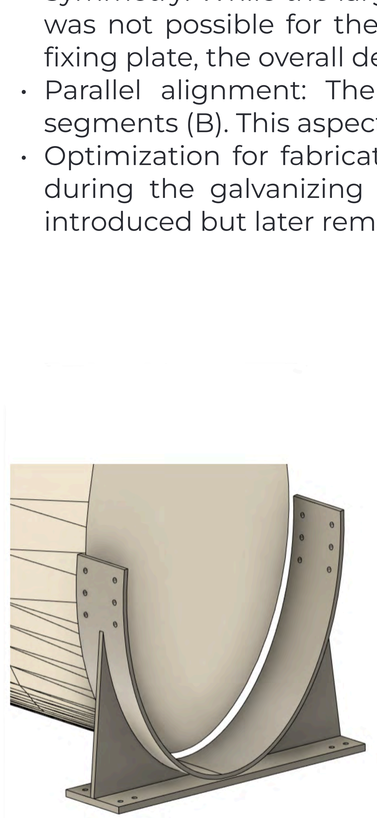


Appendix E: Frame optimization

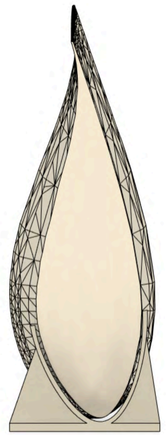
Frame design considerations

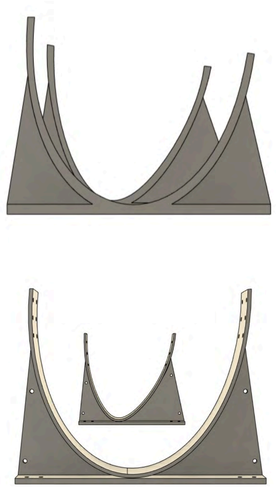
Three important considerations that guided the frame design:

- Symmetry: While the large frame could possibly be designed symmetrically, this was not possible for the small frame (A). With the addition of the extra plinth fixing plate, the overall design could no longer remain symmetrical.
- Parallel alignment: The frames must be parallel to properly fit the blade segments (B). This aspect is discussed further in the next appendix on the plinth.
- Optimization for fabrication: Corners that are difficult to access for welding or during the galvanizing bath were removed. An additional rigidity plate was introduced but later removed. The final design had the U-plate split (C).

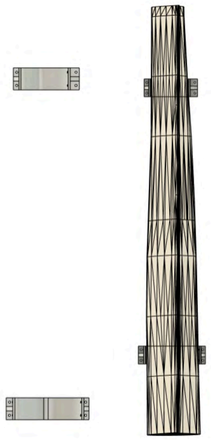


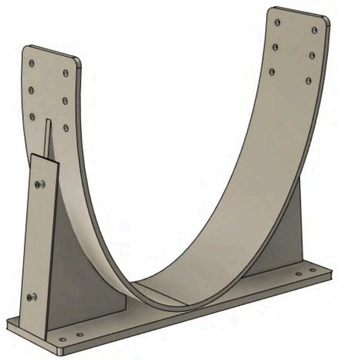
A

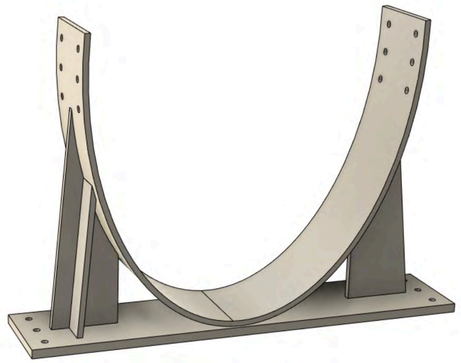




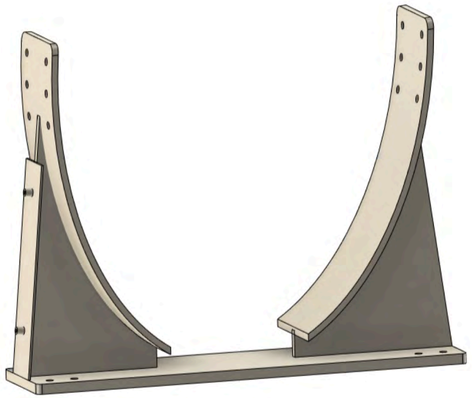
B

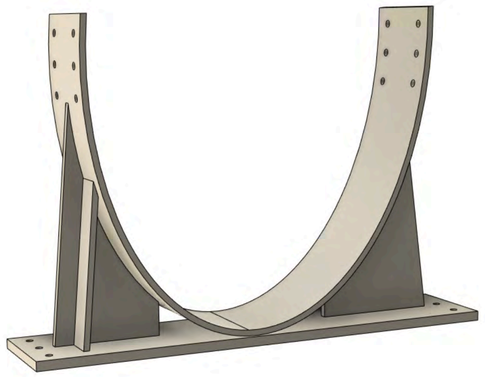






C





Technical drawing

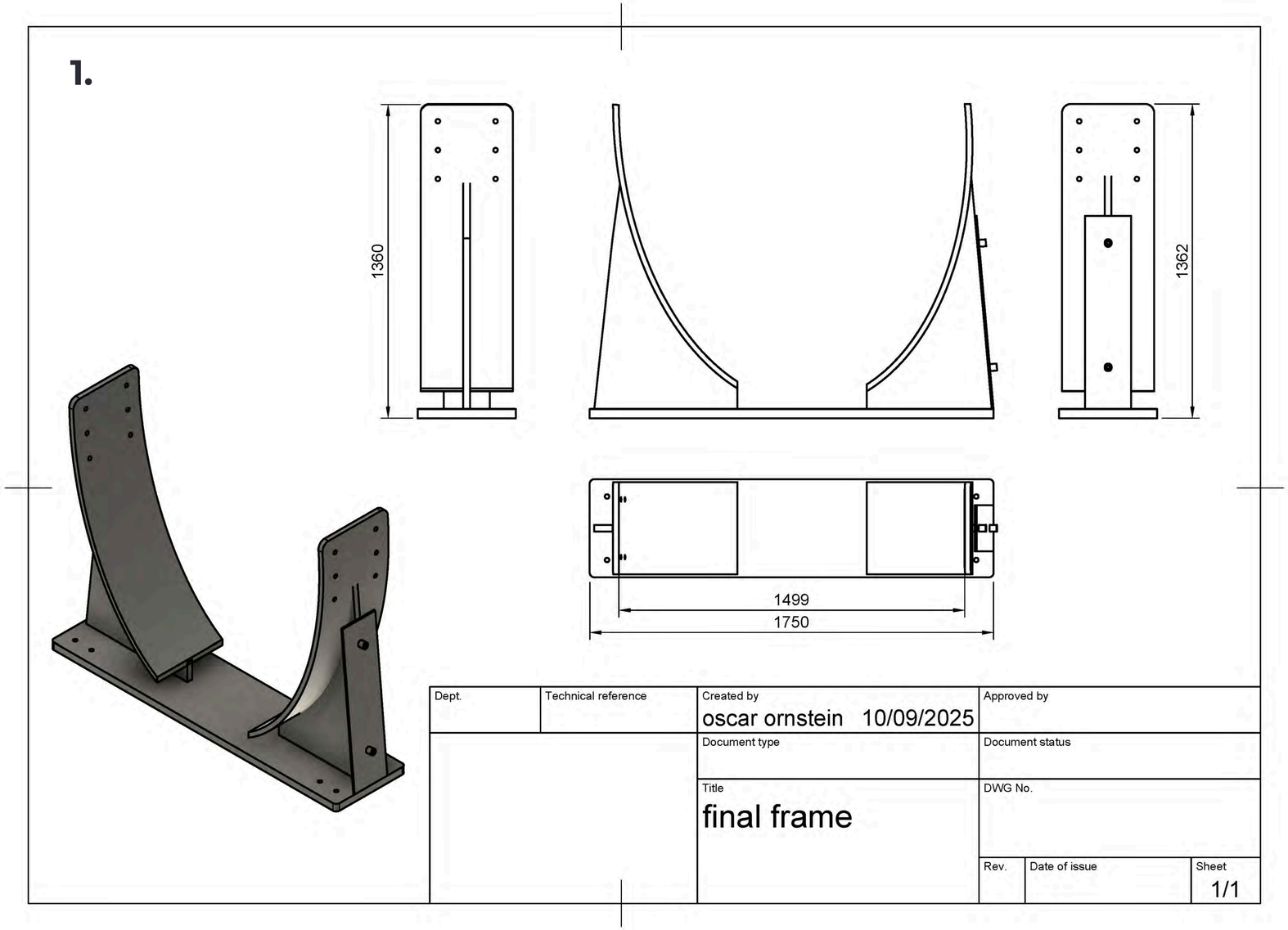
The set dimensions of the frame were evaluated with the help of load-bearing calculations by Heijmans Lead Engineer Erik Nouwen. Unfortunately, these have been lost in the process. The calculations concluded that the estimated dimension of the 3D model were a good starting point. The optimization of the thickness and steel use of the frame should be investigated in further development.

Drawings:

1. Assembly
2. U-plates
3. Triangled ribs
4. Base plate
5. Plinth plate

Notes:

- The exact radii of the bend plates is unknown.
- The holes for a M16 bolt are 19mm



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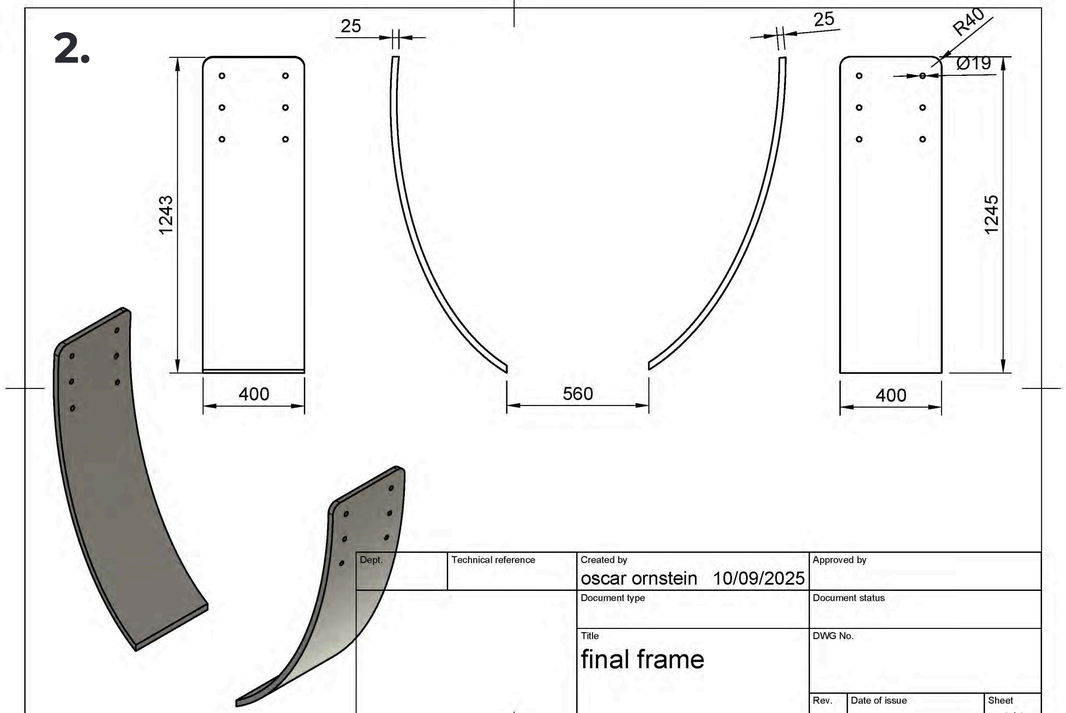

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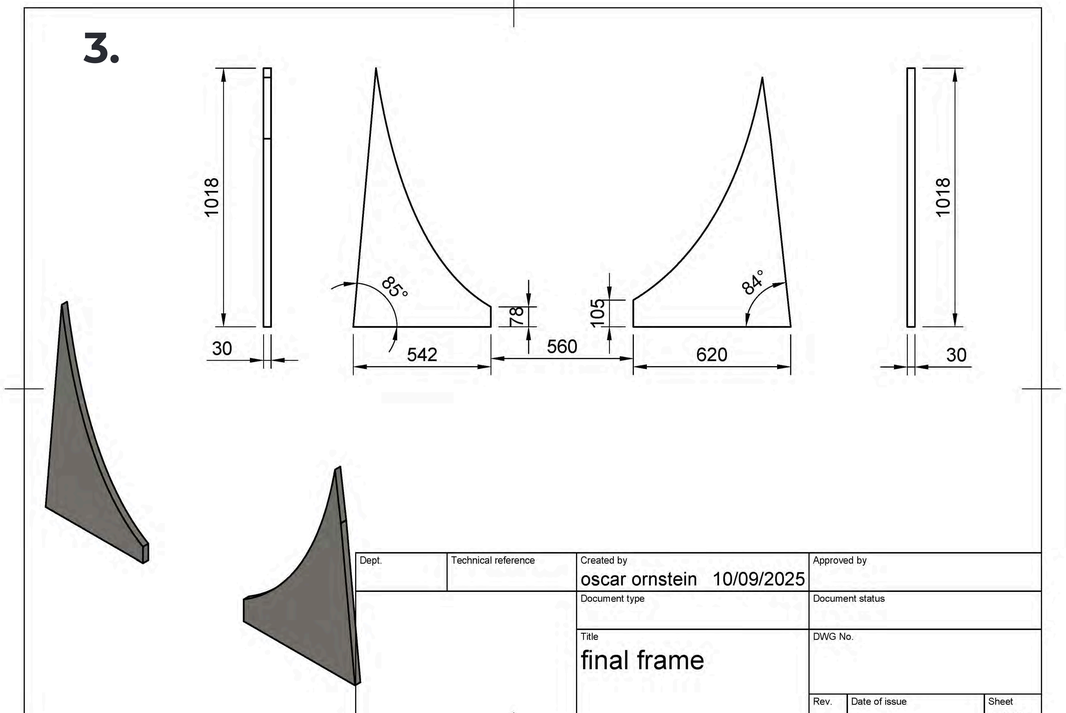

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		final frame	
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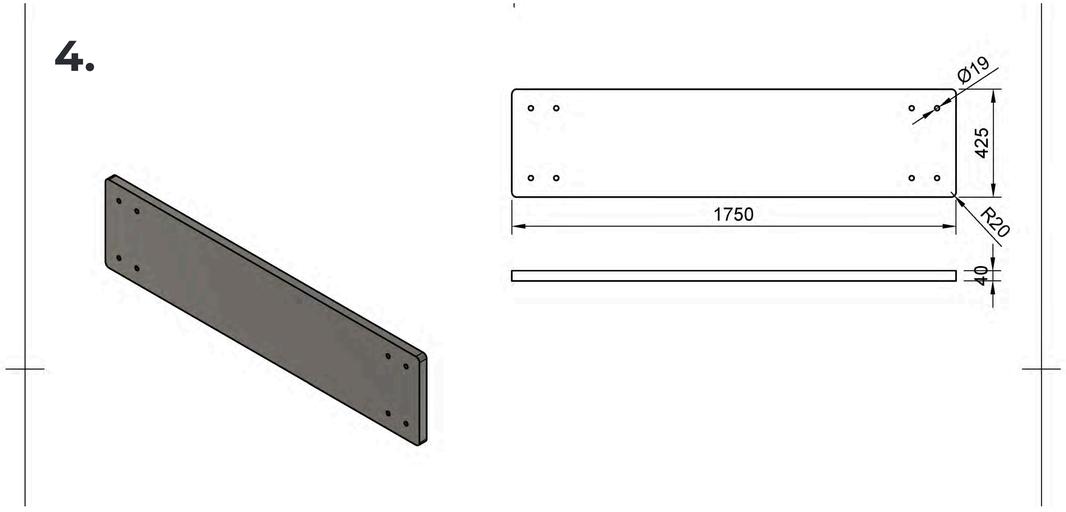

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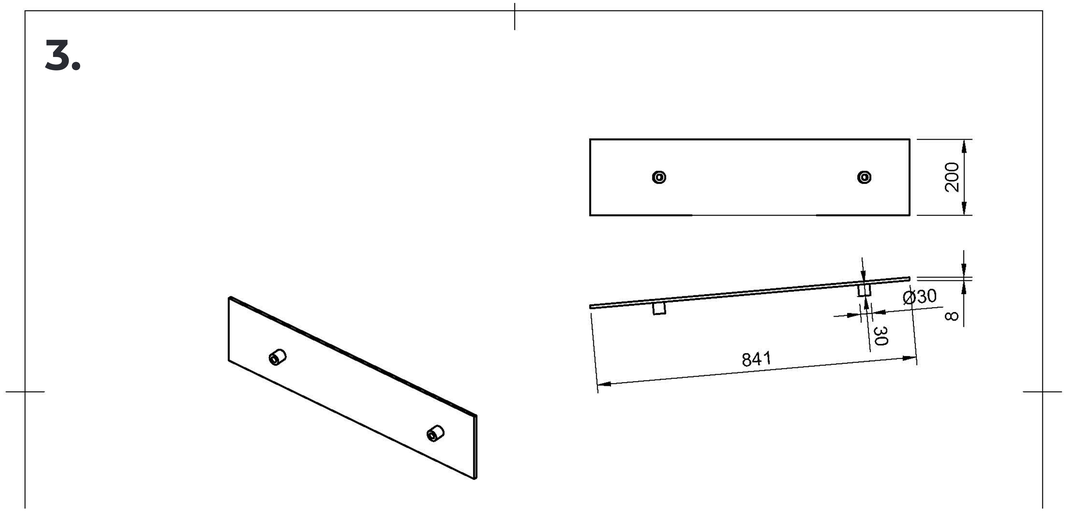


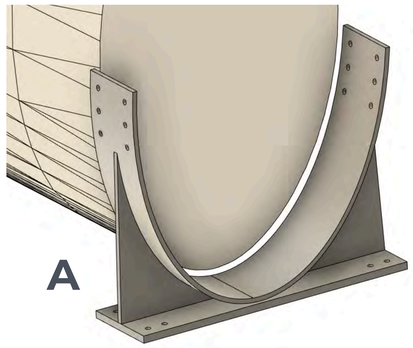
Frame steel costs calculation

Van Amstel (PC, 2025) has a lot of experience in the production of steel products. He referred to an earlier cost calculation spreadsheet from VDL (Table 5) and provided the following price indication for the frames, which serve as a useful reference for this thesis:

- Order of 1 piece: € 5,511
- Order of 2 pieces: € 4,132 each
- Order of 10 pieces: € 3,029 each

Each frame weighs approximately 750 kg and has an external surface area of 6.64 m² (for coating purposes).

The frame model used for this calculation is a slightly older version (A). Still the pricing is still relevant for the final design.



aantal:	1					Zagen	Persen	Deur	rondlas	INTERNE CALCULATIE					VBS-06-03-2020		22-08-25
door:		project															V5.0.055 d.d. 14-1-2020
pos	BIC	D	t	L[mm]	AANTAL		R	P		[kg/m]	[kg]	[m2]	[€/m]	afval%	kpl	tijd (uur)	[€]
pos	PLAAT-STRIP	B	t	L[mm]	AANTAL					[kg/m]	[kg]	[m2]	[€/kg]	afval%	kpl	tot. tijd	[€]
		400	25	3350	1					80,00	268,00	2,87	€ 0,97	15,00%	5-Plasma / Autogeen s	1,50	305,84
		450	40	1750	1					144,00	252,00	1,75	€ 0,97	12,50%	5-Plasma / Autogeen s	1,41	279,36
		920	30	740	1					220,80	98,04	0,88	€ 0,97	1,33%	5-Plasma / Autogeen s	0,80	96,38
		1000	30	900	1					240,00	129,60	1,15	€ 0,97	10,00%	5-Plasma / Autogeen s	0,91	139,68
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Materiaal				Lengte	Gewicht	Spuitvlak	€/eenheid				€ 821
Verzinken ISO 1461	D:Coaten Zware masten > 500kg/st.		L buizen m:		747,6		€ 0,58	/kg inkl. Alle Transport en Handling			€ 432
Bituum diameter:	-	mm	Lengte mm:				€ 11,00	/m²			€ -
Grondstuk gegevens	-	mm	Lengte mm:								€ -
Natlak C3 DCC=12,HS=10	€ 15,00	€/m² aantal: 1	Grondstuk NIET lakken			6,64	€ 15,00	/m²	25-Lakken	1,59	€ 100
Poedercoat C3	Geen Poedercoating		2-laags	kleurgroep 1		6,64	€ -	/m²	Transport per kg:	€ -	€ -
Poedercoat opties	Geen Poedercoatoptie			Geen Poedercoatoptie				Geen Poedercoatoptie			€ -

Indirecte dekking CAD WVB PJL	uren	kosten
Sr. Constructeur		€ -
tekenkamer uren	10,0	€ 810
werkvoorbereiding uren	8,0	€ 568
projectleiding uren		€ -
Lasuren machinegroep 300	steluren	bew.uren
Lasuren groep 300 / st	1,3	9,2
Productie steluren en kosten (zie spec.)	16,0	€ 1.379
Minimum toeslag Poedercoate	1	€ -

aantal	mat./st	coat/st	coat/kg	bon+stel/st	uren/st	kostprijs/st	KP/kg	"netto"kostprijs/st
1	€ 821	€ 531,	€ 0,71	€ 2.780	32,11	€ 5.511	€ 6,29	€ 4.701
2	€ 821	€ 531,	€ 0,71	€ 2.091	24,11	€ 4.132	€ 4,99	€ 3.727
5	€ 821	€ 531,	€ 0,71	€ 1.677	19,31	€ 3.305	€ 4,20	€ 3.143
10	€ 821	€ 531,	€ 0,71	€ 1.539	17,71	€ 3.029	€ 3,94	€ 2.948
25	€ 821	€ 531,	€ 0,71	€ 1.456	16,75	€ 2.864	€ 3,79	€ 2.831
100	€ 821	€ 531,	€ 0,71	€ 1.415	16,27	€ 2.781	€ 3,71	€ 2.773
1	€ 821	€ 531,	€ 0,71	€ 2.780	32,11	€ 5.511	€ 6,29	€ 4.701

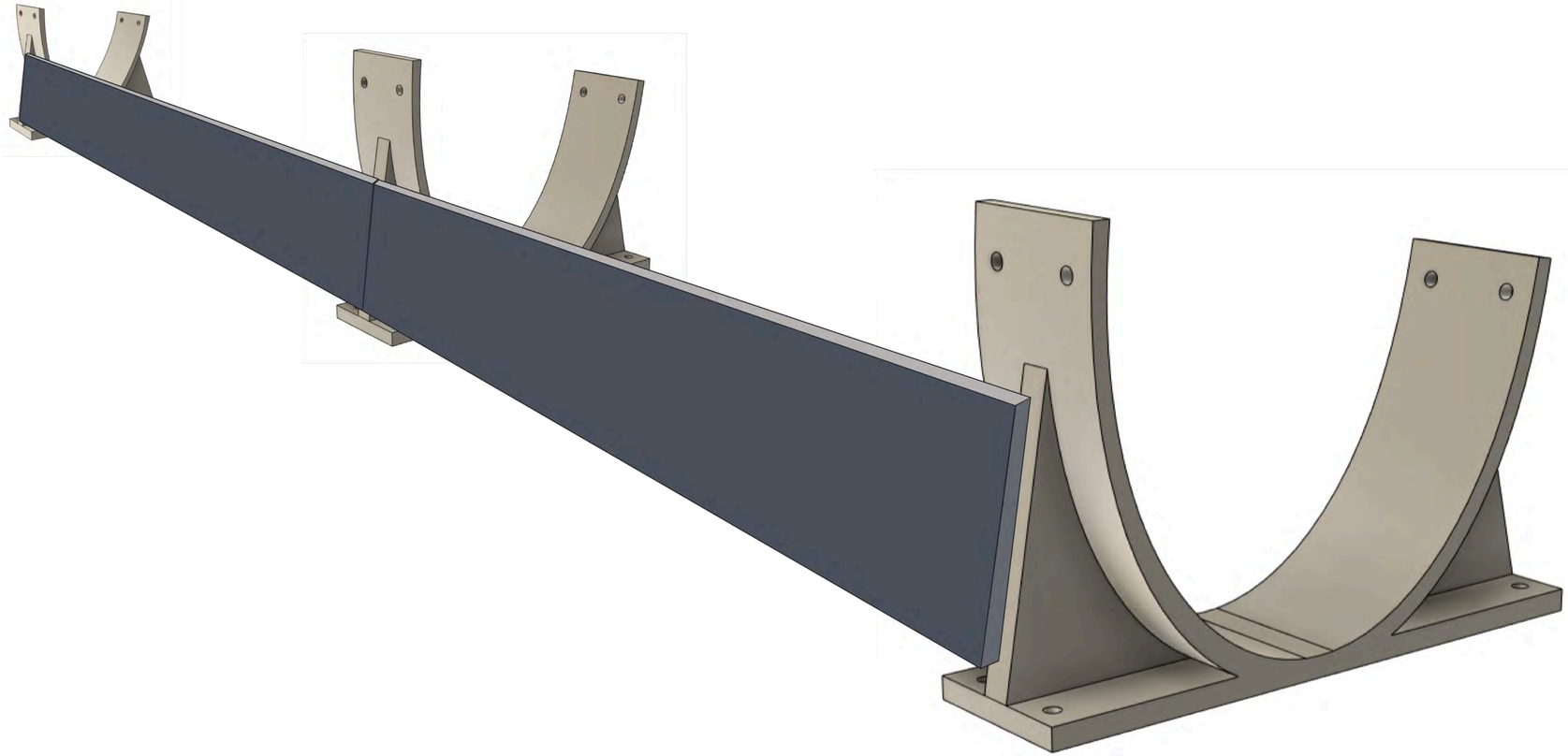
Opmerkingen:	ACCOORD :	EXW geladen	22-08-25	EXW ex. dekking Constructeur en tekenkamer uren

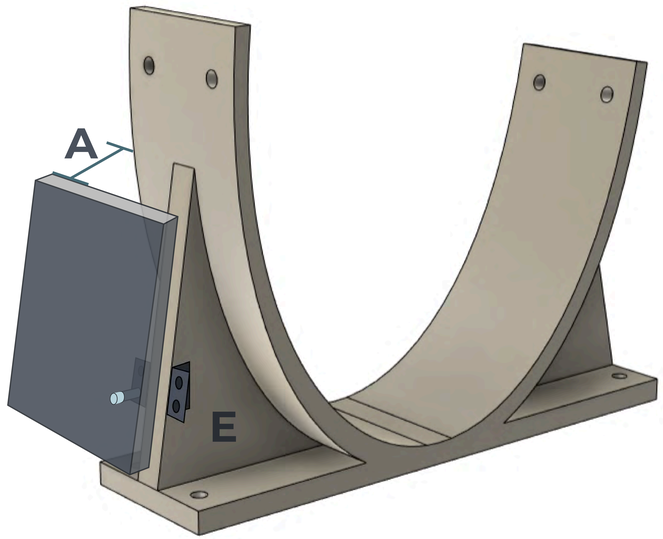
Table 5: Frame price indication.

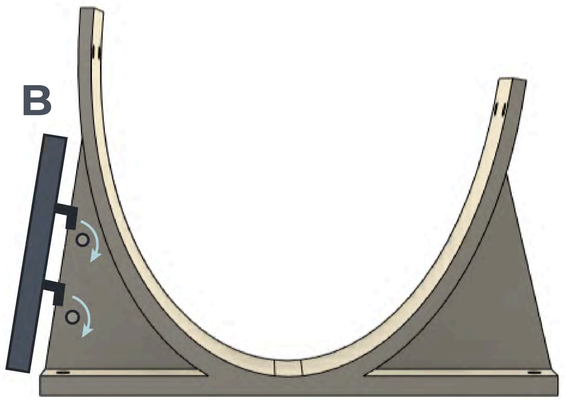
Appendix F: Plinth optimization

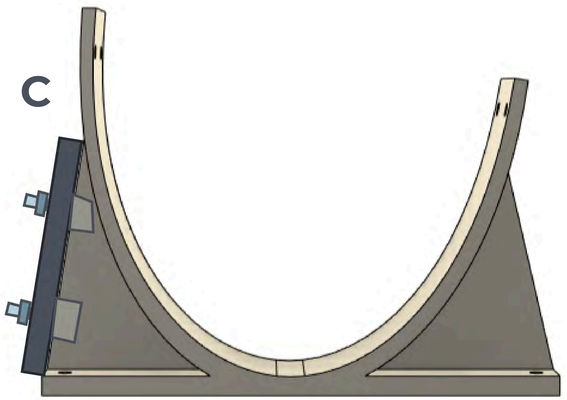
Implications

- For a smooth surface, fastening methods must be behind the plinth, meaning limited reachability when the segment is in place (A).
- Hooks (B) are easy to assemble but are not fixed (flood, vandalism, crash).
- Adding a corner profile to the frame with threaded ends through the plinth also eliminates having to reach behind it (E). However, extra holes are needed to be drilled and the surface is no longer completely smooth (C).







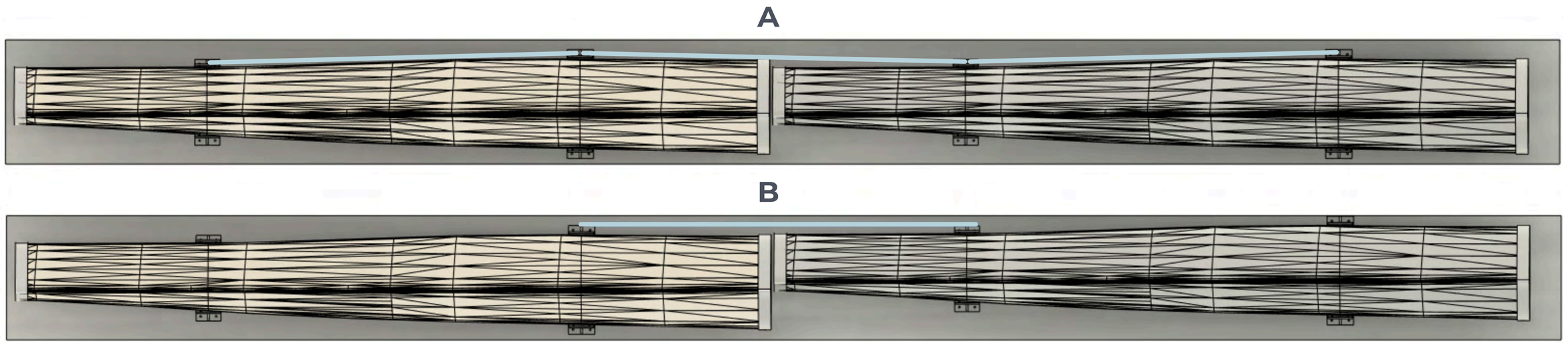


Plinth setup implications

As discussed in the frame optimization, the frames have to be parallel for the blade segments to fit properly. Because the small frame is narrower than the large frame, aligning the segments and large frames colinearly creates two problems: the surfaces at the segment caps do not line up, and the plinth intersects with the edge of the large segment end. In addition, the plinth would not be straight but appear slightly wavy, which could look messy.

The solution is to position the small frame of one segment parallel to the large frame of next (B). This ensures proper alignment at the caps, simplifies installation of the cover strip, and creates a more continuous plinth. The only consequence is that the barrier will follow a gradual angle rather than being completely straight. Since each foundation pole already has individual XYZ coordinates, and roads are almost never perfectly straight, this adjustment is not considered a major concern (Van Amstel, PC, 2025).

Note: Due to tolerances between segments, the plinth span will not always be exactly 6 meters, but may vary by ±5 cm.



Appendix G: Edge treatment

Gabriëls (2025) executed a coating test for UV-resistant and waterproof edge protection (Figure 81).

To assess suitable coatings for protecting exposed edges of sandwich material against UV degradation and water infiltration, two epoxy-based coatings were tested: EP8085 (clear) and EP510 (white). The panels of similar thickness but different cores (balsa wood and foam) were prepared, coated on their cut edges and top surfaces, and visually evaluated after 24 hours.

Key evaluation criteria (per expert input from Heijmans) included:

- **Material composition:** Preference for non-toxic, sustainable production. EP8085 offers potential for bio-based manufacturing and is more flexible than EP510, which is more brittle and prone to cracking.
- **Ease of application**: Both coatings applied similarly; viscosity differences had limited impact. Suitable for brushing, spraying, or dipping.
- **Resin uptake**: Foam cores absorbed more resin than balsa, indicating they may require additional layers. Higher viscosity (EP510) reduced uptake, suggesting fewer coats might be needed.
- **Durability:** Pull-testing could not be performed due to sample size, requiring follow-up research.

Conclusion:
Bio-based epoxy coatings with relatively high viscosity are promising candidates for protecting panel edges, especially when applied by dipping for efficient large-scale processing.

Figure 81: 24 hours after applying coating to the cutting edges, they appear smoother and less absorbed on the balsa wood panel (top) compared to the foam core (bottom). The white EP510 coating shows lower absorption on both panels, likely due to its higher viscosity (Gabriëls, 2025).

Appendix H: Interesting thoughts

Figure 82: The DinoTails serrated edge blade design by siemens reduces turbulence (Singh, 2012).

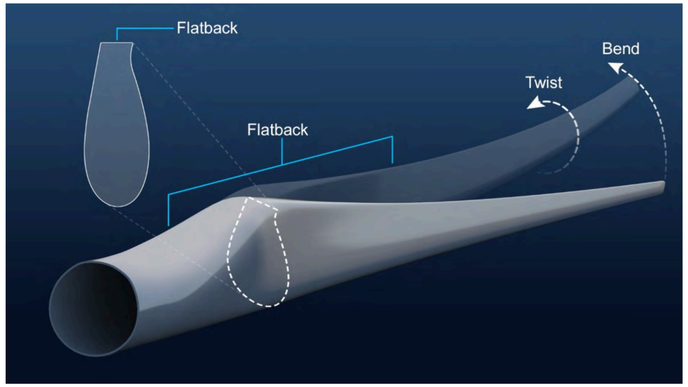


Figure 83: Flat backed wind turbine blade (Engel-Cox et al., 2022).

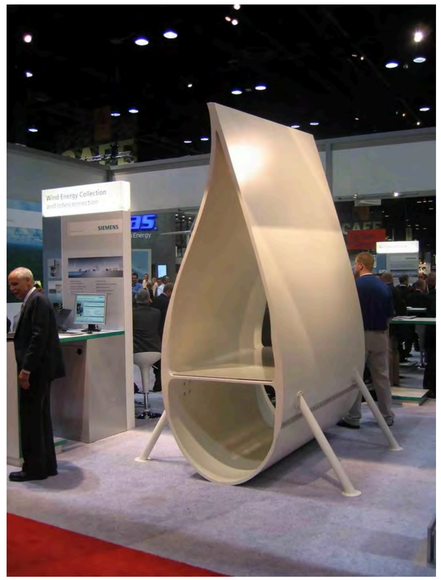


Figure 84: Segment at Siemens wind conference (Sverdrupian,2016).

Blade-racks for new turbines

Commercial Engineer and Business Developer at TWD (Nair, PC, 2025) mentioned that blade-racks to transport the blade for offshore installment are rarely reused by companies (Figure 85). They close by the blades weight and follow the shape of the cross-section. These construction could be interesting to dive into, to reuse (parts) as barrier frames.

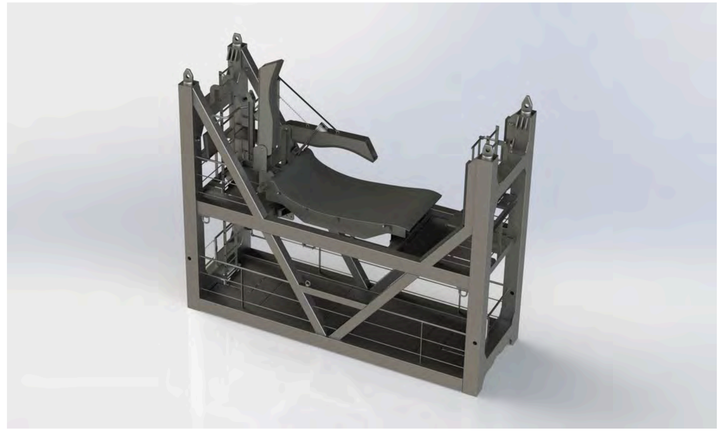


Figure 85: AAG. (n.d.). Blade stackers. https://en.aag.world/shop/blade-stacker-1165p.html (both images)

Appendix I: Assembly inspiration

These images from the construction of BladeMades blade barrier and Re-wind USA's pedestrian bridge gave inspiration to the assembly process of such a large scale blade project.

Figures 86-89: BladeMade assembly (Rijkswaterstaat, 2025).

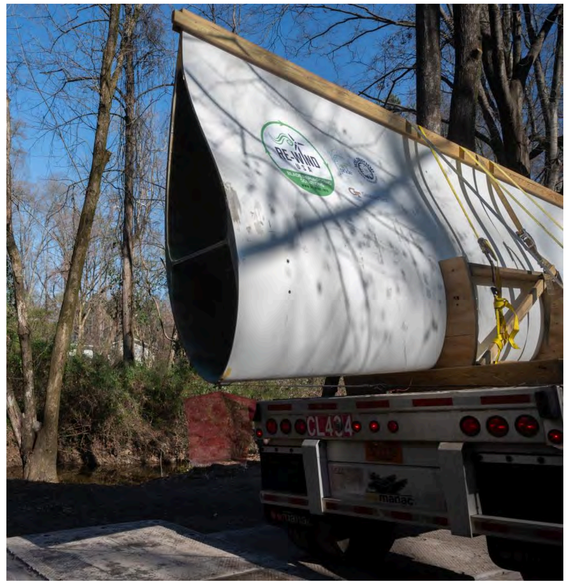
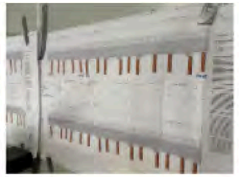


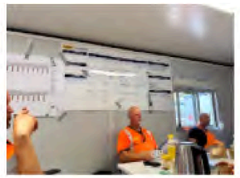
Figure 90-93: Pedestrian blade bridge (Re-Wind USA & Georgia Tech, 2025).

Appendix J: A9 site visit

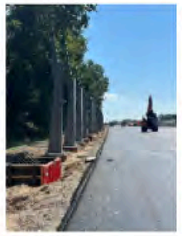
Pictures of the barrier construction project of Heijmans at A9 Amstelveen.

in de keet met tekeningen





langs de berm op het asphalt



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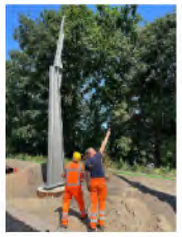
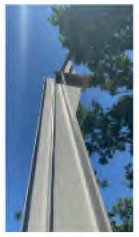
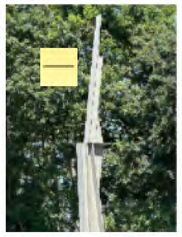
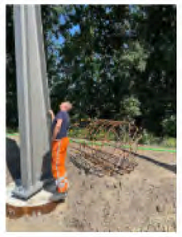






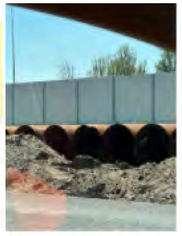
m48 bouten bevestiging

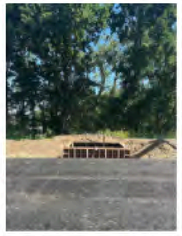
6m

stort bak voor de stukken die niet gelijk erin konden vanwege oude fundering al in de grond

gewapende beton met tapeinden

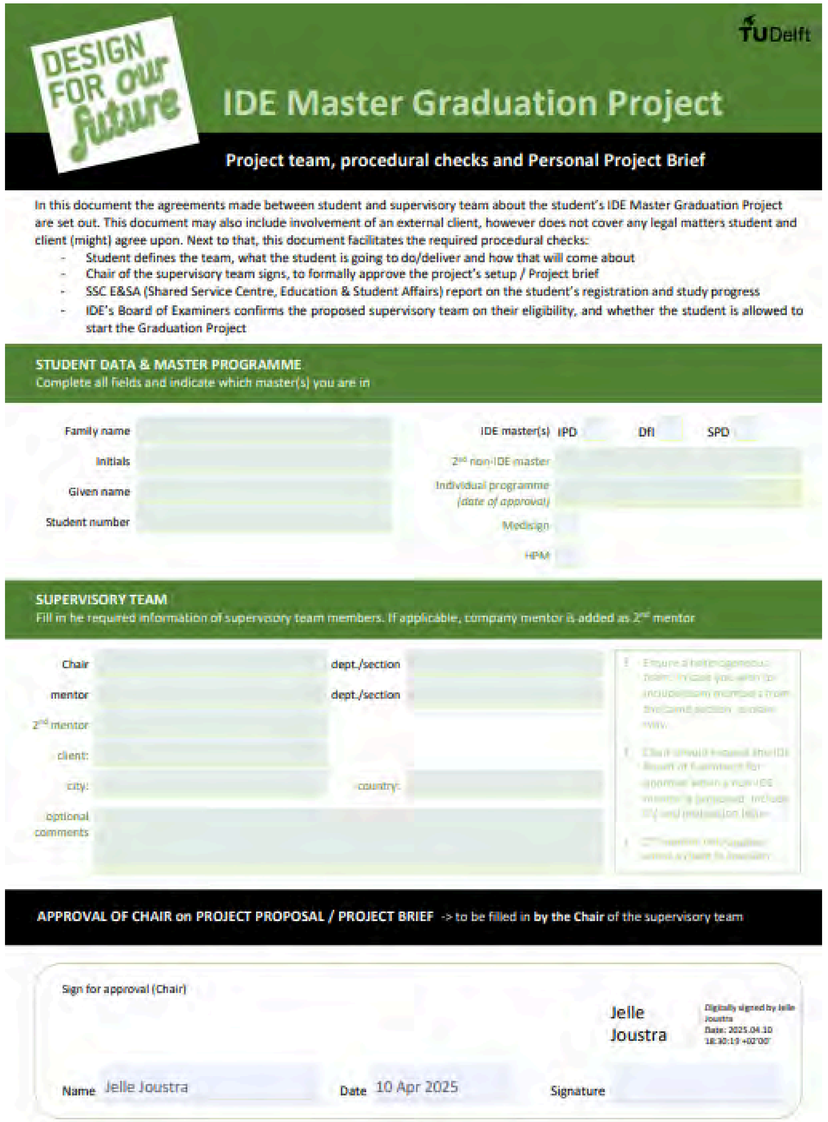
funderingpalen 8-12 meter





plek van een vluchtdeur

Appendix K: Project Brief



DESIGN FOR our future

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

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

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

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name
Initials
Given name
Student number

IDE master(s) IPD Dfl SPD
2nd non-IDE master
Individual programme (date of approval)
Medisign
HPM

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

Chair dept./section
mentor dept./section
2nd mentor
client:
city: country:
optional comments

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

Sign for approval (Chair)

Jelle Joustra

Digitally signed by Jelle Joustra Date: 2025.04.10 18:30:19 +02'00'

Name Jelle Joustra Date 10 Apr 2025 Signature

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

Master electives no. of EC accumulated in total EC

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

★	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

L. Boot

Name Lisette Boot Date 14 apr 2025 Signature

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

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen

Digitally signed by Monique von Morgen Date: 2025.04.23 10:24:12 +02'00'

Name Monique von Morgen Date 23 Apr 2025 Signature

Personal Project Brief – IDE Master Graduation Project

Name student Oscar Ornstein **Student number** 4,885,139

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Embodiment design of a highway sound barrier using horizontally oriented, decommissioned wind turbine blades.

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

Introduction

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

As the global demand for sustainable energy is growing, wind power has become increasingly important—accounting for 7.8% of the world's electricity in 2023, more than doubled since 2015 (Broadbent, 2024). Wind turbine blades (WTBs) are typically composed of fibre-reinforced plastics (FRPs). However, these materials present a significant challenge at the end of their 20–25-year service life. Most disposal methods like: landfilling, incineration, or limited recycling, fail to preserve their material value (Chen et al., 2019; Larsen, 2009).

This project builds upon the thesis of Ruben Gabriëls on how retired WTBs can be repurposed for highway sound barriers, bettering circular economy strategies for the end-of-life (EOL) and environmental impact. The project is now advancing into the embodiment phase, aiming towards a viable product ready for real-world implementation. The main stakeholder Heijmans is a construction firm with a strong ecological mission and an important member of TU Delft's LICHEN-BLADES consortium. Unlike earlier concepts that focus on vertically placed blade segments, this project continues the innovative horizontal layouts and the use of blade-section cut panels. This opens new opportunities for optimizing acoustics, aesthetics, and lifecycle extension of the composite material.

Realizing the blade barriers design requires collaboration across new stakeholder groups, including manufacturers of structural components, companies specializing in processing and cutting WTBs, and on-site assembly teams. Together with a detailed design ready for the industry, these players are essential to ensure that reused blade material becomes a scalable and logistically feasible solution with significant environmental impact.

→ space available for images / figures on next page

Personal Project Brief – IDE Master Graduation Project

Problem Definition

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

The main objective of this project is to design and develop a structurally sound, cost-effective, and easily assembled noise barrier using decommissioned wind turbine blades (WTBs). Within the 100-day timeframe, the focus lies on designing the connections between WTB panels, optimizing the cassette system/design, and selecting materials that enable quick assembly while minimizing costs and environmental impact.

A key challenge is processing the blade material in a way that minimizes excessive cutting, dust generation, and tool wear. By working with large blade segments, the project aims to retain the structural integrity of the material, preserving the potential for future subsequent reuse beyond the barrier's lifespan (Gabriëls, 2025).

This project creates added value for stakeholder Heijmans by enabling efficient construction processes with composite materials and supporting a positive image of innovation and environmental responsibility. Conciderations when developing the noise barrier can be; acoustic performance of sound dampening and the visual integration of plantings and color, improving living conditions for nearby communities. Overall, the project should contribute to circularity, reduce material waste, and set an example for the scalable reuse of composite materials in infrastructure.

Assignment

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

The embodiment of a highway noise barrier made from horizontally oriented, decommissioned wind turbine blades, considering sound reduction and ease of assembly, while preserving large panels of the material for potential subsequent reuse.

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

Analysis & Context: Diving into the world of sound barriers. Who supplies the WTB materials, facilities and tools? Who are the relevant stakeholders? Where will the full-scale prototyping take place? [Analysis, networking with Heijmans and stakeholders, interviews, online research]
Defining criteria: Learning from existing sound barrier manufacturing. What are important considerations, criteria, limitations and standards? What are suitable materials and what are sustainable processing/production steps? [Interviews, site visits, online research][Methods to consider: S.M.A.R.T, LCA]
Ideation & Development: Design iteration on the current design, is this concept suitable for the criteria? How do the frames fit on the foundation? What materials and production steps are desirable? How to optimize the assembly and logistics of constructing the barrier? What are the costs? [Ideation, prototyping, assembly tests, material studies] [Methods to consider: ID cards, weighted objectives, morphological analysis]
Detailing & validation: Realising the construction of the barrier, does it comply with structural and safety standards? What are the steps for on-site construction? Does it bring added value to residents and the environment? Does it reduce noise? [Full-scale prototyping and acoustics testing, Process planning, development plan, enquete]

Project planning and key moments

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

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

Kick off meeting	10 Apr 2025
Mid-term evaluation	17 Jun 2025
Green light meeting	21 Aug 2025
Graduation ceremony	4 Sep 2025

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

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

Comments:
Due to availability in the summer holidays the green light and graduation are close together. We are aware of that and will plan accordingly.

Motivation and personal ambitions

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

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

I've always been a hands-on designer with a strong drive to find clever, practical ways to reuse materials others might consider waste. As a nature enthusiast, I'm motivated to design for a better, more sustainable future. My interests lie in manufacturing, innovative materials, and environmentally responsible solutions.

This project aligns closely with my passion and allows me to explore the processing of thermoset composites from decommissioned wind turbine blades. I'm excited for the opportunity to work at a large scale, designing and building a physical product, conducting extensive acoustic testing, and engaging with real-world logistics.

One of my personal ambitions is to gain experience working with a large company like Heijmans to understand the dynamics of the industry, production and management. I aim to extend my knowledge in acoustic performance, large-scale prototyping, and how construction workers can work in efficient, cost effective ways. I'm also curious to explore how the final product contributes positively to the nearby environment and communities.

Ultimately, this project offers the perfect platform to combine my creative mindset with technical development, and to turn a sustainable design into a tangible, impactful solution.