Design of a noise barrier from decommissioned wind turbine blades

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Master Thesis
Integrated Product Design

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Preface & Acknowledgements

This thesis was written as part of my graduation project. With it, I will finish my study time at the Integrated Product Design master of the Industrial Design Engineering faculty, here in Delft.

Since learning about circular economy design principles in my bachelor study, I have been highly interested in design projects and courses focussing on sustainable design practices, especially through circular products and systems. I'm therefore happy to have gotten the opportunity to do this project, in which I learned tons about wind turbine blades, their materials, and how to structurally reuse them in a noise barrier. In my view it is important to stay connected with the current industry in these kinds of project, which is why I'm also grateful for the collaboration with Heijmans.

This project challenged me enormously, and I've learned (sometimes 'the hard way') that not everything I would like to do, can be done within six months. I am still convinced, however, that ambitious goals lead to good results.

I would like to express my gratitude towards everyone who helped me during the project. First of all, my supervisors Ruud Balkenende and Israel Carrete, whose invaluable feedback, expertise and experience kept me on the correct path. Ruud, thank you for your clear guidance and plentiful feedback. Israel, thank you for your feedback, support and joining me on some fun and interesting company visits. At Heijmans, I would like to thank all the Geluidsbeheersing team members for their expertise and help in designing a noise barrier. Especially Mark, for your consistent (creative) help and connecting me to the correct people, and Erik Nouwen and Johan Grevelink, for your curiosity into and efforts to help me in my project.

Finally, major thanks to my family and friends for helping me with some activities, being there for me in the tougher periods, and while celebrating the milestones. My father, Joris, and especially Yvette, thank you for your patience, support and encouragement when I could not stop thinking about the project.

Ruben Gabriëls

In honour and remembrance of my late grandfather Jan.

Summary

This thesis presents the design process of a novel noise barrier design made from horizontally arranged, decommissioned wind turbine blade material.

To address climate change challenges worldwide, wind power is increasingly being adopted. The wind turbine blades (WTBs) used for them are decommissioned after 20-25 years, at which point a problem emerges: the complex material composition makes that current end-of-life options result in the loss of material value without regaining significant economic value. The aim is therefore to structurally reuse WTB material in applications that preserve material integrity and prolong its lifetime. Scalable and long-lasting noise barriers are consequently identified as a fitting opportunity. This thesis focuses on horizontal arrangements of WTB material for use in a noise barrier as this is underexplored and will more closely resemble conventional building materials.

However, due to the variable curved shapes of WTBs, seamless assembly in noise barriers becomes challenging. Especially since gaps compromise the noise attenuation of a noise barrier. The proposed design is a solution to that challenge. It configures WTB panels in modular cassette-panel-cassette sections that allow for tackling alignment issues and can be easily (dis)assembled on frame structures. It attenuates noise by reflecting sound waves into the sky off of tilted, continuous front panels. A second column of panels further reduces sound transmission behind the barrier. Continuity and aesthetic harmony of the barrier in its surroundings is aimed for by use of climbing plants and a green colour palette.

The design follows from a process based on research. Led by a vision on durability, modularity and feasibility, ideas are developed into two concepts that are evaluated with input from experts. Subsequently, one integrated concept is further developed through (CAD) modelling, prototyping, testing, simulating, and a survey.

Three research questions are answered throughout this process. To ensure **seamless fitting**, a parametric model is developed to inform segmentation strategies. It filters out excessively curving parts to retrieve suitable panels. Alternating the orientation of cladded panels and avoiding seams in the road-side surface of the assembly further tackle alignment issues. Analysis of existing noise barriers reveals that **mounting and assembly** are facilitated by use of modular cassette-based systems. Cassettes can accommodate the WTB panels that contain variable curvature. A prototype is developed to test fastening options, resulting in an adjustable and reversible clamp design that allows for acoustic sealing. The resulting cassette-panel-cassette modules can be pre-fabricated off-location to reduce time spent on-location. **Maintaining opportunities for next material lifecycles** is found to largely depend on resizing activities. Large panels are prioritized as they can be more broadly reused than smaller ones. Additionally, protecting exposed core materials of sandwich structures (balsa wood and foam) against weathering is important. An explorative test with epoxy coatings provides starting insights to this end.

Overall, the valuable insights in this thesis culminate in a functional, feasible and desirable noise barrier made of WTB material, and highlights areas for further industry research.

Abbreviations & Terminology

CFRP	Carbon fibre reinforced polymer
EOL	End-of-life
GCW	Richtlijnen Geluidbeperkende Constructies langs Wegen
GFRP	Glass fibre reinforced polymer
IDE	Industrial Design Engineering
LE	Leading edge
PS	Pressure side
SS	Suction side
TE	Trailing edge
WTB	Wind turbine blade

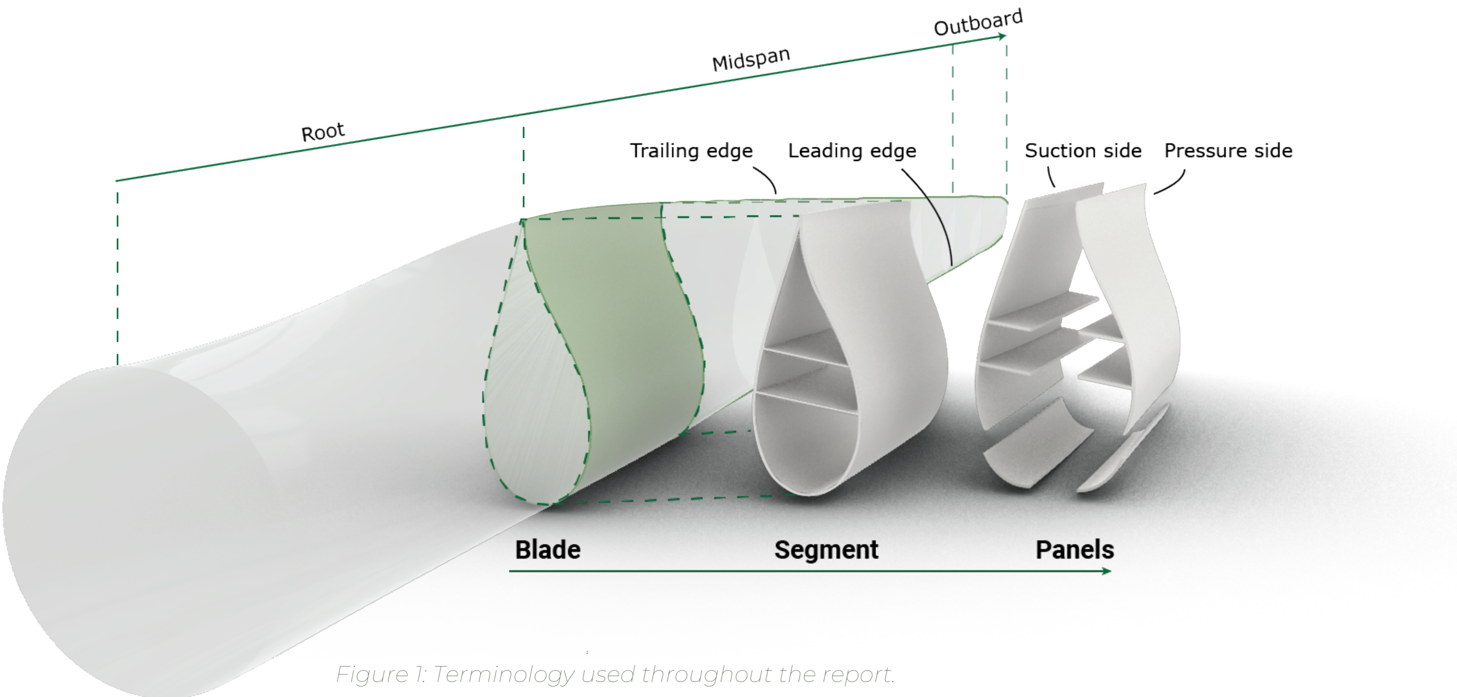

Figure 1: Terminology used throughout the report.

Sectioning levels:

Blade:	full wind turbine blade
Segment:	cross-section of a part of the blade
Panels:	horizontally cut parts from a segment

Wind turbine blade anatomy:

Leading edge:	edge of the blade that cuts through the wind first
Trailing edge:	edge of the blade that follows
Pressure side:	side of the blade with relatively high pressure
Suction side:	side of the blade with relatively low pressure
Root:	cylindrical part of the blade that transitions into the midspan
Midspan:	middle section of the blade with water droplet like shapes
Outboard:	almost flat end part of the blade

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Introduction

Chapter 1

To tackle climate change challenges that the world is facing, sources of clean energy must be further developed and scaled. In 2023, 7.8% of the world's electricity was generated by wind turbines, which has more than doubled since 2015 (3.5%)(Broadbent, 2024). Wind turbines thus play an increasingly important role in the energy transition. The service life of wind turbine blades (WTBs) is generally 20-25 years, and the end-of-life (EOL) presents a challenge as the current options either result in the loss of all the material value (landfill and incineration) or part of the value and / or are not industrialized yet (various ways of recycling)(Larsen, 2009, Chen et al., 2019). The material composition of WTBs makes recycling challenging. Glass (or carbon) fibre reinforced thermosetting polymer laminates (GFRP / CFRP) are dominantly used (Chen et al., 2019), which are inherently complex to recycle (Beauson et al., 2022). FRPs are often supported by thicker, low-density core materials like foam and balsa wood to form sandwich structures (Figure 2)(Davies, 2008) that complicate recycling further.

Simultaneously, these material combinations create the valuable properties of the blade material: high stiffness and resistance to buckling in combination with a low density (Thomsen, 2009). And although WTBs will show signs of degradation after their initial service life, decommissioning typically occurs for economic reasons rather than due to material integrity issues (Tazi et al., 2019). This makes many of them suitable for structural reuse and repurposing in applications where the properties can still be exploited (Joustra et al., 2021a). Consequently, research into such applications is in the interest of environmental protection and resource conservation. Landfilling, incineration and poor recycling of valuable material can be prevented, while virgin material needs can be reduced. Organizations such as Blade Made and the Re-Wind Network (Re-Wind Network, 2022) operate with this mission, as well as research consortium LICHEN-BLADES of which Delft University of Technology is a part of.

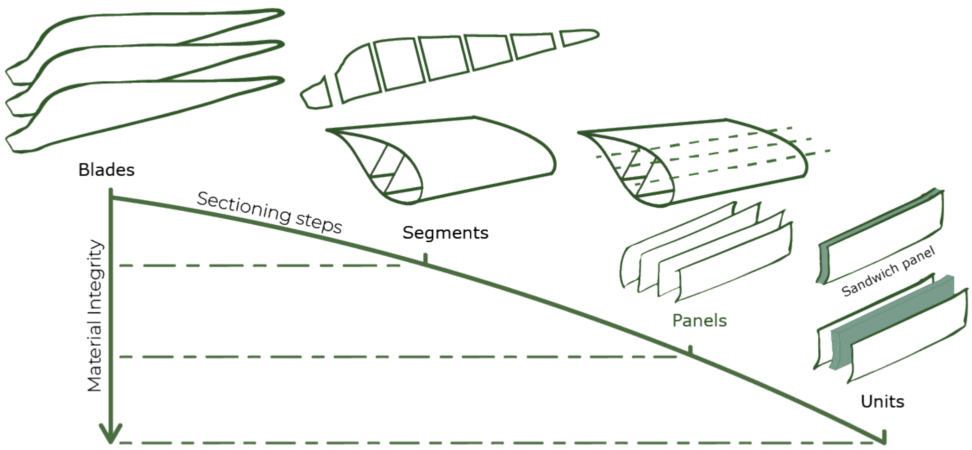


Figure 2: Material sectioning levels from left to right: blades, segments, elements (panels & beams), units (sandwich structures that are split). Based on Carrete et al. (2023).

The Dutch infrastructural developer Heijmans, part of this consortium, execute their projects with ecology and sustainability as core principles (Heijmans, n.d.-b) and see value in using decommissioned WTB material for noise barriers. This application is interesting for its scalability in terms of material use and long lifetime of 30 to 50 years (CROW, 2012). Blade Made and the Re-Wind Network have proposed several noise barrier concepts made with vertically arranged WTB material. Horizontal arrangements of sectioned WTB material have not been extensively explored. After decommissioning, the blade can be sectioned into several *segments* along the length (Figure 2). *Segments* can be further sectioned into horizontal *panels* or beams. Horizontal arrangements are interesting because they can more closely resemble conventional building material, expanding design possibilities within industry capabilities. Through making standardized sizes with limited curvature over their length and cross-section, connections between panels and structural elements are expected to become easier to standardize. In doing so, there is an opportunity of developing a noise barrier made of WTB material that dampens road noise, adds environmental value, and allows for subsequent material life cycles.

1.1 Problem definition

Organizations that try to reach valuable structural reuse applications for decommissioned WTB materials have the problem that WTB sandwich structures cannot be reshaped, and their curvature and size differ per segment. The shapes of these segments thus limit the design freedom for possible applications in subsequent lifecycles. Especially when making horizontally arranged assemblies of multiple segments, this becomes a challenge, as seamless joining and mounting is hard.

For noise barriers along highways, this problem is not only related to connections and joints, but also to the amount of noise they reduce. Gaps and openings allow more sound to pass through, reducing the effectiveness of the barriers. A horizontal arrangement of blade segments or panels has yet to be demonstrated in constructing a noise barrier without gaps. In short:

The variability in wind turbine blade sizes and shapes complicates assembly and gapless noise barriers.

1.2 Research questions

The design approach is aimed at reaching the assignment through answering research questions. The assignment is: Develop an assembly plan with accompanying prototype to explore the feasibility of a noise barrier made of horizontal WTB segments or panels. This assignment is appropriate as there are already two defined starting points: a pre-set material and an application. A targeted research phase is followed by a conceptual phase and subsequently enough time to detail and embody certain aspects of the design concept.

Three research questions are identified that will be answered throughout the report.

1. How can WTBs be segmented to obtain seamless fitting of the resulting panels to each other?
2. How can blade panels be mounted for noise barrier purposes?
3. How to maintain opportunities for applications in next lifecycles?

1.3 Approach

The followed approach can be visualized through a triple diamond (Figure 3), where converging explorations into e.g. criteria or ideas form the first half of such a diamond, and diverging activities (such as an evaluation or choice) form the second half.

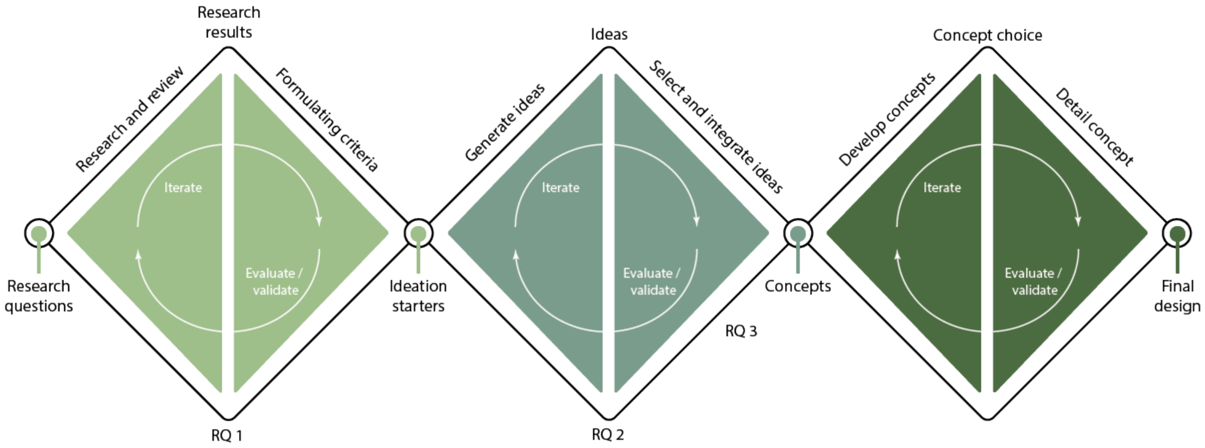


Figure 3: General process overview, variation on double diamond.

The first double diamond encapsulates the analyse & define phase as depicted in Figure 4 (see Appendix B for large version). This phase focusses on reviewing and desktop researching of WTB material and existing noise barriers and their criteria, to provide a basis for the following process. This is done through reading relevant literature and doing site visits and expert interviews (Figure 4). Ideation and shape analysis through parametric design will be done in parallel to start and accelerate the design phase and answer the first research question. The second double diamond represents the develop phase, which includes using a morphological chart to integrate ideas, interviews, drawing and lo-fi prototyping to find answers to the other two research questions. The iteration cycle connects to the detail phase, where CAD, prototyping and testing of several aspects are iteratively used to improve the concept. It should be noted that the whole process is iterative: new insights will inform and influence earlier findings, which in turn will have their influence on subsequent steps.

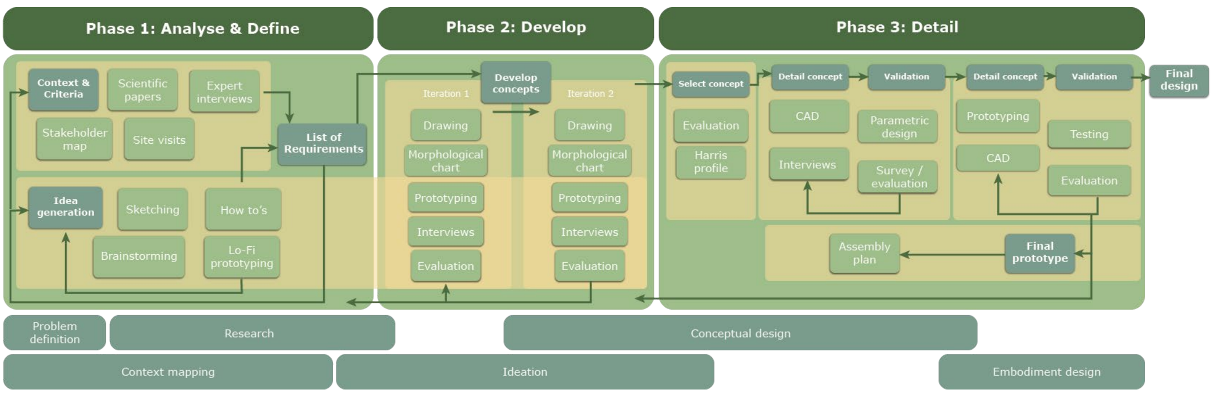


Figure 4: Overview of main methods used per project phase. Own illustration.

1.4 Reading guide

Following this introduction chapter (1), this thesis consists of eight chapters and a discussion, conclusion and recommendations section.

Phase 1: Analyse and define

Chapter 2 provides background information on WTBs, including their sizes, shapes, material composition and -properties, and processing steps towards reuse.

Chapter 3 covers background information of noise barriers and relevant design aspects and requirements.

Chapter 4 summarizes key findings from chapters 2 and 3, establishing a design vision and focus requirements and focus criteria.

Phase 2: Develop

Chapter 5 outlines How to's on noise barrier functions in the ideation process. Ideas are organized in a morphological chart and further combined into two integrated ideas.

Chapter 6 refines the combined ideas into concepts for evaluation against Chapter 4's focus criteria, identifying better design choices and next development steps.

Chapter 7 covers those development steps, forming a concept iteration. This includes panel configuration, frames and fastening options and a barrier top exploration.

Phase 3: Detail

Chapter 8 addresses embodiment design aspects of the concept, such as the development of a parametric segmentation model and a prototype for testing, as well as an explorative coatings test.

Chapter 9 presents evaluative activities, such as the results of a survey about aesthetics and vegetation options and a structural analysis of the WTB panels.

Wind Turbine Blade material

Chapter 2

In this chapter, the background and factors that impact the potential for reuse of WTB material are characterized. This includes examining the scale of this material stream (2.1), developments in size and shape of blades (2.2) and their material composition & properties (2.3). Finally, techniques to segment WTBs are discussed (2.4). This chapter provides reasoning for why it is desirable to find applications for these materials, as well as a foundation for exploring how this can be done effectively.

This is done through outlining the results of a desktop research. Google (scholar) searches were done with keywords including *wind turbine blade* and any of the following pre- or suffix: *waste; end-of-life; developments; size evolution; shape (families); material composition; material properties; composite properties; fatigue properties; fatigue stress cycles; corrosion and aging; acoustic properties; transmission loss properties; LCA; recycling.* Search results were mainly selected based on their publication website and date, where research websites like ScienceDirect, ResearchGate and MDPI were deemed reliable. Some information was gathered through personal communication with experts in the field of decommissioned WTBs, including an employee of a decommissioning company in the Netherlands.

2.1 End-of-life WTB stream

The amount of WTB material is rising with the expanding trend of exploiting (green) wind energy. Around 25.000 tonnes of blades are expected to be decommissioned annually in 2025 in Europe, which could double towards 2030 to around 52.000 tonnes (WindEurope, 2021). Liu & Barlow (2017) report their expectations of blade waste throughout their whole lifecycle, resulting in a total expected EOL blade waste that annually grows with 2 million tonnes worldwide in 2050. This amounts to a total of 43 million tonnes. Europe will have to manage approximately 25%, which is 10,75 million tonnes total or 500.000 tonnes annually. While sources vary, they agree that significant quantities of WTB waste are present now and will increase in the future. It is therefore important to look for ways to recover, reuse and recycle the materials, preferably in scalable applications that can store the materials for long periods. Noise barriers present an interesting option, as they require large amounts of material and have a lifetime of 30-50 years (CROW, 2012).

In the upcoming 5 years, WTBs of models Enercon E66 will be decommissioned frequently onshore. Offshore, mainly Vestas V80 and V90 will be decommissioned (T. Bravenboer, personal communication, 17 September, 2024). These models could thus be interesting to consider for a noise barrier project.

2.2 Sizes, shapes and segmenting

This section covers the (developments in) size and shape of WTBs, and shape- and segmenting exploration with a 3D printed WTB model. These aspects influence the approach that needs to be taken to reuse the material in noise barriers.

2.2.1 Size developments

To improve efficiency and thereby reduce the cost of wind energy, longer blades are being developed (TNO, 2022b). Since the start of commercial wind turbine usage in the 1980s, the rotor diameters of wind turbines have been growing continuously (Wiser et al., 2011). This trend is not nearing its end, as multiple blade manufacturers like Siemens Gamesa (SG14-222, 108 m blades), Vestas (V236-15.0, 115,5 m blades) and MingYang (MySE 16.0 - 242, 118 m blades) are developing longer blades still. When extrapolating this trend, TNO (2022b) expects that in 2040, rated power of WTBs will reach approximately 27MW (Figure 5) and accompanying blade lengths will have risen to 145 m (Figure 6).

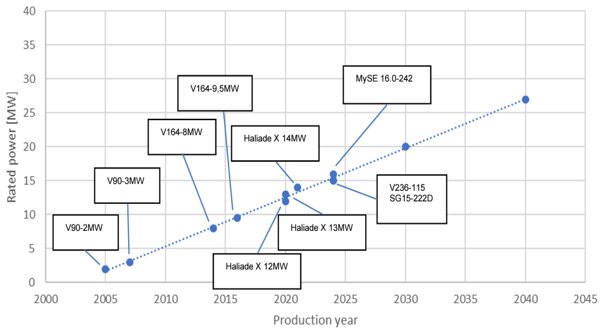


Figure 5: Rated power trend based on wind turbine models, from 2005 to 2040 (TNO, 2022b).

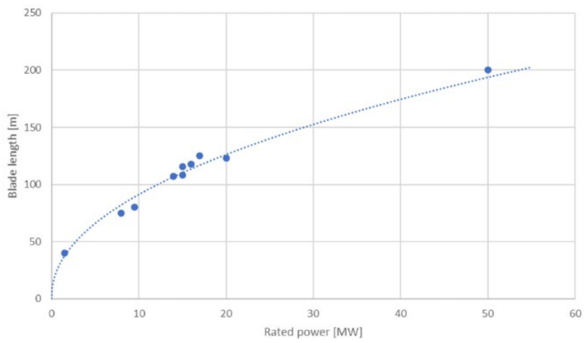


Figure 6: Future blade length projection, based on rated power trend currently (TNO, 2022b). Blue dots are blade models from previous figure.

The increase in size leads to heavier blades (Figure 7), which adds to the EOL waste stream in the future if a similar amount of WTBs are still used then. The variability in size also complicates reuse, as patterns to segment them into suitable parts for specific applications will depend on this. For scalability and cost effectiveness, efficient processes that account for size (and shape) differences are likely needed, which could include parametric segmentation models and size and shape analysis tools like 3D scanning systems.

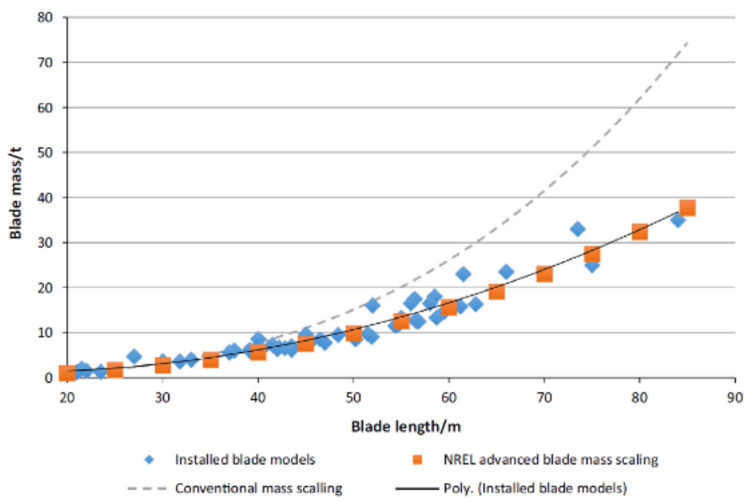


Figure 7: Evolution of blade mass related to blade length (Liu & Barlow, 2017).

2.2.2 Variable shapes

Wind turbine blades frequently look similar, though along with their sizes, shape differs per turbine model. Their shapes are described with airfoils, which are the cross-sectional shapes at certain points along the length of the blade as depicted in Figure 8. There are several airfoil series, including the DU and NACA series. Airfoils are the key factor affecting lift and drag, and thus the aerodynamic performance, as well as the structural integrity of a blade (Wind Energy Technology Office, 2023).

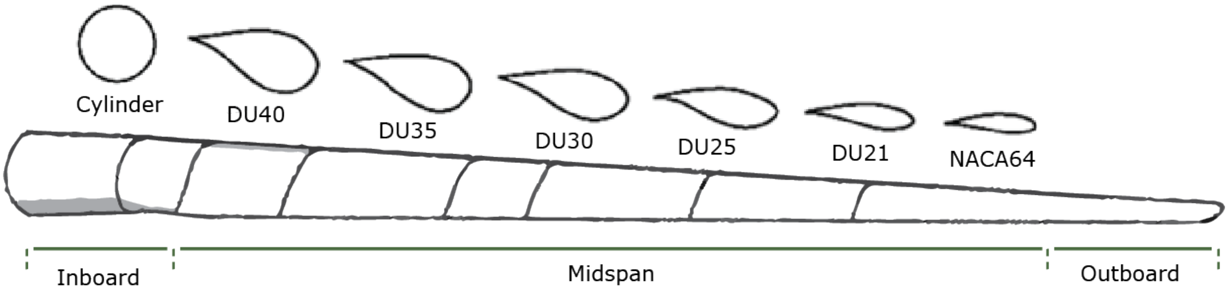


Figure 8: Sections and airfoils of the NREL 5MW blade (Joustra et al., 2021c).

Figure 8 shows how different airfoils are used to describe a blade's shape, as well as three general sections of the blade. The section nearest to the root is called the inboard, which is mostly cylindrical and then transitions into the midspan. The midspan's shape is characterized by a tilted water droplet-like shape, which becomes narrower as it progresses towards the outboard. The outboard smoothly follows from the midspan and is generally almost flat (see Figure 9).

Since almost all WTBs are made of thermoset composites and sandwich structures, it is not possible to reshape them at EOL. Consequently, their shape forms a boundary for what can be done with the material in reuse applications. Because the inboard is cylindrical and then transitions into the midspan, it is unlikely that this part of the blade will yield suitable material for use in a noise barrier, since this application normally makes use of long, straight panels. Despite their odd shape, the cross-sections along the midspan and especially outboard consist of more relatively straight parts, making those sections more attractive to salvage panels from.

Figure 9: Almost flat tip of a 45 m long Vestas V90 blade on a field.

2.2.3 Shape exploration

3D shape exploration was done physically through lo-fi prototyping to create more understanding of WTB shapes and how they may be segmented into usable parts for a noise barrier. A 3D model based on a Vestas V90 was 3D printed on approximately 1:50 scale and with a thickness of 0.8 mm. Although a broken segment resulted in six pieces as shown in Figure 10, the blade was initially printed in five segments. The three central segments were cut along the trailing- and leading edges, forming 6 panels: 2 from each segment (Figure 11). These separated panels facilitated exploration of realistic curvature noise barrier ideas. The largest segment (rightmost of the three boxed) yields two approximately 8 cm high panels, relating to 4 m at real scale. This is sufficient to form a barrier. The remaining 4 panels, retrieved from the two smaller segments complement

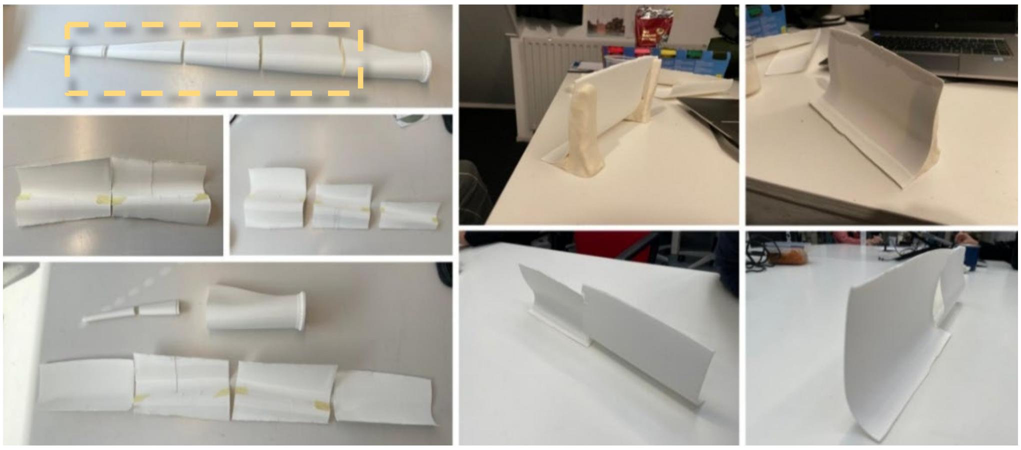


Figure 10: Initial Lo-Fi prototyping for shape exploration.

each other after rotating. This results in two more sections with approximately the same height as the large panels (Figure 10, lower left). The exploration helps to get a better sense of WTB material shapes, and of criteria that could become important, such as *modularity* and *blade material usage*.

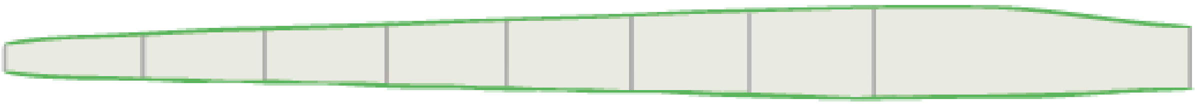


Figure 11: Cutting step along the trailing and leading edges (in green).

2.3 Composition & material properties

With an understanding of the quantity, sizes and shapes of WTBs, the next step is to examine their materials. Before specific material properties are elaborated on, the composition of materials will be described based on their location in the blade. This will inform the segmentation approach for panels for use in a noise barrier.

2.3.1 Composition of a wind turbine blade

WTBs are made of a combination of low density but highly stiff materials, to find the right balance between weight and structural requirements. A cross-section can be divided into parts often made of the materials in Figure 12 (Joustra et al., 2021c) and Figure 13:

- The leading edge (LE) panels, which form the 'front' of the blade: it is the first part to cut into the wind.
- The spar caps form the structural basis together with the shear webs. This section is made extra stiff through sole use of glass- or carbon FRP.
- The shear webs connect the top and bottom face and provide structure.
- The trailing edge (TE) panels form the 'back' of the blade.

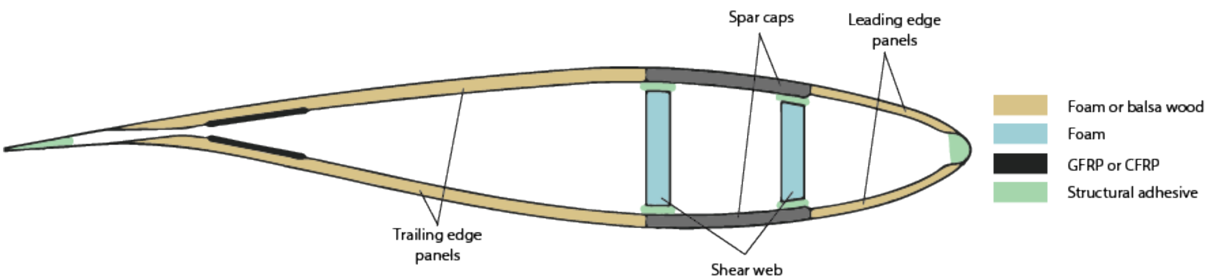


Figure 12: Cross-sectional overview of blade materials. Illustration based on (Joustra et al., 2021c).

Extending this into 3D reveals more complexity (Figure 14). Along the length of the blade, materials change and their thicknesses taper. The root end is made entirely of GFRP (Joustra et al., 2021c). Moving from the root towards the tip, the cylindrical shape makes way for specific airfoils in the midspan. Here, the material composition becomes more complex: the leading- and trailing edge panels are GFRP-balsa wood or GFRP-foam sandwich structures, connected with structural adhesive. The spar caps show additional GFRP prepreg laminate and sometimes also contain CFRP prepreg laminate, especially in longer blades. Since the shells and spar caps taper in thickness, panels retrieved from it will also taper. This should be taken into account when considering fasteners for panels to a noise barrier frame.

Figure 13: Photo of a WTB segment. The LE panels and shear web are made of GFRP-foam sandwich, while the TE panels are GFRP-balsa. The spar cap (boxed) is a complete block of GFRP.

Depending on the length and width of the blade, there can be one or multiple shear webs made of GFRP-foam sandwich structures. These are not pre-determined in the airfoil shape. The shear webs are straight and taper in height from their starting point towards the tip of the blade, as the top and bottom shell move towards each other. The tip parts are almost flat to reduce drag and soiling of the LEs, as this part moves through the wind the fastest (Wind Energy Technology Office, 2023). Over the whole length of the blade, multiple protective coats will be used to prevent water inlet and UV degradation.

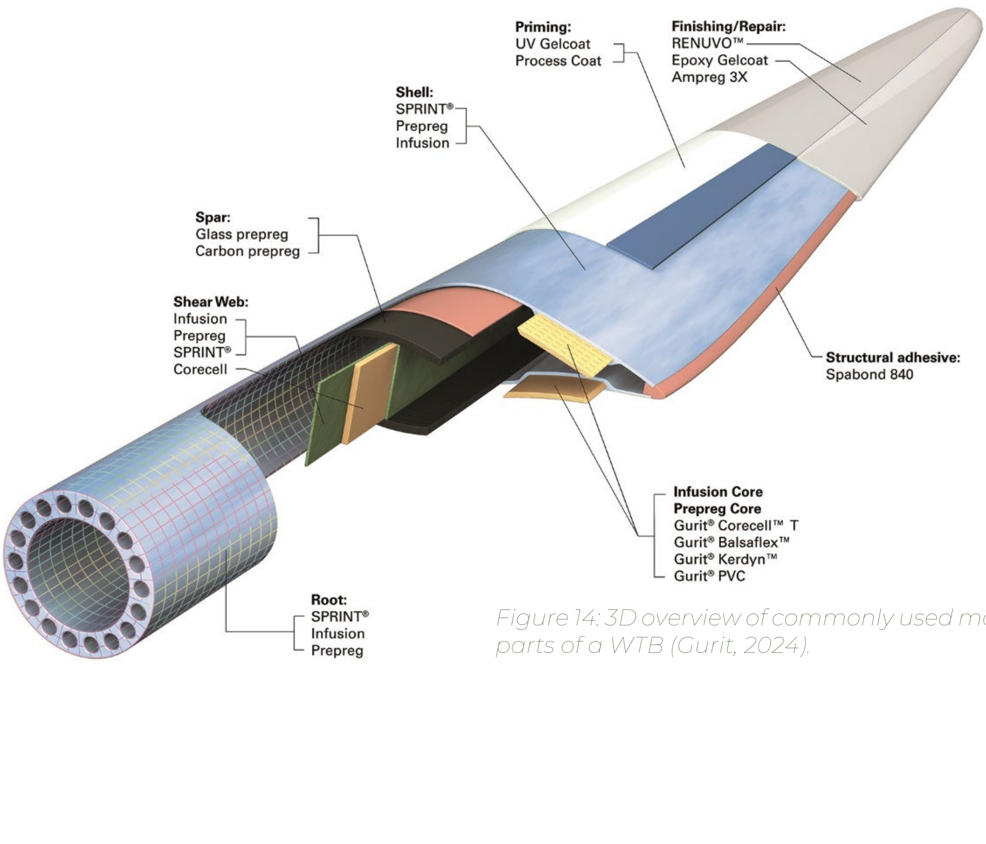


Figure 14: 3D overview of commonly used materials for specific parts of a WTB (Gurit, 2024).

The material composition and division of parts in the cross-section can inform segmentation patterns. As the far ends of the leading and trailing edges both contain a lot of structural adhesives and have sharp corners or curvature, these areas are unlikely to pose as valuable locations to get panels from. Moving a bit more inwards, however, the TE panels are relatively straight and wide, and thus form interesting areas for material salvaging. The LE panels have more curvature and are less wide than the TEs, but could also contain some interesting areas.

The spar cap and shear web combination could be used as a whole in the more structurally challenging parts of the noise barrier, if segmented properly. There is also the possibility to form L-, I-, H- or T-beams from these parts, which could be interesting for frame-components. It can also be divided into separate parts, where the shear webs are interesting because of their straight nature to form panels or beams. The spar caps are also interesting in the same function, since their width remains constant along the length, which additionally contains a 'very low' amount of twist (0.002 m per metre length, Joustra et al., 2021b).

2.3.2 Mechanical properties

Fiber Reinforced Plastics

Additional complexity is added because FRP laminates are produced in variable ways. Composites allow for a wide range of versatility because the (glass- or carbon-) fibres, their orientation and the reinforcement material (thermosetting polymers like epoxy (Chen et al., 2019)) can be controlled. Their exact lay-up is tailored towards their end use.

Table 1 shows properties of different materials and composites used in the NREL 5MW blade (Resor, 2013 & Joustra et al., 2021c). The three GFRP variations refer to the orientation and combination of fibres, which provide a specific combination of material properties. Based on these properties, interesting areas for material salvaging for a noise barrier can be identified.

Uni-directional (UD) fibres are aligned in one direction. This direction provides a lot of tensile strength and is used for stiffness in the blade's length direction. Triax refers to a triaxial combination of fibres, which can be woven or stitched. This lay-up provides strength and stiffness in more directions, making it better suited in locations where complex, multi-axial loads are present. BD refers to bi-directional lay-ups, where two fibre directions are present. This also helps to alleviate loads that act in multiple directions (Joustra et al., 2021c).

Table 1: Material properties used in the NREL 5MW blade, used to calculate mechanical properties of recovered construction elements (Resor, 2013 & Joustra et al., 2021c).

Material	E-modulus [MPa]	Shear modulus [MPa]	Poisson's ratio [-]	Density [Kg/m^3]	Tensile strength [MPa]	Compressive strength [MPa]
GFRP UD	41,800	2630	0.28	1920	972	702
GFRP Triax	27,700	7200	0.39	1850	700	292_a
GFRP DB	13,600	11,800	0.49	1780	144_a	213
Foam	256	22	0.3	200	5.6_a	4.4_a
CFRP UD	114,500	5990	0.27	1545_b	1546	1047

Core materials

Frequently used core materials (that support FRPs in sandwich materials) are selected on their low density and include end-grain balsa wood (150 kg/m3) and different types of foam. PVC, SAN, PU, XPS and PET foams (60-70 kg/m3) are used and each has their (dis)advantages for use in WTBs. Their function is to provide resistance against buckling without adding too much weight (Stoll, 2014).

For use in noise barriers, the core materials' density, durability and resin uptake are relevant. As further explained in section of 3.2.1, transmission loss of sound waves is strongly associated with the weight of a material. Since balsa wood is twice as dense as the foams, panels with a balsa wood core likely provide better prevention of sound transmission. However, a disadvantage of using balsa wood as core material in a noise barrier might be its durability, (in this report defined as *"the quality of being able to last a long time without becoming damaged"* (Cambridge Dictionary, n.d.), this encompasses resistance against corrosion in metal components, protection against rot in wooden elements, and wear resistance of the entire assembly). Balsa wood degrades when it comes into contact with moisture (Joustra et al. 2021c), losing its integrity and thereby reducing the durability of the panel. This will not happen as quickly with foams. Either way, fasteners should be aimed to not invade the material and compromise the protective performance of the GFRP, and cutting edges need to be protected (see section 2.4.2).

Properties of used WTB material

After 20 years of use, resulting material properties of WTBs could differ from initial properties. Understanding resulting properties is important to evaluate the viability of using WTB panels in a noise barrier. Alshannaq et al. (2022) analysed the (E-glass fibre and epoxy resin) spar cap of a GE37 (37 m long) WTB that had been in use for 11 years. This part carries most of the loads exerted on a WTB, making it the relevant element of the blade to be tested on fatigue levels and degradation in stiffness and strength. Results of mechanical tests revealed that the material retains promising levels of strength and stiffness. Notably, no signs of deterioration, crack propagation or delamination in the GFRP were found, even after the cyclic loading during its initial service life. The results are consistent with studies by Sayer et al. (2013)(evaluated 25 m blade used for 18 years) and Ahmed et al. (2021)(evaluated 10 m blade used for 20 years). These findings indicate that the composites retain significant structural integrity and durability, making them suitable for structural reuse. Above studies indicate that tests on sandwich parts of the blade were not conducted, and should still be done. However, if the spar caps did not degrade, these are likely also in good shape. Joustra et al. (2021c) calculated the flexural modulus and strength for sandwich structure panels, spar caps and shear webs from a research blade (Table 2). To determine whether these properties will suffice in a noise barrier, a structural analysis will be done (section 9.1).

Table 2: Properties of blade parts, calculated from blade design specifications using Granta CES Edupack 2019. The thickness of the core material dominates the resulting properties of panels (Joustra et al., 2021c).

Part	Thickness [mm]	Density ρ [x10^2 kg/m^3]	Flexural modulus E_{flex} [Gpa]	Flexural strength σ_{flex} [x10^2 MPa]
Leading & Trailing edge panels	26	5.6	9.8 – 14.6	5.1 – 8.9
	96	3.0	3.2 –4.7	1.6 – 2.8
Trailing edge reinforced panels	26	5.9	15.1	5.1 – 8.9
	103	4.1	6.7	1.6 – 2.8
Shear web panels	54	3.2	2 – 3	2.8 – 4.9
Spar cap beams	20	16.5	37.1 – 64.9	7 – 11.7
	48	16.1	52.2 – 99	8.1 – 13.3

Fatigue

In connection to the previous section, fatigue damage (deterioration, crack propagation or delamination) in WTB material as a result of its first service life is relevant for use in a noise barrier. Noise barriers are designed for a 50 year lifetime, during which they are expected to experience 100 million load cycles. Fatigue is an important aspect when designing a WTB as well, because with an average service life of 20-25 years, they experience between 500 to 1000 million load variations (Gasch & Twele, 2012), which is considerably more than noise barriers. Furthermore, the loads that WTBs need to withstand per cycle are often higher. Depending on blade length, bending moments and axial forces are in the order of magnitude of 10^4 - 10^6 Nm and 10^4 - 10^5 N respectively (at a 9 m/s wind speed, Fernandez et al., 2017). As the above named studies report good retention of material properties after the first service life of a few WTBs, fatigue damage is not expected to pose a problem during the noise barrier lifetime.

2.3.3 Acoustic properties

Acoustic experiments and research specifically on WTB material properties were not found in the desktop research. The most relevant source is Neuman (2024), who used an impedance tube and an anechoic chamber to determine the absorption coefficient and respectively transmission loss of a GFRP-balsa wood sandwich panel (Figure 15 & Figure 16). The results show that the absorption coefficient remains below 0.1 for most frequencies, which is low compared to conventional materials used in absorptive barriers, such as rockwool that can reach 0.5 – 0.6 for frequencies between 250 and 2000 Hz (Zannin et al., 2018). In the relevant frequency range, which is mainly 10 - 8000 Hz (see Figure 17), the transmission loss also remains low as compared to conventional materials (see Table 3). It increases gradually from 5 to just below 20 between 570 Hz and 2070 Hz. These results imply that one layer of a TE or LE panel sandwich material will not be sufficient for a noise barrier, which should be tested further to be sure.

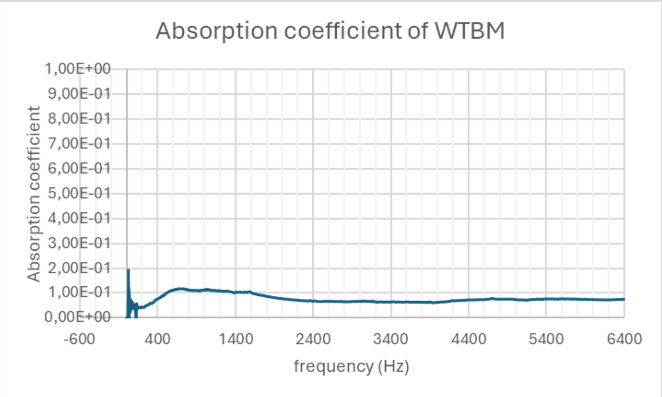


Figure 15: Absorption coefficient results from an impedance tube test on GFRP-balsa wood sandwich material (Neuman, 2024).

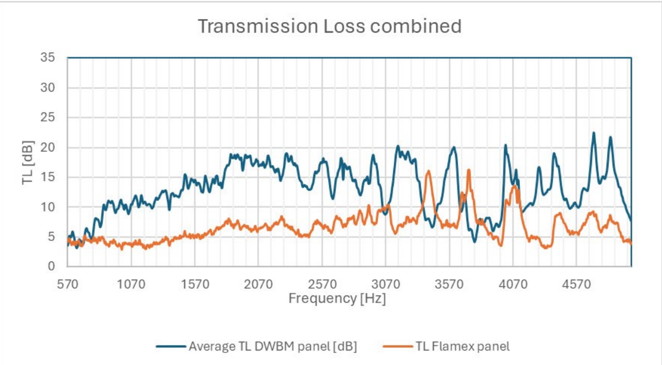


Figure 16: Transmission loss results in (unweighted) dB of an acoustic test in an anechoic chamber, on GFRP-balsa wood sandwich material (Neuman, 2024).

Table 3: Airborne sound isolation values (dB) per frequency bandwidth and road noise for a selection of materials (DGMR, 2007 & Neuman, 2024).

Material	Isolation per third-band in dB					Road noise dB(A)
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	
4 mm glass	19	23	26	30	32	27
10 mm glass	24	28	31	30	31	29
4 mm opaque plastic	9	15	21	27	33	24
4 mm aluminium	12	17	23	29	32	22
3 mm steel sheet	19	24	26	36	40	29
18 mm plywood	18	21	24	23	24	23
25 mm GFRP-balsa	n.a.	n.a.	+- 5	+- 10	+- 18	n.a.

2.4 Segmentation and preparation

After decommissioning, WTB material will have to be made suitable for reuse through a combination of processes. These processes include cutting or sawing to produce pieces of usable sizes, sanding edges to eliminate sharp glass fibres, and applying surface treatments through repainting or coating to prevent degradation through UV radiation and moisture (Medici et al., 2020).

2.4.1 Segmentation tools

Table 4 outlines cutting / sawing options, their (dis)advantages and proposed application of those tools for structural reuse.

Table 4: Advantages, disadvantages and proposed application of several segmentation tools. Sources: Jensen & Skelton, 2018 & Joustra et al., 2021c.

Tool	**Advantages**	**Disadvantages**
Circular saw (diamond tip)	Variable sizes, can handle most blade sizes through multiple cuts.	Has safety risks. Releases GFRP dust, which is harmful for operators and environment.
	Large freedom in movement of saw, relatively precise cuts.	Quick tooling degradation, even with diamond tips.
	Can be equipped with a dust collection system using water or vacuum.	
Proposed application	Cutting panels out of whole segments: requires specific cuts of smaller pieces.	
Wire saw (diamond tip)	Can cut through complete WTB cross-sections in a straight line.	Releases GFRP dust, but to a lesser extent than circular saws.
	Produces clean and precise cuts.	Quick tooling degradation, even with diamond tips.
	Runoff water can be collected and filtered.	Requires firm holding in place of large parts

		Time-consuming cuts
Proposed application	Large cuts for retrieving segments from a blade, as well as panels from segments.	
Water jet cutting	No tooling degradation possible.	Time-consuming cuts
	Reduced safety risks: dust spread is reduced due to water, which can be collected and filtered.	Using water to cut sandwich panels might result in water ingress in core materials.
	Produces clean and precise cuts.	
Proposed application	Smaller cuts, cuts in spar cap regions where other tools would degrade quickly.	

With consideration of the surrounding environment, segmentation could be done on location to ease transport activities. However for larger scale segmentation, which is required for noise barriers, a more automated and adaptable segmentation system should probably be developed. During an interview with an employee of Vlasman, a circular demolition company, sawing-rails were found to be interesting for this (J. Stokman, personal communication, December 13 2024).

Segmentation vs. material integrity trade-off

Segmentation operations preferably consider the design of the next lifecycle application, in this case a noise barrier. Maintaining opportunities for third, fourth and possibly more material lifecycles should also be taken into account during this design process. This is aimed for by finding a balance between retrieving suitable pieces and keeping those pieces as large as possible. Because in essence, the opportunities for subsequent lifecycles are kept broadest when the integrity of the WTB material is kept largest. How that may be done for a noise barrier will be covered in section 8.1.

2.4.2 Pre-processing of retrieved panels

After panels have been retrieved from the blade, cutting edges can be rough and sharp due to the glass fibres in the material. Additionally and as mentioned earlier, the core materials need to be coated to enlarge their corrosion- and wear resistance against UV and water. Both those aspects have previously been tackled by applying an epoxy resin with glass fibres to these edges (Medici et al., 2020).

Because the core materials are porous, they will uptake coatings or resins, which will result in the need for more coating material or bad surface quality of the edges. The cell size of the pores largely influences this, which is advantageous in XPS, PVC and SAN because of their small cell sizes. PET has a higher resin uptake, although there are methods to reduce this (Stoll, 2014). Though selection of panels on this aspect is likely not as relevant as others, it should be noted. Considerations for suitable coatings are covered in section 8.3.

Finally, a (paint) coating might need to be applied to panels for fire-safety and aesthetic reasons. Since WTB material is flammable (rated as combustible, fails to meet flame-retardant standards)(Wang et al., 2024), a flame-retardant addition to a coating is likely needed to prevent the spread of fire (see section 3.2.3).

2.5 Takeaways

- WTB models that are planned to be decommissioned in the next 5 years are mainly Enercon E66 (onshore) and Vestas V80 & V90 (offshore).
- Size and shape of blades differ per WT model, and will adapt in the future. Segmentation approaches should therefore be adaptable to make reuse of as many types of WTBs possible.
- Shapes of WTBs are set, forming a boundary for structural reuse initiatives.
- Retrieved WTB panels often taper in thickness, requiring adjustable fasteners.
- The TE panels form interesting areas to retrieve material from for noise barriers. The LE panels to a lesser extent. The spar cap and shear webs are interesting for panels as well as more structural components.
- Studies on the material properties of used WTBs show that they are still in structurally stable condition.
- Core materials degrade if exposed to environmental influences and should consequently be protected from them.
- For sufficient transmission loss, it is important to look at ways to make a noise barrier in which at least two layers of material are behind each other, with air, absorptive panels or other absorptive material like soil in between them.
- To maintain opportunities for subsequent material lifecycles, maintaining WTB material integrity is important. This can be done by keeping it as large as possible, but has to be balanced by the aim for retrieving suitable pieces.

Noise Barriers

Chapter 3

In this chapter, roadway noise barriers and their context of use are described. The main questions addressed are: What are the functions of noise barriers? Where and when are they used? How do they reduce noise? How can they add value for the environment, residents, and road users? What safety concerns exist? What loads should they withstand? How should maintenance be carried out?

To answer these questions, multiple methods were used. Literature provided by the Geluidsbeheersing team specializing in noise barrier design at Heijmans was reviewed. This includes guidelines, criteria, and requirements for noise barriers (GCW-2012 of CROW and Richtlijnen Ontwerp Kunstwerken (ROK) of Rijkswaterstaat), covered in sections 3.1 and 3.2. Additionally, site visits to noise barriers along the A13 near Delft and examples of similar materials contributed to section 3.3. Meetings with Geluidsbeheersing team members (W. Groenewoud - project manager, M. van Amstel - project manager and E. Nouwen – constructor) provided further input. This chapter outlines key takeaways (3.4) and criteria for the concept and embodiment design phase, culminating in a List of Requirements covered in chapter 4.

3.1 Introduction to noise barriers

This section introduces noise barriers in the Netherlands and the important aspects to consider when designing one.

3.1.1 Noise barriers in the Netherlands

Noise barriers, also called sound barriers or acoustical barriers, serve the purpose of reducing road- or railway noise for areas adjacent to them. Especially in locations where roads are close to residential areas, noise barriers are key to preventing noise pollution, which can have significant detrimental health effects as well as well-being of humans (Heijmans, n.d.-a). Long-term impacts include contributions to annoyance, stress and sleep disturbance, making it a significant public health concern (EEA, 2022)(RIVM, 2004). Noise barriers consequently are no new concepts: they have been around since 1975 in the Netherlands and in 2017 about 500 km of noise barriers were present along state roads (rijkswegen). Yearly, about 20 km of noise barriers are added (CLO, 2002).

There are approximately 3.000 km of state roads, which easily realize noise of approximately 70 dB, at 50 meter from the road (Rijkswaterstaat, 2023), in primarily low frequency ranges (Figure 17). This is about the same amount of noise a vacuum cleaner produces. Regulation has adapted to increasing road noise, requiring more (effective) noise barriers and other noise mitigation strategies (LBP Sight, 2017).

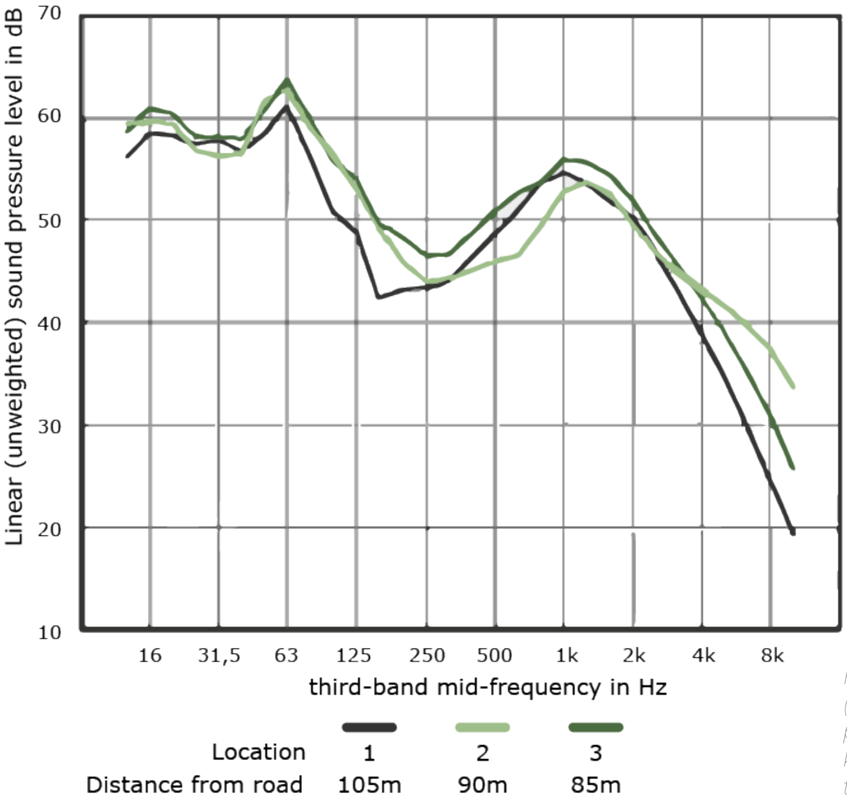


Figure 17: Frequency spectrum (in Hz) of the unweighted sound pressure levels (in dB) at 120 km/h highways, measured in three locations (LBP Sight, 2017).

3.1.2 Design process of noise barriers

Noise barriers can be placed along roads, railways, airports and industrial areas. Noise barriers around railways are similar to roadway noise barriers in terms of load bearing structure, however its experience, safety, accessibility and shape will often differ (CROW, 2012). Within the boundaries and time constraints of this thesis, development of a noise barrier for state roads will be the main goal. Specific requirements for railways will not be primarily considered.

To ensure that all relevant aspects of highway noise barriers are considered during their development, guidelines have been set-up in the GCW-2012 (Richtlijnen Geluidbeperkende Constructies langs Wegen), by the national knowledge centre CROW. Their reports integrate knowledge of the state, provinces, municipalities, consultancies, executive construction companies, suppliers and transport companies. The GCW report provides the basis for the next section (3.2) and largely covers location specific requirements, meaning that requirements follow from the exact location of the barrier. These requirements are important for a viable noise barrier, but not always applicable to the design that follows from the project goal, which is to explore the feasibility of a noise barrier made of WTB material. This project will thus not follow the GCW process blindly and not all requirements in it will be applied to the noise barrier design.

3.2 Design aspects of noise barriers

This section covers the main design aspects for noise barriers: acoustics, aesthetics, safety, loads and maintenance. Takeaways from this section for a noise barrier made of WTB material are listed in section 3.4.

3.2.1 Acoustics

Factors influencing noise barrier performance

The primary goal of a noise barrier is reducing noise pollution or nuisance that people experience from a road. The noise attenuation requirement for a sound-reducing construction for road noise is determined through the norm NEN-EN-1793-2 and is expressed as ***DLr***, in decibels (CROW, 2012, p. 15):

$$DL_R \geq \Delta L_{SW} + 10 \text{ dB} + \text{extra value for lifetime}$$

Appendix C elaborates on this requirement. In what ways do noise barriers reach this goal? In principle, a noise barrier absorbs and / or reflects sound waves to prevent them from reaching the areas behind the barrier. The goal is to minimize the amount of 'lines of sight' of the sound waves that directly or indirectly reach the receiver (Murphy & King, 2014). The amount of realized sound reduction at a certain location thus depends on the variables depicted in Figure 18 (CROW, 2012, p.13-15).

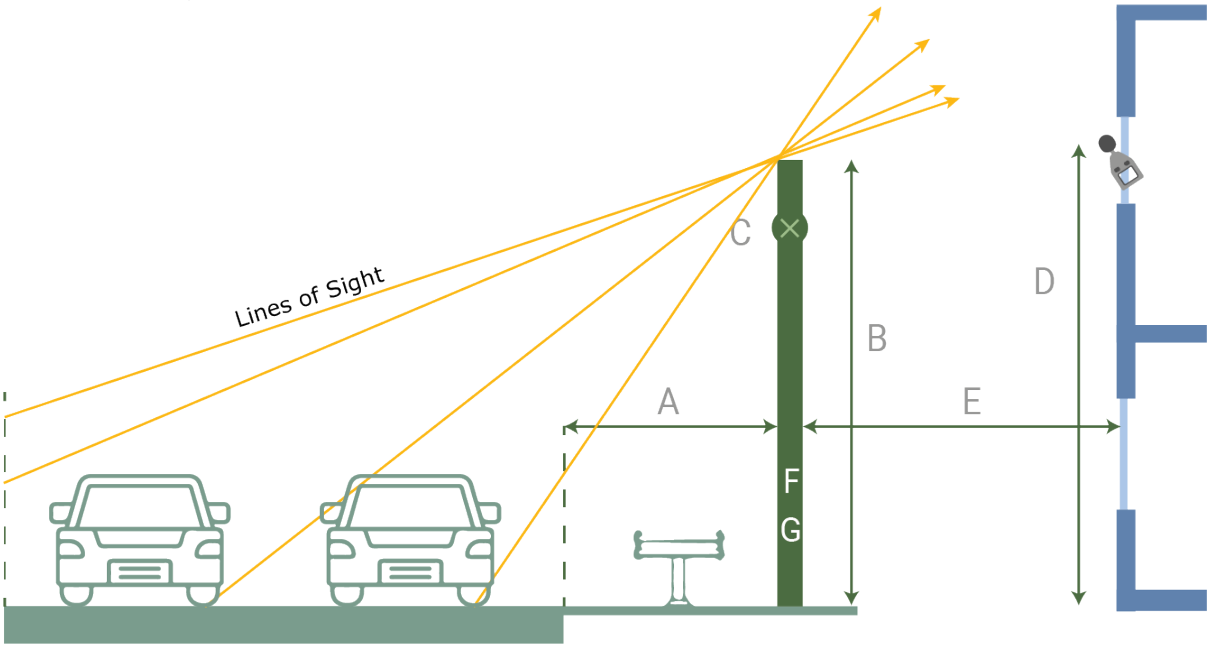


Figure 18: Factors influencing the sound isolation of a noise barrier. Illustration based on CROW (2012).

Factors A to E are all dependent on the specific location in which the barrier will be placed. How those variables affect the performance of the barrier is described in Appendix C. Factors F and G are closely related and mainly influence the airborne sound isolation that the barrier realizes. These variables are what this project will mainly cover. The acoustical properties of a noise barrier (G) can be described by analysing the way in which it influences the road noise. Sound can end up behind a noise barrier in three ways (see Figure 19). In principle, the effect of these three on the receiver needs to be reduced: transmission, diffraction and reflections on the opposite road side. Another important occurrence here is absorption of sound in the barrier. In many barriers (not all), the aim is to maximize the absorption.

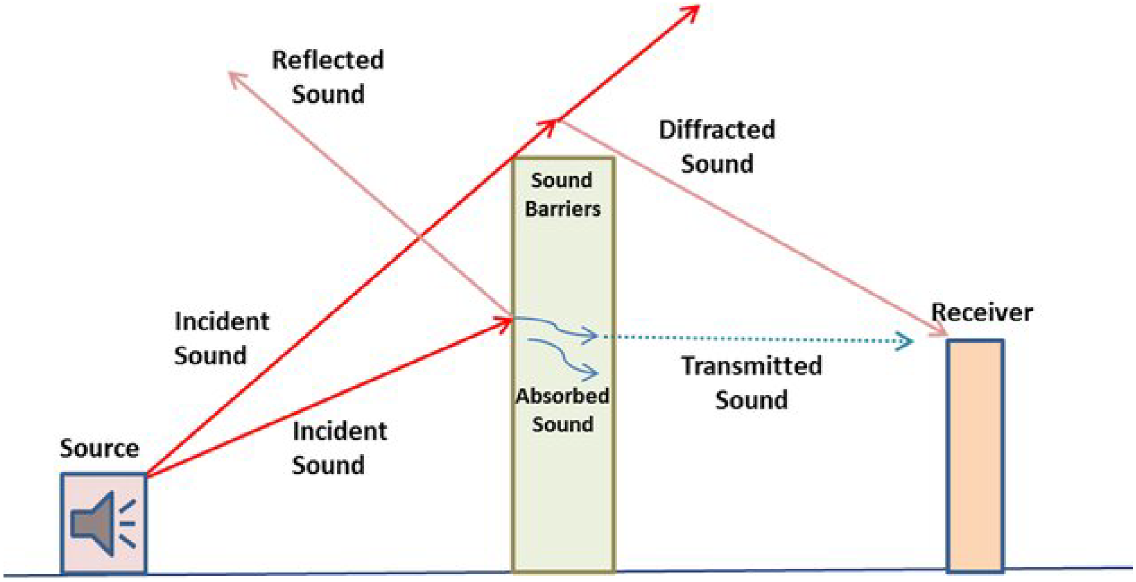


Figure 19: Sound wave behaviour around a noise barrier, including diffracted sound (Laxmi et al., 2021).

Sound wave physics

When sound waves hit a barrier:

1. Part of the sound is reflected into the opposite direction;
    a. When it hits a corner, waves will bend around it. This is called diffraction.
2. The remaining part of the sound travels into the material, where it will lose some of its energy through friction and heat, which is called absorption;
3. If there is sound energy left when it reaches the other side of the barrier, this sound will be transmitted to the other side.

In the coming paragraphs, the ways in which reflection, diffraction and transmission influence the design is discussed. Absorption is excluded here because it poses no design implications. Theoretical background on all principles is in Appendix C.

Reflection

The portion of a sound wave that is reflected upon meeting another medium depends on that medium’s surface properties (University of Cambridge, 2021), and the direction of reflected sound depends on the shape and tilt of the surface of that medium(Halliday et al., 2017). If noise barriers cannot be made absorptive, a reflective barrier that is tilted backwards (see Figure 20) is an effective alternative (CROW, 2012). The tilt namely directs the majority of sound waves up into the sky, where no receiver will be influenced by it. This seems like an interesting direction for the design of this project, since WTB material reflects almost all and absorbs almost no sound (Neuman, 2024), resembling more conventional materials like glass.

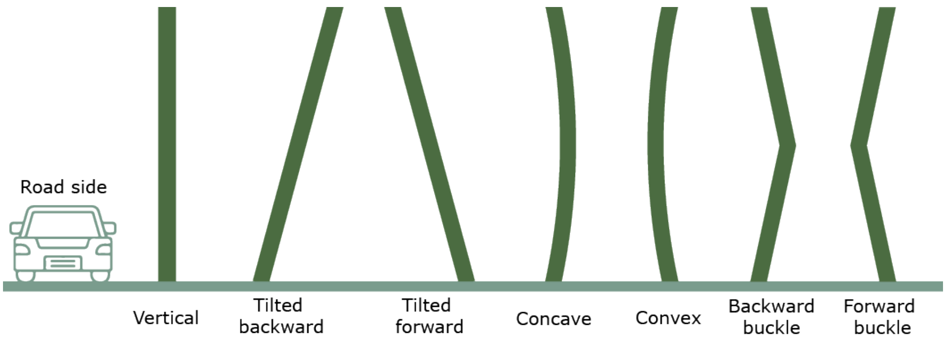


Figure 20: Barrier shapes and orientations. Based on CROW (2012).

Notably, material retrieved from WTBs will likely be concavely or convexly shaped, resulting in reflections that converge or diverge respectively (Wulfrank et al., 2014). This should be taken into account when designing the noise barrier.

Diffraction

Sound waves hitting edges or passing through small gaps will act as a sound source, redirecting them, including to the area that should be protected (Figure 19)(Laxmi et al., 2021). This happens at edges in the barrier itself and is therefore an important consideration for alignment of panels, as diffraction should be minimized. Tenpierik (personal communication, November 26, 2024), an acoustic expert at the faculty of Architecture of TU Delft, noted diffraction is often the principal way in which sound will travel into an unwanted direction behind the barrier. It can be reduced effectively by rounding the top edge of the barrier, and by using vegetation near the top to diffuse diffracting sound waves.

Transmission

Transmission of sound through the barrier should be minimized, consequently gaps and openings my only be negligibly small (CROW, 2012). Alignment of WTB panels or segments should therefore be well done (section 7.1.1). Increasing the mass or thickness of the barrier is also effective, as is adding layers of material with a cavity in between (Oelze, n.d.). As covered in section 2.3.3, a double layer of WTB material is likely required to reduce the effect of transmission sufficiently.

Interdependency and noise barrier types

The four sound principles influence each other: the energy in sound waves is divided over them based on the specific situation. Since reflection and absorption have an inverse relation, a noise barrier cannot be highly reflective and absorptive at the same time. The acoustic research performed prior to designing the barrier will determine whether a barrier needs to be designed as reflective or absorptive (CROW, 2012). There are multiple noise barrier types that are deemed effective (Kloth et al., 2008):

- Absorbing barriers that use absorptive material;
- Angled and dispersive barriers reflect sound upwards. The goal is to direct sound waves into areas where no noise-sensitive receivers are present;
- Capped barriers, which refers to barriers with a cap top near the top of the barrier, which include T-tops or L-tops. This cap reduces the amount of sound waves traveling over the top of the barrier. They have the potential to reduce barrier height (see Figure 21 for examples);
- Embankments and earth berms are made of soil;
- Covering barriers, which cover part of or all of the area above the road.

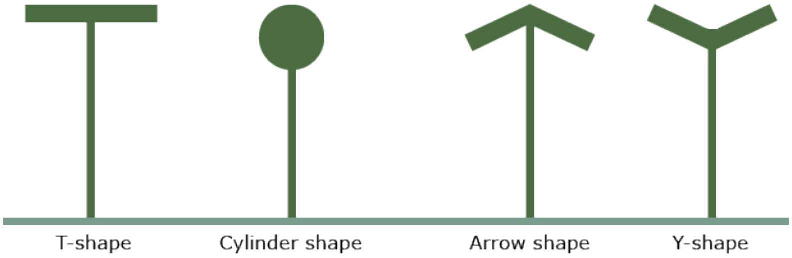


Figure 21: Various top shapes (Laxmi et al., 2021).

Since the WTB material's acoustic properties are mainly reflective, angled and dispersive barriers are likely the most suitable to aim for. Designing an absorptive barrier with this material would require different materials to be added in large amounts. There are likely opportunities to add absorptive material in some places in the design, however. The possibility of capping the barrier is also interesting because of the curved shapes in WTBs. There are possibly segments in the blade that could lend their curvature towards achieving that. Embankments and covering barriers are not primarily applicable within the context of this project.

3.2.2 Aesthetics and experience

Due to their size, noise barriers leave their mark on the environment in which they are placed. This affects both the urban environment 'behind' them, as well as the view from the road 'in front'. It is consequently essential to prioritize aesthetically pleasing and harmonious designs that add to the surrounding environment (Bendtsen, 2010). The approach of Rijkswaterstaat accordingly prioritizes continuity in design - longitudinally for a coherent road theme, latitudinally to enhance landscape identity, and temporally to enable modular adaptations for future needs (CROW, 2012).

Residents

Residents that live near noise barriers constantly see and experience them from a single point of view. The noise barrier will affect them the most, making them the most important 'user'. A new barrier will reduce the noise around their homes, making it a more comfortable space. However there are also downsides to the barriers, mainly in the form of a loss of field of view (CROW, 2012, p.32-38). It is important to reach acceptance under the residents during the design phase of the barrier. Important aspects for this are:

- Style: the scale of the barrier should be in harmony with the residential area. Correct use of the area behind the barrier can play an important role in acceptance of the residents, especially if this area is furnished towards use by residents.
- Colour: the experience of green is often regarded as good, and colour gradients from dark on the bottom to light at the top help to reduce the oppressive feeling that a barrier may have.
- Expression: the barrier should fit into the area and surrounding environment. The social safety of the neighbourhood behind it should stay the same or improve.

Road users

Road users perceive a noise barrier often at high speeds, and at differing angles due to curves or height differences in the road. The most important aspect for them is that the noise barrier does not influence the driving performance (CROW, 2012, p.31). This means that it may not be distracting: the driver should experience the noise barrier effortlessly. At the same time it should also not be too monotonous. To keep the drivers at attention, some variety in the design should be present. Sometimes the locally defined features already facilitate this.

Another important aspect for road users is their ability to orientate themselves in the landscape. Recognizable elements like church towers or high buildings should stay recognizable when a new barrier is constructed. If this is not possible, other ways to orient should be available. For example by using the barrier itself as a new orientation point or by adding art to the barrier (CROW, 2012, p.32).

The height of noise barriers influences the experience that a road has. High, vertical walls will create an oppressive feeling which should be limited by e.g. putting the barrier at an angle, adding vegetation, adding transparency or a colour-gradient. What also helps, is to use horizontally aligned building blocks and detailing (CROW, 2012, p.32).

The correct use of colour can help to reach the desired outcomes for variation, orientation and experience of the barrier. Colours should also be used to make safety features clear. Frequently used colours for other road features like signs should not be used to prevent confusion (CROW, 2012, p.32).

3.2.3 Safety

Since noise barriers are often close to traffic traveling at high speeds, safety is of high importance. The positioning of the barrier in the road's cross-section, flight routes- and roads and access roads for emergency services need to be considered. Also, safety in regard to fire needs to be assessed.

Cross-sectional positioning

Highways and roads in general have so-called obstacle free zones which differ depending on the speed at which traffic is allowed to travel. If a noise barrier is placed within this area, it needs to be protected by a guard rail (Figure 22a). Additionally, if a barrier has a T-top or L-top, it may not overlap with the clearance profile. It is assumed that the noise barrier design of this project is protected by a guard rail. Even with one, it is advised to design barriers with a smooth or flat surface area on the road side, to prevent escalation of possible accidents (CROW, 2012, p.48-49).

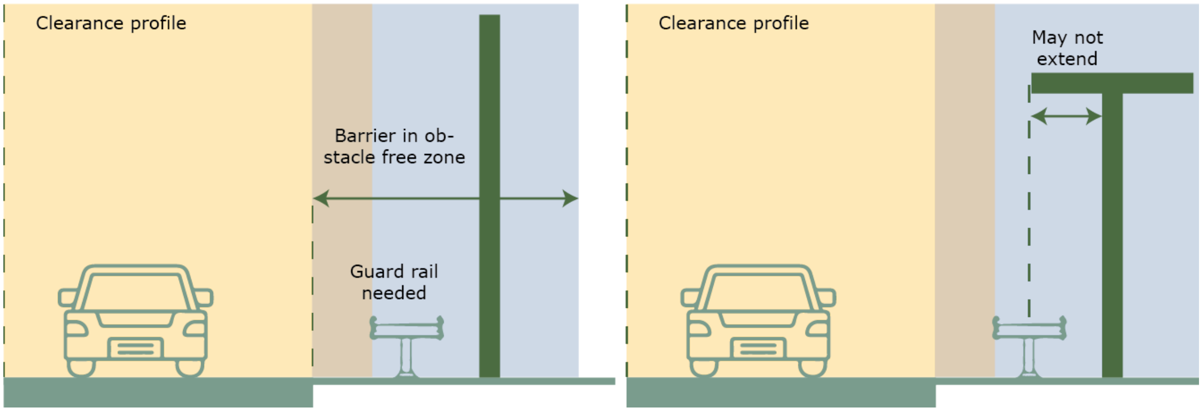


Figure 22: Visualization of the clearance profile and the obstacle free zone. Own illustration based on information in CROW (2012).

Flight doors

Placement and frequency of flight doors should be determined per route segment of the noise barrier and are thus local requirements. The maximum distance is 400 m between each. They may not decrease the acoustic performance of the barrier (CROW, 2012, p.52).

Fire safety

There are several scenarios in which fires can spread near noise barriers. There can be wildfires on the roadside next to them, as well as vehicle fires caused by accidents or breakdowns. Spread of fire and generation of (toxic) smoke should be hampered by the barrier, so normally materials would be selected that are not flammable and do not produce much smoke. In barriers with flammable material, strips of fire-resistant material with sufficient width are added at set intervals to prevent spread of fires, or flame-retardant coatings are applied. Keeping vegetation within limits is also an important measure (CROW, 2012, p.54-55 & 72).

3.2.4 Structural and environmental aspects

This section will cover some relevant details that need to be considered when designing a noise barrier, including the loads the structure needs to withstand, allowed deformations, the foundations and corrosion and water management.

Loads on and deformations of barrier filling

Wind-loads are the most frequent and important loads. The net loads are calculated by dividing the barrier into a few sections (over its whole length, order of magnitude of hundreds of meters)(Figure 23), which all have their load coefficients (determined in NEN-EN 1991-1-4). For most barriers, zone D will thus pose as the largest 'middle' section. For a 4 m high barrier, zone D starts at 16 m from the start of the barrier and ends 16 m before the end. Within zones A, B and C, the barrier design might be altered to be more structurally stable, e.g. by lowering the distance between frames or gradually lowering the barrier (E. Nouwen, personal communication, January 7 2025).

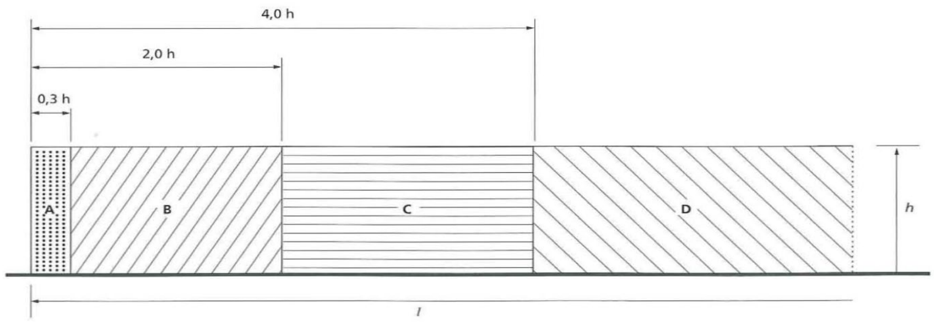


Figure 23: Sections of frame components and their calculation coefficients for wind loads (CROW, 2012).

Tilted barriers have a surcharge on these coefficients, depending on their tilt. Barriers tilted more than 20 degrees require additional research. For this design the tilt will consequently be kept between 10 and 20 degrees. Additionally, if a T-top is used, the coefficients needs to be surcharged with 0,1.

Zone D poses the largest section, and the barrier will likely be tilted, so an eventual structural analysis of WTB material used in a barrier should prove to be useful to determine how long barrier sections can be without reaching the limit of deflection, for which the guideline is set at 50 mm (CROW, 2012, p.65).

Foundations and corrosion

Similar to buildings, noise barriers require foundations that prevent them from sinking or moving (Holland Scherm, n.d.). Depending on type and material (concrete, steel), they reach up to 20 meter deep (M. van Amstel, personal communication, October 14, 2024). The frame components of a barrier are placed on top of these foundations, as depicted in Figure 24. Although specifications for foundations are not covered in this thesis, the base plate of the frame component should be placeable on existing foundation options. Steel foundations and frame components are prone to corrode: to account for any structural deficiencies due to this, these components should be a fraction thicker, or be protected by using a paint coating (CROW, 2012, p. 65). To prevent a mass gain in frames, a coating is deemed more suitable in the design. It additionally allows for colouring of the frames, which facilitates aesthetic options.

Water management

Where this is needed, drainage slits should be added at the bottom of the construction, so that water collected on the road does not form pools between the road and the barrier. Additionally, elements that could collect water have to be made in a way that they directly and quickly drain the water. Drainage slits can be continuous or consistently discontinuous. Continuous slits are better for the durability of the panels at the bottom, since they will not be in contact with soil. This is of importance for the WTB materials, making continuous slits more fitting.

3.2.5 (Dis)assembly processes

Before a noise barrier can be placed, analysis of the building site is done, where ground and soil types are determined per area. The site is then prepared by removing debris, levelling it and addressing drainage issues to prevent pooling. Additionally, utilities that might be located under the site are located and marked so they do not pose problems during construction. This preparation is essential for a smooth assembly process (W. Groenewoud, personal communication, January 13, 2025).

Construction of noise barriers starts with forming the required foundations of the structure. These are often made of concrete that is poured into a large hole, or of steel frames. The above-ground frames are placed on top of the foundations, after which the filling can be placed in. These are often made in a pre-fab structure to reduce the assembly time at or near the road, for which the road needs to be (partly) closed. Finally, aesthetic features like paint, artwork and vegetation will be added, as well as safety signage and lighting.

Disassembly processes also should be facilitated in a way that (CROW, 2012, p.81):

- Parts can be disassembled without cutting or sawing them on location.
- The resulting parts are transportable and easy to handle.
- The surrounding neighbourhood does not get contaminated with harmful substances or residues of the barrier.
- The barrier does not collapse in its temporarily instable state.

3.2.6 Maintenance

The useful lifetime of a noise barrier depends on the quality of the used materials, the construction and corrosion resistance. Maintenance and inspection can help to improve the state of barriers. Well maintained noise barriers will thus have a longer lifetime.

Additionally, well maintained barriers add to the social safety of residential areas (CROW, 2012, p. 91). Maintenance is consequently important. Tasks include cleaning, replacement of broken parts or panels, and trimming vegetation that has grown.

Cleaning might occasionally be needed to improve the state of the barrier and restore its appearance. Over time, barriers tend to be graffitied, which is considered as visual pollution. To prevent this, anti-graffiti coating can be applied to barriers to a height of 2,50 m. Vegetation and other planned artwork might also help to reduce graffiti. Replacement of broken parts self-evidently are needed to restore the performance of the barrier. Trimming and pruning of vegetation is required to prevent overgrowing plants that could extend towards the road, or obstruct sight of flight paths (CROW, 2012). These maintenance tasks should be kept in mind when designing, so that it can be facilitated. Replacement of broken parts should preferably be possible without the need for the whole barrier (segment) to be disassembled. Cleaning and trimming of vegetation should be facilitated locally by leaving enough room for machinery on both sides of the barrier.

3.3 Existing barriers review

To analyse and derive insights from existing noise barriers, a site visit was done along the A13 highway near Delft. Additionally, noise barriers were examined during travels over the course of the project, and google images was consulted to find more examples.

3.3.1 Site visits

Along a 3km highway section of the A13 near Delft, there were more than 5 different barriers, tailored to their location. There are variations in height, length, aesthetic features, transparency and types of frame-structures used. Three are analysed here.

The green barrier in Figure 24 consists of perforated sheet cassettes with absorptive material, supported by horizontal beams and steel IPE frames that are anchored to concrete foundations. It blends in well with its surroundings, with well-growing vegetation on a wire-structure. According to takeaways from this chapter, this barrier seems easy to (dis)assemble, except for some intertwined vegetation, and is compact. Interesting features include the bolted frame-to-foundation connection and the cassette-to-frame attachment (circled), which accommodates lengthwise tolerance.

Figure 24: A green barrier located next to the A13 in Delft.

The barrier in Figure 25 is located on an embankment, where lanes merge. The transition into a similar barrier can be seen. Made of glass for transparency, it is tilted backwards to reflect sound waves into the sky. The triangular frame design supports the tilted weight. There are also horizontal beams present to prevent the glass panes from resting on each other. Like the green barrier above, it contains a concrete base. As WTB material is also reflective, this barrier contains noteworthy design aspects.

Figure 25: A reflective, tilted barrier made of glass and uses a triangular frame.

Figure 26 shows a white, graffitied barrier consisting of an I-beam structure with corrugated metal sheets. The graffiti and algae on the panels are clearly visible on the white background, which is not preferred. As WTBs are also white, it should be considered to paint the panels or use vegetation to mask the white colour. Whether this barrier was meant to block sound is unclear, as it distinguishes itself from others: it is neither absorptive, nor tilted to be reflective. A notable detail is the bend in the I-beams, showing how turns can be adapted for. Allowing for a tolerance in the mounting structure also makes a bend possible.

Figure 26: A white corrugated metal sheet placed in between H-beams.

3.3.2 Example of similar material

Since glass panes are similar to WTB materials in the way they need to be connected to frame components, they can provide inspiration for fastening methods. As can be seen in Figure 27, glass panes are often connected through a form fit in a frame, supported by rubber profiles. In the left most picture, the rubber profile can be seen between the glass pane and metal frame. These kinds of rubber profiles can also be used for WTB panels if they can adapt to their variable thickness. Clamping the rubber might be a solution, for which an idea is worked out in section 5.1.4.

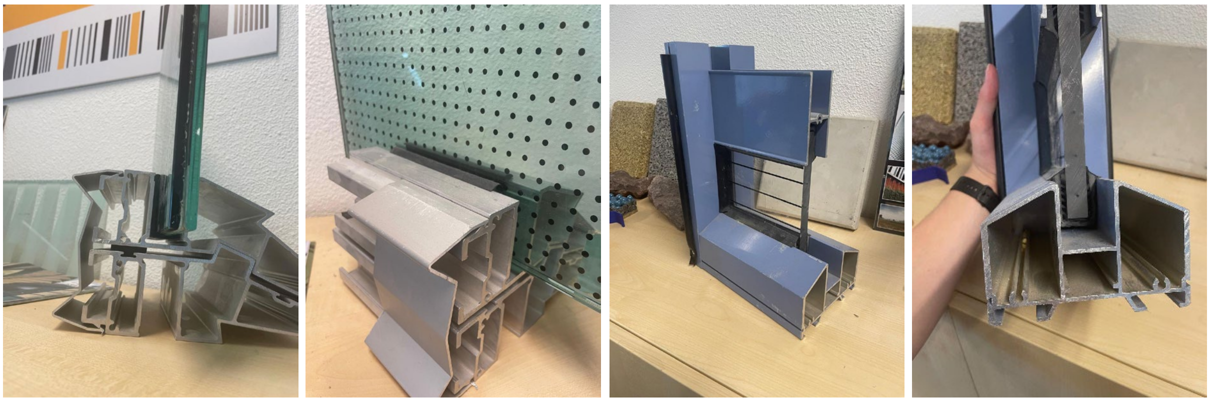


Figure 27: Examples of how glass panes are positioned in aluminium extrusions.

3.4 Takeaways

Acoustics

- The goal is to minimize the amount of 'lines of sight' of the sound waves that directly or indirectly reach the receiver (Murphy & King, 2014).
- The effect on the receiver of transmission, diffraction and reflection on the opposite side of the road, needs to be reduced.
- Tilted barriers reflect sound into the air, reducing noise. Since WTB material is reflective, a backwards tilted barrier is appropriate.
- Reflection on convex and concave shapes spread out or focus the sound into one location (Wulfrank et al., 2014).
- Diffraction can be limited by rounding the top edge and using vegetation near the top edge. T-tops or L-tops also help with this, which can also reduce the needed height of barriers. Creating such tops might be made possible through the inherent curvature of WTB material.

Aesthetics

- Continuity in the appearance of the design should be the aim.
- For road users the design should not be distracting but also not too monotonous. Correct use of colour is important to facilitate this, as well as ways to orient themselves in the landscape.
- For residents, the noise barrier design should harmonize with the area through correct colour use and placement of vegetation.

Safety

- The noise barrier design of this project should be protected by a guard rail.
- A smooth barrier surface is advised to prevent escalation of accidents.

- Flight doors have to be facilitated in a barrier segment, every 400 meter.
- Fire spread should be prevented through use of flame-retardant coating materials and / or fire-resistant strips of material.

Structural and environmental aspects

- The tilt of the barrier should be kept between 10° and 20° from vertical.
- A T-top poses additional structural requirements.
- The middle section, zone D, is the most interesting area to determine structural aspects of a WTB barrier.
- Steel frame components should be protected from corrosion with a coating, which can also facilitate aesthetics.
- Continuous slits at the bottom of the barrier are better for the durability of the panels, since they will not be in contact with soil.

(Dis)assembly processes

- Preparations for assembly are an essential part of a smooth assembly process.
- Process steps are: foundations – frames – pre-fab filling production – placing pre-fab filling on frames – adding vegetation, safety signage, etc.
- Disassembly processes have to be facilitated for in the design.

Maintenance

- Maintenance should be facilitated to extend noise barrier lifetime.
- Anti-graffiti coating can be used to prevent visual pollution of the barrier.
- Replacement / repair of parts should be facilitated in the construction.
- Vegetation should be kept within limits by regular maintenance.

Existing barriers

- IPE-frames with cassettes can be advantageous for modularity, making them easy to (dis)assemble.
- There is a tolerance needed in the length direction.
- Tilted barriers show to make use of triangular frames.
- Turns in the road and thus in the barrier can be enabled through using adapted frame parts, or allowing for a tolerance in the mounting structure.
- A white background is prone to get visually polluted by algae. Graffiti is also clear on this background.

Vision and Requirements

Chapter 4

This chapter will start with an overview of the previous two chapters in the form of a context map. Summarized findings from this context map will provide input for the design vision, which will be covered in the subsequent section. The design vision will formulate the focus of the designing phase, which translates to a set of focus requirements and criteria, as discussed in section 4.3.

4.1 Context map

The context map in Figure 28 summarizes the findings of chapter 2 and 3 along the life cycles of the WTB material, providing an overview of the project. The noise barrier context and WTB material lifecycle steps come together at the segmentation process, where the green box starts and encompasses the design space of this project. The most important findings are summarized per design aspect of a noise barrier, and per lifecycle step of the WTB material.

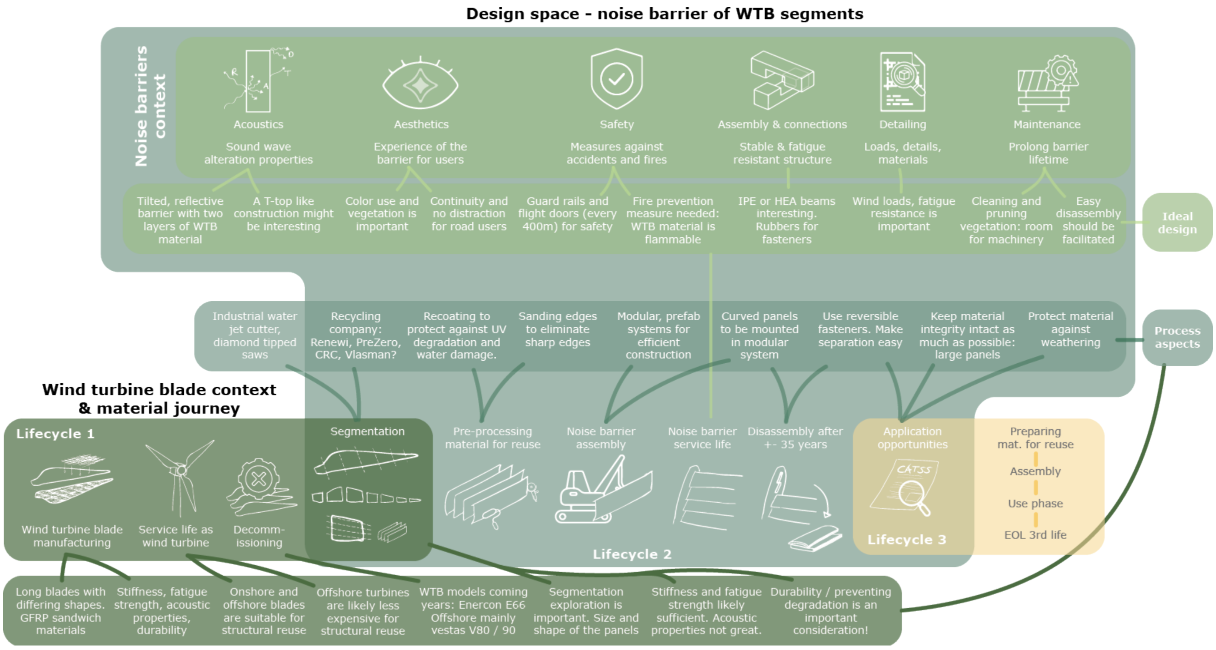


Figure 28: Context map of the project, showing both the noise barrier and WTB material contexts, and the following design space. Findings from chapters 2 and 3 are shortly summarized in the post its.

These separate findings are integrated into summarized findings: ideal design outcomes and process aspects. Criteria used to select the most relevant findings here are as follows:

- For the ideal design outcomes, the amount of influence of a finding on the embodiment of the design or on its acoustic performance are criteria, e.g. that a tilt is integrated, or a double layer of the material is needed.

- For process aspects, the influence of a finding on development of an efficient and scalable preparation process is a criteria. For example, segmentation patterns and a smooth assembly process is expected to be the most influential, while sanding is less important.

The summarized findings in turn provide the basis for design questions or ideation starters (in Table 5), in which aspects (from the context map) omitted in the summarized findings do return. The ideation starters either represent a design goal or knowledge gap that needs to be aimed for or answered in the design process. They can be used in how to's, brainstorming and sketching sessions to generate ideas. Although ideation has been done during the research phase, this marks the transition into the second diamond as depicted in section 1.3; the developing phase, which is focussed on generating ideas and concepts.

Table 5: Ideal design statements, process aspects and important findings from the summarized findings of the context map.

	Summarized findings	*Ideation starters*		
Ideal design	Dispersive / reflective barrier (tilted) that is double-walled and incorporates a T-top-like structure.	How to make double walls from curved material?	How to use shape for a top that bends towards the road?	How to make the tilted barrier structurally stable?
	It incorporates vegetation and correct colour use to provide a good experience on both sides. Safety concerns can be integrated into the standard module of the design.	How to incorporate vegetation?	How to include aesthetic features?	How to integrate safety doors?
	The assembly and connections are structurally solid, prevent fatigue damage in fasteners, and can be easily (dis)assembled and maintained through reversible connections.	How to use existing, reversible, non-invasive fasteners?	How to align curved material to prevent gaps and allow assembly?	
Process aspects	Outline an efficient process to segment a variety of blades into standard-sized panels with appropriate protection, sanding, etc., for good durability.	What is needed to execute the post-processing efficiently?	Which partners are interesting for this process?	How to make a modular / prefab structure for a barrier?
	A parametric model to inform segmenting patterns on variable blades should be developed.	What are the assembly steps?	How to combine variable shapes with modularity?	

4.2 Design vision

The assignment of this project is to explore the feasibility of a noise barrier made of WTB material in horizontal arrangement. The motivation for this is to find more circular ways to deal with the EOL material stream of WTBs. Kirchherr et al. (2023) conceptualized circularity by defining its core principles, aims and enablers. In this project, the circular principle is structural reuse through resizing (Joustra et al., 2021b), of which the aim is sustainable design, and for which the enabler is to make sure that the reused material remains at a high value during its lifetime. As covered in section 2.4, this is aimed for by **preserving WTB material integrity** as much as possible through finding a balance between retrieving (for a noise barrier-) suitable but as large as possible pieces. It is also aimed for by reducing the amount of exposed core material after cutting, to prevent water damage and UV degradation. Essentially, those two aims can be grouped under **durability** (as defined in section 2.3.2). Another goal of these is to maintain **opportunities for subsequent material lifecycles.**

From previous chapters it becomes clear that **scalability** of reuse applications is important to make a more significant impact. This can be achieved by making use of modular design, enabling interchangeability and adaptability of noise barrier modules. Rijkswaterstaat et al. (2023) define modular as "A system for a noise barrier that consists of detachable elements with certain design aspects that enable replacement *of varying noise barriers*". Since most noise barriers make use of straight panels, this is less of a challenge. In the case of WTB material, this does become challenging, so to allow for a broader design space, the 'of varying noise barriers' part of the definition is not taken into account. A focus on exploring **modular** design options that enable detachment and replacement is thus important.

Thirdly, harmony of a barrier in its surroundings is an important step in achieving **acceptance** under residents. Finally, technical **feasibility** is an important aspect since exploring that is the end goal of the project. Because feasibility is a broad term, there are no requirements related directly to it, however it is aimed for through analysing the lifecycle steps of making a noise barrier from WTB material. Details that make assembly and realization of a barrier technically plausible, e.g. how fasteners are designed and implemented, will thus be a focus point. Combined, these aspects form the vision statement (Figure 29):

To design a feasible sound barrier that effectively attenuates noise and incorporates variable, horizontal decommissioned wind turbine blade material in adaptable and interchangeable modules. The barrier harmonizes with its surroundings through continuity, creating value for and acceptance by residents. Preserving material integrity over its lifetime stand central in this process, aiming to maintain opportunities for subsequent material lifecycles.

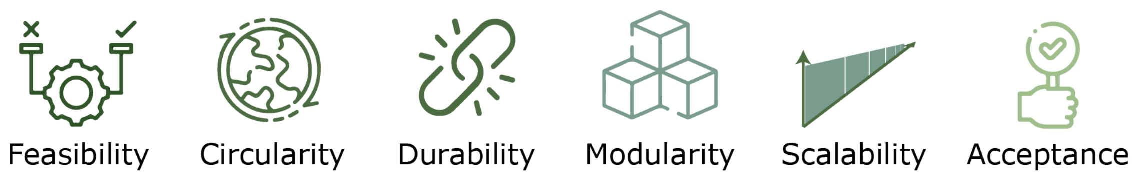


Figure 29: Vision statement icons.

4.3 List of Requirements

The findings and takeaways of both chapter 2 and 3 provide great input for a comprehensive list of requirements and criteria for a noise barrier made of WTB material. The full list of requirements also includes personal criteria of the designer, and incorporates criteria that follow from circular product design methods. It can be found in Appendix D.

The design vision provides additional scope to the rest of the process through the focus on durability, modularity and acceptance. Based on these aspects, the requirements and criteria list can be shortened to a list of focus requirements (Table 6) and list of focus criteria (Table 7). There is a difference between the two, as requirements pose (theoretical) statements that all concepts eventually need to adhere to, while criteria pose statements that are not measurable or testable, but can differ between the concepts. These will thus be used to base choices on and identify trade-offs.

Table 6: Focus requirements

Vision	*Requirement*	*Key aspects*
Durability	The lifetime of the compartment filling of the noise barrier needs to be at least 30 years, and that of the frames and foundations at least 50 years.	Lifetime, structural stability
	The noise barrier design needs to allow for manual and mechanical dis- and re-assembly.	(Dis)assembly
	The design of the noise barrier needs to allow for at least 1 subsequent lifecycle of the WTB material.	Third lifecycle
	The fasteners need to withstand 100 million load cycles of differing wind loads, as defined in the ROK.	Fatigue
Modularity	The noise barrier makes use of replaceable or exchangeable sub-assemblies: can be interchanged (e.g. when damaged).	Interchangeability and maintenance
	The noise barrier design needs to be adaptable to safety needs such as emergency exits or flight routes.	Safety features / adaptability

Table 7: Focus criteria

Vision	*Criteria*	*Key aspects*
Durability	The noise barrier design should prevent material degradation during use, of the WTB panels as well as frames.	Material integrity, expected lifetime
	Use connections / fasteners that can be accessed, opened and reused where appropriate.	Reversible fasteners
	The prospect of using more material of a WTB in the concept should be sought after, to enlarge blade material reusage.	Blade material usage
	Maintenance operations should be facilitated to prevent material degradation.	Ease of maintenance

Modularity	The noise barrier should be adaptable in height to adhere to local requirements that can change over time (such as new buildings behind it).	Adaptable design
	Combine multiple components and functions into one part, that is accessible, removable and interchangeable, to simplify repair.	Interchangeable design
	The assembly of the noise barrier can be carried out within a normal timeframe.	Assembly time
	The space usage of the barrier in its width direction should be kept low to make it applicable in more locations.	Space usage, width
Feasibility	The frame structure's weight should be kept low to reduce costs.	Weight
	The array of fastening possibilities for WTB material should be kept large to enlarge feasibility.	Possibilities for fastening
Acceptance	The noise barrier adds value to the environment in which it is placed (residents, natural environment).	Aesthetics, vegetation, value
	The noise barrier design should harmonize with its surroundings through correct use of aesthetic features	Harmony, continuity

Ideation

Chapter 5

This chapter covers ideation steps, methods and criteria for certain sub-solutions. Section 5.1 discusses the brainstorming method 'How to' and outlines resulting ideas, that are also sketched. A morphological chart in section 5.2 provides overview of promising ideas per sub-function, which is also used to combine ideas into starting points for concepts. These are further developed in subsequent chapters.

5.1 Brainstorming and sketching

Section 5.1.1 outlines a function analysis of a noise barrier made of WTBs, which is informed by a process tree, based on findings from chapters 2 and 3. The identified sub-functions (as well as the ideation starters from section 4.1) pose as starting points for 'How to's'. 'How to' is a brainstorming method aimed at discovering ways to solve problems without judgement. Sections 5.1.2 to 5.1.7 each cover a How to (listed in section 5.1.1), of which the ideas are shortly explained and supported by sketches. Criteria related to those ideas are discussed. Some How to's (5.1.4 and 5.1.6) were done together with peers at IDE to expand the exploration space.

5.1.1 Function analysis

Figure 30 outlines the results of use of the process tree method, and subsequently the function analysis. The process tree divides the lifecycle into the originate, distribute, use and end-of-life phases, and provides inspiration for relevant processes based on an example in the Delft Design Guide (Van Boeijen et al., 2013). In the originate phase, research and design stand central, and the processes related to assembly are covered. Assembly should be facilitated by some features in the design, such as it consisting of prefab modules. Consequently, 'Facilitate easy (dis)assembly' is one of the sub-functions. The distribute phase is not applicable to noise barriers as this mainly concerns selling channels related to store products. The use phase processes provide most input for functions that the noise barrier should fulfil, such as that residents 'enjoy less noise', translating to sub-functions like 'reflect sound waves' and 'absorb sound waves'.

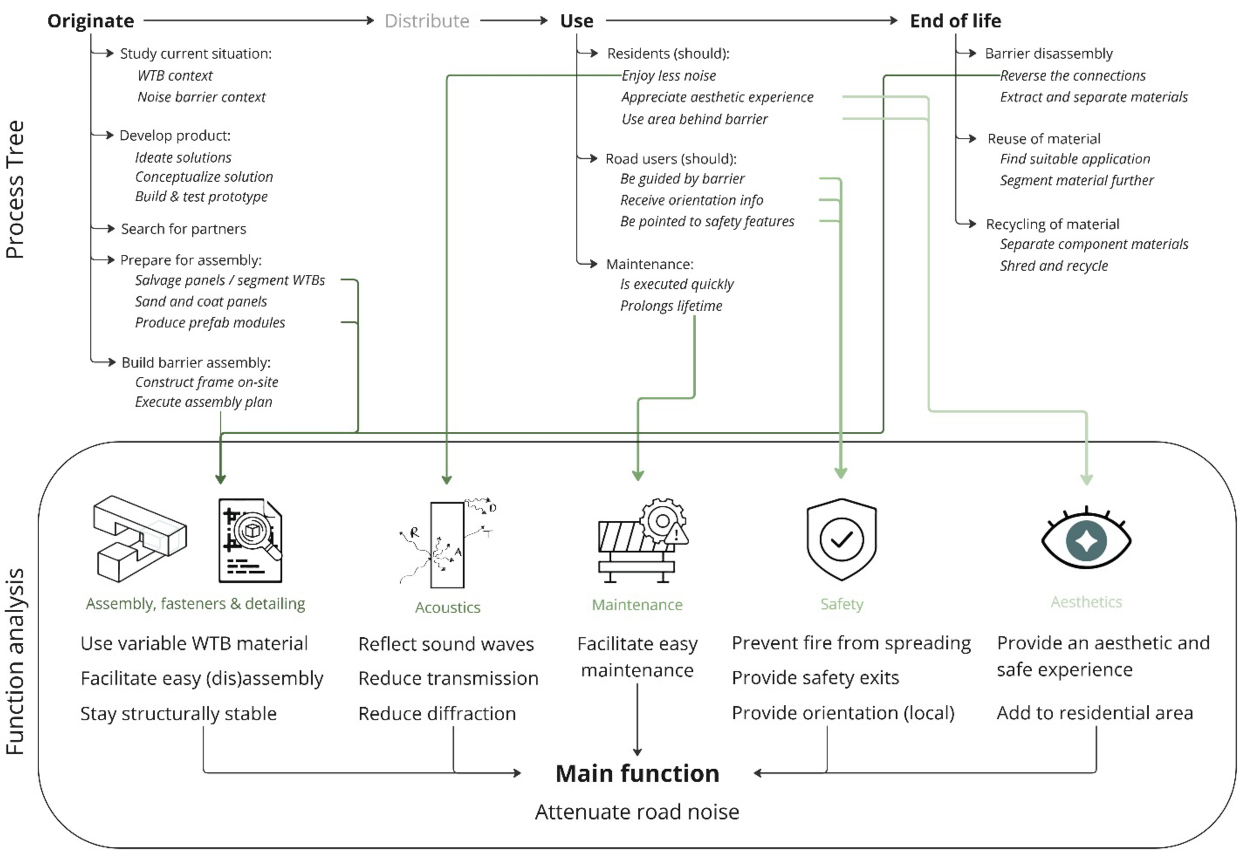


Figure 30: The process tree outlines important processes during the whole lifecycle, which informs the functions the barrier should fulfil to reach its main function.

The How to's listed below follow from sub-functions in Figure 30, supported by ideation starters from section 4.1. Reduce transmission and reduce diffraction were selected for their importance in making the barrier functional, and their large influence on the shape of the design (through which Use variable WTB material is also tackled). Reflect sound waves is not chosen as the material does this inherently. The third and fourth sub-function combinations are the ones left for the Assembly, fasteners & detailing and Aesthetics aspects respectively.

Sub-functions for which no specific How to's were done, related to Maintenance and Safety, can be fulfilled in various ways that do not require thorough ideation as there are established solutions for these already and have no direct effect on how WTB material can be used for a noise barrier design. They do pose criteria.

1. Reduce transmission & Use variable WTB material:
   5.1.2: How to make double walls from curved material;
   5.1.2: How to neatly align curved panels to prevent gaps and allow assembly.
2. Reduce diffraction & Use variable WTB material:
   5.1.3: How to use shape to make a top that bends towards the road.
3. Facilitate easy (dis)assembly & Stay structurally stable:
   5.1.4: How to create reversible, non-invasive connections / fasteners;
   5.1.5: How to make the tilted barrier structurally stable.
4. Add to residential area & Provide an aesthetic and safe experience:
   5.1.6: How to incorporate vegetation and aesthetic features.

5.1.2 Reduce transmission

Double walls

Figure 31 shows ideas for making a double wall of WTB material (section 2.3.3). Full **segments** (of e.g. 6m long) provide a simple solution as they already consist of two walls and can reach the height of an average noise barrier when rotated upright (Figure 32). Further segmentation into panels or half segments allow for a broader domain of double walled options, as panels can be placed together more tightly:

- Using the **equivalent panels of two blades**, enabling closely spaced (large) panels due to matching curvature, without the presence of alignment seams;
- Adopting a **cladded system** to overlap panels, where alignment seams of the first row are shifted in height from the alignment seams of the second row;
- Using a **combination of standardized panel sizes**, which can make use of a large part of the retrieved WTBs because of the variable sizes;
- Making slits to allow for **intertwined panels**, that can be self-supporting.

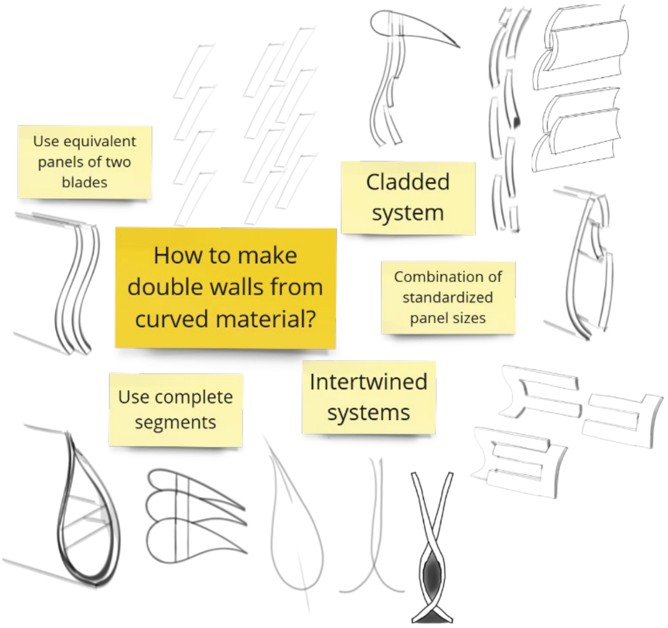


Figure 31: How to make double walls from curved material, with ideas.

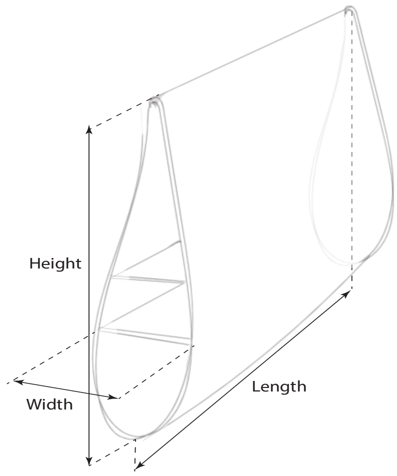


Figure 32: Length, width and height of segments as defined in this report.

In Figure 33, promising ideas (intertwined systems were excluded as it was deemed too complex) from Figure 31 are evaluated in a Harris profile on relevant criteria from section 4.3, in order of importance. Shortly summarized, the equivalent panels and segments ideas score well on *noise attenuation* because they contain less alignment seams than the other ideas. In terms of *blade material usage*, the equivalent panels scores low because this option works best if only large panels are used, while the other ideas score well: they can use a larger portion of the blade. The segments idea scores worst on *space usage* due to the width of some segments, reducing modularity of the barrier in comparison to the other ideas, where panels can be placed together more tightly. Finally, *material integrity* is kept highest when segments are used (less pre-processing) and lowest when smaller (cladded) panels of e.g. 1 m high are used. Elaboration for the ratings can be found in Appendix E. The evaluation provides a basis for choices in section 5.3 and 7.1.1: none of the ideas are discarded or chosen here.

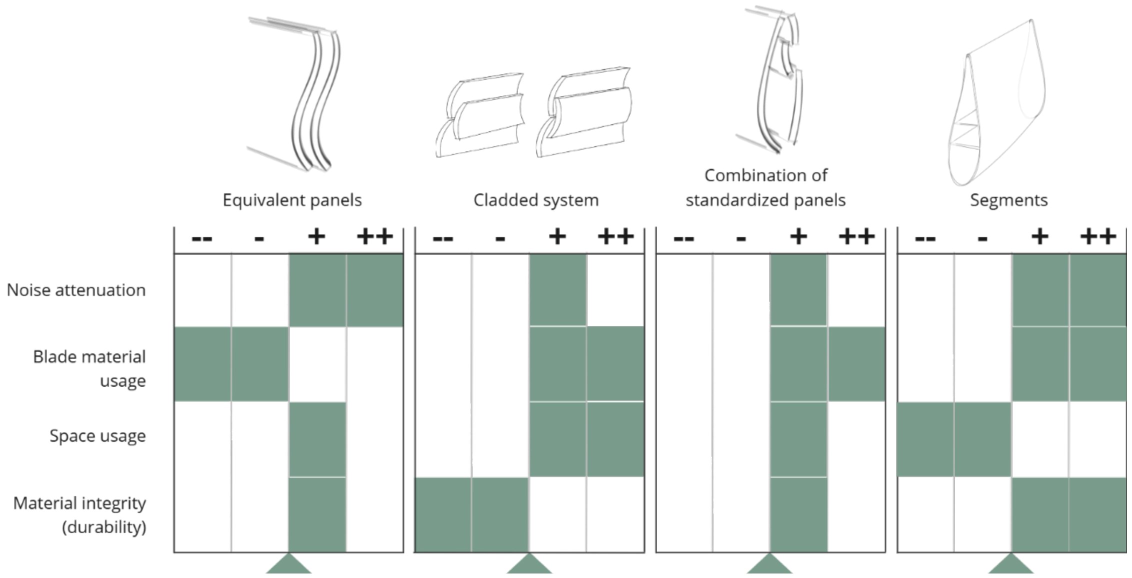


Figure 33: Harris profile with relevant criteria ratings for three panel-based ideas for double walls.

Panel alignment

Gaps and openings are in principle not allowed in noise barriers, since their performance will reduce. Reaching this with variably curved panels is a challenge. Figure 34 shows ideas to tackle alignment issues. Ideas include:

- **Cladded systems** that mis-align their horizontal seams. This can be done in two columns, or even three;
- Making **panels small**, so that deflections due to curvature are limited, making combining somewhat easier;
- **Foam- or rubber profiles** that fill these gaps and allow for some tolerance, such as compriband, which is a foam-tape that can be pasted on alignment faces. Similarly, **3D printable filling materials** can work.
- Avoiding alignment seams in the front panels by **alternating panel orientation** to match convexly and concavely curvature or using large continuous panels.

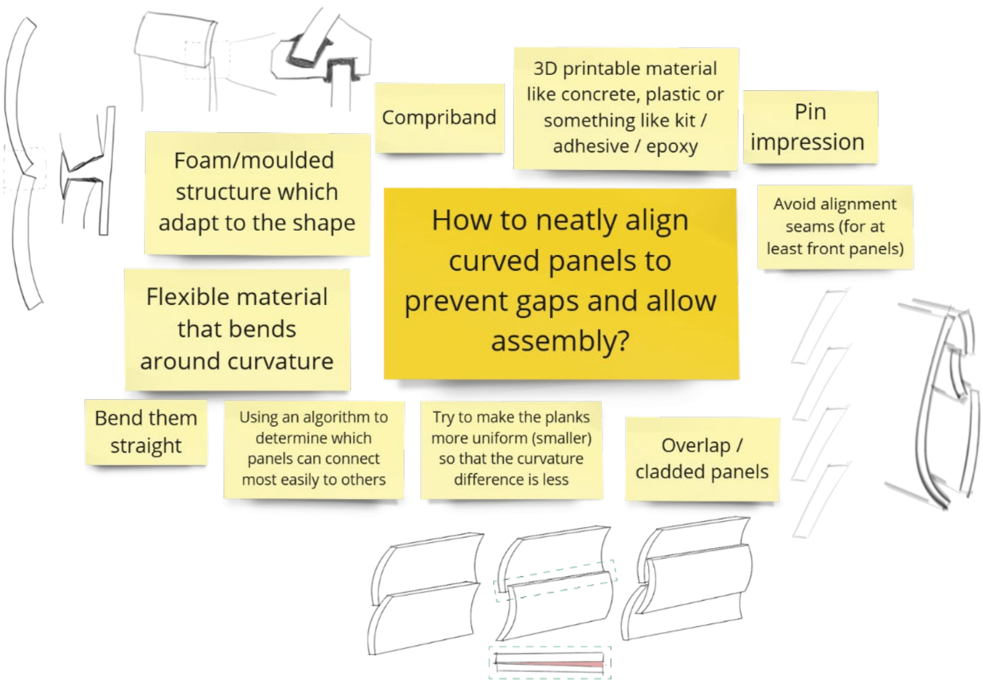


Figure 34: How to neatly align curved panels to prevent gaps and allow assembly, with ideas.

Preferably, adding materials is prevented, especially if they form separation issues at EOL of the barrier, such as 3D printable filler materials. Tape-based foams or rubber profiles that are clamps are then already better, but still add materials. The issue of alignment should preferably be tackled by avoiding these seams altogether.

5.1.3 Reduce diffraction

Figure 35 shows possibilities for using the curvature of the WTB shape for a T-top, or top that bends towards the road (reflection section in 3.2.1). Ideas include using the structure of the **shear web and spar cap beam** to form a T-top structure, which can be extended to using **full (small) segments** that cover more width and have a somewhat rounded front edge, which should be advantageous to reduce diffraction. Another idea is to use the curvature of WTB panels with their **convex side towards the road** to form an L-top.
While these types of tops bring additional or stricter *structural requirements*, they can

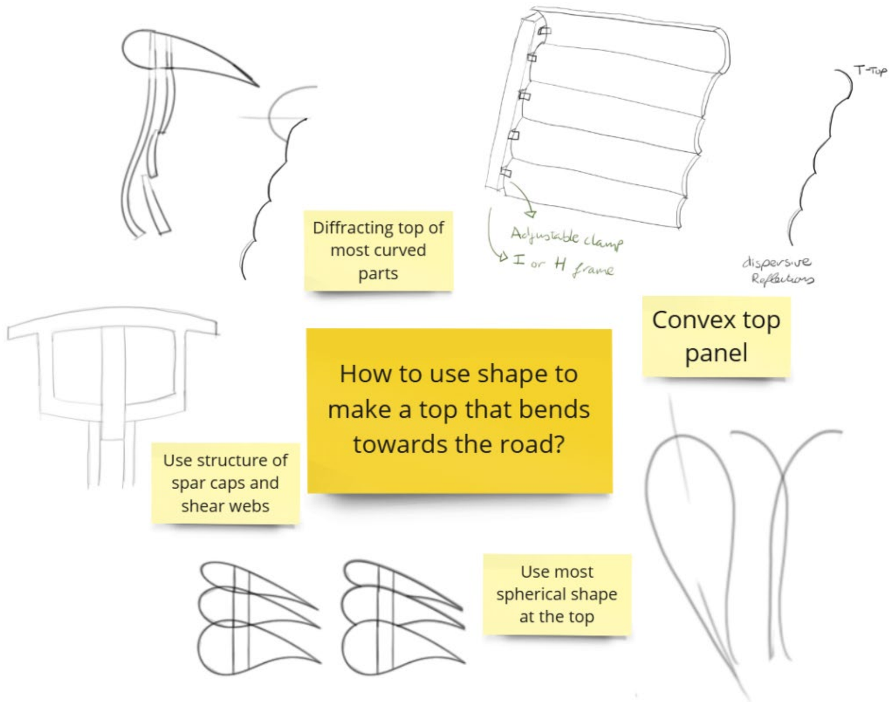


Figure 35: How to use shape to make a top that bends towards the road, with ideas.

potentially make it possible to reduce the height of the barrier in certain locations. Important aspects to consider for T-tops are their *weight, width,* and *possibilities for fastening*.

The shear web and spar cap beam can be very heavy and wide, but does look to have sufficient and easy ways to mount, as the shear webs are straight along the length of the blade. This is also the case for the full (small) segment option. Convex L-top panels are presumably a lot less heavy, and should also be mountable to a frames structure. However, they still have a sharp edge which will be less effective than a rounded edge at attenuating diffraction (M. Tenpierik, personal communication, November 26, 2024). Both options seem to be applicable, where the convex top panel looks easier to implement, but less effective than the full (small) segment top.

5.1.4 Facilitate easy (dis)assembly

As determined in chapter 2, reversible, non-invasive and (thickness) adjustable fasteners should be used. Figure 36 shows ideated options, including **wired buttons** on the corners of panels (with wiring tightened between frames and the buttons) and **hanging systems** to hang panels onto. Inspiration from the examples shown in section 3.3.3 can be taken to imagine **adjustable rubber clamps**, which can be tightened by a bolt, and the rubber U-profile in between it can form towards the thickness of the panel and ensure a firm grip. Similar ideas include:

- Tightening a panel in place that slides into frame part or cassette (**form fit**).
- A **double clamp** with rubber, that automatically spaces two panels with e.g. an equivalent curvature profile;
- A rubber clamp that connects two partly overlapping panels at their top and bottom edge corners (**form fits with rubber**).

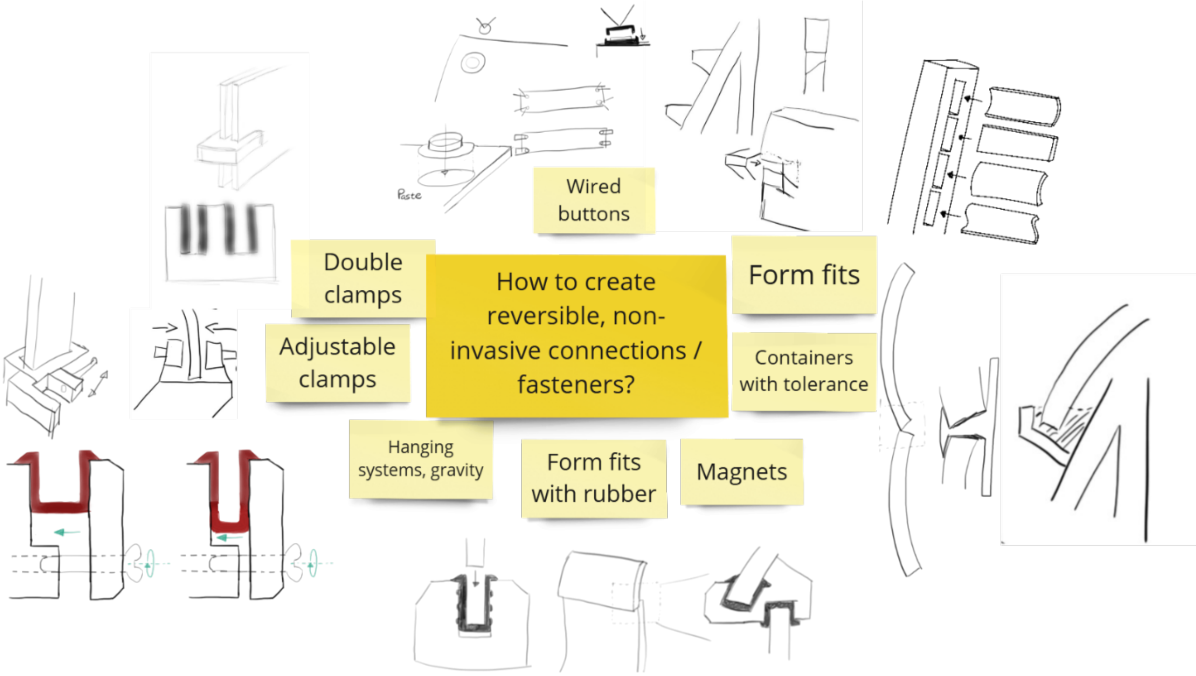


Figure 36: How to create reversible, non-invasive connections / fasteners, with ideas.

Besides above named requirements, criteria for fasteners include their *load carrying performance* and *fatigue resistance* (see section 4.3). The wired buttons idea is somewhat out-of-the-box, and hard to evaluate on these aspects, while most of the ideas that include rubber would score well on *fatigue resistance*. Rubbers can deal with load cycles very well (E. Nouwen, personal communication, October 22 2024). Hanging systems (e.g. a hook) make use of gravity to keep themselves in place, which leaves some small tolerance to move. That is another way to counter fatigue damage. In regards to *load carrying performance,* many of these ideas can be embodied / designed to carry the expected wind loads. The clamps and hooks can be made with thicker or stronger steel if required.

5.1.5 Stay structurally stable

To find fitting frame structures that could work with WTB segments or panels, inspiration was taken from existing (tilted) noise barriers as discussed in chapter 3 (see Figure 37). For example, the tilted noise barrier from the site visit in section 3.3.1 provides inspiration for **triangular frames**. These could be made with hollow beams, or IPE / HEA beams (H-shaped beams that distinguish from each other by the ratio between flange width and length of the centre profile)(Fortuin et al., 1993), which are often used steel frame structures for noise barriers (J. Grevelink, personal communication, 11 November 2024). There are also examples of noise barriers that make use of **tilted IPE / HEA beams** without a supporting vertical beam. Additional ideas include **concrete beams** at the back of panels or that intertwine the panels, as well as using supporting (**space frame**) structures at the back and using the **shear webs** for frame material.

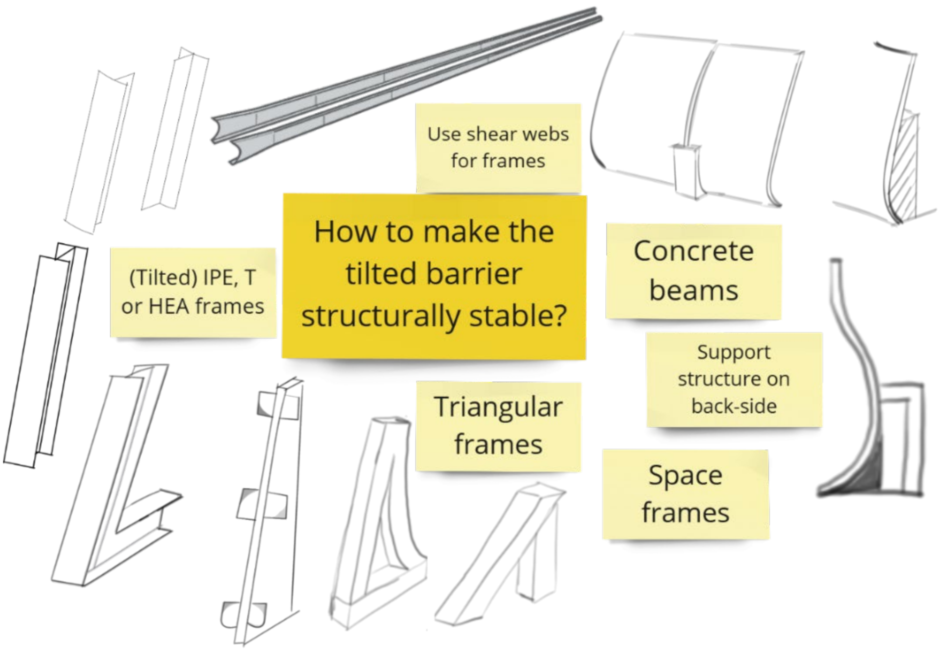


Figure 37: How to make the tilted barrier structurally stable, with ideas.

Frames are required to provide *structural stability* over the barriers whole lifetime. The criteria for frames focus on expected lifetime (*durability*), *weight* and *possibilities for fastening / mounting* (relating to *modularity*). Mainly the latter two criteria were taken into consideration during ideation.

Tilted IPE beams score well on weight, as they are lighter than HEA beams and hollow triangular frames of similar dimensions and profile (Fortuin et al., 1993). Concrete beams of similar dimensions are likely also heavier. Space frames could prove to be light, but they are often complex. The shear webs are expectedly the lightest option.

The options including an IPE or HEA – type profile provide a similar amount of freedom to mount panels, because they have an equivalent amount of flanges to fasten other components to. Concrete beams, space frames and shear webs are deemed to provide less *possibilities for fastening*.

5.1.6 Add to residential area

To add value to the noise barrier for residents, vegetation and aesthetics are important (see section 3.2.2). Figure 38 shows options to incorporate vegetation, including:

- Filling a double-walled section (in between panels, or bottom of segment) with **soil**, which absorbs sound and provides ground for vegetation.
- Providing a structure, like a **fence or grid**, for climbing plants. These could be placed on panels or in between panel rows.
- Using the **area behind the barrier** for vegetation or e.g. a bench.

Other aesthetics options include:

- Using **colour gradients** to reduce the oppressive feeling of the barrier;
- Considering panel orientation and combinations;
- **Preventing graffiti** through anti-graffiti coatings or deliberately making art.

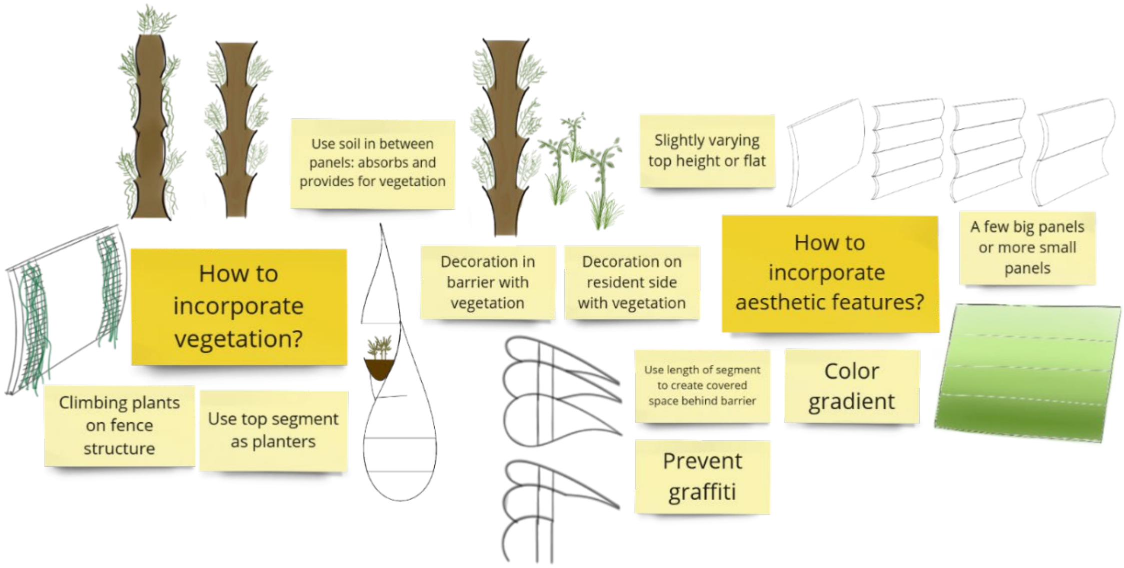


Figure 38: How to incorporate vegetation and aesthetic features, with ideas.

Important criteria for vegetation are the *durability* of panels and e*ase of maintenance*. The vegetation should not damage the material over time, and moist soil should not corrode the outsides of the panels. A fence or wire structure for climbing plants is thus likely better for *durability*. Plants growing from soil in a (integrated) plater box does seem to be easier to maintain than climbing plants, however. Climbing plants can cling onto material, which complicates disassembly.

The other aesthetics options, can sometimes be simultaneously used. Aspects here include *continuity* and *orientation*, and *harmony in surroundings* are important (section 3.2.2). A colour gradient can be used to reduce the oppressive feeling of the barrier in dense locations. The panels should be painted then, however, which adds costs and might not always be needed. Using paint can however also help to orient road users, for example by the use of art that can be associated with a specific location or a changing colour palette in certain locations. The curvature and amount of alignment seams at the front should also be considered. Horizontally aligned seams help to reduce the oppressive feeling of a barrier for road users, so a multiple of panels might help in that case.

5.2 Morphological chart

To combine the ideas presented in the previous section into one or a few concept(s), a morphological chart is useful (Figure 39). A morphological chart also creates overview and is a first selection step of the ideas that are deemed to be promising. The chart consequently outlines promising ideas from the How to's, for sub-functions from the function analysis. Some sub-functions fulfil the same goal or process, leading to presented sub-solutions that could substitute each other. There are also solutions for the same sub-function that can be combined (within one row).

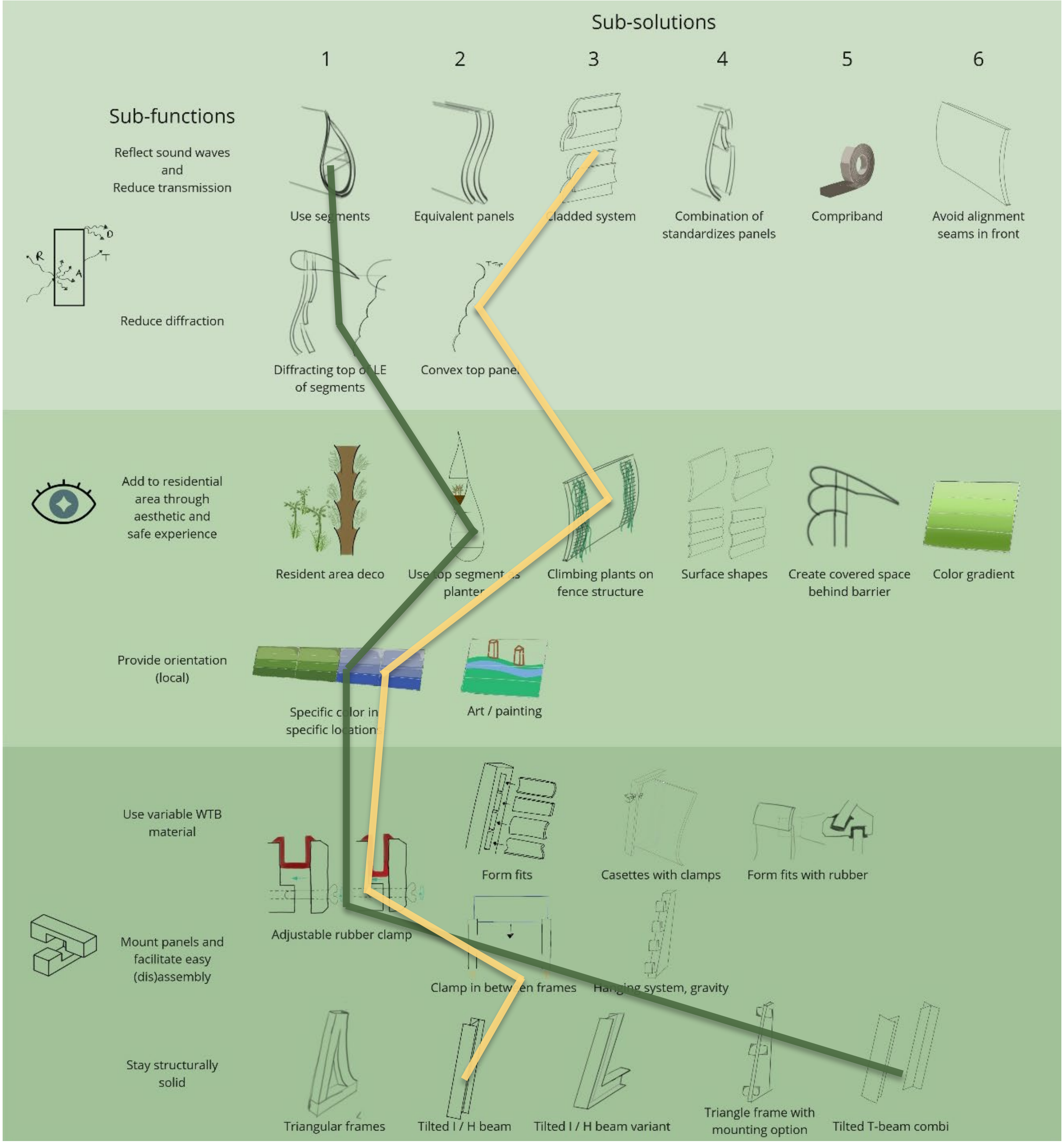


Figure 39: Morphological chart with ideas from how to's. The green and yellow lines indicate two combinations of sub-solutions. By integrating the sub-solutions that the lines cover, a combined idea can be made that should incorporate all sub-functions of a noise barrier.

5.3 Combined ideas

Two combination lines are chosen, based on the overarching aims for *durability* (green) and *modularity* (yellow) from the focus criteria (section 4.3). Figure 40a shows the green line combination in the morphological chart, with *durability* as the core aim:

- *Preventing material degradation* (or keeping *material integrity)* by minimizing resizing pre-processing activities, leading to a choice for segments to reduce transmission. Rounded edge parts of segments might be used for a T-top addition.
- Having good *blade material usage*. The whole blade can be divided into segments. Smaller segments may be stacked, this options should be explored.
- Using reversible fasteners (such as an adjustable rubber clamp) to *facilitate disassembly*, allowing for more lifecycles and longer functional lifetime.
- Facilitating maintenance or *interchanging* of barrier sections when they are damaged, by choosing for tilted IPE- or T-beams. Segments can be slid into these from the top.

Furthermore, stacked smaller segments can incorporate soil and vegetation on the resident side. Colours may be used to provide orientation to road users.

Figure 40b shows the yellow line combination, chosen with *modularity* as the core aim:

- *Space usage* is aimed to be low, resulting in a choice for a cladded system which scored best on this aspect (see Figure 33 in section 5.1.2) because the width of a resulting barrier is low as compared to other ideas.
- *Adaptability* in height (also over time): using standard sized 1 m high panels allows for easy down- or upscaling of such a barrier design.
- *Interchangeability and facilitating (dis)assembly* are aimed for by using a IPE-beams as frames, in which the panels can easily be slid into place. Reversible adjustable clamp facilitate this as well.

Furthermore, a convex top panel can be incorporated to reduce diffraction. Vegetation can be added on a wire structure for climbing plants to grow on. Colour gradients are easy to incorporate with separate panels, to reduce the oppressive feeling of the barrier for road users. This colour might also change over the course of the length to facilitate orientation.

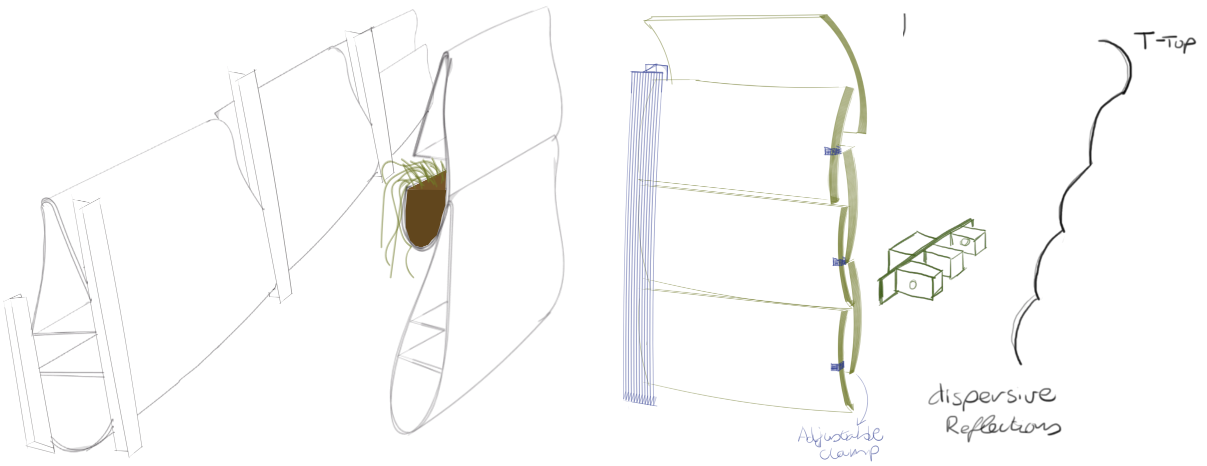


Figure 40: A) Combined idea focused on durability, B) Combined idea aimed at enhancing modularity.

These ideas will be developed further into concepts in the next chapter, to be able to evaluate them on the criteria from chapter 4. If required, other suitable options or adaptations based on solutions in the morphological chart can be used later.

5.4 Takeaways

- The sub-functions of a noise barrier made of WTB are determined by using the process tree and function analysis methods. In combination with ideation starters stemming from section 4.1, these functions were deemed important to ideate on with How to's: reduce transmission, reduce diffraction, facilitate easy (dis)assembly, stay structurally stable and add to residential area.
- Reducing transmission can be done using segments, equivalent panels, cladded systems or by combining standardized panel sizes into double walled constructions. Issues with alignment can be tackled by making panels small, using foam or rubber profiles or alternating panel orientations and overlap them.
- Reducing diffraction can be done by using a convexly oriented top panel or pointing LE parts of the WTB blade towards the road.
- Facilitating easy (dis)assembly can be done by using hanging systems, adjustable rubber clamps or form fits (with rubbers).
- Staying structurally stable can be achieved by using triangular frames, IPE / HEA frames, concrete beams or even shear webs.
- Adding value to the residential area can be done by using vegetation in soil or on a wire grid for climbing plants. The area behind the barrier is also important here. Colour gradients can be used for good expression, and graffiti should be prevented.
- Promising ideas in a morphological chart are combined into two concepts: one aiming for enhanced *durability,* using segments, and one aiming for *modularity*, using standardized panels.

Conceptualization

Chapter 6

This chapter presents the development of the combined ideas from section 5.3. Section 6.1 and 6.2 cover the concepts. In section 6.3, an evaluation method is used to test the two concepts on the focus criteria (section 4.3) using a Harris profile.

6.1 Segments concept

The segments concept (Figure 41) makes use of complete segments of 6 m in length, which is chosen because this is a frequently used length for noise barriers (M. van Amstel, personal communication, September 23 2024).

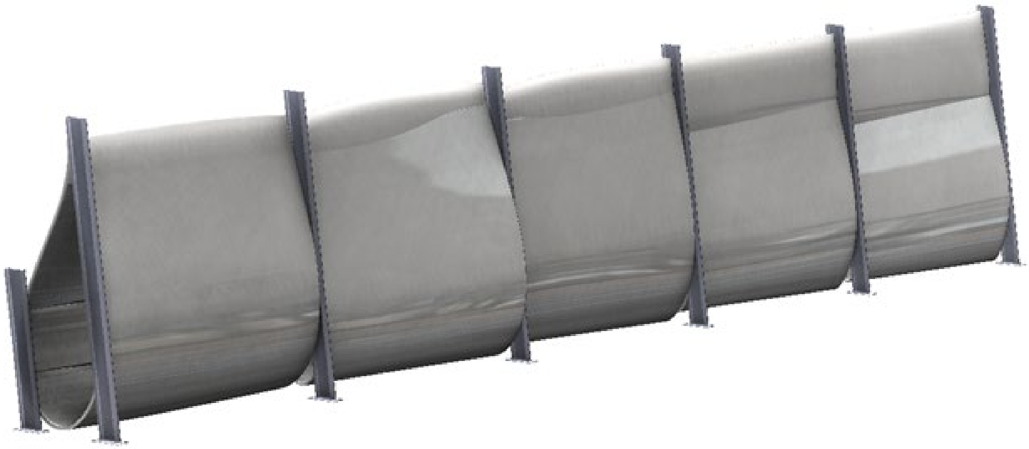


Figure 41: Segments concept with tilted, opposing T- or IPE-frames. The irregularities in all sections but the leftmost one come from stacking of segments which was needed to reach a common height.

The 6 m long segments are connected to opposing IPE- or T-frames by using an adaptable clamp design that slides over the frames from the top, and connects to the shear webs (Figure 42 and Figure 43).

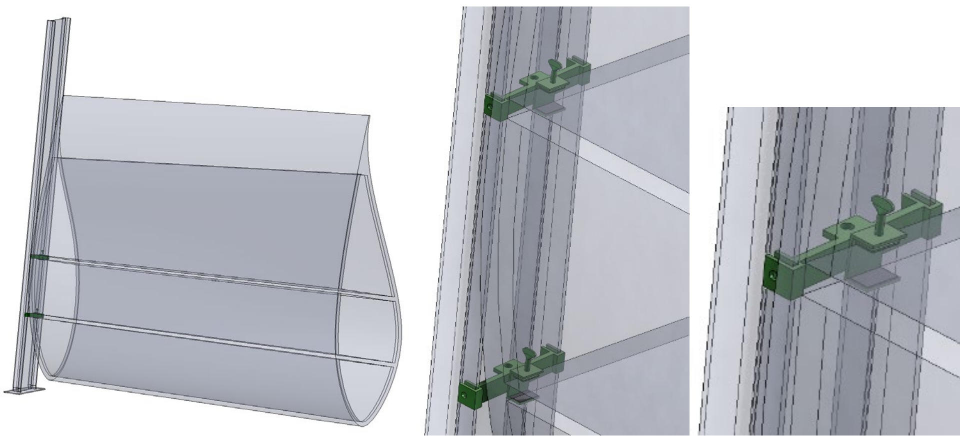


Figure 42: The segments can be connected via the shear webs to the frames with an adaptable clamp.

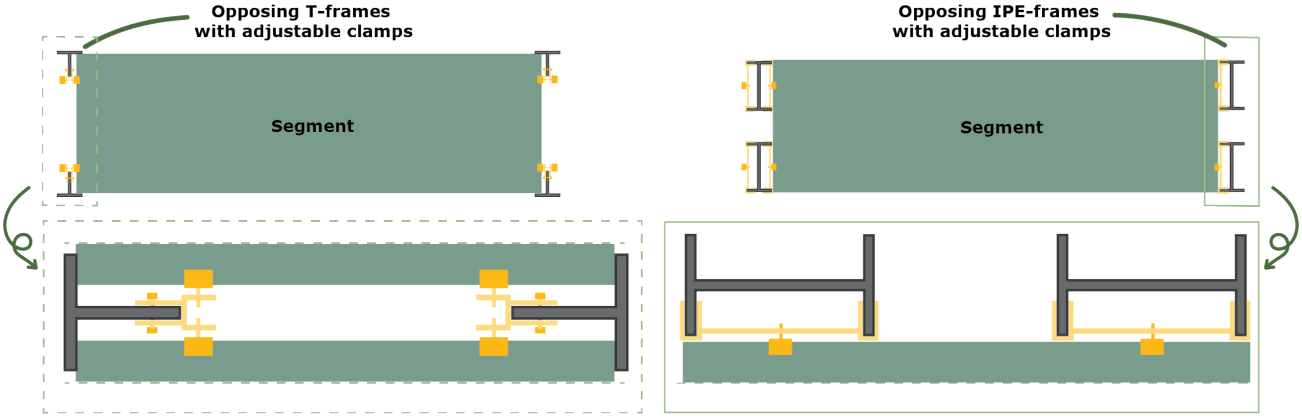


Figure 43: Top view of two options in the segments concept: T-frames (left) or IPE-frames (right). Lower images show possible clamps (yellow) that can slide over the opposing IPE- or T- frames and rotate.

The larger (and higher) segments can be used as single modules. Smaller segments can be stacked when their rotation is the same as the bottom segment (trailing edge pointing up), to reach the same height as the biggest segments (see Figure 44: opposite rotation complicates stacking). Additionally, using stacked segments makes it possible to incorporate soil and vegetation in the upper segments, since the material overlap (4 layers) allows for one side to be cut open.

To enable presentation to and discussion with others, a lo-fi prototype is made. 6 m segments of the NREL blade were 3D printed at 1:50 scale, as well as tilted IPE frames (not to scale for printing purposes). It can be seen how segments are slid in from the top, how smaller segments are stacked and align, and that wide segments do not fit, even in a frame with a larger scale(Figure 45).

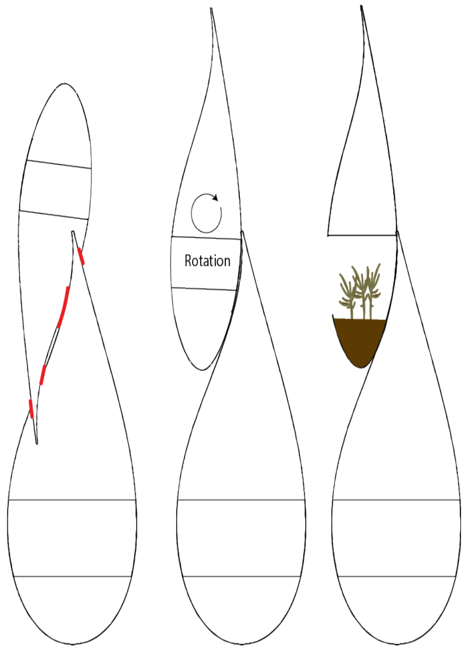


Figure 44: Rotation of the segments is easier when both segments are rotated with their TE facing up.

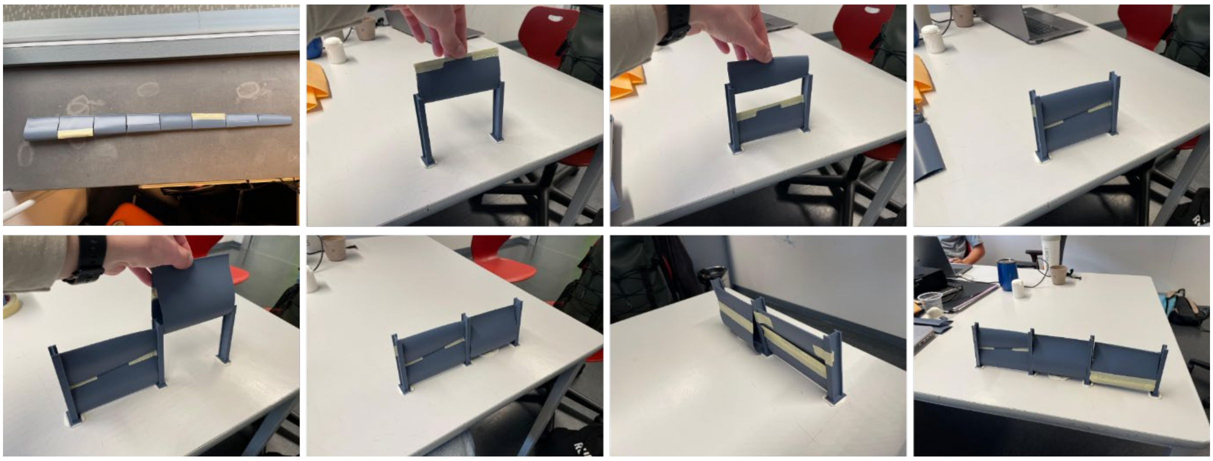


Figure 45: Photos of lo-fi prototyping of the segments concept. The segments are scale 1:50, and the IPE frames are not to scale to be able to print them.

6.2 Panels concept

The panels concept (Figure 46) makes use two columns of 6 m long by 1 m high panels with a maximum curvature *d/w* of 0.08 (see section 7.1). They are slid into tilted IPE-frames from the top and clamped on their sides to restrict movement.

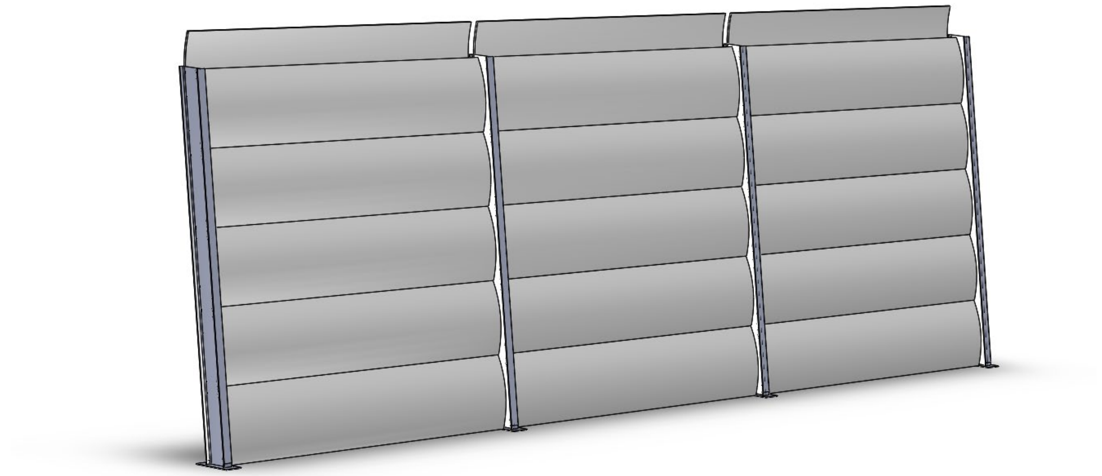


Figure 46: Isometric view of the panels concept.

By aligning the second column of panels so that their seam is at the middle of the height of the first row (Figure 47), transmission can be reduced. Either way, the alignment of panels within one column should be considered more closely. Because of the curvature, the cutting edges likely do not match, creating seams or gaps as shown in Figure 47. There are multiple options to improve this, e.g. by cladding the panels partly and using compriband at the alignment faces to seal any remaining gaps. If use of compriband can be avoided however, this is preferable as it adds processing steps and material use.

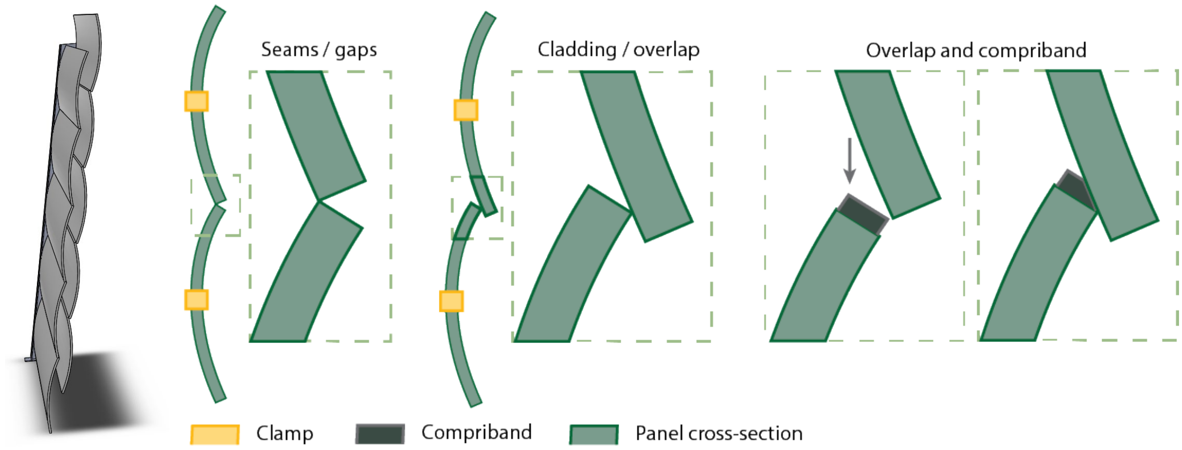


Figure 47: Two columns with their horizontal seams mis-aligned to reduce transmission, and a closer look at ways to reduce transmission by overlapping panel edges and using compriband.

To connect the panels to the frames, adjustable clamps can be connected to both sides of the panels in the middle. This way, the curvature of the panels will result in the least amount of deflection in the width direction. Clamping on the bottom or top will result in more deflection (Figure 48a), which is not preferred as this will result in a wider barrier. Additionally, the front surface area of the panels is optimized that way (for panels with a curvature maximum of $d/w < 0.08$, see chapter 7).

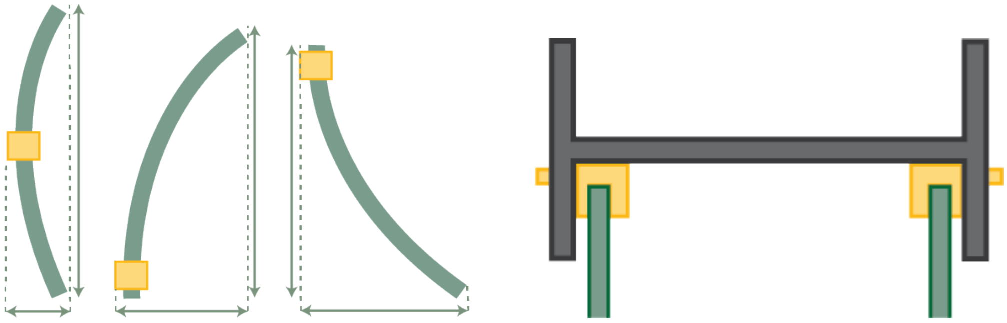


Figure 48: A) Clamping the panels at their middle height minimizes their deflection and maximizes the frontal area they cover, B) Top view of clamps in an IPE-frame, fastened on two columns of panels.

The panels, with clamps attached, are then slid into the IPE-frame from the top. The spacing of the frames (6 m) already restrict panel movement, and additionally the clamps are bolted into the flanges of the frame (Figure 48b). That also makes it possible to place them at the correct height, as panels should align closely but not rest on one another. The clamps need to carry the weight.

Adding soil for vegetation in the panel concept will help to reduce transmission, as the weight increase is significant and alignment gaps are sealed by it. This is complicated without the addition of other materials that can contain the soil, however. Soil in between the columns might be possible, but it likely reduces the panel durability, and vegetation should not grow between the panels as this will likely create gaps over time. A different panel orientation is then required, depicted in Figure 49a. An option that does not use soil are wire structures as depicted in Figure 49b, which enables climbing plants to grow.

Figure 49: Vegetation options for this concept. A) soil in between panel rows. B) wire structure with spacers.

To envision required cutting operations and enable presentation and discussion, a lo-fi prototype of this concept was made using a 3D printed WTB model at 1:50 scale, as well as the same IPE-frames as used in the segments concept (Figure 50 and Figure 51).

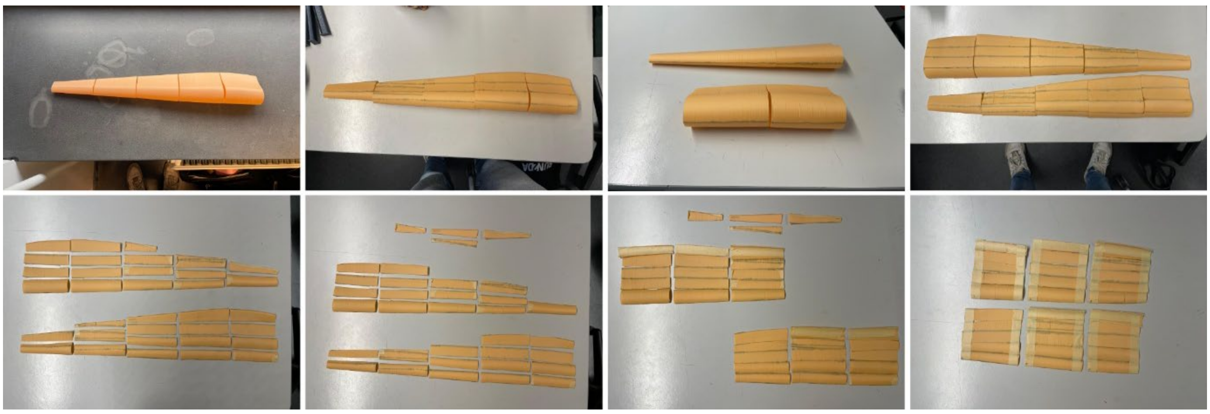


Figure 50: Sectioning steps taken to retrieve 6 m by 1 m panels at 1:50 scale: 1) cut along the length, 2) halves further sectioned into panels +- 1 m high, 3) filter triangular panels, 4) tape panels into columns, 5) top panels are oriented convexly to form a half T-top.

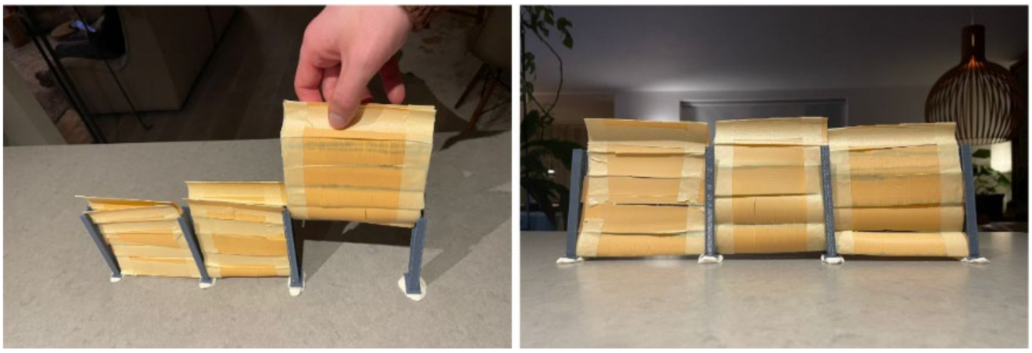


Figure 51: The lo-fi prototype of the panels segment, showing how columns can be slid in from the top.

6.3 Concept evaluation

In this section, the two presented concepts will be evaluated. Initially, a more specific evaluation of the *noise attenuation* of the concepts is covered, using their extrinsic assembly properties. Subsequently, the criteria from section 4.3 will be used to evaluate the concepts and come to concrete development steps, which are covered in Chapter 7.

Noise attenuation performance

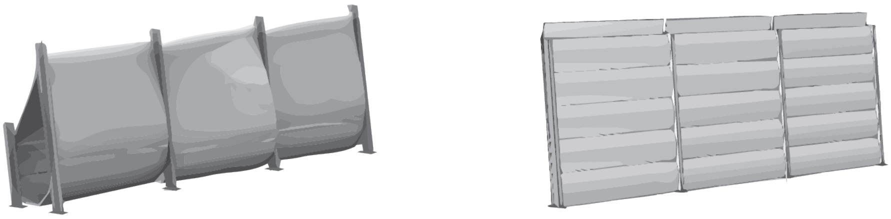
The acoustic principles discussed in section 3.2.1 are affected by the intrinsic properties of the material as well as the external properties of the assembly. The external properties (shape of cross-section and front surface, continuity of front surface) are expected to be more influential on the difference in acoustic performance of the concepts, as the intrinsic properties are similar. Table 8 summarizes how the concepts differ. The ratings are based on findings in literature and interviews with an acoustic expert from the TU Delft (M. Tenpierik), as well as employees of the Geluidsbeheersing team (M. van Amstel, J. Grevelink, W. Groenewoud, J. Peters). Reasoning to support the ratings can be found in Appendix F. The results of this sub-evaluation are also summarized in Figure 52, where the concept ratings for the other focus criteria are also incorporated.

Table 8: Summary of performance on noise attenuation principles of the segments and panels concepts. Ratings are between 1 (bad influence on noise attenuation) and 5 (good influence on noise attenuation).

Acoustic principle	*External internal*	*Property*	*Segments*	*Panels*
Reflection	External	Front surface shape	2	4
		Continuity of surface	5	1
Absorption	External	Continuity of surface	3	2
	Internal	Absorption coefficient	3	3
Transmission	External	Continuity of surface	5	1
	Internal	Weight	3	2
		Transmission Loss	3	3
Diffraction	External	Continuity of surface (presence of edges)	5	1
		Shape of top	2	1

Overall evaluation

Figure 52 summarizes the evaluations of the concepts per design criteria stemming from section 4.3. Appendix G covers the pros and cons more elaborately.



Criteria	Segments concept --	-	+	++	Explanation	Panels concept --	-	+	++	Explanation
Durability			■	■	Inherent double-wall construction enhances material integrity and longevity.		■			More sawing may reduce material strength and durability and thus requires more preprocessing.
Modularity	■	■			Difficult to standardize due to variability in height and width; low interchangeability.			■	■	Easy to standardize with fasteners and standard frames, offering high flexibility.
Noise attenuation			■	■	Continuous surface offers better noise attenuation performance than surfaces with seams.	■	■			Allows for noise-absorbing material to be added, but gaps or seams will reduce effectivity.
Required space	■	■			Wide segments take up more space and are less practical for certain locations.			■	■	Compact width makes it more space-efficient and versatile for different locations.
Aesthetics and vegetation			■		Subtle variation in shape offers a unique visual effect. Adding vegetation is possible in various ways.			■		Uniform / continuous and neat appearance. Adding vegetation is possible.
Safety		■			Segments' road side surfaces curve more, reducing safety.			■		More uniform and flat front surface is better for safety.
Weight		■			Heavier segments; fewer components but higher structural demands for fasteners.			■	■	Lighter individual parts, though overlaps can increase total material weight.
Assembly time			■		Fewer components result in faster assembly but require precise levelling and alignment.		■			Complex alignment of multiple panels leads to longer assembly time.

Figure 52: Harris profile with ratings / the pros and cons of the segments and panels concepts, based on criteria from section 4.3. The importance of the criteria is in order, from high at the top to low at the bottom. By seeing the tables as a block balancing on the triangle below, the better concept will tend to fall over to the right more quickly than the one with worse ratings.

Where the segments concept scores well, the panels concept scores worse, and vice versa, except for aesthetics. While the panels concept scores better on more criteria, it does not on two important ones: durability and noise attenuation. It is therefore important to find a combination of the good aspects of each concept, and consider trade-offs.

There is a trade-off between *durability, modularity* and *noise attenuation*. The results from Table 8 indicate that the segments concept is expected to offer more effective noise attenuation as compared to the panels concept, primarily because of the continuity of the front surface. **A continuous front surface** (facing the road side) should thus be aimed for, to minimize transmission through gaps of mis-aligning panels and reduce diffraction from sharp edges. However, segment width is excessive for *space usage* (*modularity*) and should be reduced. This can only be done by making additional cuts in the material (compromising *durability*), or opting to use only thin enough segments from the outboard or midspan. Since the latter bypasses use of valuable WTB material (*blade material usage*), cuts should be considered but minimized for *durability* purposes (section 2.4). This can be achieved by sawing segments in half (Figure 53). How this can be done according to curvature requirements is covered in section 8.1.

Notable however is that the reflection property set is a key factor, as WTB material is mainly reflective. This is the only property at which continuous front surfaces (such as those of the segments concept) score worse than the panels concept due to the concave bottom. The impact of these concave parts should thus be further analysed (section 7.1.2). Furthermore, both assemblies perform poorly at attenuating diffraction at the top. A rounded top facing the road will likely help to improve this (M. Tenpierik, personal communication, 26 September, 2024), **or a T-top assembly** (section 7.3). Alternatively, vegetation at the top of the barrier can help to diffuse diffracting sound (section 9.2).

6.4 Takeaways

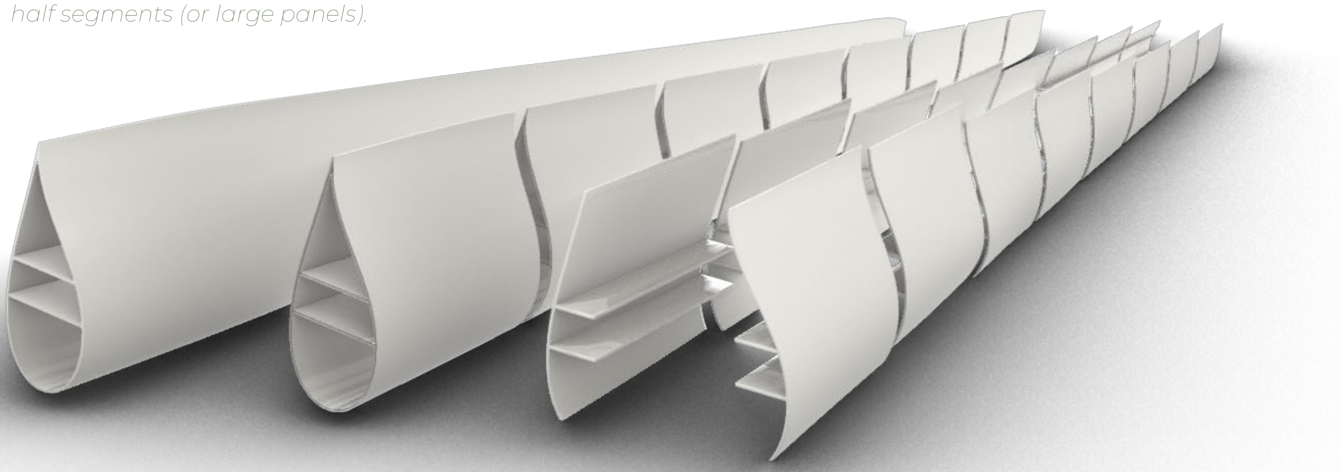
Segments & panel concepts

- While lo-fi prototyping emphasized the advantage of using segments (as compared to smaller panels) for pre-processing of WTB material, the width of segments complicate assembly and stacking segments will be challenging.
- By overlapping panels slightly, alignment problems can be tackled.
- Clamping panels in the middle minimizes their deflection in the width direction.

Concept evaluation

- Continuous front panels should be pursued for noise attenuation. Half segments or large panels may be used for this.
- A T-top assembly should be explored to reduce diffraction.
- Vegetation can be integrated using a wire structure, but a more elaborated set of options should be developed and evaluated (9.1).
- The subtle variation in large continuous front surfaces might be beneficial for the barrier's expression, but might also be less safe than a flat front surface.
- Although a second panels column is required behind the continuous front panel (section 7.1), the weight of this construction is likely lower than full segments.
- Assembly time is expected to be longer for a panels-based concept than a segments based one since there are more separate parts.

Figure 53: From blade to segments to half segments (or large panels).



Concept iteration

Chapter 7

This chapter builds upon retrieval of large panels from a WTB, as proposed in chapter 6, forming the basis for a subsequent concept iteration. The evaluation results and development steps from chapter 6 are integrated into a unified concept, with specific design considerations per section. Section 7.1 covers panel configuration options, while section 7.2 explores their integration into a frame structure and how they are fastened in the cassettes. Section 7.3 covers an exploration of how WTB material can be used for a T-top like addition. Chapter 8 continues with embodiment aspects. Aesthetics and vegetation options are not included in section 9.2 as they are also evaluated in a conducted survey, adding to the coherence of that section.

7.1 Panel configuration

7.1.1 Second column panel alignment

The continuous front (or road side) panels require to reach a certain height without having seams. For the purpose of this design, a 4 m high barrier is chosen because this is sufficient for most barriers, that frequently are between 2 to 4 m high in recent years (E. Nouwen, personal communication, December 9 2024). This asks for WTBs that can supply 4 m high panels. The NREL 5MW blade can provide 4 of such panels (see section 8.1.2), but also many panels with a lower height. These can be used for the required second column:

1. To aim for more *blade material usage.*
2. Most sound waves are reflected by the front panel, lowering the effect of diffraction and transmission at the second column's alignment edges. The second column therefore does not need to be continuous.

Reviewing the Harris profile in Figure 33 (section 5.1.2), it can be seen that the combination of standardized panels idea scores better on *blade material usage* than the cladded system idea (as used in section 6.2), as it makes use of larger panel sizes (e.g. 1, 2 and 4 m high panels instead of just 1 m. In addition to the large 4 m high front panel, standardized panel heights of 1 and 2 m high can be used. This is convenient, because virtually all heights (1, 2, 3, 4, 5 , …, m) of a barrier can be built with this, and using three sizes will allow for modularity.

When using a maximum curvature d/w of 0.08 (section 8.1), the deflection of the panels in the width direction is 0.08, 0.16 and 0.32 m respectively. The material thickness will add a small part to this as well. Their length is still set to the standard 6 m, which might change due to structural considerations. Using these panels, multiple combinations can be made (Figure 54).

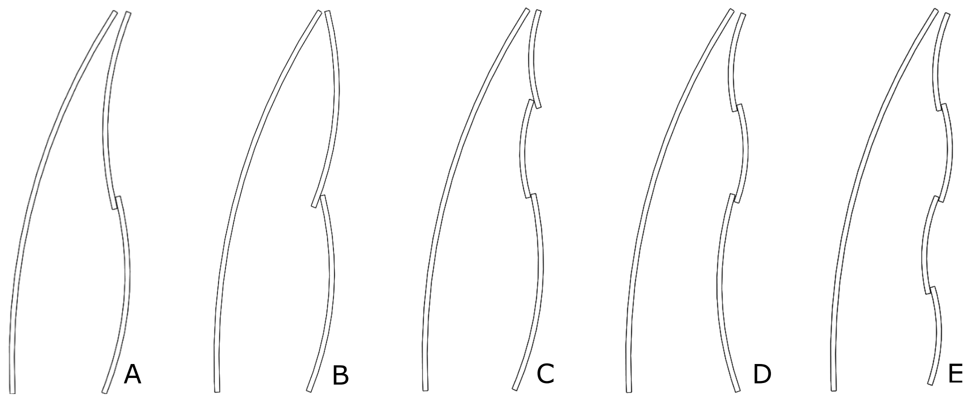


Figure 54: Combination options of 1m and 2m high panels in the second column.

As done previously, panels will overlap partly to avoid gaps at the alignment seams. The panels concept used columns with either concavely or convexly oriented panels towards one side. Alternatively oriented panels were not considered in detail yet, but they align relatively well as opposed to single-orientation columns (Figure 55).

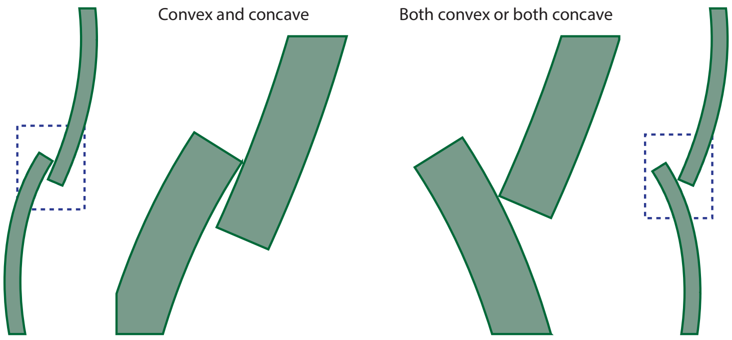


Figure 55: Alignment of panel combinations in the second column. Concave and convex align well, whereas both convex or concave panels align less coherently.

In the 'both convex or both concave' option, use of compriband as a seam-filler is likely unavoidable, which might not be the case for the alternatively oriented option. This is assuming that the cuts will be made approximately perpendicular to the outside surface of segments. If cuts are made (purposefully) differently, or additional cuts of small corners are considered, possibilities to align panels differently open up, e.g. as in Figure 56. Because the alternatively oriented panels align well without using compriband or additional cutting efforts, this seems to be the best option. Panel combinations that are alternatively oriented and reach a height of 4 m can consist of four 1 m panels, two 2 m panels or one 2 m panel and two 1m panels, as in options E, A and D respectively in Figure 54. Preferably, any combination is possible to enlarge the *interchangeability* (*modularity*) of panels. This depends on how the panels are fastened, which is covered in section 7.2.

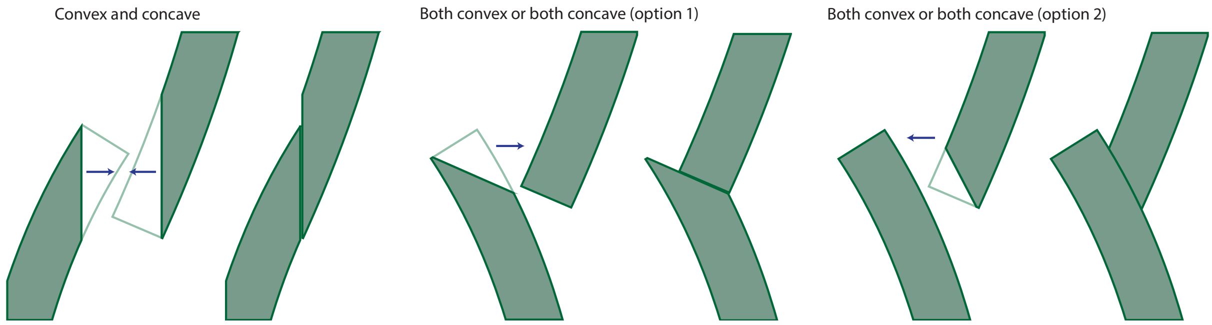


Figure 56: Alignment options when cuts to retrieve panels are made at fitting angles, instead of perpendicular to the segment outside surface.

7.1.2 Front panel tilt angle

As determined in section 3.2.4, the angle at which the front panel is tilted should be between 10 and 20 degrees from vertical to reflect sound waves into the sky. The curvature of the retrieved panels (when looking at their cross-section) also influences the reflection direction. Additionally, pressure side panels differ from the suction side panels in curvature (see Figure 58). This section aims to determine a suitable tilt angle, balancing three considerations: (1) maintaining sufficient barrier height to block noise effectively, (2) keeping the *space usage* in the width direction to a limit and (3) optimizing panel tilt to direct reflections into the sky.

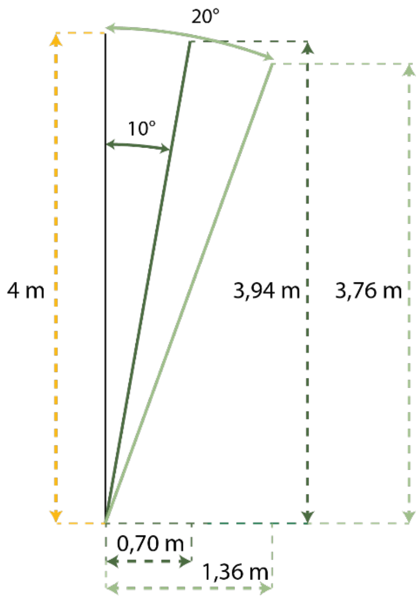


Figure 57: Tilt angles and accompanying height and width changes for a 4m high panel.

The height of the barrier decreases only slightly when the tilt angle is increased. A 4 m long (straight) panel at a 20° angle has an effective height of approximately 3.76 m, which is a 6% decrease Figure 57). This is no issue: panels retrieved from blades can be segmented slightly larger than 4 m, to compensate for the decrease. The width (and consequently *space usage*) increases significantly however, starting from approximately 0,7 m at 10° tilt to approximately 1,3 m at 20° tilt. This is an important consideration, since a wider barrier will be applicable in less locations, but a barrier with a higher tilt is likely to reflect more sound into the sky. As opposed to straight panels, a large part of the retrieved curved panels is already tilted without adding width due to tilting (Figure 58).

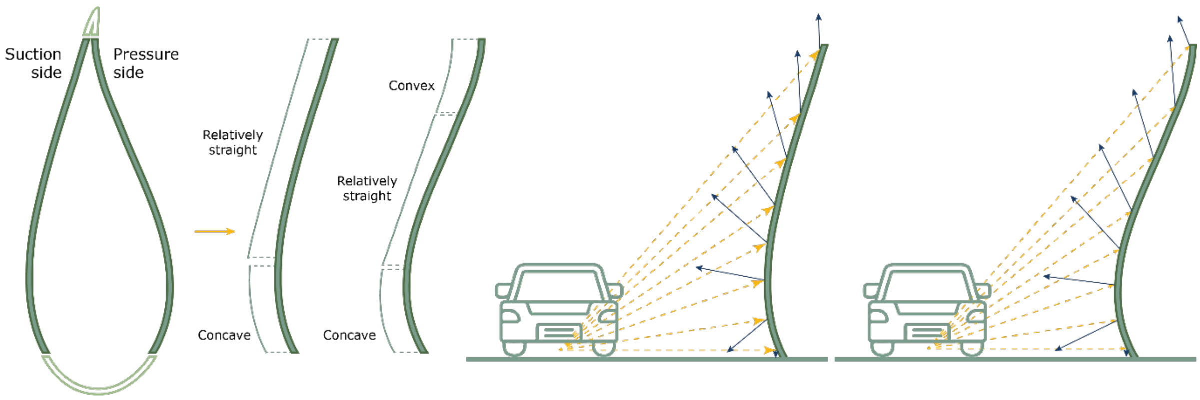


Figure 58: Difference in curvature of suction- and pressure side panels, and resulting reflection directions.

In Figure 59, the front panels have been rotated so that their *space usage* in width direction has been minimized. When segmenting the panels into straight-edge polylines, three or four general angles can be determined for both panels. These are then rotated to 10° and 20°, and show the resulting general angles. Based on these results, a 10° tilt of the panels seems most appropriate: large parts of the panels are then actually oriented at a 20° angle from vertical. Additionally, this was the limit as determined in section 3.2.4. Simultaneously, additional width due to the tilt angle is limited.

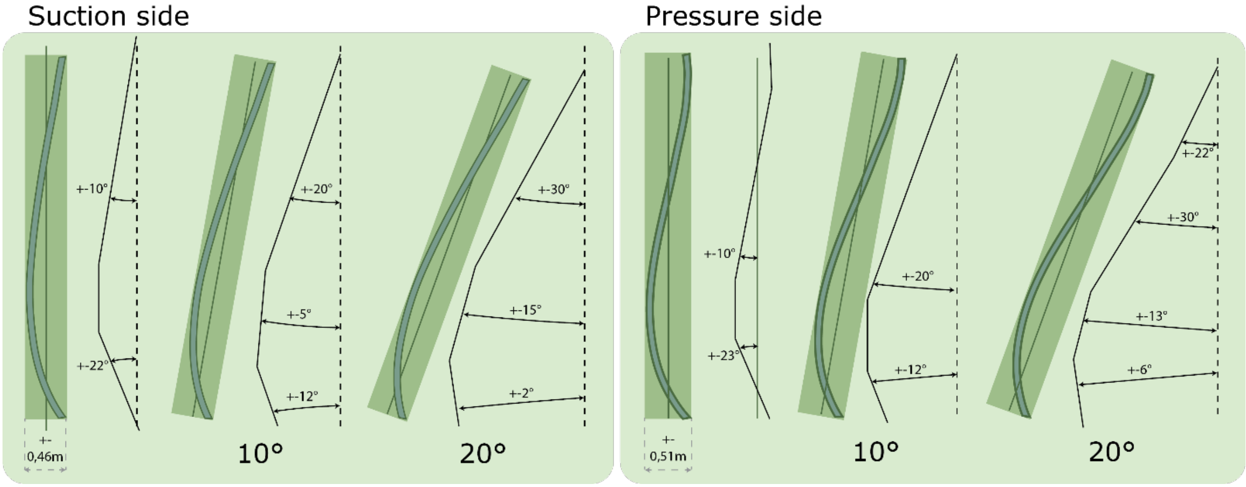


Figure 59: Three tilt angle situations for both the suction- as pressure side panels. Due to panel curvature, tilt angles result in a multitude of angles present over the front surface..

As a final note, in Chapter 6 it was determined valuable to analyse if the concave parts at the bottom of the panels pose a problem for sound reflecting back from the ground surface. This is not the case, since often the asphalt or road surface, or the verge, absorb most of these (M. van Amstel & E. Nouwen, personal communication, December 16 2024).

7.2 Frames and fastening

7.2.1 Frames

The tilted IPE-frames used in the panels and segments concepts were chosen for their relatively low *weight* and large *possibilities for fastening* of panels. An additional criteria is their *structural stability* (over lifetime, implicitly includes *durability*, see section 4.3). When reconsidering earlier options and considering that only the front panel is required to be tilted, a triangular frame follows the configuration of the panels and is likely more structurally stable than a tilted IPE frame at the same time. The triangular frame additionally provides an evenly large array of *possibilities for fastening* panels when it is made from an IPE-like profile. This is less large for the flanged triangle. Figure 60 shows a Harris Profile with frame-options and their ratings on the criteria as compared to one another. Elaborated reasoning behind the ratings can be found in Appendix H. The triangular frame option is chosen for its 'great' score on structural stability and freedom to mount panels. Additionally, its weight has potential to be reduced.

7.2.2 Fastening and mounting

Many of the focus requirements and criteria have a relation to mounting and fastening. The design needs to allow for dis- and re-assembly, withstand *fatigue* and use *interchangeable* sub-assemblies. Additionally, *assembly time* is preferably low, with reversible fasteners that do not invade the material to prevent degradation (*durability*), and additions (in height) are preferably facilitated (*adaptable design*).

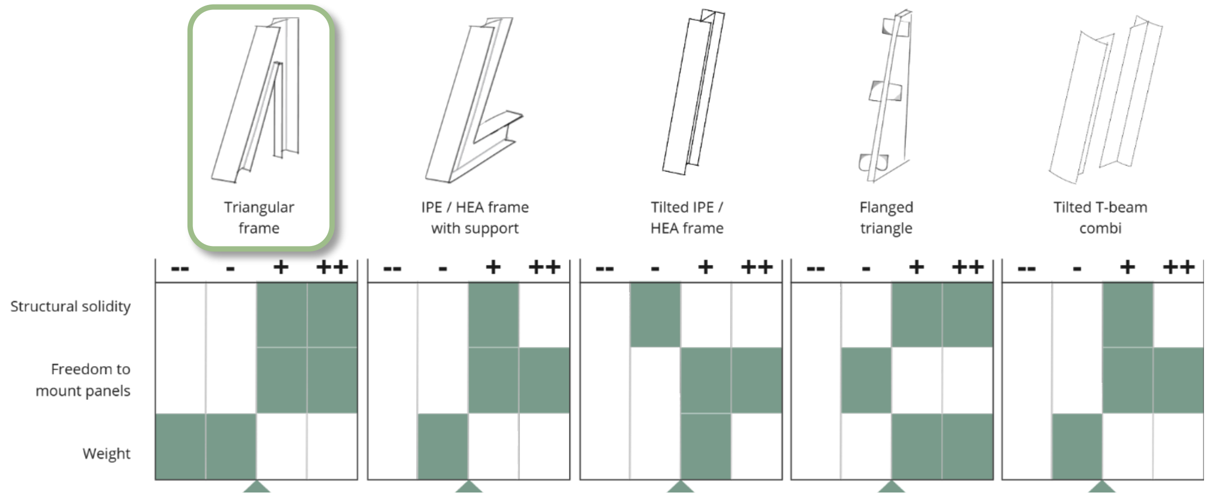


Figure 60: Presented and updated frame structure options in the morphological chart from section 5.2.

Cassette design

The ‘cassettes with clamps’ idea in Figure 61 is inspired by an industry example. It is a promising option for reversible and non-invasive fastening of panels in cassettes, which can be mounted on frames. Cassettes are long, rectangular and shallow boxes in which panels fastened at their sides. Advantages of using cassettes with (adjustable) clamps are 1) fastening of panels can be done before they are placed in between frames on location (pre-fab), reducing time spent on road locations (for which roads sometimes need to be closed down) and 2) they enhance modularity of the assembly: a cassette-panel-cassette sub-assembly can be easily interchanged if required.

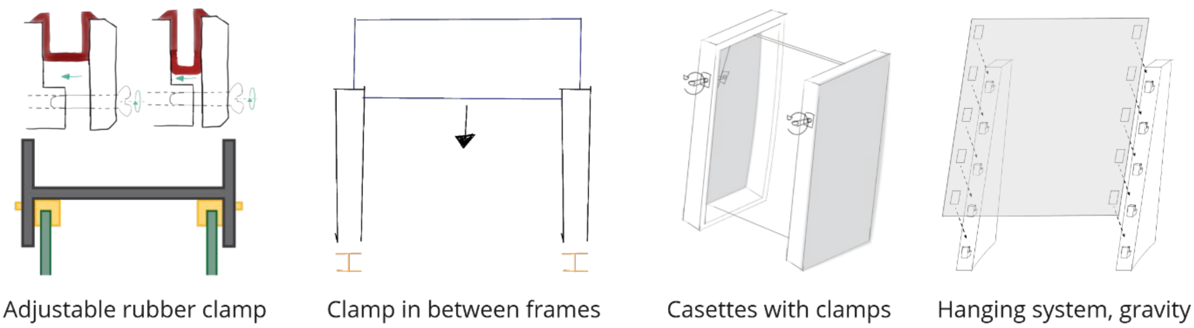


Figure 61: Fastening and mounting options from the morphological chart and first concept iteration.

To enable this, cassettes should be mountable into the IPE-frame from the top, which automatically clamp in between the frames that are spaced accordingly. For a triangular IPE frame, the vertical frame component requires a partially cut cassette to allow for the tilted cassette to slide in afterwards (Figure 62). Making them both complete is possible, but then the frame would become wider. The vertical cassette needs to fit a panel thickness at the top, however.

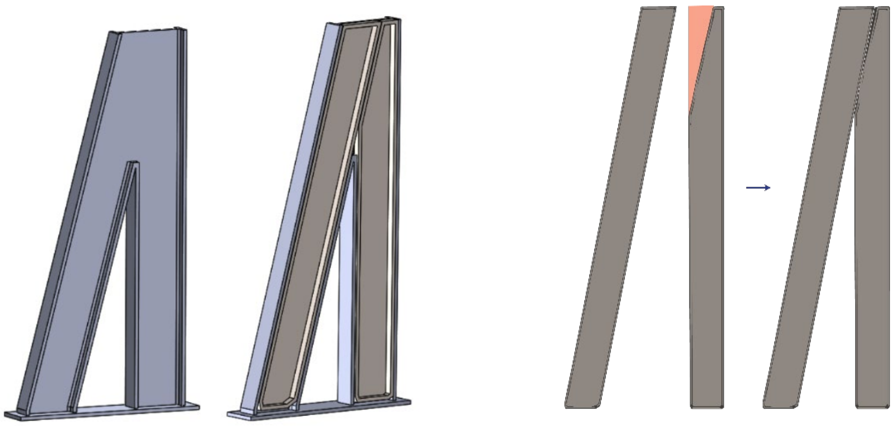


Figure 62: Triangular IPE frames, combined with cassettes. The tilted cassettes carries the front panel, and the vertical cassette carries the second panel column. A corner is cut off from its top.

Since the cassettes of Figure 62 are the same shape as the inside of the IPE frames, the IPE-profile in the frames might not be required if a different mounting option is chosen. By adopting the negative shape of the triangular IPE-frame (which closely resembles the ‘flanged triangle’ frame option), combined with the hanging system, a more compact frame can be made (Figure 63). This frame will be lighter, less expensive and the complete width of the barrier is covered up by the cassettes, allowing for a wide range of variable WTB panel curvatures without acoustic leaks.

Panel combinations that need to be configured in the cassettes have differing width and cross-section shape (section 7.1.1). The large front panels require a wider cassette (45-50 cm) to be placed in than the panels in the second column (between 22-30 cm). How can panels be mounted in the cassettes uniformly? The available room for fasteners is not

Figure 63: Frame structure with cassettes, and a zoom in on the top, where the green hooks can be seen, as well as two sets of cassettes besides each other. One vertical cassette is excluded.

large. Behind a set of cassettes, another set will be mounted to carry the panels of the next barrier section (Figure 63, right image) and close off the gap created by the frames, to prevent reduction of noise attenuation. The cassettes therefore should incorporate space for fasteners at their backs, as shown in Figure 64.

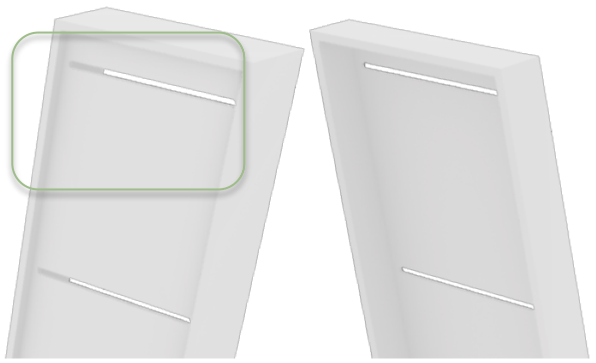


Figure 64: Front and backside of a cassette at the top. The 'shell' allows fasteners to be placed in slots or perforations.

Fastener design

Given that the cassettes closely encompass the height of the 4 m panels (with some tolerance), there is only a fastener needed to restrict movement of the panel in the width direction, as the width of the cassette might be higher than the deflection of the panels in some cases. Fasteners for panels that are on the bottom of the cassette do not need to carry the weight of the panel. These panels can rest on the cassettes' bottom, which is then placed on the foot of the frame to convey the load to the frame and foundations. Fastening options are depicted in Figure 65.

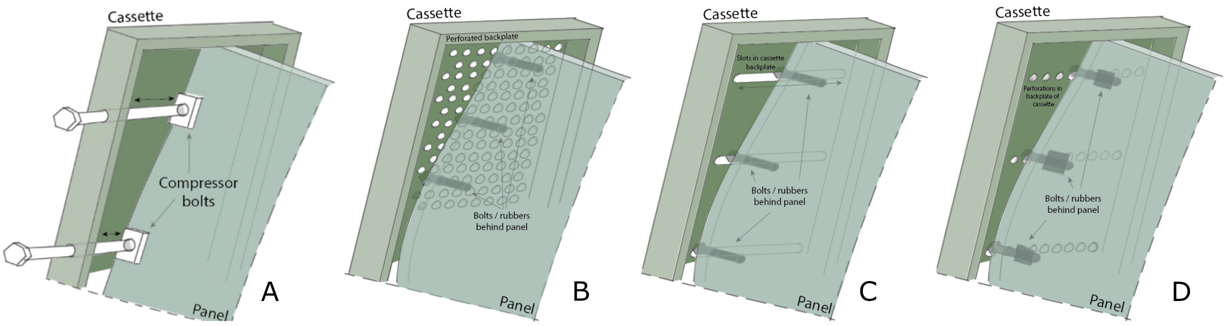


Figure 65: Panel fastening options. A) adjustable compression bolts, B) perforated back with bolts and C) slotted bolts that can be adjusted in their position and push the panel against the side of the cassette, D) combination of B and C, with rubbers.

The adjustable compression bolts (A) protrude from the road- or resident side of the cassettes and should be tightened until a rubber compressor pushes the panel against the back of the cassette. A disadvantage of this option is that bolts will protrude, reducing safety on the road side. Option B makes use of a perforated back wall in the cassette, allowing bolts to be placed at suitable places to support the panel. Such an amount of perforations is however not preferable, since a lot of material will be lost in the process of making the cassette. The slotted bolts of option C is then a better option, also regarding noise attenuation. The bolts' position can be manually adjusted to push the panel against the front side of the cassettes to clamp it. Spacing rubbers in between the bolts and panels can be used to reduce material degradation due to scrubbing Spacing rubbers also provide more resistance to fatigue. Finally, option D has perforations only at certain heights in the cassettes. An advantage of this option in comparison to C is that bolts are more firmly supported by rigid material than in slots. Rubbers can also be used in this option to accommodate tolerances.

The *adjustability* of option C is somewhat lost in option D, while option D is more likely to carry load cycles (*fatigue*) better, since there is no additional material 'behind' bolts to keep them in place in option C. Section 8.2 covers a prototyping process and test focussed on fasteners, which could point out which of these options is best.

Smaller panels in the second column that are not resting on the bottom of the cassettes should be carried by fasteners that can carry the weight of them. These will thus be different from the ones presented above. A combination of a joist hanger and an adaptation of the adjustable clamps used in the concepts of Chapter 6 could work for this (Figure 66), but it should be tested.

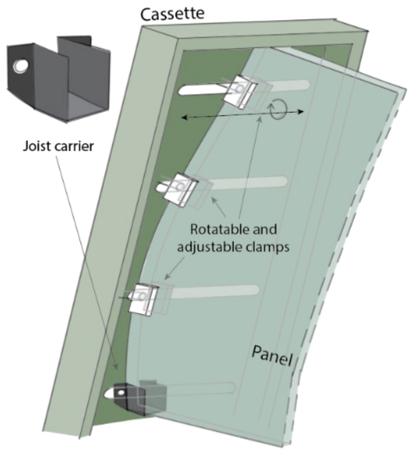


Figure 66: Adjustable, rotatable rubber clamps that follow panel curvature and a joist carrier to carry the weight.

7.3 T-top addition

As an additional feature, T-tops have the potential to reduce the required height of the barrier. Similarly, barriers that may not exceed a certain height can be equipped with a T-top to reach a certain amount of noise attenuation. Creating such tops might be made possible through the inherent curvature of WTB material. This section consequently outlines an exploration into possibilities of a T-top addition, made from the WTB material that is not yet used in the concept (Figure 67). The proposed ideas are recommendations for further development.

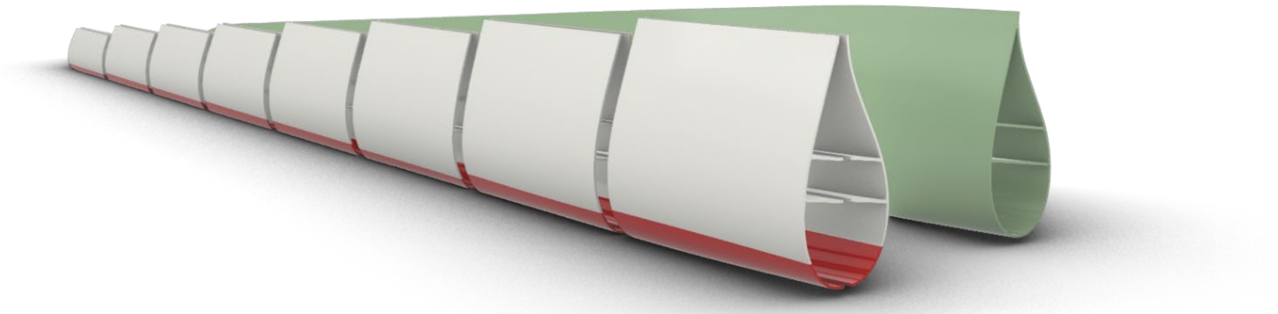


Figure 67: Unused material in yellow / brown colour, green is used and blue is reference blade (without root).

The main unused material sections are the LE parts of segments, which were previously identified as parts with a good ‘roundness’ to reduce the effect of diffraction. These could thus be suitable parts. Depending on the size of the segment they are taken from, the size of these parts can vary (Figure 68). The first four segments of the NREL blade could provide usable pieces, of which the largest seem to be most applicable.

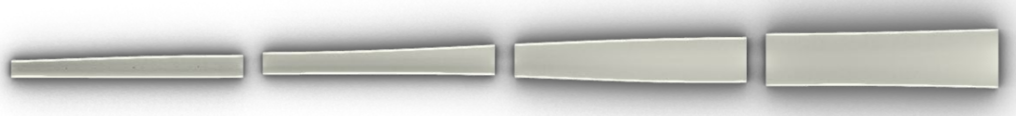


Figure 68: LE ‘leftovers’ from first 4 segments, after the maximized segmentation approach has been used, possibly valuable for T-tops.

Figure 69 shows an exploration of configurations with LE parts. The half circle shape can be variously used depending on rotation. The first, third and fourth option in the top row could be interesting. The first option is not per se a T-top, but uses the roundness towards the road as recommended by Tenpierik. This option also has two possible connection points to allow it to withstand wind loads. The third and fourth options only have one connection point, but cover a larger area to block sound waves than the first two options.

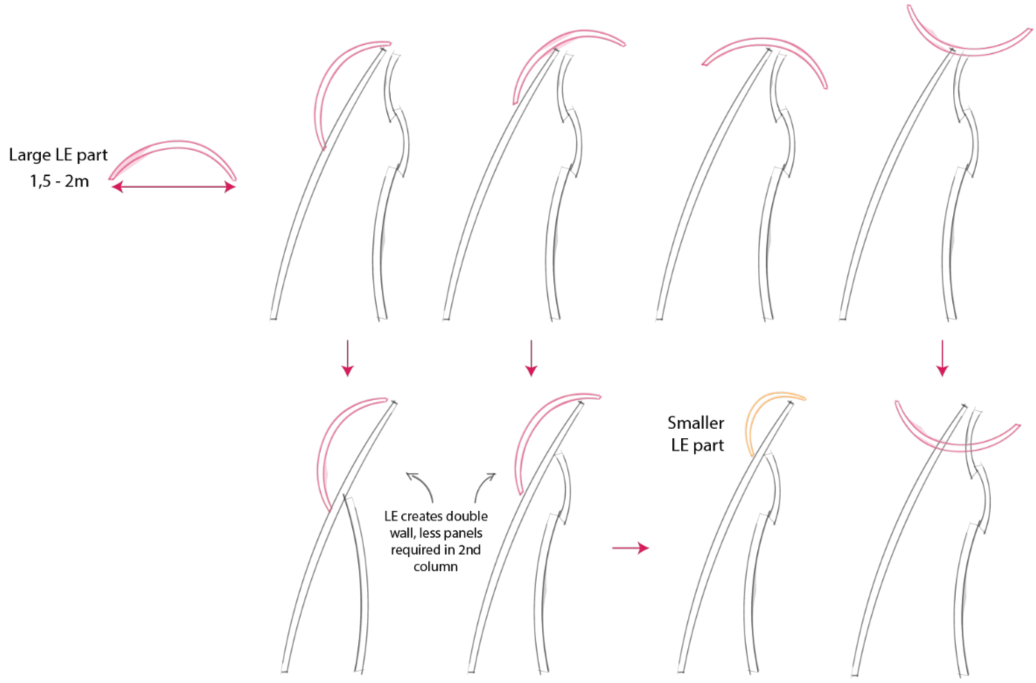


Figure 69: Exploration of the LE parts as T-tops in cross-section of the barrier design.

The variable size of the LE parts from differing segments complicate forming coherent T-tops, as can be seen in the back rows of the lower two designs in Figure 70. Alignment problems arise, making these less interesting. Using equivalent LE parts forms more coherent T-tops (front rows in Figure 70). While the first option is arguably the most realistic, the fourth (Y-shaped) could be multifunctional as a planter or as a water collection system. Although the proposed T-tops enlarge the blocked lines of sight (section 3.2.1) of road noise, the WTB material is still reflective. Its eventual performance is therefore hard to determine now. Existing T-tops are effective, but often applied with absorptive materials, so there is likely a difference. This should be researched further.

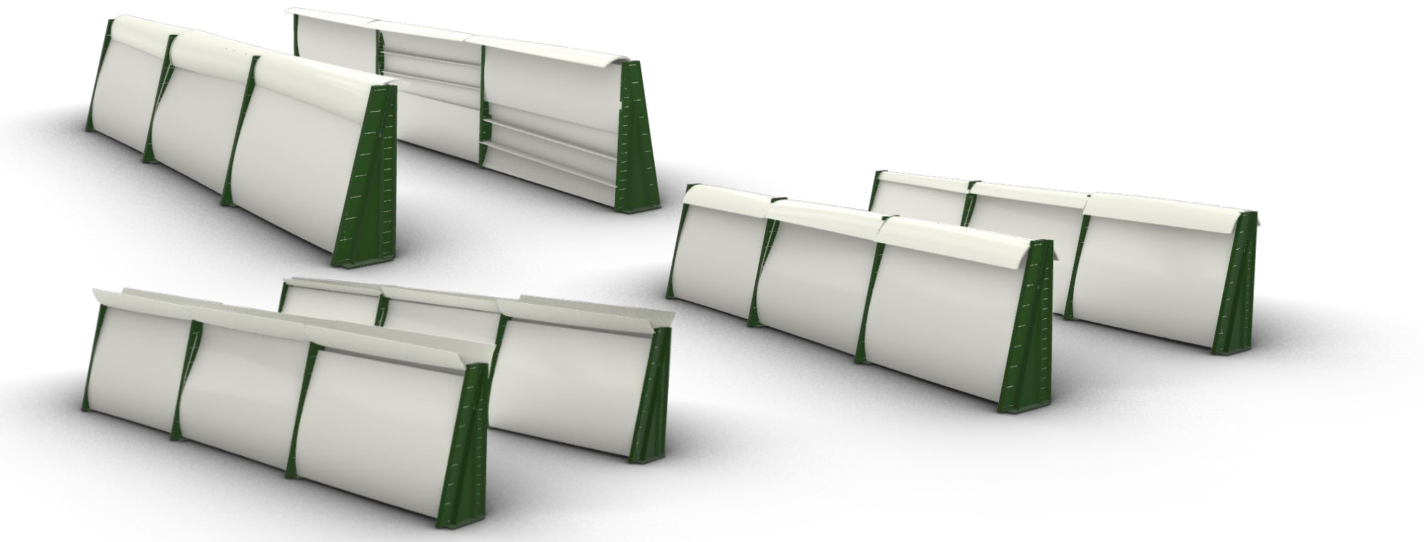


Figure 70: Three T-top options with leftover LE parts, shown on the barrier in 3D.

7.4 Takeaways

Panel configuration

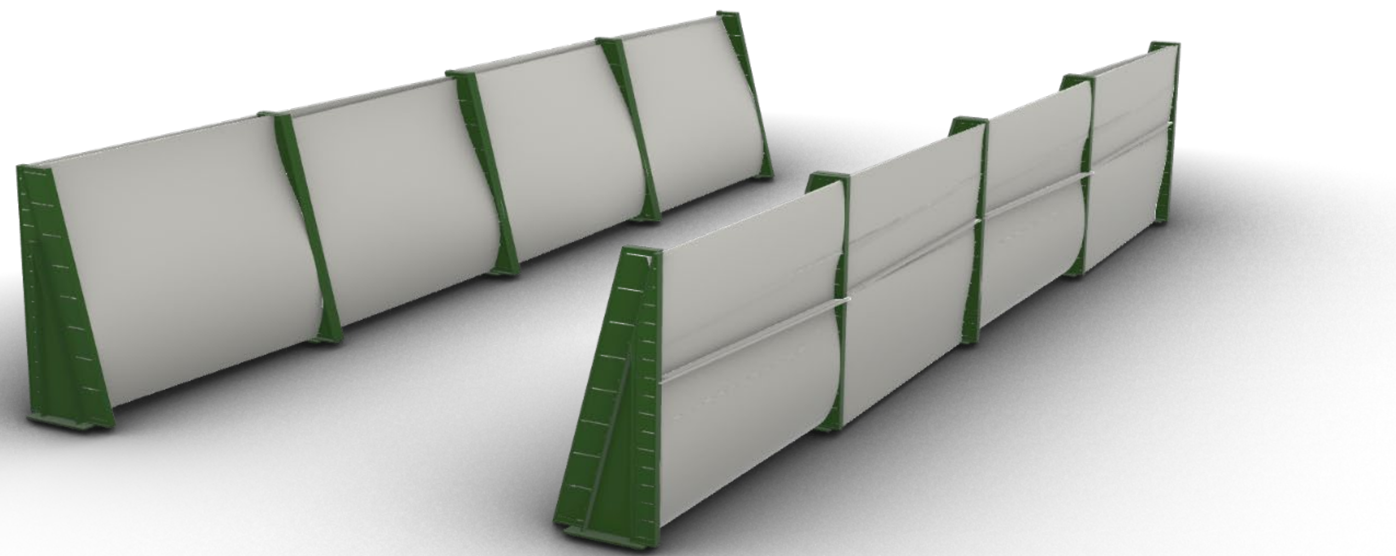
- Second panel columns may be discontinuous to increase *blade material usage.*
- The second column of panels consists of 1 or 2 m high panels that are alternatively oriented for improved horizontal alignment.
- The front panels are tilted at a 10 angle from vertical to not exceed the 20 degree angle that some parts of the panels may have due to their inherent curvature. This also ensures that the majority of sound waves is reflected up.
- Concave bottom parts reflect sound waves into the ground or asphalt, where they are absorbed.

Frames and fastening

- Using cassettes in which panels can be fastened with adjustable, reversible fasteners, enhances the modularity of the assembly. They also allow a wide range of variable WTB panels to be placed in without having acoustic leaks.
- An improvement of the triangular IPE-frames resulted in a triangular frame component that carries four cassettes on a hanging system that should allow for relatively quick mounting of cassette-panel-cassette sub-assemblies.
- The large front panels require a wider cassette (45-50 cm) to be placed in than the panels in the second column (between 22-30 cm).
- Three fasteners should be prototyped to evaluate them: the perforated bolts, slotted bolts and an adjustable clamp design. They can be tested with a prototype cassette.

T-top addition

- An exploration of using (unused) LE parts for a T-top addition was done, which could pose as inspiration for further development.



Embodiment design

Chapter 8

In this chapter, embodiment design aspects are covered, with the aim to enhance the feasibility of the noise barrier concept. Towards this aim, section 8.1 covers the developed parametric segmentation model, which helps finding segmentation patterns for suitable panels from variable WTBs. Section 8.2 covers the process and results of prototyping and testing a cassette and fasteners with the objective to evaluate the fastening options. Section 8.3 presents a coating test on cutting edges of WTB panels, as an explorative step in defining what types of coatings might be suitable.

8.1 Parametric segmentation model

To scale up structural reuse of variable WTBs, an adaptable segmentation strategy will be needed. This section covers the steps executed in and the results of a parametric model in Rhino Grasshopper. It has the goal of finding suitable segmentation patterns to produce usable panels while limiting cutting losses and reducing unusable material from the blade. Appendix I covers intermediate steps of the model and its results more thoroughly.

8.1.1 Parametric model steps

The NREL 5MW blade (without inboard section) is used as a reference to build the parametric model. This blade is representative for both onshore and offshore application (Resor, 2013) and contains common geometric features of WTBs that pose as reference points for the model. The following segmentation steps are proposed:

1. To enable curvature analysis of the pressure- as well as suction side of the blade, it will be cut in half over its length along the LE & TE (Figure 71).

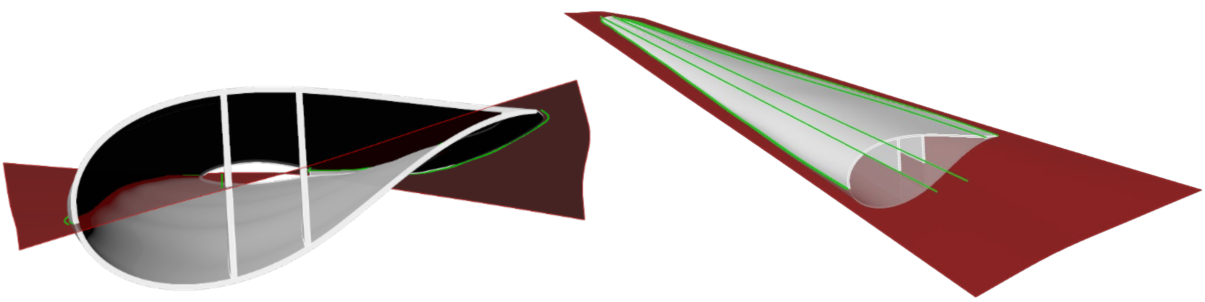


Figure 71: View from root end of the NREL 5MW blade model, without root section. A scaled surface (red) is built up of LE & TE curves and shear web mid-height curves (green) for sectioning the 3D model.

2. The resulting halves are rearranged and their LE is aligned as horizontally as possible (Figure 72a & b), to ensure that cuts can be made at a 90 degree angle with the horizontal. This is key for proper alignment of panel sides with the insides of the cassettes, where the assembly needs to be acoustically sealed.

3. The triangular shaped tops are cut off to finalize a rectangular front surface. This material is not valuable as it likely mainly contains adhesive (Figure 72d).

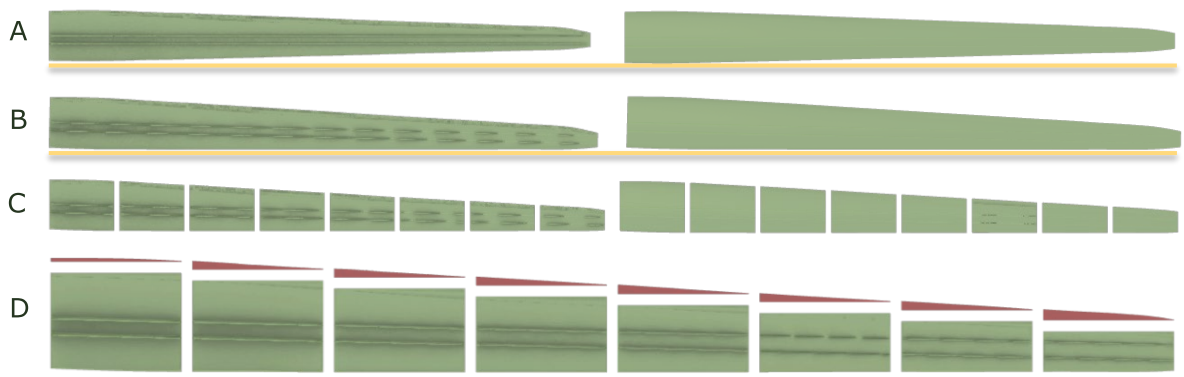


Figure 72: A) unaligned blade halves, B) LE-aligned blade halves, C) spaced out large panels. D) removing triangular shaped tops (in red) to finalize a rectangular front surface.

4. One panel at a time, cross-section contours of the panels are divided into equal length sub-curves, of which the start- and end-points (Figure 73a, red dots) are used to create a straight line (green). Ratio *d/w* can then be calculated, where *w* is the length of the straight line and *d* the distance between the mid-point of the straight line and the accompanying sub-curve Figure 73b).

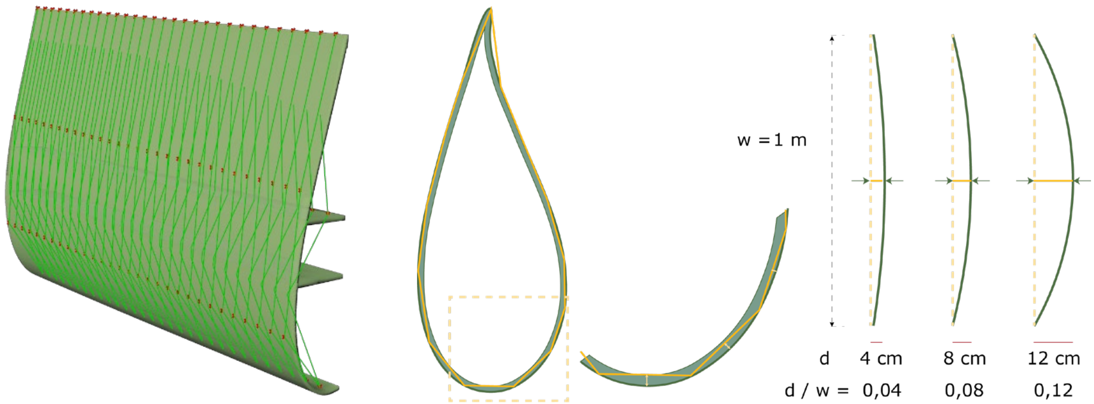


Figure 73: A) Red start- and endpoints of sub-curves of the contours are connected by straight lines in green. B) 2D view of the deflection / curvature analysis.

5. The maximum allowed ratio *d/w* and desired panel height can then be set. The model filters out unsuitable parts and present usable pieces (Figure 74).

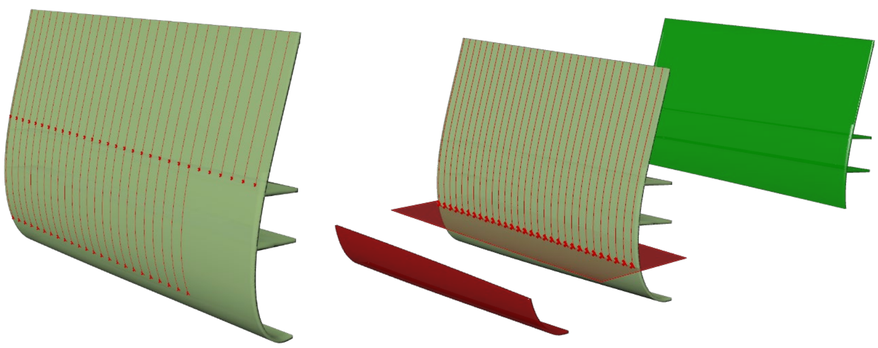


Figure 74: A) Red lines reach as far as that specific contour adheres to the set curvature requirement (i.e. the lower right part does not adhere), B) All contours reach a certain panel height and can be used as starting points for a plane, to cut through the mesh and create a usable panel and 'leftover'.

8.1.2 Results for NREL 5MW reference blade

The above method was also used for analysis of deviations in the blade's length direction. For the NREL 5MW blade, these were not large enough to pose issues.

According to Joustra et al. (2021c), timber standards from NEN 5461 are a fair equivalent to use on recovered WTB material. There are no standards for this material yet, and timber compares to it in the sense that their elements depend on raw material shape as well as the envisioned application areas. Table 9 lists the standards, where curvature $d/w < 0.08$ is used for the panels in the design of this project. The large dimensional deviation is chosen because it allows for retrieval of large panels required for the road side of the design, but also puts a limit on the deviation that can be reached. This is relevant to limit the width of the design (*space usage*).

Table 9: Boundary conditions for dimensional deviation of a curved construction element, based on NEN 5461 timber standards (Joustra et al., 2021c).

Dimensional deviation	NEN 5461	Curvature d/w	Deflection d [m]
Small	$d/w < 0.02$	$d/w < 0.02$	$d < 0.02$
Medium	$0.02 < d/w < 0.04$	$d/w < 0.04$	$d < 0.04$
Large	$d/w > 0.04$	$d/w < 0.08$	$d < 0.08$

Two approaches were taken, of which the specific results can be found in Appendix I. The first approach maximizes the height of panels with the curvature limit enabled, resulting in 16 panels (one per half segment) and some leftovers, which are LE pieces (Figure 75). The second approach aims to retrieve panels with heights of either 4, 2 or 1 meter, depending on what is possible in the specific half segment (Figure 76). This approach yields 4 panels of at least 4 m high, 10 panels of at least 2 m high and 8 panels of at least 1 m high.

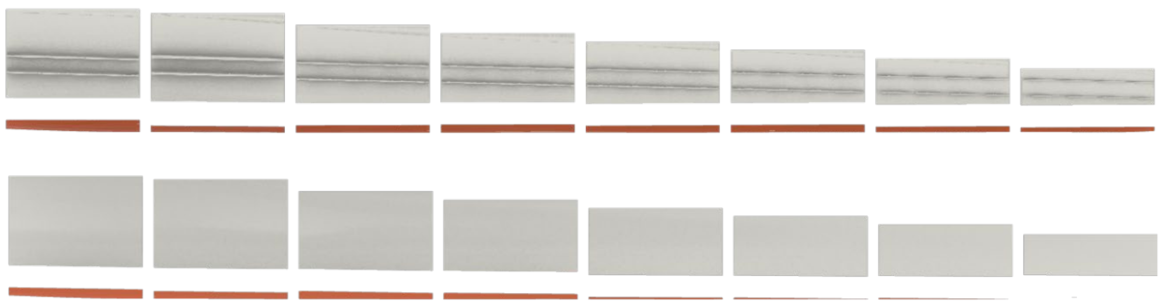


Figure 75: Maximized results: in red are the 'leftovers' after the curvature limit has been applied.

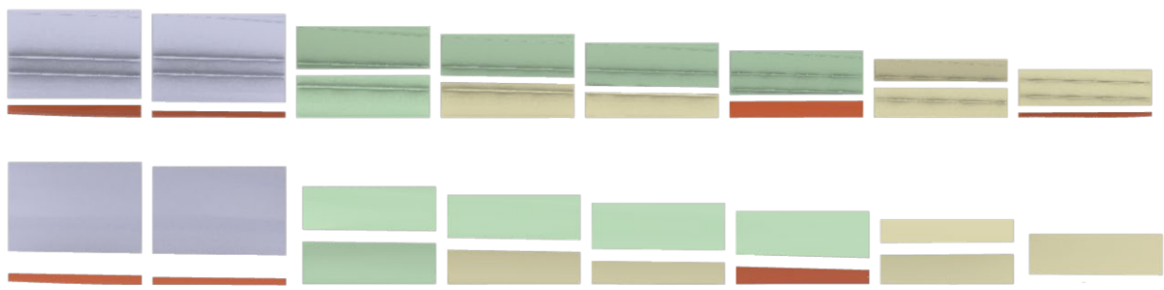


Figure 76: Standardized heights results: in red are the 'leftovers' after the curvature limit has been applied. The blue / lilac panels are at least 4 m high, the green panels are at least 2 m high and the yellow panels are at least 1 m high.

8.2 Prototype

An important part of the design are the cassettes that connect the noise barrier filling with structural frames and enable mounting of modular sections of variable WTB panels. This section covers the results of a prototyping process and fastener test that has the purpose of evaluating presented fasteners (see section 7.2.2) on their influence on assembly operations and acoustic sealing of the cassette-panel alignment edge. Furthermore, the prototype serves as a first step in embodiment of the cassettes and fasteners, and as a demonstrator at an approximate 1:2 scale. In Appendix J, the prototyping process and choices made during it are further elaborated.

8.2.1 Prototyping process results

Three parts are required: a suitable WTB panel, a cassette (with support structure / frame), and the fasteners. A suitable panel that was retrieved from a WTB was available to the researcher. It has an approximate 1:2 scale with the real design and had a well-sawn edge, for alignment in the cassette. The cassette is made of laser-cut wood and determined to have a backplate of 20 x 185 cm at a 10° tilt. The width of the sides was determined to be 75 mm, which is half the length of the flanges of the frame structure, which needs to carry two cassettes. A hanging system is made into the frame structure for mounting of the cassettes, and the cassettes contain both perforations and slots for the fastener test. The three parts can be seen in Figure 77.

Figure 77: A) the wooden cassette with perforations and slots in the backplate and the mounting structure on the frame part. B) the three parts assembled into the demonstrator prototype.

The bolt-based fasteners were imitated using M12 bolts and nuts, and compriband supplied by Heijmans as spacing material (Figure 78).

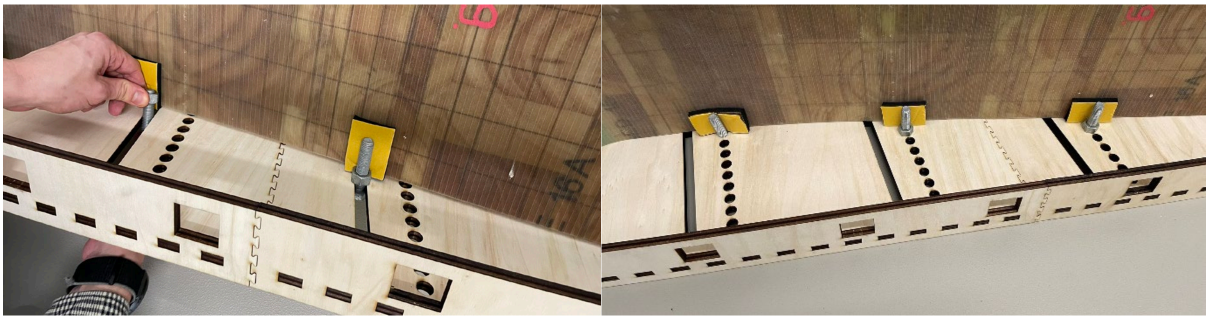


Figure 78: Slotted bolt (left) and perforated bolts in the connection points along the height of the cassette. Rubbers are placed between the bolt / nut combination and the panel.

The adjustable clamp was iteratively designed in CAD and 3D printed (Figure 79b), containing a clamping range of 44 mm, sufficient for clamping the 25 to 40 mm thick panel. It can incorporate M12 bolts or threads and is lined with compriband to imitate rubber. The clamp is not expected to actually carry the panel's weight. In reality, this clamp has to be made of (stainless) steel. The added functionality in comparison to the bolt options is that this clamp will restrict panel movement in two directions, and can be placed in a perforated hole and still have the same adjustability as in the slotted hole. The joist carrier of Figure 66 is not tested as a 3D printed design was not expected to carry the panel. A (stainless) steel version should be tested instead.

Figure 79: A) Adjustable clamp designs, multiple iterations. Improvements mainly covered better 3D printability (thinner flanges), stiffness (larger thickness, ribs) and fitting of steel M12 bolts. B) tested clamp.

8.2.2 Fastener test

The influence of the fasteners on assembly operations are tested by going through the expected assembly steps. The acoustic closure (possibilities) of the cassette-panel aligning edge are evaluated after completing those steps.

Assembly process

Slotted holes vs. perforated holes

For the perforated holes option, the assembly process involves the following steps:

1. Lay the cassette on the ground.
2. Position the panel inside the cassette with its front touching the front flange of the cassette and its back touching the back flange (as in Figure 80a).

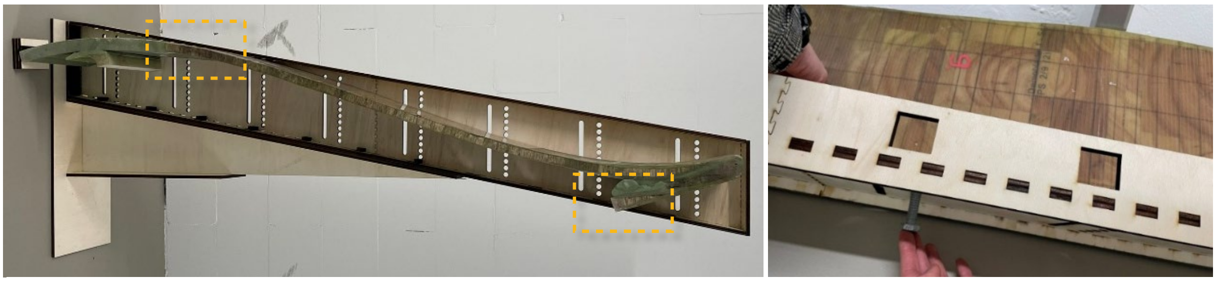


Figure 80: A) positions where the panel touches the front and back of the cassette, B) gaining access to the backplate by tilting the cassette and panel.

3. Insert bolts through the most suitable perforations, from the back of the cassette. To access the backplate, the cassette with panel is tilted slightly (Figure 80b). For larger panels (e.g. 4 x 6 m) this is not practical. For smooth assembly, these panels should be elevated to allow the cassette to be slid over its edges, providing access to the backplate (Figure 81).
4. Fasten the bolts with a nut, inside the cassette.
5. Insert a spacing rubber or compriband between the bolts and panel.

The slotted holes option follows the same assembly process, however the bolts can be adjusted, leading to a few advantages over the perforated holes option, as experienced during the prototype assembly test:

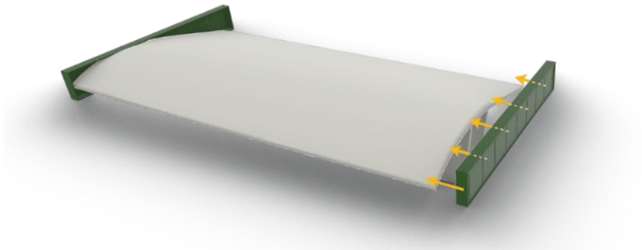


Figure 81: Sliding cassettes over panel edges, so that cassette backplates are accessible.

- Better alignment of the bolts with the panel curvature. In perforations, fixed bolt positions lead to inconsistent spacing between bolts and the panel. Some touch the panel while others leave gaps of up to 10 mm. The panel might lean on only a few bolts along its height rather than being supported by all.
- Fine-tuning of the bolt's placement allows for more proper clamping of the spacing rubbers as compared to the perforated holes option.

While the slotted holes fastener likely works better, a limitation is the lack of rigid material that prevents the bolts from sliding. In real-world application, bolts might loosen over time, losing their supporting function. This should be tested.

Adjustable clamp

The adjustable clamp option was assembled following these steps:

1. Lay the cassette on its side so that the backplate is accessible.
2. Insert the bolt that allows it to rotate into either a perforation or slot.
3. Screw on the clamp part.
4. Adjust the clamp rotation to approximately match panel curvature.
5. Position the panel in the cassette in between the clamps.
6. Tighten the clamps until they properly support the panel.

This worked relatively well due to adjustability (Figure 82).

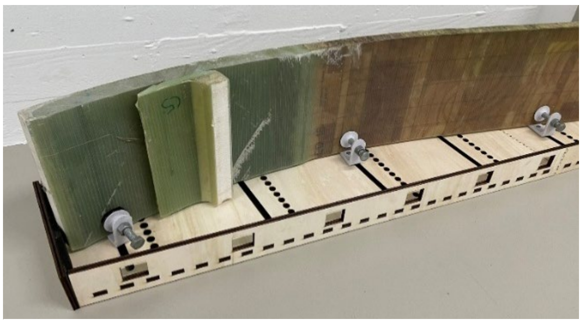


Figure 82: Demonstrator panel fastened in the cassette using adjustable clamps.

Improvements can be made for a more efficient assembly process. When clamps can be fastened to the panel sides at the correct heights before positioning them into the cassette, the panels can be placed with the clamps already attached, reducing manual positioning steps. A thread-nut combination instead of a bolt is required (Figure 83).

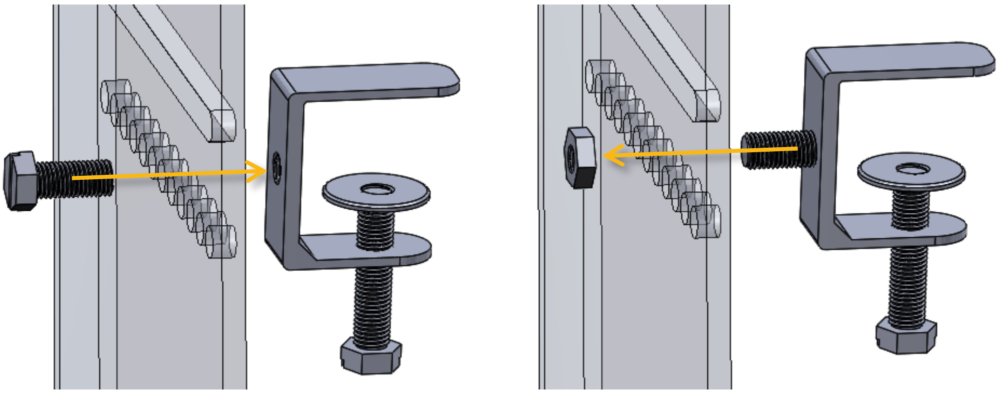


Figure 83: Small adaptation to the clamp design allows the clamps to be fastened to the panel sides before they are placed into the cassettes. Slot heights need to be indicated on the panel side.

In areas where the panel is close to the side of the cassette (Figure 84), the bolt may collide with it, preventing clamp placement. This can be dealt with by enlarging the clamp flanges so that the bolt extends over the cassette side, or shortening the bolts.

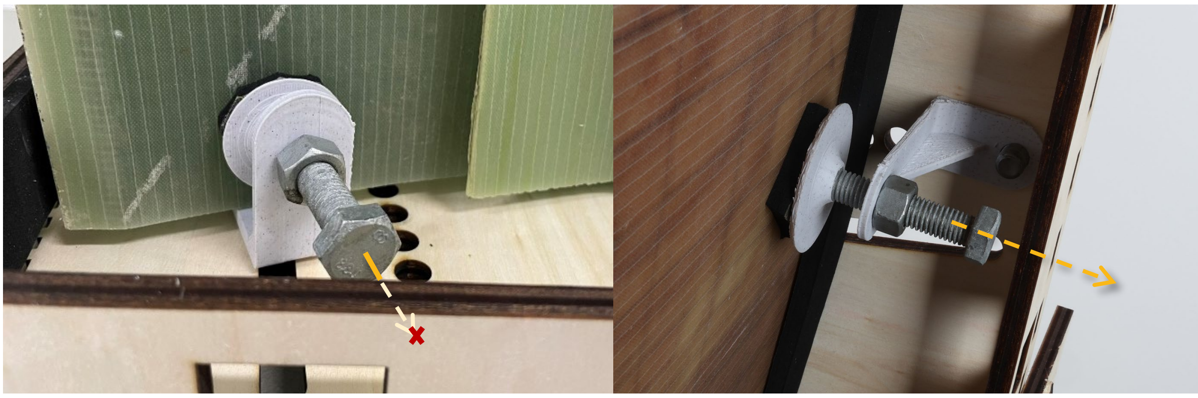


Figure 84: By making longer clamp flanges (as done in right image), extending clamp bolts will move over the cassette side instead of colliding into it.

Acoustic sealing

Acoustic sealing of the seams where the panel edges make contact with the backplate of the cassette is important for noise attenuation. In existing barriers, these kinds of seams are sealed by using rubbers. For testing the acoustic sealing possibilities per fastening method, compriband was used. U-profile rubber was also tested, however due to thickness variations of the panel, placement of such a U-profile rubber is complicated and unsuitable (Figure 85a). Compriband was consequently used.

For both the slotted hole fastener and perforated hole fastener, the panel edge touches the backside of the cassette. Compriband can be placed between the fasteners and the panel backside, as shown in Figure 85b. The compriband adjusts to the panel curvature naturally, easing assembly. It does not have to be pasted on the panel backside because it is clamped by the bolts, making separation at EOL easier. However, shear web parts pose a complication similar to the one in Figure 85a. The compriband strips might have to be separated in those locations.

Figure 85: A) U-profile rubber on panel edge. B) Compriband strip between the bolts and panel backside.

As can be seen in Figure 86a, the adjustable clamp facilitates placement of compriband between the panel edge and cassette: a gap of approximately 5 mm is created. Figure 86b & c show how this spacing makes it easier to deal with inconsistencies in panel thickness. However, compriband is a straight strip of material, while the panel curvature is not. A large surface area of compriband might thus be needed, to cover the whole seam.

Figure 86: A) The clamp creates a +-5 mm gap between the panel edge and backplate of the cassette. B) allowing for good acoustic sealing, C) without the problem of inconsistent panel thickness.

Fastener test evaluation

The evaluation of the assembly process highlights the importance of adjustability of the fasteners, as demonstrated by the slotted bolts or adjustable clamps. However, both options have disadvantages. The slotted bolt fastener has the risk of loosening over time, and the adjustable clamp creates a gap between the panel and cassette backside. A final iteration tackles these as shown in Figure 89. The clamp is fastened in a perforation rather than a slot and does not create a gap. This clamp also facilitates the use of compriband as in Figure 85, which is found to facilitate effective assembly more than the configuration of Figure 86.

8.3 Coating for cutting edges

To start an exploration into a suitable UV resistant, waterproof coating, an application and pull test will be conducted with two epoxy-based (EP) coatings. Cutting edges and top surfaces of two panels are coated, which have similar thickness but different core materials: balsa wood and foam. Figure 87 shows the application process, and Figure 88 shows the panels and coating result 24 hours after application. With input from an expert on coatings at Heijmans (J. Nijskens), a few criteria are deemed important:

- Material composition (e.g. no harmful substances, relatively sustainable prod.)
- Ease of application
- Amount of resin uptake (relating to porosity of core materials)
- Durability / longevity of coating (suture strength)

Figure 87: Taping and sanding the panels, mixing the epoxy coatings, applying them on cutting edges and front surfaces, and letting them dry for the pull-test.

Figure 88: 24 hours after coatings were applied to cutting edges. The coatings seems to be smoother and less absorbed by the balsa wood (top), as compared to the foam core (bottom). The white EP510 coating seems to be less absorbed by both panels. This might be due to its higher viscosity.

Material composition

The EP coatings, EP8085 (clear), and EP510 (white) were chosen from a limited selection at Heijmans due to their superior resistance to UV degradation and water infiltration compared to available PU-based coatings. Other EP coatings contained reactive solvents that are harmful to flora and fauna (L. Baijens, personal communication, January 20, 2025) which were therefore excluded. EP510 is less flexible (more brittle) than EP8085, making it more prone to degrade due to repeated forces such as wind loads. EP8085 can be manufactured with biobased components (J. Nijskens, personal communication, December 17, 2024). This was not the case for the tested sample. Although biobased materials are not inherently sustainable, its dependence on fossil fuels is reduced. Whereas the complete material composition has not been evaluated, EP8085's increased flexibility and possibility to be manufactured biobased give it a slight advantage over EP510.

Ease of application

There is no apparent difference in ease of application between the coatings during the application process (Figure 87). Although EP8085 showed to be less viscous than EP510, viscosity does not have a large influence on ease of application according to coating expert L. Baijens. Additionally, both coatings can be applied through the same methods of brushing, spraying and dipping (L. Baijens, personal communication, January 21, 2025). When application is required on large (amounts of) panels, dipping might be the most efficient way. Brushing requires more manual labour, and spraying likely results in unprecise application where front surfaces might also be hit.

Resin uptake

The porous core materials have an influence on the effectivity of the coatings. 24 hours after application (when well-cured) of one layer of coating, both cores were inspected, which seemingly showed that the foam core had more resin uptake (Figure 88). Foam cores might require more (layers of) coating to be protected sufficiently. The less viscous EP8085 shows more uptake than the EP510 on both cores. For both of the coatings, (an) additional layer(s) have to be applied to properly protect the edges well (L. Baijens, personal communication, January 21, 2025).

Durability

Finally, the durability can be evaluated through a pull-test, for which a suture gauge was supplied. The suture strength of the coating with the surface is an indicator of the coatings functional lifetime (J. Nijskens, personal communication, December 17, 2024). It was however not possible to test the suture strength of the coatings to the cutting edges: the test appliance requires a 50 mm diameter surface area, and the cutting edges were only +-25 mm thick. This should consequently still be done in subsequent research.

This exploration provides starting insights for further research. Biobased EP coatings seem like an interesting direction, as well as more viscous variants that may require less layers to be applied. Dipping of cutting edges into baths of coating might be an efficient way of application.

8.4 Takeaways

Parametric segmentation model

- Based on the NREL 5MW reference blade, a parametric segmentation model is built. It consists of 5 general steps to retrieve rectangular panels with limited curvature.
- Curvature or deflection in the length direction of the NREL 5MW blade is negligible.
- Two approaches can be taken with the parametric model: maximized panel height, resulting in 16 panel with differing heights, or the standardized heights approach, which retrieves 4 panels of 4 m high, 10 of 2 m high and 8 of 1 m high.

Prototype test

- A prototype at approximately 1:2 scale is developed with the aim to test several fastener options. To this end, a cassette, frame structure and fasteners are embodied. A suitable WTB panel represents the edge piece of a large front panel.
- An assembly process test points out several findings that will help to smooth assembly processes. A key finding is that adjustability of fasteners is important for ease of assembly. Adjustable clamps and the slotted bolts allow for this, but also have disadvantages. A final iteration is done to tackle those (Figure 89).
- Compriband is used to test acoustic sealing of the panel-cassette seam, leading to the choice to place it between the fasteners and panel backside (Figure 89).

Coating test

- To protect exposed core materials of panels, (biobased) epoxy coatings with a relatively high viscosity are an interesting direction to explore further, as well as dipping of the edges for efficient processing.

Figure 89: Final iteration of the adjustable clamp with compriband for acoustic sealing

Evaluation

Chapter 9

This chapter covers evaluation of the noise barrier concept on two aspects: a structural analysis of the WTB panels (section 9.1), and aesthetics and vegetation (section 9.2). The evaluations help to further define the concept and determine additional recommendations for future research.

9.1 Structural analysis of panels

A structural analysis is done to analyse the deflection of panels under wind loads, and if these pose a limit on the length of the panels. Wind pressure acting on panels that are fastened at their sides are prone to deflect in the middle, which can cause damage to these panels (E. Nouwen, personal communication, December 17 2024).

9.1.1 Analyses set-up

The shape of the WTB panels is somewhat simplified for the analysis (Figure 90): the curvature of the panels is not taken into account. In reality, the curved shape of the panels is expected to make them less prone to deflect, consequently the deflection results of the analysis should be higher than in reality. The spar cap regions, sandwich panels and shear webs have different material properties (E modulus and density) and thicknesses and are therefore modelled separately. The properties used are linearly interpolated from values in Table 2, and can be found (bold) in Table 10. Their heights follow from the configuration in Figure 90, and the separate parts are rigidly connected in the analysis software. The initial length is set at 6 m. After combining the panels, they are rigidly fastened at their sides to represent fastening to the cassettes.

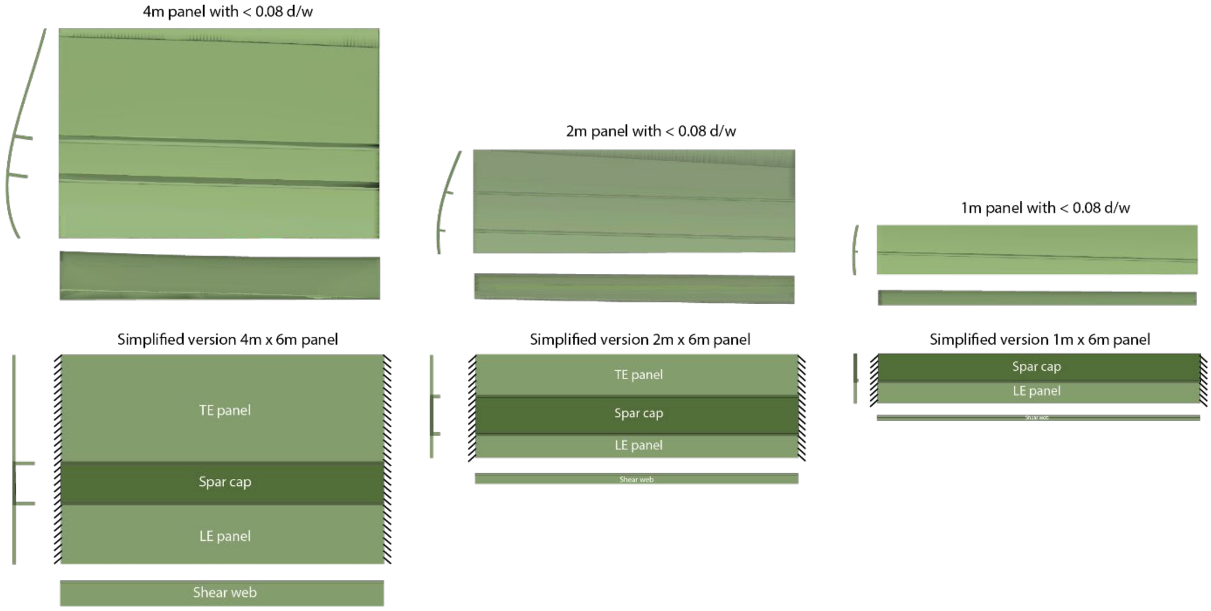


Figure 90: Side, front and top view of actual panels of differing heights, and the simplified versions as modelled in the simulation software.

With help from a constructor at Heijmans, the wind pressure load was determined conform NEN-EN 1991-1-4 (see Appendix L). The analysis was set in zone D of the barrier (see section 3.2.4), resulting in a wind load of 1,11 kN/m2. Th constructor rated this as an above average wind pressure load. This load is divided into two components: a pressure on the front (factor of 0.8), as well as suction on the back (factor of 0.4).

Table 10: The bold values in the tables are values for Eflex and thicknesses used in the analysis, based on Joustra et al. (2021c).

	Spar cap			LE & TE panels			Shear web
	20mm	**34mm**	48mm	26mm	**60mm**	96mm	**54mm**
Eflex (GPa)	37,1 - 64,9	**44,7** - 81,9	52,2 - 99	9,8 - 14,6	**6,5** - 9,6	3,2 - 4,7	**2** - 3
Average	51	**63,3**	75,6	12,2	**8,1**	4,0	**2,5**

9.1.2 Deflection results

Figure 91 shows the deflection results in two columns. The left column shows the results for the panels in which the lower end values for Eflex are used, and the right column shows the results when the average Eflex values are applied. The 1 m high panels are in the top row, the 2 m panels in the middle row and the 4 m panels in the bottom row. It can be seen that the 1 m high panels have the highest deflection of around 65 mm for the low Eflex and 52 mm for the average Eflex. The 2 m and 4 m high panels show less deflection (28 mm, 24 mm, 20 mm, 16 mm), staying within the allowed limit of 50 mm (see section 3.2.4). Appendix L covers the results separately.

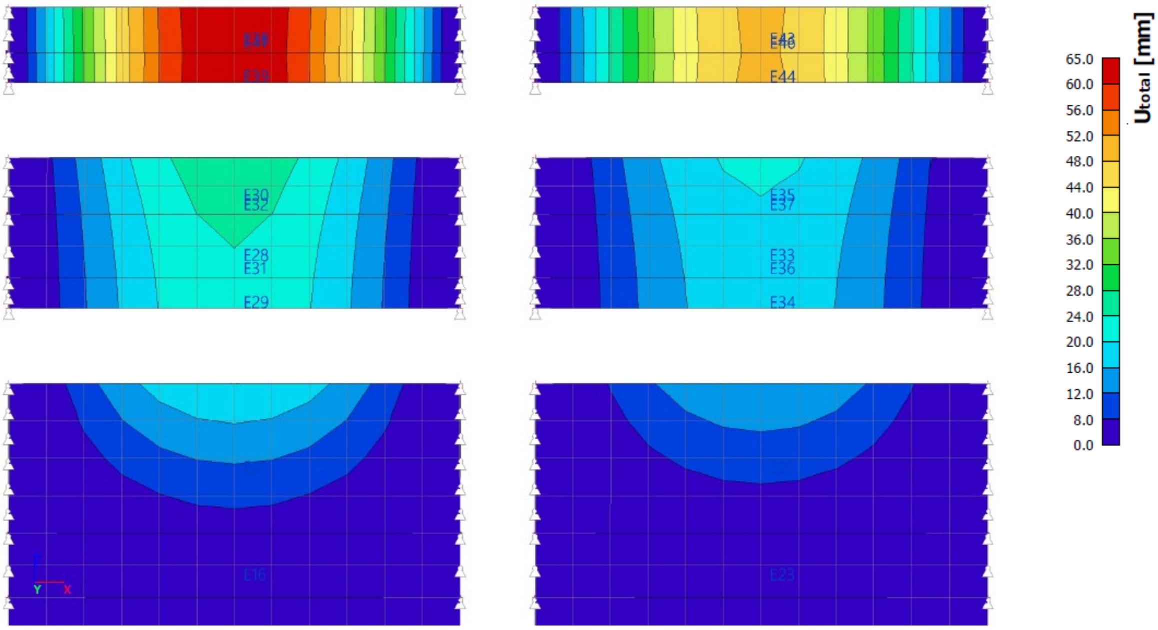


Figure 91: Results of the structural analysis for 1m, 2m and 4m high panels. Left column shows deflection when low Eflex is used, right column shows deflection when average Eflex is used.

Before the results were retrieved, several other analyses were conducted. Initially, 6 m long panels without shear webs were tested, showing excessive deflections of 126 mm for the 4 m high panels and approximately half of that for the 1 m high panels. Subsequently, 5 m long panels were tested, showing significant improvement, with a maximum deflection of around 60 mm for the 4 m high panel. Compared to the 6 m long panels, this reduction demonstrates how sensitive deflection is to changes in panel dimensions.

The shear webs were subsequently introduced, leading to above results. These emphasize the substantial bending stiffness that the shear webs provide. The 4 m high panel, which initially exhibited the largest deflection, now deflects the least because the shear web of this panel can be approximately 32 cm wide without exceeding the 'deflection' of the panel itself in the width direction. For the 2 m and 1 m panels, the shear web(s) can only be 16 cm and 8 cm respectively, making these panels less stiff. Additionally, the 1 m high panels will likely only possess 1 shear web to provide extra stiffness, where the 4 and 2 m high panels have two.

9.1.3 Structural analysis discussion & conclusion

It should be noted that the analysis was done with averaged material properties. While lower end values for flexural modulus were purposefully chosen to get conservative results, this averaging limits the analysis' reliability. However, based on above results, the retrieved 6 x 4 m and 6 x 2 m WTB panels are concluded to withstand an above average wind load if the shear webs are not removed completely (but partly). The shear webs have a large influence on the resistance of panels to deflecting in the middle. Consequently, the segmentation approach should include information about where the shear webs should be cut off. The 6 x 1 m panels are not able to withstand the same wind loads because they only contain one shear web with a limited width. Depending on the width of the vertical cassettes, the width of the shear web of these panels can be enlarged to provide more stiffness, presumably resulting in sufficient resistance to deflection.

9.2 Aesthetics and vegetation survey

Section 3.2.2 covers aesthetics considerations for both road users and residents. In this section, aesthetics and vegetation options for the noise barrier are proposed. Building on earlier ideas, a range of options regarding colour, vegetation and panel combinations are presented. Since continuity and harmony is important, this is dependent on its context of use: in a more urban- or rural environment. A survey was set-up and distributed among acquaintances of the researcher to gather insights on the preferred aesthetics in both contexts. The results are discussed and a proposal is done. Appendix K includes all questions and results. Because the results of the survey were quite similar for both contexts, they will be discussed per aesthetics aspect instead of per context of use.

Generally, the aesthetics of noise barriers is an important aspect for most respondents. The majority of the 25 respondents (18) experience noise barriers mainly from the road, whereas 7 respondents live near a noise barrier. Most respondents primarily encounter noise barriers in urban areas, and the age group is predominantly 18-34 (21). A final general note is that while some respondents mentioned they could appreciate well-done art works, a significant majority of the respondents (16) finds graffiti to not make noise barriers more appealing.

9.2.1 Vegetation

In both the rural and urban contexts, the presence of vegetation on or around noise barriers is highly valued by the respondents. The majority of respondents (15, 14) answered 'very important' on this question for respectively rural and urban contexts, while one respondent finds it 'somewhat not important' for rural barriers and 'not at all important' for urban barriers. Climbing plants (Figure 92 and Figure 93) are a clear preference for the way in which vegetation should be included on rural (14 votes) and urban (11 votes) barriers. Nameworthy however is that for the urban barriers, 7 respondents voted for the integrated planter box option. Additionally, multiple respondents answered differently, often pointing out their preference for a combination of the three options ('the more the better'), in both contexts. A few mentioned that this would enhance blending of the barriers into the surroundings.

Figure 92: The noise barrier design in a rural environment, with three vegetation options: climbing plants, integrated planter box and vegetation around the barrier. This can also be done on the resident side.

Figure 93: The noise barrier design in an urban environment, with three vegetation options: climbing plants, integrated planter box and vegetation around the barrier. This can also work on the resident side.

Because of the strong preference for climbing plants, this option is chosen for both contexts. However, it is important to try to separate the climbing plants from the WTB panels to prevent *durability* issues that might arise over the lifetime of the barrier. The wire grid for the climbing plants to grow onto should thus preferably be separated from the panels. The front flanges of the cassettes offer attachment points for such a grid. To prevent complicating the design, the integrated planter box in the top will not be chosen. Climbing plants have the potential to grow on top of the barrier as well, which can help to diffuse sound waves that would otherwise diffract. In areas where there is space, vegetation can also be planted around the barrier for better harmony and biodiversity.

9.2.2 Colours

The questions about frame and panel colours (Figure 94 and Figure 95) were answered very similarly for both contexts. Most respondents expressed a preference for a light green frame (14 votes for both contexts), followed by a dark green frame (10 votes for rural, 7 votes for urban). The other colours was barely voted for.

Regarding the panel colour combinations, the majority of respondents preferred the green gradient option (17 votes for rural and 13 for urban), while the green alternating was voted for 7 times in both contexts. The blue panel colour combinations were chosen just once for the rural barrier, and 5 times for the urban barrier.

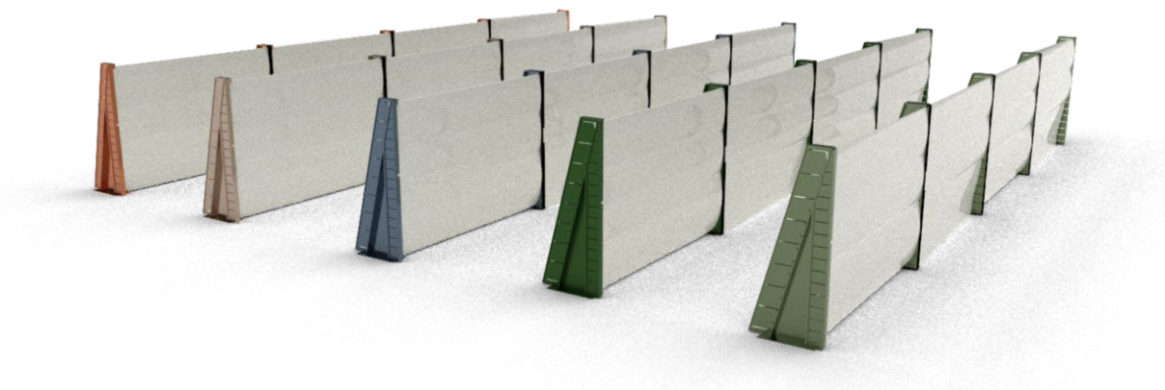


Figure 94: Colour options for frames. From left to right: red brick colour for blending in a location with close homes, a neutral taupe, grey-blue for a more luxury expression, and a dark- and light green, both to blend in well in more rural areas or green urban areas.

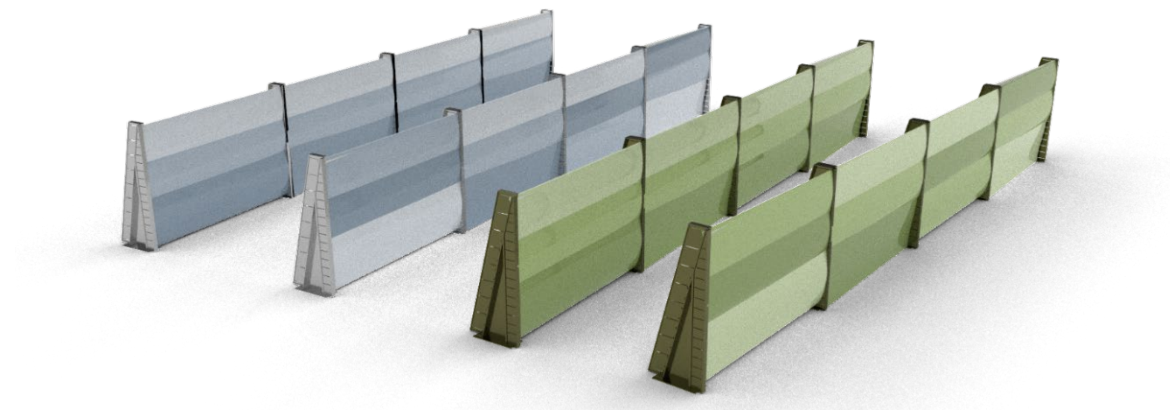


Figure 95: Neutral blue and natural green colour palettes, alternating or gradient.

The clear preference for a green colour palette can be seen in both contexts. Light green frames can be well combined with a green gradient panel colour combination, which is consequently chosen. This green gradient will likely only be applied to the resident side, as separate panels are used there. The front panel is chosen to stay white, because this side of the barrier should not be distracting (see section 3.2.2 and 3.2.3). Additionally, this saves resources. The application of coloured paint or coatings and accompanying required resources should be carefully considered. In locations where not many people will interact with the barrier, it might be unnecessary to paint the panels.

9.2.3 Panel combinations

The questions regarding panel combinations were answered similarly for both contexts as well. Respondents prefer all panels to be concavely oriented, whether it is an all 2 m high panel combination (option 1 (Figure 96), voted for by 9 respondents for the rural barrier and 6 for urban) or the 2-1-1 m panel combination (option 2, voted for by 12 respondents in both contexts). The 2-1-1 m alternatively oriented option (option 3) was only preferred by 4 respondents for the rural barrier, and by 7 for the urban barrier. As this last option was the only one to include protruding shear web pieces, this is likely the reason. As covered in section 8.1.1, this option allows for better panel alignment and fitting in the cassettes. Those aspects influence the functionality of the barrier, making them more important than aesthetic reasons. The panel combination will thus stay alternating. Additionally, as found in the structural analysis (see section 9.1), removing the shear webs of 1 m high panels results in too weak panels.

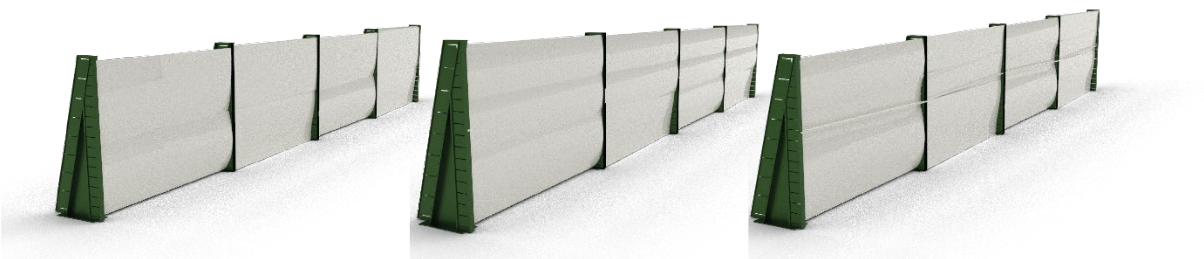


Figure 96: Panel orientation combinations. The leftmost (option 1) shows 2m panels all concavely oriented, the middle one (option 2) shows 2-1-1 m panels all concavely oriented, and the rightmost (option 3) shows 2-1-1 m panels which are alternately oriented, to enhance their alignment.

9.2.4 Integration of aesthetic choices

By use of in-context renders, this section shows how aesthetic design choices of above sections integrate into a cohesive concept in-context. Figure 97 shows the final choice for the colour palette. The perspectives of both residents / landscape users ‘behind’ the barrier as well as road users ‘in front’ are shown in Figure 98 and Figure 99 respectively.

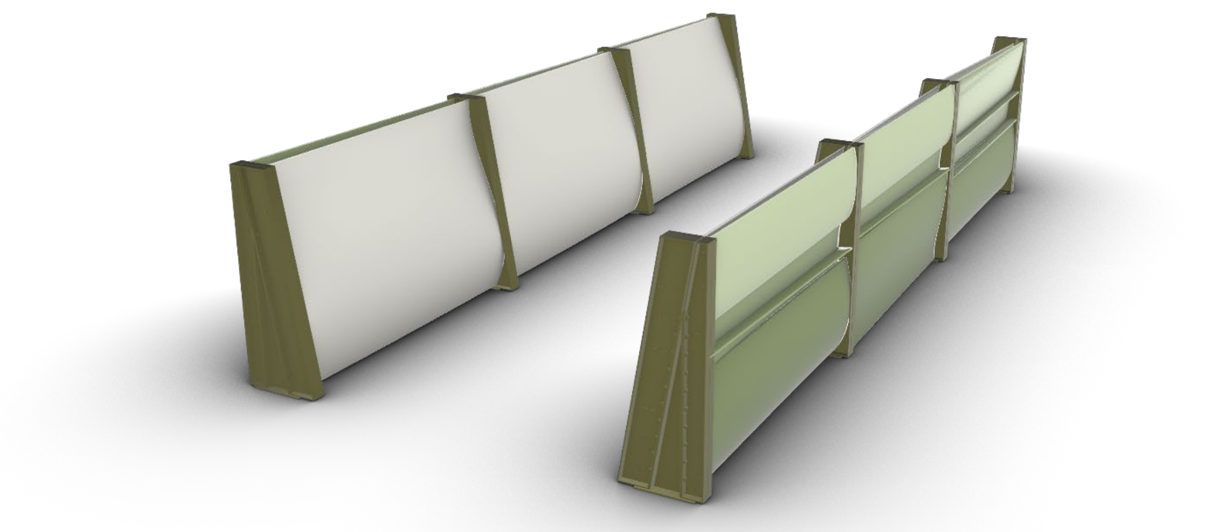


Figure 97: Final colour palette choice based on survey results.

Figure 98: Perspective of the residents or landscape users, showing the back of the noise barrier design with climbing plants and alternatively oriented panels.

Although the protruding shear webs can be seen from the perspective of the residents or landscape users, the barrier looks to fit in well when vegetation is placed around the barrier, and the climbing plants have grown.

Figure 99: Perspective of the road users of the road with the noise barrier design on both sides.

Though it is hard to determine from a still, the subtle variation of the curvature in the front panels is relatively hard to see from the perspective of the road users. This should be beneficial for the continuity of the design.

9.3 Takeaways

Structural analysis

- Retrieved 6 x 4 m and 6 x 2 m WTB panels can withstand an above average wind load if the shear webs are not removed completely. They have a large influence on the resistance of panels to deflecting.
- Retrieved 6 x 1 m WTB panels need to be analysed further with a wider shear web part still attached.
- The segmentation model should include where shear webs are cut off. The shear webs still need to fit within the cassettes.

Aesthetics and vegetation

- A significant majority of the respondents finds graffiti to not make noise barriers more appealing.
- Vegetation on or around noise barriers is highly valued by survey respondents, Who prefer climbing plants. A wire structure can be attached to the cassette front flanges to facilitate this, while also keeping distance between the vegetation and panels to prevent them from affecting panel durability.
- Green colours options for the frames and resident side panels (green gradient) are predominantly preferred by respondents.
- Aesthetically, panel combinations were preferred to be all concave instead of alternatively oriented. However, improved alignment of alternatively oriented panels was determined to be more important as this affects noise attenuation.
- The aesthetic choices integrate well into a cohesive noise barrier design, for both residents / landscape users as well as road users.

Discussion

This thesis proposes a novel design of a noise barrier, made from horizontally arranged, decommissioned WTB material. Key findings towards this solution are:

- Panel alignment issues can be tackled by informing segmentation approaches with a curvature limit for panels, in combination with adopting alternatively oriented, cladded configurations. Alignment seams can also be avoided, by using continuous (front) surfaces in the noise barrier.
- Variably shaped panels can be mounted modularly to facilitate (dis)assembly and maintenance, by adopting adjustable, reversible fasteners in cassettes.
- Opportunities for next lifecycle applications of the WTB material can be enlarged by using as large as suitable panels in the noise barrier design, and protecting the retrieved panels sufficiently against weathering.

This section provides a zoomed-out interpretation of above results, including their implications for the industry and research field, their validity and limitations.

Implications of findings

The findings are important because they are key to enabling structural reuse of horizontal WTB material in scalable and long-lasting noise barriers. Such barriers previously proposed were underdeveloped and not seamless and therefore not desirable. These findings thus contribute to the domain of structural reuse of WTB blades, by making a step towards realization of such barriers. This partly tackles the EOL waste problem of WTBs and reduces virgin material needs that eventually should result in a more circular society.

For the noise barrier industry, this project serves as an inspiration for (enlarging circularity by) using (EOL) composites, which has not been done extensively. Initial reactions from the industry players (LICHEN-BLADES) on the prospects of the design proposal were positive, and the researcher was given the opportunity to present to a broad audience at Heijmans. See Appendix M for the invitation.

Validity

As design is often a mirror of personal preferences or biases of the designer, some decisions may have been influenced by them. The design process outlined in chapters 4 to 9 is however mainly fuelled by findings from relevant research about WTBs and noise barriers, interviews with experts in both fields and visits to industry companies. This formed a comprehensive basis of arguments needed to make well-balanced design choices, which was referred to as much as possible to enlarge choice validity. A few important examples include the choices to 1) use a continuous front surface, for which acoustic expert M. Tenpierik and noise barrier experts (M. van Amstel, J. Grevelink, J. Peters and W. Groenewoud) provided the main input, 2) use a frame structure based on IPE or HEA beams to enhance modularity of the barrier, as proposed by J. Grevelink, lead engineer at Heijmans and 3) include part of the shear webs at the back of 6 m long panels to reach structural requirements, after a structural analysis done in collaboration with E. Nouwen, constructor at Heijmans.

Limitations

The goal of this project was to explore and point out the feasibility of a noise barrier made of WTB material, and provide a starting point for further development of it by the industry. Noise barriers have many integrated facets, of which a large portion is covered. Not all facets could be thoroughly covered within the allocated time of approximately 6 months, however. The time limitation required to exclude some factors and form a scope in the process. In addition to the time limitation, several limitations of the design process can be identified:

- The aim was to increase circular use of EOL WTB material and thereby improving sustainability. While steps have been taken towards reaching this first goal, an environmental comparison (e.g. LCA) to conventional noise barriers should point out if improving sustainability is an actual result.
- The design proposal is aimed to be applicable in a broad range of locations, while normally the locational context is an important factor for the design of noise barriers. This design thus should be adjusted to specific locations to adhere to important requirements, before application.
- Although the assembly process of the final design was discussed with a project manager at Heijmans, who approved it, the assembly process has not been tested with experienced noise barrier assemblers.
- While an exploration into protective coatings was done, the long term effects of resizing WTBs into smaller pieces on their durability are hard to determine.
- The proposals in the aesthetics and vegetation survey were made with subjective influences of the researcher. Additionally, it had 25 respondents, of which 7 live near a noise barrier. Both numbers are not very high, reducing the validity of the results. However, survey results do align with established sources proposing green colours and use of climbing plants, such as CROW (2012).
- Regulatory bodies such as Rijkswaterstaat will have an influence on the applicability of the design proposal. As (WTB) composites are not commonly used in the industry yet, regulation for these materials still needs to be developed (M. van Amstel, personal communication, December 9, 2024).

More limitations of this study, e.g. related to costs and the business case behind the design, that were not in the scope of the project, form recommendations that are covered after the conclusion.

Conclusion

To address climate change, clean energy sources like wind power are being expanded (Broadbent, 2024). The wind turbine blades used for this consist of a complex material combination, which complicates their EOL after 20-25 years of service (Beauson et al., 2022). As a strategy aligning with circular economy principles, structural reuse was determined to pose an interesting EOL option, by preserving material integrity and prolonging its lifetime. The scalable, long-lasting application of horizontal WTB material in noise barriers was found to carry potential, and this thesis covers the design process of a solution. Three research questions were identified as being key to answer during this process, of which the first one is:

How can wind turbine blades be segmented to obtain seamless fitting of the resulting panels to each other?

Several steps have been taken to answer this question. In section 2.4, the practical aspects of segmentation were covered. It is notable that there is not yet a (semi) automated way of cutting large numbers of WTBs into smaller pieces. During ideation (section 5.1.2), it was determined that deflection of horizontal panels due to curvature can be limited and similar to other panels if their height is set at a relatively low amount of e.g. 1 meter. Additionally, ideation and a concept iteration (section 7.1.1) pointed out that orienting panels alternatively concave and convex allows them to align relatively well when they have a small overlap. Finally, in section 8.1, a parametric segmentation model developed in Grasshopper Rhino pointed out the importance of aligning the leading edge as horizontally as possible, to allow for 90° angled cuts. When applied to a reference blade, this model yielded panels with a standardized height and limited curvature of $d/w<0.08$, suitable for use in a noise barrier with expectedly seamless alignment.

How can blade panels be mounted for noise barrier purposes?

To address this question, existing noise barrier panel mounting methods were analysed during site visits and at Heijmans (section 3.3). Many noise barrier designs make use of prefabricated modules, facilitating easy (dis)assembly, maintenance and interchangeability of filling materials. To this end, a cassette was developed (section 7.2.2) that can incorporate WTB panels with variable curvature. Another finding was that glass panels use non-invasive rubber fasteners, which are also suitable for WTB panels: these are non-invasive (preventing core material damage), fatigue-resistant, and allow for thickness variations that WTB panels will have. Based on these findings, section 5.1.4 outlines more fastener options that are also reversible, to allow for disassembly. Section 7.2.2 discussed a refined selection of fastening methods, including an adjustable rubber clamp and two bolt-based fasteners. These fastening and cassette mounting options were developed and evaluated in a prototype, leading to an adjustable clamp design that facilitates effective assembly processes and acoustic sealing. Overall, variably shaped WTB panels can be mounted modularly to support easy (dis)assembly and maintenance by integrating adjustable, reversible fasteners within cassette-based systems.

How to maintain opportunities for applications in next lifecycles?

Maintaining opportunities for subsequent material lifecycles largely relates to the segmentation approach and level of material integrity that is kept (section 2.4). Large WTB sections such as segments can be more broadly applied in a subsequent lifecycle than small panels. It was consequently a goal to use as much large panels as suitable, balanced with what was realistically functional for a noise barrier. Protecting exposed core materials after segmenting was also found to be an important step in maintaining application opportunities in next lifecycles (section 2.4). Epoxy coatings were identified as a solution, for which an explorative test was done on differing core materials, to evaluate their uptake and ease of application (section 8.3).

The answers to the research questions have contributed to the development of a noise barrier design using horizontally aligned WTB panels. This thesis' design process furthermore provides valuable insights into the application of WTB material in noise barriers, integrates aesthetic features to add value to the environment in which it is located and highlights areas for further research. Combined, a functional, feasible and desirable design is presented. Recommendations for further research and development can be found on the following page.

Recommendations

Research gaps

During the research phase of this projects, several knowledge gaps in available research were identified, or further research should be done:

- Acoustic research on recovered WTB material is not largely available, apart from Neuman (2024) which tested transmission loss to be less than conventional materials. The lack of this research complicated forming requirements for the noise barrier of this material.
- Structural research on recovered WTB material now mainly cover spar caps. While these are the most relevant, sandwich panels should still be researched.
- The environmental implications of reusing WTB material in noise barriers are not yet clear. They should be evaluated in comparison to conventional noise barriers (e.g. through LCA) to determine the effectiveness of such a project.
- Coating options for the exposed core materials have to be further researched to ensure they are environmentally safe in noise barrier applications.

Design gaps

The proposed design is not finished. A few relevant development steps are:

- Further embodiment design is needed to produce the cassettes and frame component. The cassettes are likely suitable to be made from aluminium, while the frames are likely made of steel. Subsequently, user tests should be conducted on the assembly process with experienced noise barrier assemblers.
- After further development, an acoustic test is essential to validating the functionality of a WTB material noise barrier, including more thorough analysis of reflection patterns off the front surface, and research into a T-top addition.
- The parametric segmentation model can be improved by making it more easily applicable to other WTB types than just the NREL 5MW reference blade. A professional coder should develop it if such a model is used in reality. Implementing it into a cutting strategy also requires further development of e.g. 3D scanning systems and adaptable and efficient cutting processes. Interesting partners for this might be Vlasman, focussing on circular demolition of infrastructure, Blade-Made, an architectural firm focusing on structural reuse of WTBs, and Business in Wind who focus on decommissioning WTBs.
- The integration of safety features such as doors should still be demonstrated. This can however be as simple as placing a door between two more closely placed frame structures.

Noise barrier industry

- The design proposal has not yet been evaluated on costs. Due to enlarged preparatory needs and the novelty of this design, costs are expected to be higher than conventional noise barriers. The main driver behind such a project should be sustainable goals such as reducing virgin material needs, preventing premature material loss, or a better ECI (MKI) indicator (Hillege, 2024).

- In 2027, larger amounts of WTBs will be decommissioned. Enercon E66's will be decommissioned frequently onshore, while mainly Vestas V80 and V90 will be decommissioned offshore. These models could thus be interesting to consider for a noise barrier project.

Wind industry

To ease structural reuse initiatives, the wind industry should aim for minor, effective changes to their WTBs. In this design process, these would have been valuable:

- Indicators of where the far ends of the LE & TE are located, to make sectioning steps easier.
- Enlarged availability of (simplified) CAD models. The complex shape and material composition of WTBs are hard to imitate without reference.

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Appendices

Appendix A

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		IDE master(s)	IPD ✓ DfI SPD
Initials		2nd non-IDE master	
Given name		Individual programme (*date of approval*)	
Student number		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	The members of my supervisory team complement each others expertise. Ruud brings years of experience in circular product design and sustainable design knowledge, while Israel's expertise focusses on specifically reuse of WTB materials. He also has an extensive network in this field.		

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

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

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

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

Sign for approval (Chair)

Digitally signed by Ruud Balkenende - IO
Date: 2024.09.24 18:17:40 +02'00'

Name	Ruud Balkenende	Date	24 Sep 2024	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)

K. Veldman Digitally signed by K. Veldman Date: 2024.09.26 13:17:40 +02'00'

Name K. Veldman Date 26 Sep 2024 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: 2024.10.01 09:21:13 +02'00'

Name Monique von Morgen Date 1 Oct 2024 Signature

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Ruben Gabriëls **Student number** 4,869,176

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Design of a highway noise barrier from reused 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)

To tackle the climate change challenges that the world is presented with, sources of clean energy must be further developed and scaled. In 2023, 7.8% of the world's electricity was generated by wind turbines, which has more than doubled since 2015, when this part was only 3.5% (Broadbent, 2024). Wind turbines thus play an increasingly important role in the energy transition. To make them efficient, developments in wind turbine blades (WTBs) focus on making longer blades, made of low density but highly stiff materials. These are mainly fibre reinforced plastics (FRPs), with termosetting polymers (Chen et al., 2019). The service life of WTBs is generally 20-25 years, and the end-of-life (EOL) presents a challenge as the current options either result in the loss of all the material value (landfill and incineration) or part of the value and / or are not industrialized yet (various ways of recycling) (Larsen, 2009, Chen et al., 2019). The value of the material is captured in the stiff, lightweight potential which can be retained and exploited to an optimal extent in structural reuse applications, which fit in the circular economy (as presented by the Ellen Macarthur Foundation).

Consequently, research into how structural reuse applications can be designed from decommissioned WTB composites is interesting for wind turbine manufacturers to recapture material value. More importantly, it is in the interest of environmental protection and resource conservation to prevent landfills, incineration and poor recycling, and promote reuse of this growing material stream. Organizations such as BladeMade and the Re-Wind Network operate with this latter goal as their mission, as well as the research consortium LICHEN-BLADES of TU Delft. Infrastructural developer Heijmans is part of this consortium and they execute their projects with ecology and sustainability as core principles (Heijmans, n.d.). They see value in using decommissioned WTB material for highway sound barriers. This application is interesting for its scalability and because WTB composites posess advantageous acoustic properties. Replacing virgin materials by reused WTB material can make a significant impact on the WTB waste stream and virgin material needs.

The above organizations have proposed several sound barrier concepts made with vertically arranged WTB segments. Horizontal arrangements have not been extensively explored, nor has the use of panels rather than blade segments. In doing so, there is an opportunity of developing a blade barrier that dampens sound, adds environmental value, and allows for subsequent material life cycles.

➔ *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)

Organizations that try to reach valuable structural reuse applications for decommissioned WTB materials have the problem that WTB sandwich structures cannot be reshaped, and their curvature and size differ per segment. The shapes of these segments thus limit the design freedom for possible applications in a second life cycle. Especially when making horizontally arranged assemblies of multiple segments, this becomes a challenge, as joining and fitting them together is hard.

For sound barriers along highways, this problem is not only related to connections and joints, but also to the amount of noise they reduce. Gaps and openings allow more sound to pass through, reducing the effectiveness of the barriers. A horizontal arrangement of blade panels has yet to be demonstrated in constructing a sound barrier without gaps, but doing so has the potential of better retaining the structural integrity of the blades for potential third lifecycles.

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:

Develop an assembly plan with accompanying prototype to demonstrate the feasibility of highway sound barriers made with decommissioned wind turbine blades that are arranged horizontally.

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)

Research questions to be tackled during my graduation project per phase: Analysis & Context: What current problems with WTB highway sound barrier concepts need to be tackled? How are WTB materials made available and suitable for reuse, and who supplies them? Who are relevant stakeholders? How does sound reduction work? [Interviews, online research]

Defining criteria: What can I learn from existing sound barriers? What are important considerations, criteria, limitations and standards for them? How can the barrier create added value for the direct environment and residents? [Interviews, site visits, online research]

Ideation & Develop: How can blade segments be neatly arranged and connected to each other, as well as to frames? How are the frames designed and what kind of foundation is needed? How to assess the lifetime as a barrier, and what are possibilities for a third lifecycle? [Brainstorming, sketching, interviews, harris profile, weighted objectives, prototyping, testing]

Detailing & validation: How is the barrier produced and constructed? Does the design comply to structural and safety standards? Does it reduce noise? Does it bring added value to residents and environment? [Prototyping and testing, CAD simulations, interviews / 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	5 Sep 2024
Mid-term evaluation	14 Nov 2024
Green light meeting	23 Jan 2025
Graduation ceremony	19 Feb 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	10
Number of project days per week	4,0

Comments:
I would like to work for 1 day per week alongside my GP, for 10 of the project weeks. The rest will be full time.

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).

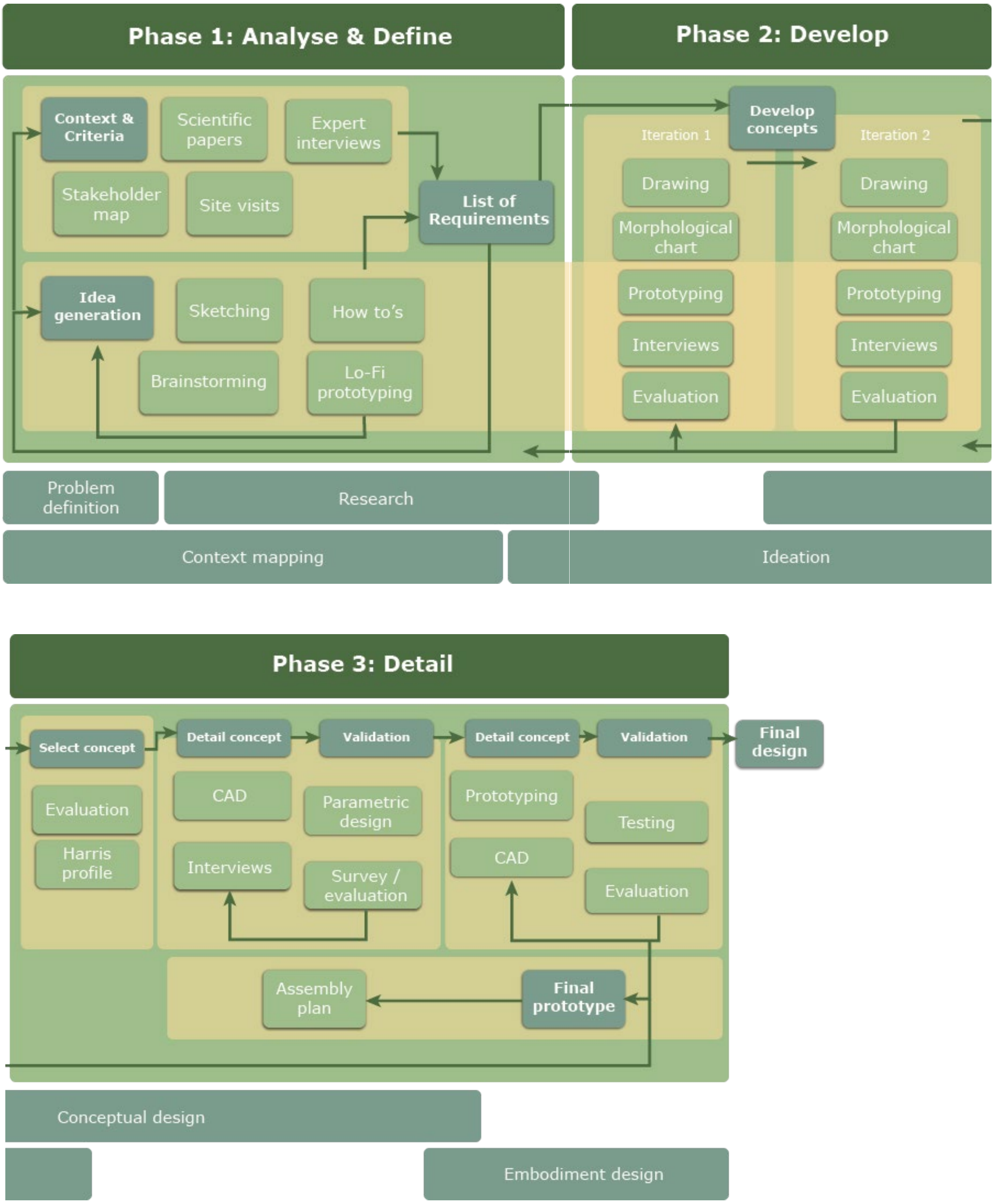
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or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

Since the introduction into the circular economy design principles in my bachelors study, sustainable design through circular products and systems has interested me a lot. With the goal to specialize myself towards this field, I therefore extended my elective semester to follow master courses like Repair, ECAM and Sustainable Business Models. Development of EOL strategies and designing with these in mind motivate me (which is the primary goal of setting up my project) and also play into my other interests as a designer. These are prototyping and testing, and manufacturing processes. They challenge me to work with both my head and my hands through diverse tasks, in which physical materials are present. This project already starts with a specific application and material stream. Consequently, the 'fuzzy front end' of the design cycle can be of less importance, so I can focus my contributions mainly on designing details, prototyping and testing and activities that contribute to a next step in realising WTB sound barriers.

Throughout this process, I expect to gain extensive knowledge about the specific topics of wind turbine blades, thermoset composite materials, reuse of big waste streams and designing in an infrastructural setting. This contributes to orient my design career further into the circular (product) design field.
Some personal ambitions that I have are that at the end of the project I will have a physical prototype or demonstrator product that shows what my graduation project has contributed to this research field. Also, I want to focus on time management in this big project, as I can be perfectionistic about things that do not immediately require perfect outcomes.

Appendix B

Methodology



Appendix C

Acoustics theoretical background

Noise attenuation requirement

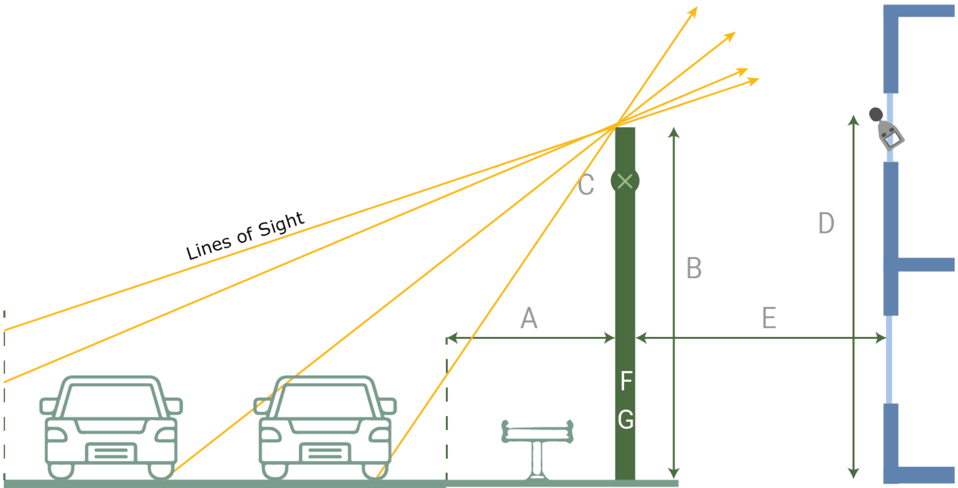
The 'barrier performance' ***ΔLsw*** is determined through acoustic research at a certain location and sets the base for the requirement of sound isolation reached by the barrier. It will be highest at homes that are close to the road. In this research, an assumption is made that transmission of sound through the barrier is negligible, which is achieved when the sound isolation is 10 dB higher than the barrier effect. An extra amount needs to be added to compensate for a reduction in performance over the lifetime of the barrier. Generally this can be 3 dB, but should be determined per barrier (CROW, 2012, p.15).

The barrier performance on noise attenuation has to be tested in an isolation chamber in its final state, i.e. how it will be placed along the road with all details. However, as Table 11 shows, if the barrier has a front surface weight of more than 40 kg/m2, the isolation chamber test is not necessary as the weight is assumed to provide a 25 dB or higher ***DLr***. Using Table 2, the front surface weight of LE&TE panels ranges from 14,5 to 28,8 kg/m2. For spar caps, this is between 33 and 77,3 kg/m2.

Table 11: Sound isolation achieved on the basis of front surface weight (CROW, 2012).

40 kg/m² < oppervlaktegewicht < 100 kg/m²	$DL_R \geq 25$ dB
oppervlaktegewicht ≥ 100 kg/m²	$DL_R \geq 30$ dB

Factors influencing barrier performance on specific location



A Position in the road's cross-section
B Height of the barrier
C Length of the barrier (along road)
D Height of the destination
E Distance to the destination
F Design of the barrier
G Acoustical properties

Figure 100: Factors influencing the sound isolation of a noise barrier. Illustration based on CROW (2012).

Factors A to E all influence the possible lines of sight between the road and the receiver. For example, it can be imagined that a change in the dimension A results in a narrower or broader field of possible lines of sight: the closer the barrier is to the road, the more sound waves it will block. An increase in height (B) also reduces the possible lines of sight. Height increase is a good way to improve the performance of a noise barrier, but it also increases the structural requirements: it will be heavier and needs to withstand higher wind forces.

The length of the barrier (C) depends on the area that needs to be protected from road noise. The height of the destination (D) depends on the point of measurement and cannot be adjusted in the barrier design. It is thus a factor that determines the requirements for the barrier. Factors A to E are all dependent on the specific locations in which the barrier will be placed. Finally, factors F and G are closely related and mainly influence the airborne sound isolation that the barrier realizes. These variables are what this project will mainly cover. With the situational aspects addressed, these factors will now be examined in greater detail.

The acoustical properties of a noise barrier (G) can be described by analysing the way in which it influences the road noise. Sound can end up behind a noise barrier in three ways (see Figure 101). In principle, the effect of these three on the receiver needs to be reduced: transmission, diffraction and reflections on the opposite road side. Another important occurrence here is absorption of sound in the barrier. In many barriers (not all), the aim is to maximize the absorption.

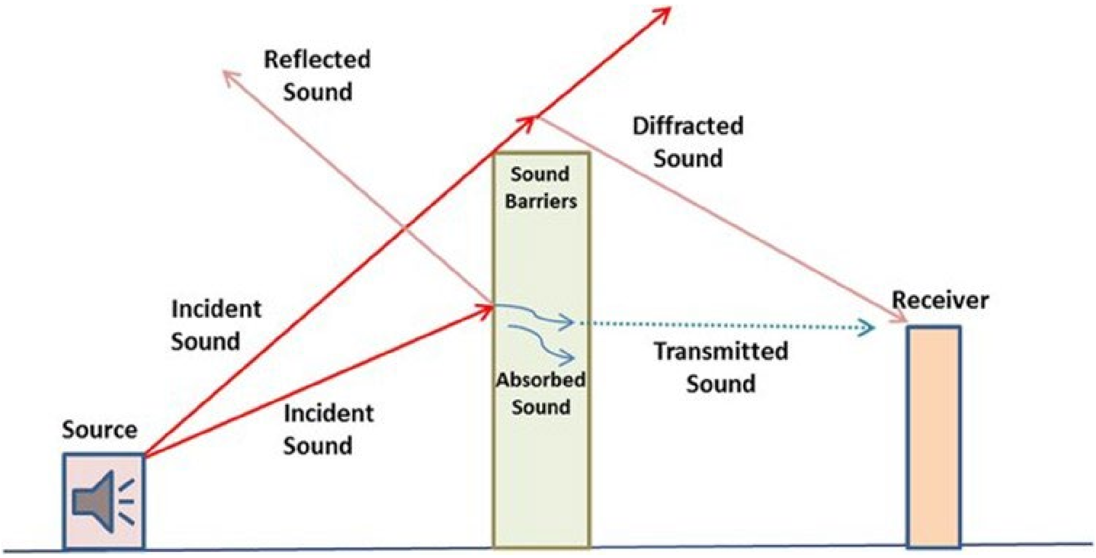


Figure 101: Different ways in which sound may act and travel around a road with a noise barrier (Laxmi et al., 2021).

Theoretical background on sound wave physics

Reflection

The amount of reflection is influenced by the surface of the material. Hard, smooth materials such as concrete, metal or glass are highly reflective, whereas soft, porous materials like foams and mineral wools reflect only a small amount of sound, but do absorb a lot of it (University of Cambridge, 2021). The direction of the majority of the reflected sound depends on the shape and tilt of the barrier. This is because the angle at which the sound reflects will be the same as the angle with which it approached the material (Halliday et al., 2017). Consequently, if the barrier is tilted backwards somewhat, the sound will reflect in more upwards directions. Accordingly, it can be imagined how sound reflects off of any of the barrier shapes depicted in Figure 102.

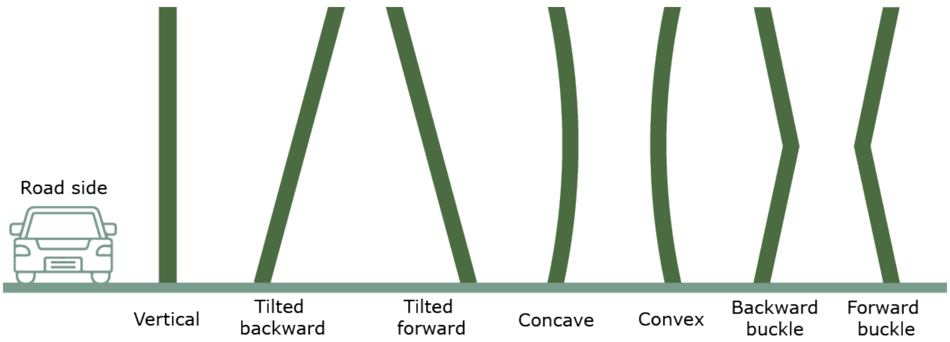


Figure 102: Barrier shapes and orientations. Own illustration based on CROW (2012).

The concave and convex shapes need some extra attention, as the panels that will be salvaged from the WTBs will often have similar cross-sections. As can be seen in Figure 103 the reflections on these shapes either spread it out (convex) or focus the sound into one location (concave)(Wulfrank et al., 2014).

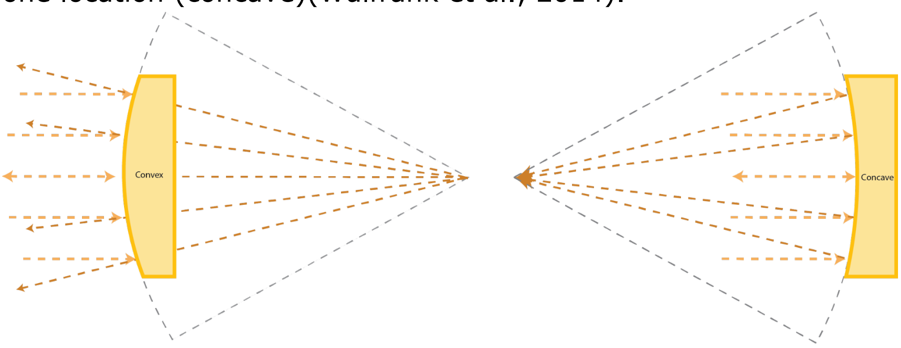


Figure 103: Convex and concave shape with similar radii reflect sound coming from the left side. Convex spreads out the sound, while concave focusses it into one location. Own illustration based on (Keeley & Keeley, 2021).

Reflected sound can travel over the noise barrier at the opposite end of the road, creating an extra noise source for the area behind that barrier (CROW, 2012). This should be prevented which is why the aim is initially to reduce the amount of reflection of a barrier. In some situations, however, this cannot be avoided. An example is when the barrier needs to be made of glass to provide road users and residents with a view of the other side. Glass reflects almost all the sound, so these barriers need to be tilted backwards to ensure that the sound reflects into an upwards direction, where often there will not be a receiver. This method is quite effective in many cases, so it has also been done with other hard and smooth materials. Since WTB material is also hard and smooth and absorbs almost no sound (Neuman, 2024), a reflective barrier that is tilted backwards seems like an interesting direction for the design of this project.

Diffraction

Diffraction can be defined as the redirection of waves around a corner or gap (Szabo, 2004). It is the phenomenon that makes it possible to hear sound that comes from other locations that are not directly in your line of sight. Waves hitting edges or passing through small gaps will start to act like a second sound source, redirecting them, including to the area that should be protected (Figure 101). This also happens at edges in the barrier itself. This is an important consideration for alignment of panels: the more edges there are, the more diffraction that will happen.

Diffraction happening at the top should be minimized, since this source is often the principal way that sound will travel into an unwanted direction behind the barrier (M.

Tenpierik, personal communication, November 26 2024). Tenpierik noted that this can be done effectively by rounding the top edge and / or using vegetation near the top edge to diffuse the sound waves.

Absorption

Absorption is defined as the decay in sound wave energy as the wave passes through a material with a given thickness (Shrivastava, 2018). As briefly explained above, reflection and absorption generally have an inverse relationship. Soft and porous materials absorb a lot of sound, because of their discontinuous nature and surface area. Sound waves become 'trapped' in the pores of the material, where they dissipate into heat (Paris, 1927).

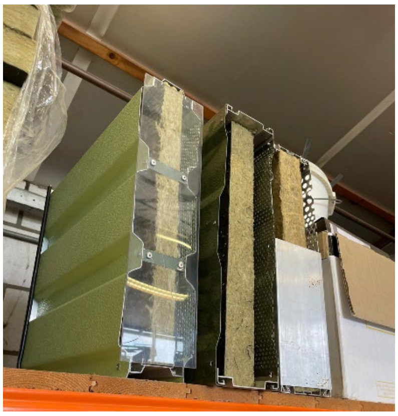


Figure 104: Examples of cassettes containing rockwool and perforated sheets.

In principle, absorption should be maximized in noise barriers to minimize the amount of hindering reflections and transmission through it. Absorptive barriers often make use of glass wool, mineral wool, or other panels specifically designed to absorb sound (Bendtsen, 2010). Around this material, perforated aluminium sheets are placed to protect it and at the same time trap the sound waves that travel through the perforations, into the absorptive panels (Figure 104).

Transmission

Sound transmission refers to the propagation of sound through a medium (Cheung, 2001). Transmission behind a barrier occurs when sound waves pass through the material, losing some of its energy along the way through absorption, but still propagating to the other side (Figure 105). Transmission loss accordingly refers to the decrease of energy of the transmitted sound, in dB (Parsekian et al., 2018). Transmission should be minimized. Gaps and openings may therefore be only negligibly small. It can also be done through increasing the mass or thickness of the barrier. An increase in layers of material also works well. Sound moving from one medium to another that have differing acoustic impedances (e.g. air to composite laminate), will partially reflect and partially transmit through the material (Oelze, n.d.). The greater the difference in impedance, the greater the amount of reflection and lesser the amount of transmission.

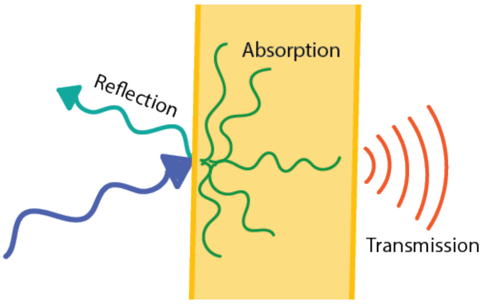


Figure 105: Illustration on how sound waves interact with materials.

Appendix D

List of Requirements

Table 12: List of Requirements

Category	Requirements	Comments	Keywords
Overall	The lifetime of the compartment filling of the noise barrier needs to be at least 30 years.		lifetime, durability
	The lifetime of the frames and foundations need to be at least 50 years		lifetime, durability
	At the start and end of the noise barrier, the vertical height of the barrier changes gradually, or has more tightly placed frames.	Improves road user experience, structural aspects.	gradual heightening, user experience
Safety	The noise barrier does not act as a guard rail: traffic directing measures are separately set-up. The barrier needs to be protected by a guard rail.	No integrated barrier	safety needs
	An eventual T-top like construction may not extend out towards the road over the guard rail.		
	Flight doors may not be further apart than 400m and have to be clearly indicated every 100m.		safety needs
	Fire mitigation efforts need to be added sufficiently to prevent the spread of fires.		Fire, safety
Acoustics	The noise barrier needs to reduce highway noise volume by 25 dB (category B3)	See section 3.2.1	Noise reduction
	The noise barrier needs to be a gap- and hole free construction		Noise attenuation
	Aspects of detail may not reduce the sound reduction of the barrier by more than 5 dB	Regarding dilation seams, drainage slit, doors, etc.	Details
	Drainage slits under the construction are only admitted if sound transmission through the slit is negligible in regards to sound that diffracts over the top of the barrier		drainage slits, noise reduction
Construction	The fasteners need to withstand 100 million load cycles of differing wind loads, as defined in the ROK		construction standards
Assembly	Assembly of 300 m of the noise barrier design may not take longer than 8 weeks.	Average assembly time	Assembly time
	Cutting / sawing and post-processing of the wind turbine blade material needs to be done safely and with sufficient measures to protect people and environment.		Safety during assembly
Use	The noise barrier design needs to be adaptable to safety needs such as emergency exits or flight routes, and different surroundings such as bridges.		safety needs
	The noise barrier makes use of replaceable or exchangeable sub-assemblies: can be interchanged (e.g. when damaged)		panels, interchangeability
	Vegetation needs to be kept within limits, to prevent extension over the road surface or block sight of flight doors.		Maintenance
EOL	The design of the noise barrier needs to allow for at least 1 subsequent lifecycle of the WTB material		third lifecycle

	The noise barrier design needs to allow for manual and mechanical dis- and re-assembly		end of life, disassembly

Category	Wishes / criteria	Comments	Keywords
Overall	The noise barrier reduces as much highway noise as possible	Most important	noise reduction
	The noise barrier design allows for a wide range of possibilities in subsequent lifecycles		circularity
	The assembly of the noise barrier can be carried out quickly	Most important	assembly
	The noise barrier can be placed in as much as possible locations		location specific
	The costs of the barrier should be in the ballpark of normal barriers, and in relation to the innovative and sustainable nature of it	Not 'as cheap as possible': not realistic	Costs
	The noise barrier should be modular in such a way that it facilitates adaptation of the design to changing local requirements	Since lifetime may be >35 years	Adaptation to ageing
	Special elements in the landscape (e.g. church towers) still have to be recognisable from the road, for road users to orientate themselves		orientation
	The noise barrier design should prevent material degradation during use		material integrity / degradation
	Anticipate and enable changes and adjustments that might be made to the product during successive lifecycles		Adaptability
	Use connections / fasteners that can be accessed, opened and reused where appropriate	Connection selection	
	Combine multiple components and functions into one part, that is accessible, removable and interchangeable, to simplify repair		Modularity, function integration
	Select coatings that are appropriate for use, reuse and reprocessing	Trade-off: extending lifetime vs. recovery	Coating selection
	A smooth barrier surface is preferable to prevent escalation of accidents, when vehicles crash into the barrier.		Safety
Experience	The noise barrier adds value to the environment in which it is placed (residents, natural environment)		Experience
	For road users, the noise barrier should contain some variety, but has to be observable without effort	Variation every 300-400m	Experience
	The noise barrier fits into the TAG and VRA guidelines of the specific location		Experience
	The noise barrier reduces the feeling of cramped space as much as possible on the road side		Experience
	The noise barrier compensates the loss of field of sight by through aesthetic value on the resident side		Experience
	The noise barrier contributes to a socially safe environment		Experience

Appendix E

Reducing transmission – double walls ideas evaluation

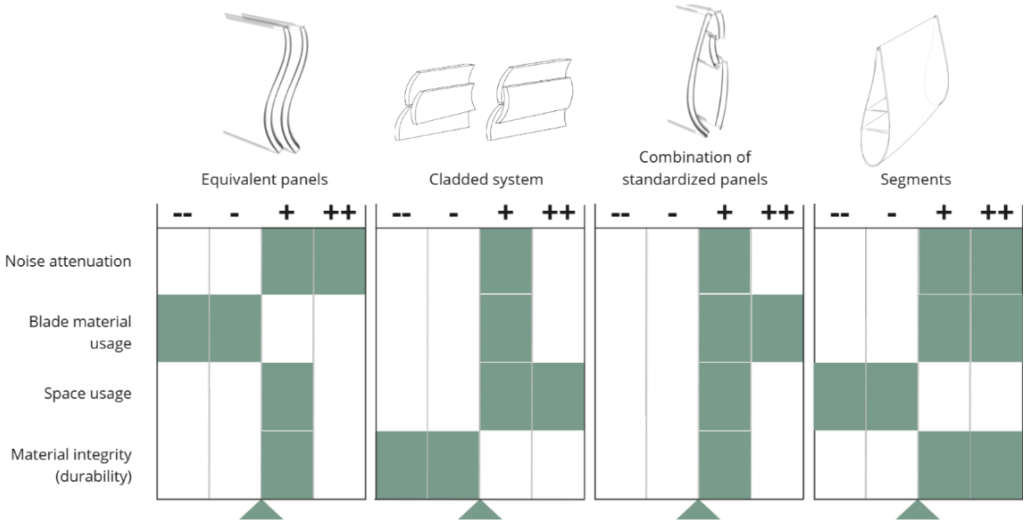


Figure 106: Harris profile with relevant criteria ratings for three panel-based ideas for double

Because the segments idea and equivalent panels idea have large continuous surfaces, they are expected to perform better on *noise attenuation* than panel combinations such as the cladded system or combination of standardized panels, as they will have alignment seams because they use smaller panels.

However, the noise attenuation advantage of equivalent panels diminishes when this idea is used with smaller panels: they will still need to be stacked, forming alignment seams. This is also the case for small segments that need to be stacked to reach a common height. Their *blade material usage* may thus not be very good: a balance should be found between these two criteria. The cladded systems and combination of standardized panels ideas do score well on this criteria, as smaller panels or a range of sizes of panels can be retrieved from more parts of the blade than just large continuous pieces that span the height of the barrier (e.g. 4 m).

Space usage in the width direction is also an important criteria for the double walls. The panel combination ideas (equivalent panels, cladded systema and combination of standardized panels) require less space than the segments, since they can be placed more closely together. Equivalent panels score best on this as matching curved panels can theoretically be placed next to each other with a very small air gap between them. This is a bit more challenging for the cladded system and combination of standardized panels.

Finally, *material integrity* (*durability*) is an important aspect as well. Segments score very well on this as they require the least amount of resizing. The equivalent panels and combination of standardized panels score relatively well, as these make use of large panels as much as possible. The cladded system options scores worst on this criteria as it uses mainly smaller panels, requiring the most amount of pre-processing.

Appendix F

Noise attenuation performance ratings

For the amount of reflection and absorption, the surface texture (at small scale, in size orders of the cells of a porous foam) of the material is dominant, which will not differ between segments or panels. The absorption coefficient is likely the same or closely similar. The direction of reflected waves is however determined by the front surface shape of the assembly and continuity of this surface, which does differ between the two.

When using segments, the bottom part of the barrier will always curve towards the road concavely (Figure 107), which reflects sound waves into the ground or road surface that could increase noise levels on the other side of the road. A concept using panels has a higher degree of control over the angle at which sound waves are reflected and can have a lower variance in front surface shape and angle.

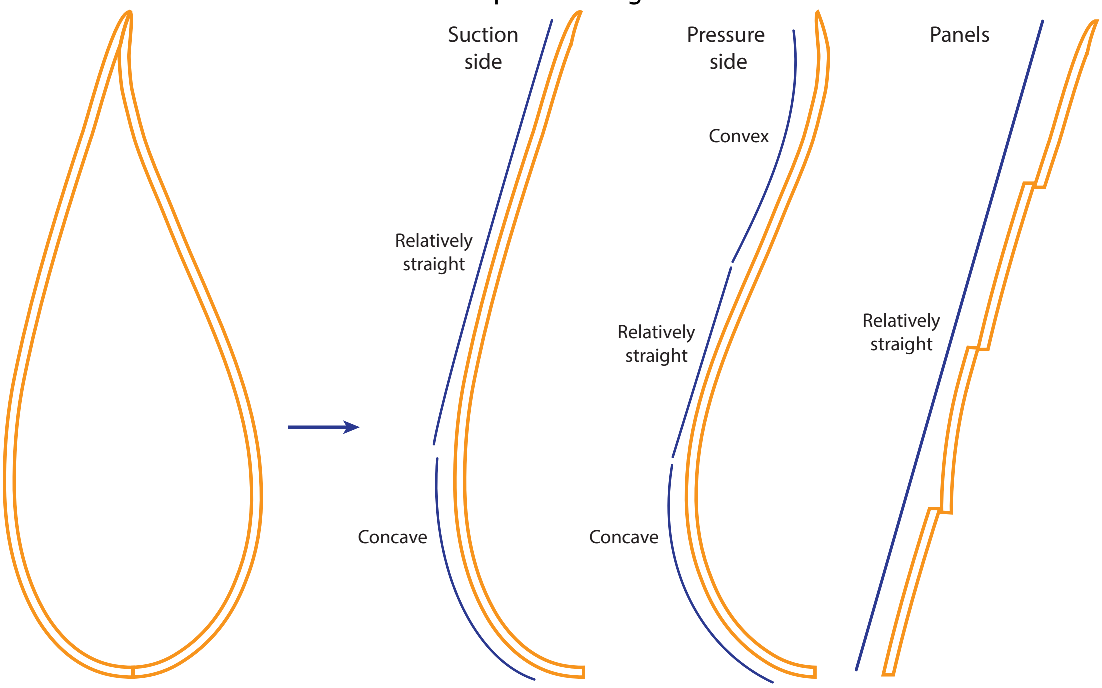


Figure 107: Front surface shapes of the suction- and pressure side of segments, and of 4 panels in a column. The road is located at the left of the image, where sound will come from.

The external properties related to transmission and diffraction are also influenced by surface continuity. For transmission, one internal property might play a small role: the average weight per square meter of front area of the assembly will be slightly higher for segments than for panels. For diffraction, also the shape at the top of the barrier will have an important influence (M. Tenpierik, personal communication, November 26, 2024). Additionally, sharp edges in the barrier's front surface will increase diffraction.

Appendix G

Concept evaluation reasoning

Segments concept

Using large segments offers advantages in *durability* and *noise attenuation*. Their double-wall construction improves material integrity and longevity because a low amount of sawing operations are needed. Additionally, their continuous surface enhances acoustic performance. Large segments also allow for relatively fast assembly due to fewer components, and their subtle variation in expression can enhance aesthetics.

However, these benefits come with drawbacks. The variability in width and height of large segments complicates modularity, as multiple types of frames may be required and segments are hardly interchangeable. Furthermore, the widest segments create space challenges, as barriers of almost 2 meters wide are generally undesirable (the widest segments retrieved from the NREL blade are 1,8m wide). This width also needs to be covered up on their sides to ensure noise attenuation performance, which is not aesthetically pleasing without cutting those pieces in the same cross-sectional shape as the segments themselves (Figure 108). The weight of segments may require stronger support structures with increased structural requirements, and levelling and aligning smaller segments is a challenge.

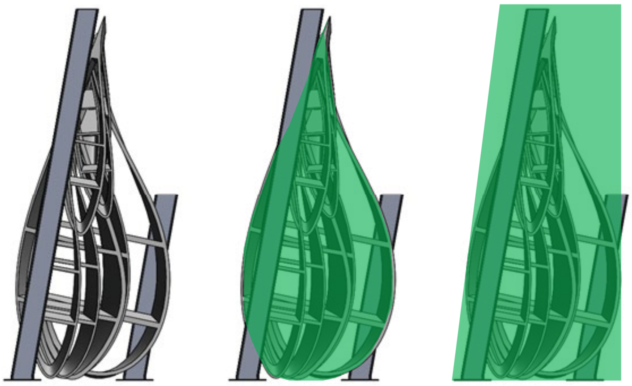


Figure 108: Three side views of the segments concept, showing its variable width and open sides of segments that need to be covered up for noise attenuation.

Panels concept

On the other hand, smaller panels are easier for standardization and flexibility. Using panels reduces the overall width of the barrier because their curvature and deflection can be reduced to adhere to a requirement, which makes them more practical for many locations. By using standardized fasteners and frames within the concept, these panels are easier to assemble into a modular system. Their continuity offers a neat aesthetic and provides a flat front surface, which is preferred for safety. There is space for additional noise-absorbing material between panel columns, potentially enhancing noise attenuation.

However, this approach increases assembly time due to the complex alignment of multiple panels and larger number of fasteners. Sawing the panels may compromise material durability and thus require more preprocessing with coatings on sawing edges. Additionally, while individual components are lighter, the overlapping materials required for modularity may increase the total weight.

Appendix H

Frames ratings

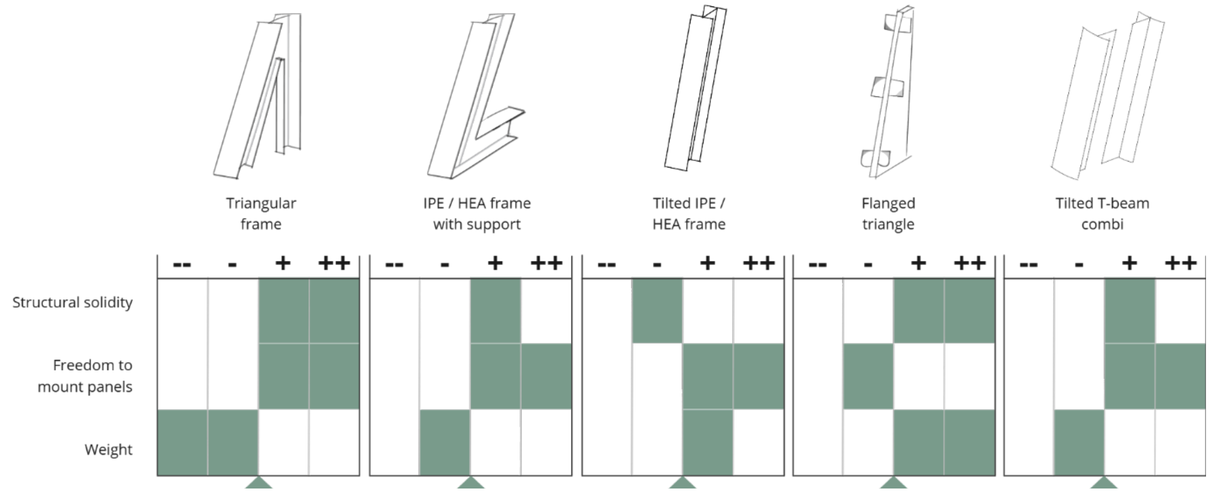


Figure 109: Presented and updated frame structure options in the morphological chart from section 5.2.

The structural solidity of the frames were rated for their likelihood of durable support of the panels. Since the front panel is tilted, a single tilted beam without vertical support (such as the tilted IPE and T beam options) are deemed to carry this weight in a less durable way, since larger moments will have to be carried at the base of the frames as compared to a frame with vertical support, such as the triangular frames (triangle frame and flanged triangle). The horizontal addition of the IPE / HEA frame with support option does help to counter this moment, but is more likely to corrode in the (sharp) corner.

The freedom to mount panels ratings are based on the surface area and amount of flanges in both horizontal and vertical axes. Since all the frames except the flanged triangle are proposed to consist of an IPE-like or H-like shape, the flanged triangle is the only frame scoring low on this criteria.

Finally, the weight ratings are determined by assuming the frames are equally high and use equally thick flanges of steel. The flanged triangle is then the most lightweight, and the next heavier one is the tilted IPE frame. The tilted T-beam combi uses an additional flange in the width, and the IPE / HEA frame with support has an additional support frame part, so they are heavier again. Finally, the triangular frame is the heaviest because of the full vertical IPE-frame like part.

Appendix I

Parametric segmentation model steps

The NREL 5MW blade was used as reference to build the parametric model, since this blade is representative for both onshore and offshore application (Resor, 2013). A parametric model that is capable of adapting to various WTB models requires the identification of common geometric features or reference points of a WTB. This was aimed for as much as possible. The reference points serve as anchors for the parametric model to work with. The initial input should be a 3D blade model (boundary representation) without the inboard section, which is removed as it will likely not provide interesting panels (see section 2.2.2). Additionally, the scale, orientation and preferred panel length should be put in.

To enable curvature analysis of the pressure- as well as suction side of the blade, the first step will be to cut the blade in half over its length. This is done by finding the curves that follow the leading and trailing edges, as well as curves that follow the middle height of the shear webs (Figure 110). Because of the twist in the blade, both edges and especially the TE are not straight. An offset curve is then made from the leading and trailing edge curves, to ensure that the following surface cuts through the 3D volume. Moving inwards, the offset curves, the trailing- and leading edge curves and the two curves at the middle height of the shear webs are then used to form a surface (Figure 111), that can be used to cut the blade in halves. This surface is scaled with a factor of 1.1 from its centre, to make a cutting surface that cuts through the volume.

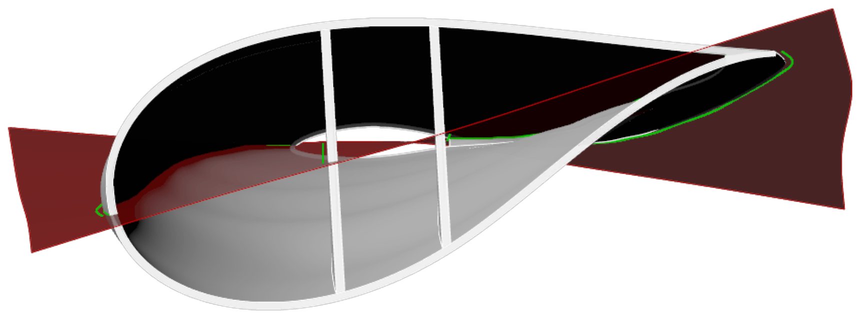


Figure 110: View from root end of the NREL 5MW blade model. Green lines show the offset curves of the trailing and leading edges, as well as the shear web middle curves.

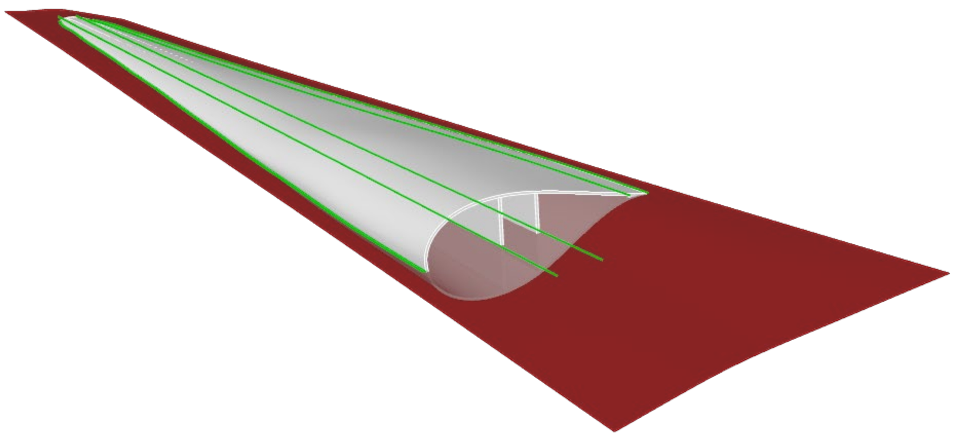


Figure 111: The reference curves together form a scaled surface that can be used to cut the blade in half along the trailing and leading edges.

The resulting halves can be seen in Figure 112. They are rearranged to prepare them for further sectioning into half segments with a preferred length, as well as the curvature analysis.

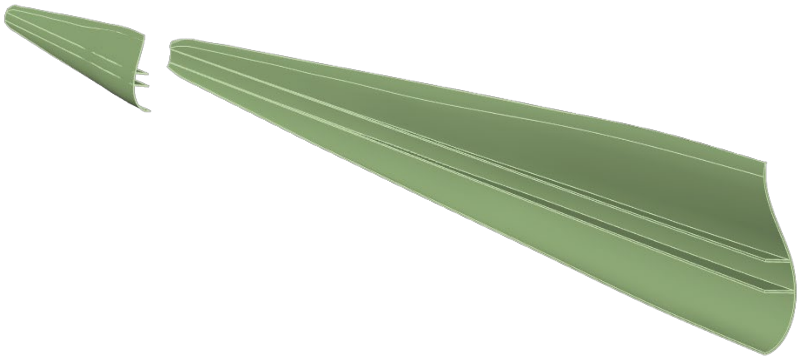


Figure 112: The resulting halves, rearranged to prepare them for following steps.

Next, the halves are aligned so that their LE is horizontal as much as possible (Figure 113a and b). This is done so that the sectioned panels can be cut at a 90 degree angle with the horizontal, which is important for good alignment of panel sides with the insides of the cassettes. Starting from the root end, splitting planes are then put in series with equal spacing that is set to the preferred panel length. In many cases, a small outboard segment will be leftover (e.g., 50m / 6m = eight 6m segments and one 2m segment) which may not be suitable for use. After splitting, they are spaced out to make their separation clear (Figure 113c).

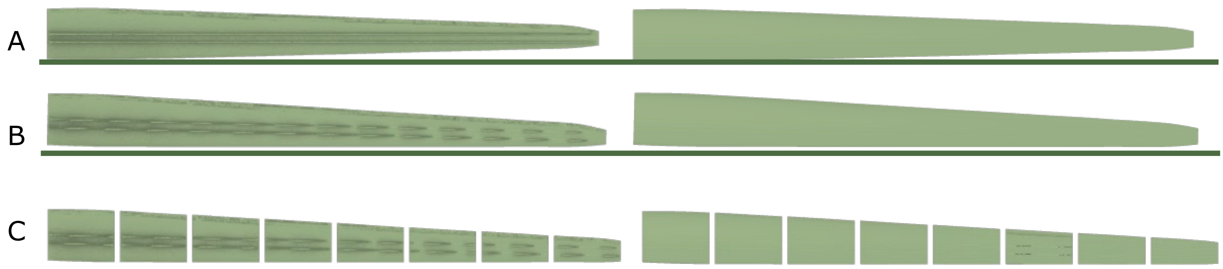


Figure 113: A) unaligned blade halves, B) LE-aligned blade halves, C) spaced out large panels.

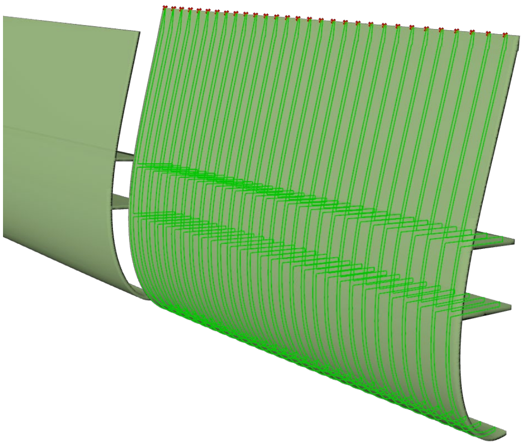


Figure 114: A large panel with light green contours that follow its outer shape and red dots that form starting points.

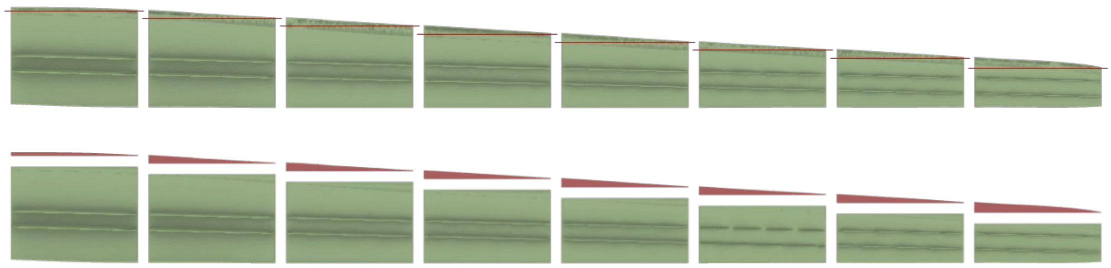


Figure 115: Removing triangular shaped tops (in red) to finalize a rectangular frontal surface.

Then, by adding contours of the cross-section at a set interval (e.g. every 25mm, see Figure 114), the shape of the cross-section is analysed along the length of one panel at a time. The narrower the interval of the contours, the more accurate the results for curvature, but also more computing power is needed. The starting points of the curvature analysis are set at the TE (red dots in Figure 116). To make sure that the analysis starts at the same height for every contour in a panel, the triangular shaped tops are cut off in advance (Figure 115). This does not lose too much valuable material, since these areas are mostly made up of adhesive.

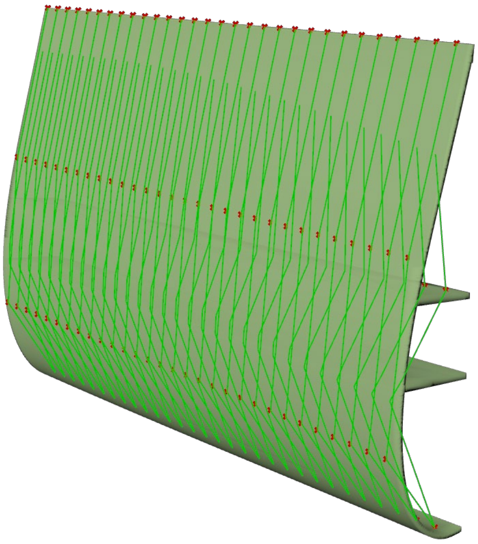


Figure 116: Red start- and endpoints of sub-curves of the contours are connected by straight lines in green.

To retrieve information, the cross-section contours are divided into equal length sub-curves, of which the start- and end-points are also used to create a straight line, seen in Figure 116. The curvature can then be analysed by calculating the ratio between the length of the straight line (***w***) and distance between the mid-point of the straight line and the accompanying sub-curve that follows the contour (***d***), as shown in Figure 117.

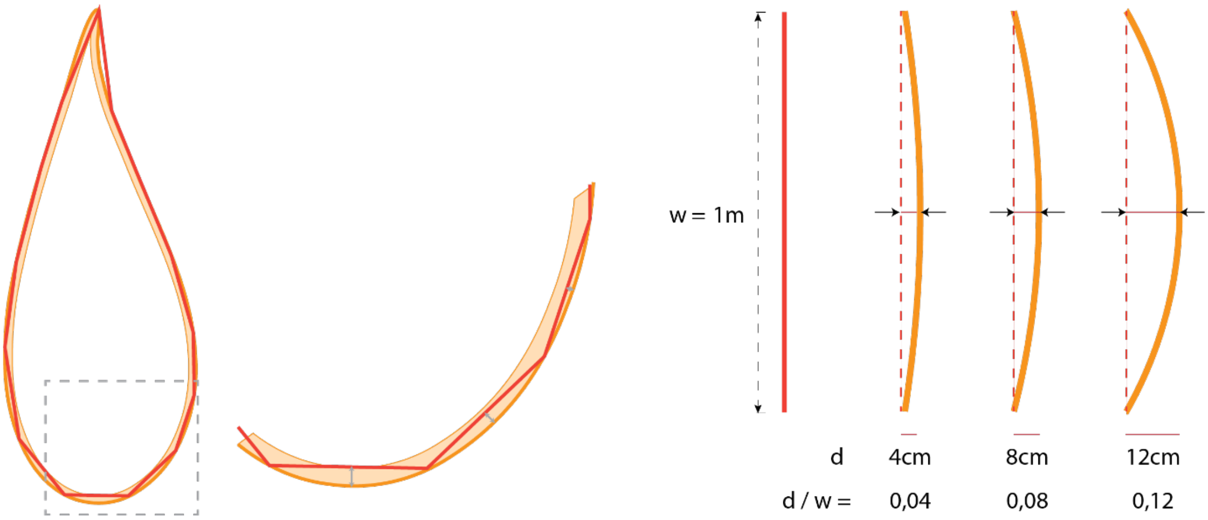


Figure 117: : 2D view of the deflection analysis.

The maximum allowed ratio *d/w* can then be set, as well as the desired panel height, and the model will filter out any parts that are not suitable and present usable pieces. Figure 118 shows a panel with red lines that reach until the deviation has become too large (i.e. the lower right part is not adherent to the curvature requirement). This method can also be used for deviations in the length direction before the covered sectioning steps are done.

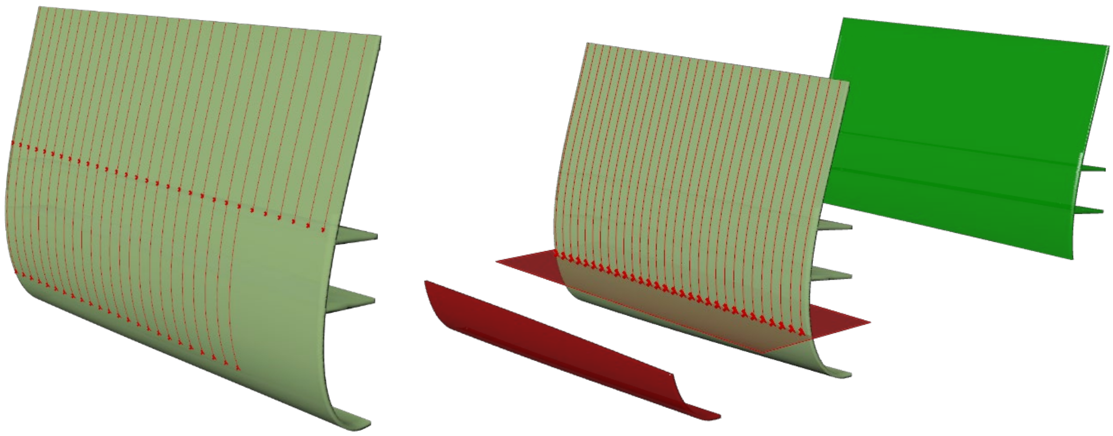


Figure 118: A) Red lines reach as far as that specific contour adheres to the set curvature requirement. B) All contours reach a certain panel height and can be used as starting points for a plane, to cut through the mesh and create a usable panel and 'leftover'.

Segmentation model results

Figure 119 shows how the (half) segments are named for referral to Table 13: Results for NREL 5MW blade in the segmentation model, with two approaches., which shows the results of two approaches that can be used in the parametric segmentation model.

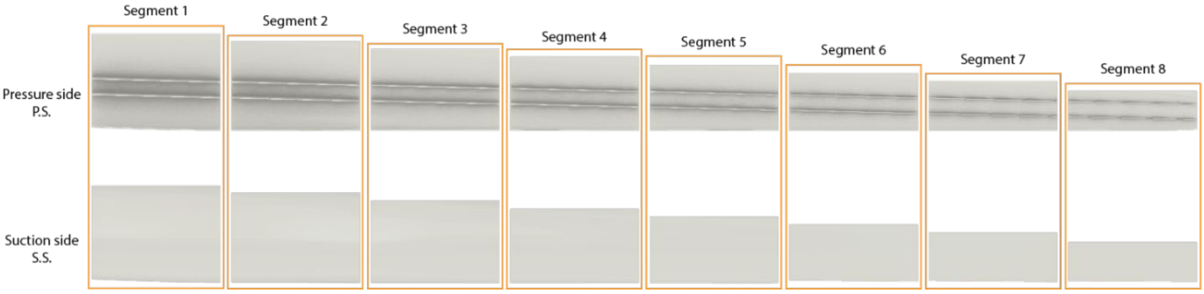


Figure 119: Pressure and suction side panels, grouped by segment. For example, pressure side of segment 3 is PS3, and suction side of segment 7 is SS7.

Table 13: Results for NREL 5MW blade in the segmentation model, with two approaches.

Maximize panel height

Panel ID	Max. curvature	Curve length (1:50 scale)	Height when optimally rotated (mm)	Rounded height (m)
PS1	0.079	86	4170	4,1
SS1	0.079	83	4031	4,0
PS2	0.079	82	4009	4,0
SS2	0.079	81	4002	4,0
PS3	0.079	74	3576	3,5
SS3	0.079	72	3551	3,5
PS4	0.079	66	3244	3,2
SS4	0.079	64	3163	3,1
PS5	0.079	62	3048	3,0
SS5	0.079	57	2824	2,8
PS6	0.079	55	2743	2,7
SS6	0.079	49	2444	2,4
PS7	0.079	48	2384	2,3
SS7	0.079	43	2145	2,1
PS8	0.079	38	1888	1,8
SS8	0.079	34	1713	1,7
Standardized heights (4m, 2m, 1m)				
PS1	0.079	86	4170	4,0
SS1	0.079	83	4031	4,0
PS2	0.079	82	4009	4,0
SS2	0.079	81	4002	4,0
PS3.1	0.079	41	2044	2,0
PS3.2	0.079	40	2016	2,0
SS3.1	0.079	40	2008	2,0
SS3.2	0.079	40	2006	2,0
PS4.1	0.079	41	2045	2,0
PS4.2	0.079	32	1646	1,0
SS4.1	0.079	41	2051	2,0
SS4.2	0.079	38	1958	1,0
PS5.1	0.079	41	2144	2,0
PS5.2	0.079	24	1140	1,0
SS5.1	0.079	41	2050	2,0
SS5.2	0.079	23	1181	1,0
PS6.1	0.079	41	2106	2,0
PS6.2	0.079	17	872	-
SS6.1	0.079	41	2073	2,0
SS6.2	0.079	15	775	-
PS7.1	0.079	27	1386	1,0
PS7.2	0.079	21	1044	1,0
SS7.1	0.079	21	1341	1,0
SS7.2	0.079	22	1107	1,0
PS8	0.079	38	1888	1,0
SS8	0.079	34	1713	1,0

Appendix J

Prototyping process

Three parts are required: a suitable WTB panel, a cassette (with support structure / frame), and the fasteners. A selection of panels that were retrieved from a WTB were available to the researcher (see Figure 120). The highest (TE) panel was used as reference to determine dimensions for the cassette, as the other panels would then also fit, and the resulting cassette would have an approximate 1:2 scale with a real design. Additionally, the other panels contain a larger portion of spar cap and were wider, making them significantly heavier and harder to handle and fasten. The chosen demonstrator panel was not adapted (cut or sawn) for the prototype, as this would take a significant amount of time and its dimensions and shape were already quite fitting.

Figure 120: Selection of panels that were available.

Cassette

The noise barrier design contains two differing cassettes. The tilted cassette is chosen for the prototype because the demonstrator panel's curvature and height closely resemble a 1:2 scale pressure side front panel (except for thickness and length). After measuring the panel's height (+-183 cm), thickness (25 to 40 mm), and curvature deflection (+-17cm), the cassette's inner dimensions (i.e. those of the back plate) were set to 20 x 185 cm, at a 10° tilt. The dimensions of the sides need to be half the length of the front flange of the frame component (150mm at 1:2 scale is 75 mm for its width) and the same height as the back plate (185 cm), so that two cassettes fill the space (Figure 121). The side width (75mm) needs to incorporate space for fasteners at the back and the thickness of the back plate.

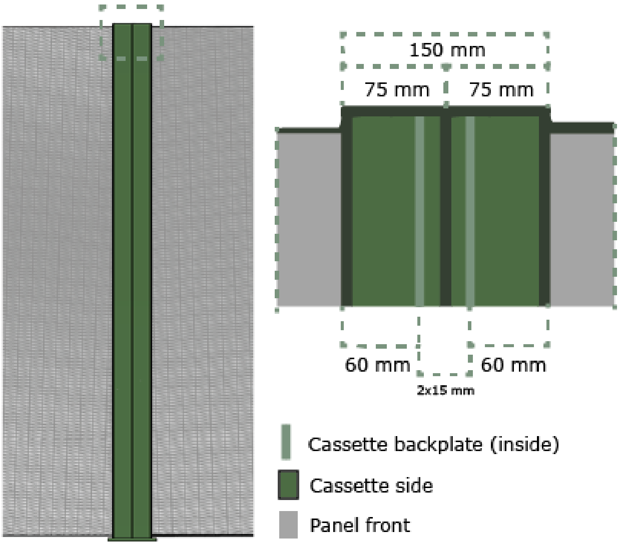


Figure 121: Sizing details of the prototype cassette sides.

Laser cutting was determined as a suitable and quick prototyping option, as the cassette dimensions require relatively large parts that needed to be precisely cut for neat and coherent assembly. 9mm thick plywood was consequently chosen as the prototype material. Figure 122 shows the prototyping process. A support structure, representing the frame component of the barrier design, was similarly made to carry the tilted cassette with WTB panel (D, E and F in Figure 122).

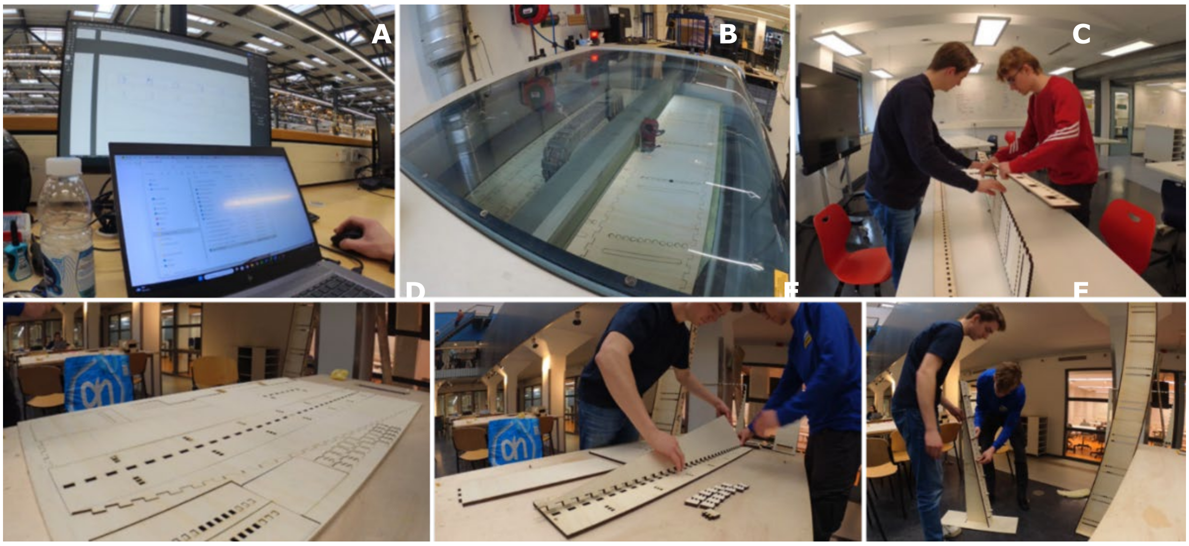


Figure 122: The prototyping process. Using the online tool boxes.py, a precise drawing (A) could be made for laser-cutting (B). The cut pieces could then be easily assembled (C) to form the cassette. D, E and F show a similar procedure for the support structure.

Fasteners

As outlined in section 7.2.2, there are several possible fastening options that can be integrated into the cassettes. Both the slotted fastener and the perforations fastener utilize M12 bolts and nuts, in combination with a rubber that prevents scratching of the WTB panel as well as accommodate a small tolerance for movement of the panel when it is under load (Figure 123).

Figure 123: Slotted bolt (left) and perforated bolts in the connection points along the height of the cassette. Rubbers are placed between the bolt / nut combination and the panel.

An adjustable clamp design was additionally (iteratively) designed based on existing clamps, and 3D printed to work with M12 bolts and nuts. It can adjust its thickness and rotation (Figure 124: A) Adjustable clamp designs, multiple iterations. Improvements mainly covered better 3D printability (thinner flanges), stiffness (larger thickness, ribs) and fitting of steel M12 bolts. B) tested clamp.), and rubber pieces can be pasted on the insides of the clamp.

Figure 124: A) Adjustable clamp designs, multiple iterations. Improvements mainly covered better 3D printability (thinner flanges), stiffness (larger thickness, ribs) and fitting of steel M12 bolts. B) tested clamp.

Realistically, this clamp should be made of stainless steel, but these were not available to the researcher. This clamp is also meant to attach to the cassette through either the perforated holes or slotted holes, in at least 4 places along the height of it. The added functionality in comparison to the bolt options is that this clamp will restrict panel movement in two directions, and can be placed in a perforated hole and still have the same adjustability as in the slotted hole. Additionally, these clamps could be tested on their potential to carry the panels on the second columns that do not rest on the ground, if made sufficiently strong.

Appendix K

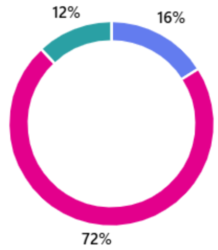
Aesthetics survey

Generally, the aesthetics of noise barriers is an important aspect for most respondents, where 4 said ‘extremely important’, 11 voted ‘Somewhat important’, and 8 responded with ‘neutral’. The majority of the 25 respondents (18) experience noise barriers mainly from the road, while the rest is mainly a resident (4) or both (3). Most respondents primarily encounter noise barriers mainly in urban areas (16), followed by both urban and rural (5), and mainly rural areas (4). The age group is predominantly 18-34 (21), while a small portion of the respondents is between 55-74. A final general note is that while some respondents mentioned they could appreciate well-done art works, a significant majority of the respondents (16) finds graffiti to not make noise barriers more appealing.

The questions asked and results of the survey can be found below.

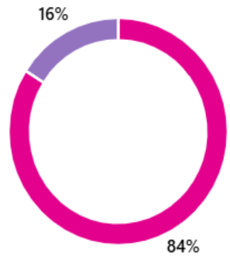
1. What is your primary perspective when considering sound barriers?

Resident (I live near a road with a sound barrier)	4
Road user	18
Both	3
Andere	0



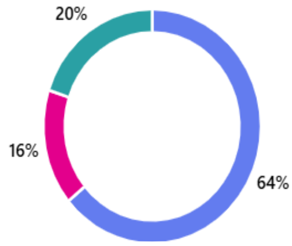
2. In what age group are you?

Younger than 18	0
18-34	21
35-54	0
55-74	4
74+	0



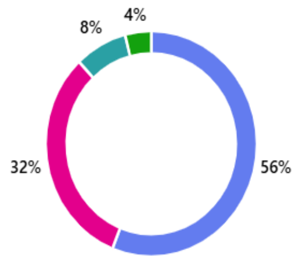
3. Where do you primarily encounter sound barriers?

Urban areas	16
Rural areas	4
Both	5



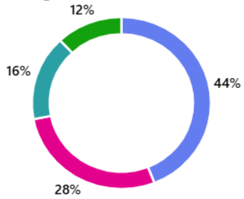
4. How important is it to include vegetation on sound barriers in **urban areas**?

Very important	14
Somewhat important	8
Neutral	2
Somewhat not important	0
Not important at all	1



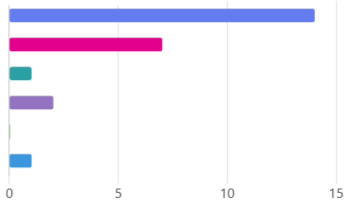
5. How do you prefer vegetation to be added on or around **urban** sound barriers? (This image contains all three, earlier i

Climbing plants	11
Integrated planter boxes in the top	7
Vegetation around barrier (e.g. bushes)	4
None, a clean look is better	0
Andere	3



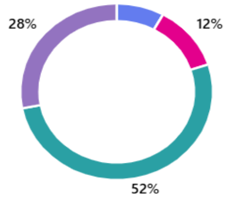
6. Which color do you find most suitable for the frames of sound barriers in **urban areas**?

Light green	14
Dark green	7
Blue	1
Taupe	2
Red brick	0
Andere	1



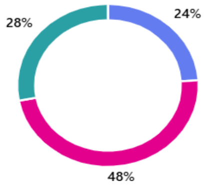
7. Which color combination / pattern do you find most suitable for resident side panels of sound barriers in **urban area s**?

1: blue gradient	2
2: blue alternating	3
3: green gradient	13
4: green alternating	7



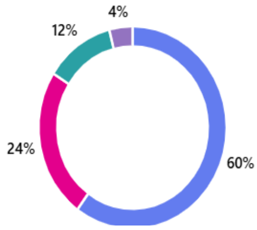
8. Which combination of panels on the resident side appeals most to you in urban settings? (disregard colour and vegeta tion)

Option 1	6
Option 2	12
Option 3	7



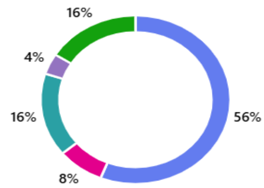
9. How important is it to include vegetation on sound barriers in **rural** areas?

Very important	15
Somewhat important	6
Neutral	3
Somewhat not important	1
Not important at all	0



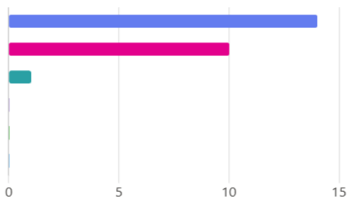
10. How do you prefer vegetation to be added on or around **rural** sound barriers? (This image excludes the integrated pl anter box, which is present in the earlier image)

Climbing plants	14
Integrated planter boxes in the top	2
Vegetation around barrier (e.g. bushes)	4
None, a clean look is better	1
Andere	4



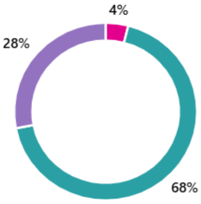
11. Which color do you find most suitable for the frames of sound barriers in **rural areas**?

Light green	14
Dark green	10
Blue	1
Taupe	0
Red brick	0
Andere	0



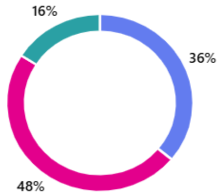
12. Which color combination / pattern do you find most suitable for resident side panels of sound barriers in **rural area**

1: blue gradient	0
2: blue alternating	1
3: green gradient	17
4: green alternating	7



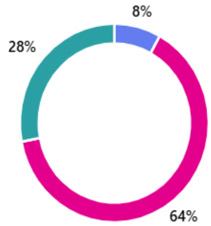
13. Which combination of panels on the resident side appeals most to you in **rural** settings? (disregard colour and veget ation)

Option 1	9
Option 2	12
Option 3	4



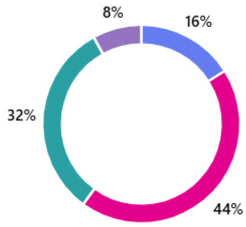
14. What do you think about sound barriers that have graffiti on them?

Graffiti makes the barrier more interesting / appealing	2
Graffiti does not make the barrier more interesting / appealing	16
Andere	7



15. How important is the aesthetic appeal of sound barriers to you?

Extremely important	4
Somewhat important	11
Neutral	8
Somewhat not important	2
Extremely not important	0



16. Do you have any additional suggestions or comments about the aesthetics of sound barriers in either urban or rural environments?

For me, there are three key aspects to consider with sound barriers: Graffiti Prevention: I dislike graffiti, so creating a sound barrier that is graffiti-resistant is important. Features like climbing plants or uneven surfaces could reduce the likelihood of graffiti by making it harder to paint on. Improving Biodiversity: Sound barriers offer a great opportunity to enhance biodiversity. Adding flowering plants for insects and providing shelters for other animals can make them valuable habitats. Dual Purpose Functionality: It would be fantastic if sound barriers served a secondary purpose. For instance, while your barriers already recycle materials like wind turbine blades, incorporating solar panels could further increase their utility.

Sound barriers should be integrated in the natural view in rural areas and in the overall view of the urban area

Aesthetic appeal from resident side is more important than from road user side

The greener the better or maybe you can include like a water saving system for watering farmers land or instal solar panels on them or maybe you can gain energy from sound that would be perfect

I think that a nice sound barrier aesthetic can really improve an area. Maybe include the neighbourhoods in creating the design for on the sound barrier?

I think including vegetation on the sounds barriers makes them less invasive in the overall view, so adding vegetation also on the resident Side might be nice

Appendix L

Separate structural analyses

For a more specific look at the deflections per panel height, the structural analyses results are shown in Figure 127 (1m), Figure 126 (2m) and Figure 125 (4m).

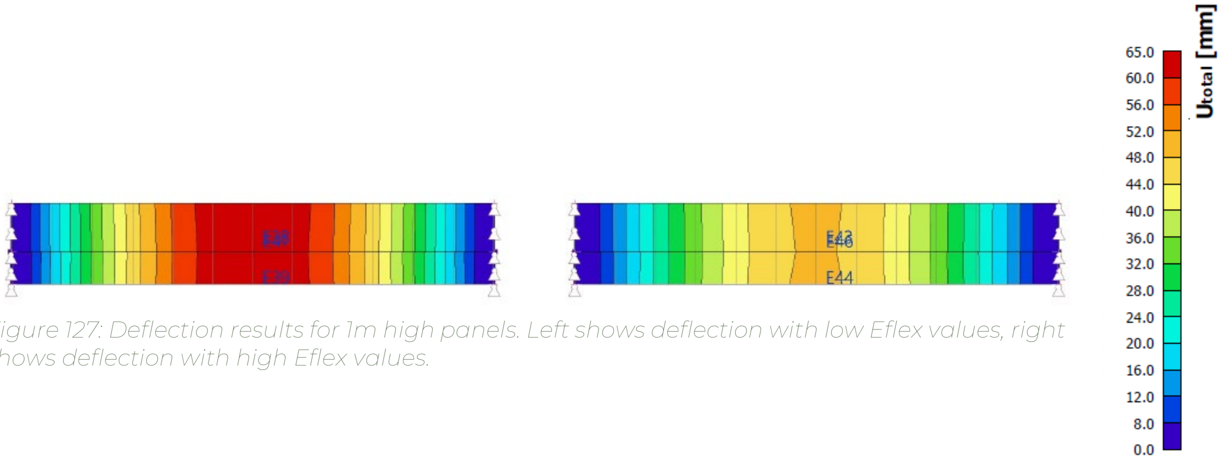


Figure 127: Deflection results for 1m high panels. Left shows deflection with low Eflex values, right shows deflection with high Eflex values.

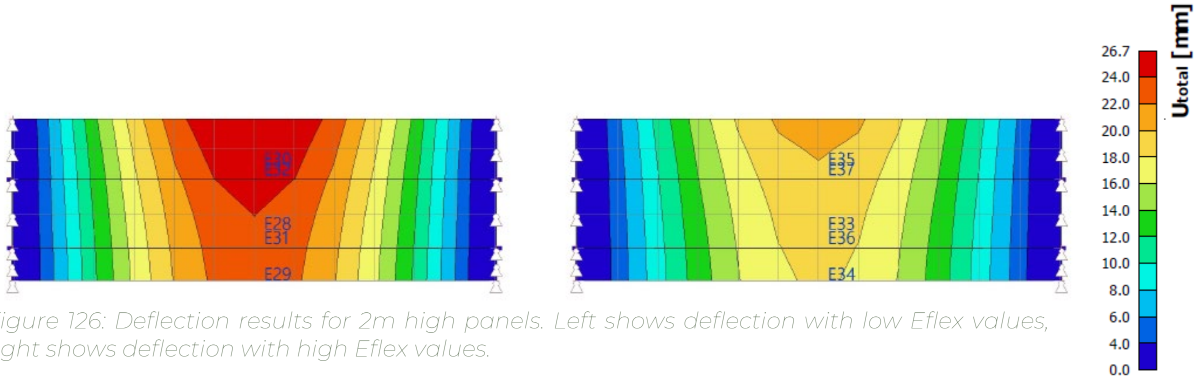


Figure 126: Deflection results for 2m high panels. Left shows deflection with low Eflex values, right shows deflection with high Eflex values.

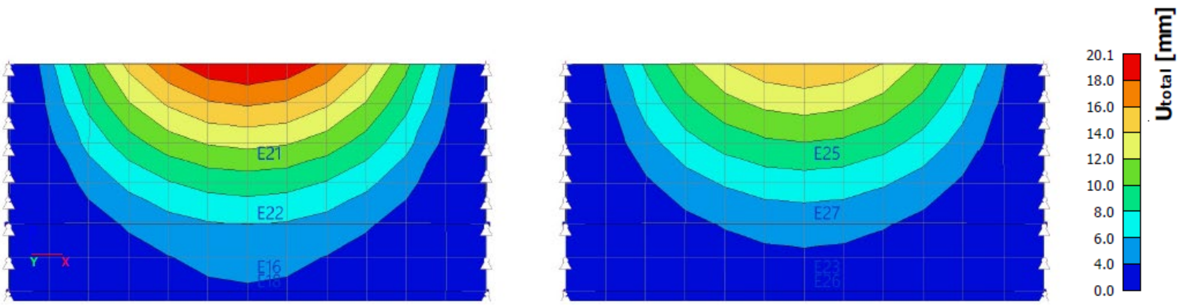


Figure 125: Deflection results for 4m high panels. Left shows deflection with low Eflex values, right shows deflection with high Eflex values.

Wind load

Heijmans Infra

Project:	*Beschouwing geluidsschermen met windmolenbladen*
Onderwerp:	*berekening windbelasting voor analyse panelen*
Onderdeel:	*Windgebied II onbebouwd*
Datum:	*7 januari 2025*
Auteur:	*E. Nouwen*

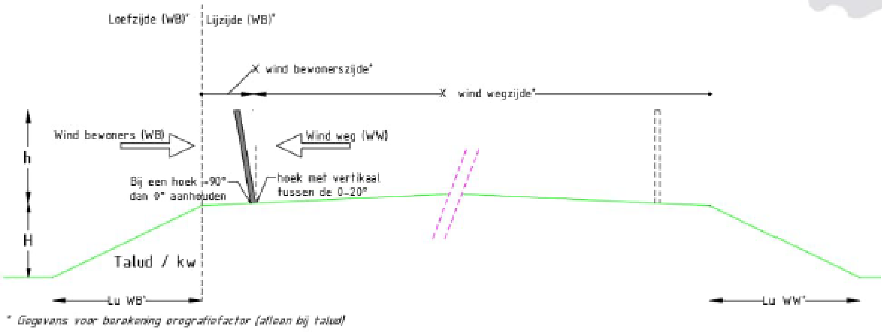
Versie: *0.4*
Versiedatum: *29-3-2024*

Berekening windbelasting op geluidsschermen

Maximale waarde conform NEN-EN 1991-1-4 en GCW2012

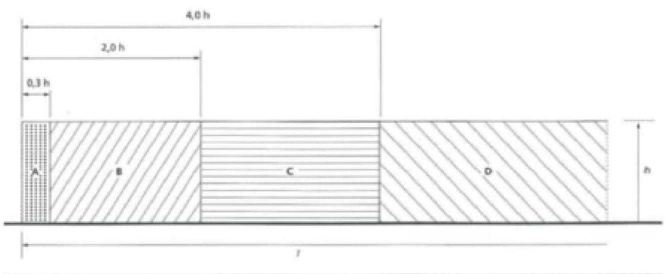
Invoer gegevens

		Bewonerszijde	Wegzijde
Windgebied		II	II
Bebouwingsgraad		onbebouwd	onbebouwd
Ontwerplevensduur	jaar	50	50,0
Schermhoogte	m^1	4,0	4,0
Hoh-afstand stijlen	m1	6,0	6,0
Hoek met vertikaal	graden	0	0
Hoogte Talud	m^1	4,0	4,0
Factoren t.b.v. orografiefactor			
Hor. afstand scherm tot de heuveltop, X	m^1	2,0	2,0
Werkelijke lengte van de helling aan de loefzijde, L_u	m^1	8,0	8,0
Werkelijke lengte van de helling aan de lijzijde, L_d	m^1	8	8
Hellingshoek talud, ϕ		0,50	0,50
Effectieve lengte van de helling aan loefzijde, L_e	m^1	13,3	13,3

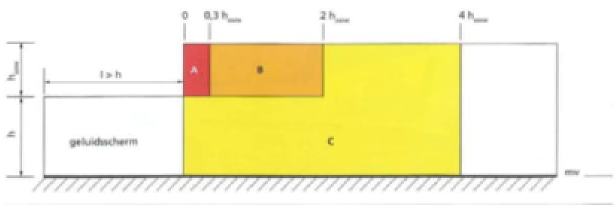


SAMENVATTING

Maximale waarde conform NEN-EN 1991-1-4 en GCW		Bewonerszijde	Wegzijde
Windzone A	**kN/m²**	**3,13**	**3,13**
Windzone B	**kN/m²**	**2,58**	**2,58**
Windzone C	**kN/m²**	**1,57**	**1,57**
Windzone D	**kN/m²**	**1,11**	**1,11**



Figuur 24. Randzones bij een sprong in de schermhoogte



Windbelasting conform GCW2012

BEREKENING $q_{p(z)}$ — NEN-EN 1991-1-4:2005+A1:2010+NB:2011

		Wind bewonerszijde	Wind wegzijde	
ρ	(vol.massa lucht)	1,25	1,25	kg/m³
z = h+H	Hoogte scherm + omliggende MV-hoogte	8,00	8,0	m
z_0	(ruwheidslengte)	0,20	0,20	m
z_{min}		4,00	4,00	m
$V_{b;0}$		29,50	29,50	m/s
K		0,20	0,20	
n		0,50	0,50	
p	kans	0,02	0,02	
$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0}$		29,50	29,50	m/s
$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$		22,78	22,78	m/s
$c_{prob} = \left(\frac{1 - K * \ln(-\ln(1-p))}{1 - K * \ln(-\ln(0{,}98))}\right)^n$		1,00	1,00	
$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$		0,77	0,77	
$k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0,07}$	NB: $Z_{o,II}$=0,05	0,21	0,21	
$I_v(z) = \frac{\sigma_v}{v_m(z)}$		0,2711	0,27	
$\sigma_v = k_r \cdot v_b \cdot k_I$		6,18	6,18	
$q_p(z) = (1 + 7 * I_v(z)) * 0{,}5\rho * (v_m(z) * c_{prob})^2$	**$q_p(z)$=**	**0,940**	**0,94**	**kN/m²**

Tabel 5.1 — Berekeningsprocedures voor de bepaling van windbelastingen

Parameter	Naslag
extreme stuwdruk q_p	
basiswindsnelheid v_b	4.2 (2)P
referentiehoogte z_e	hoofdstuk 7
terreincategorie	tabel 4.1
karakteristieke extreme stuwdruk q_p	4.5 (1)
turbulentie-intensiteit I_v	4.4
gemiddelde windsnelheid v_m	4.3.1
orografiefactor $c_o(z)$	4.3.3
ruwheidcoëfficiënt $c_r(z)$	4.3.2
Winddruk, bijvoorbeeld voor bekleding, bevestigingen en constructiedelen	
uitwendige drukcoëfficiënt c_{pe}	hoofdstuk 7
inwendige drukcoëfficiënt c_{pi}	hoofdstuk 7
nettodrukcoëfficiënt $c_{p,net}$	hoofdstuk 7
uitwendige winddruk $w_e = q_p c_{pe}$	5.2 (1)
inwendige winddruk: $w_i = q_p c_{pi}$	5.2 (2)
Windkrachten op constructies, bijvoorbeeld voor algemene windeffecten	
bouwwerkfactor $c_s c_d$	6
windkracht F_w berekend met krachtcoëfficiënten	5.3 (2)
windkracht F_w berekend met drukcoëfficiënten	5.3 (3)

BEREKENING CsCd — NEN-EN 1991-1-4:2005+A1:2010+NB:2011 Bijlage C Procedure 2

$$B^2 = \frac{1}{1 + \frac{3}{2} \cdot \sqrt{\left(\frac{b}{L(z_s)}\right)^2 + \left(\frac{h}{L(z_s)}\right)^2 + \left(\frac{b}{L(z_s)} \cdot \frac{h}{L(z_s)}\right)^2}}$$

$$L(z) = L_t \cdot \left(\frac{z}{z_t}\right)^{\alpha}$$

Voorwaarde z ≥ zmin

α = 0,67 + 0,05 * Ln(z_o)

$$c_s = \frac{1 + 7 \cdot I_v(z_s) \cdot \sqrt{B^2}}{1 + 7 \cdot I_v(z_s)}$$

$$c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s) \cdot \sqrt{B^2}}$$

$$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)}$$

B2 =	0,8057	0,81				
Z =Zs =	8,00	8,00	m			
Lt =	300	300	m			
zt =	200	200	m			
L(z) =	45,0	45,0				
α =	0,59	0,59				
Cs =	0,93	0,93				
Cd =	1,05	1,05				
h =	4,00	4,00	**< 50m**	OK	OK	
h/b =	0,67	0,67	**< 5**	OK	OK	
CsCd =	**0,980**	**0,980**	0,0%			

WINDBELASTING PER ZONE

Windzone A	3,13	3,13	kN/m²
Windzone B	2,58	2,58	kN/m²
Windzone C	1,57	1,57	kN/m²
Windzone D	1,11	1,11	kN/m²

Windbelasting conform NEN-EN 1991-1-4

Versie 2005+A1:2010+NB:2011

Bouwwerk	**Geluidsscherm**		
	Wind	**Wind**	
Gebied	**II**	**II**	
Bebouwingsgraad	**onbebouwd**	**onbebouwd**	
Schermhoogte	**4,0**	**4,0**	**m'**
Hoh-afstand stijlen	**6,0**	**6,0**	**m'**
Ontwerplevensduur	**50,0**	**50,0**	**jaar**
Hoek met vertikaal	**0,0**	**0,0**	**graden**

BEREKENING $q_{p(z)}$ (extreme stuwdruk, art. 4.5)

ρ	(vol.massa lucht)	1,25	1,25	kg/m³
Z = h	Hoogte scherm	4,00	4,00	m
Z_0	(ruwheidslengte)	0,20	0,20	m
Z_{min}		4,00	4,00	m
$V_{b;0}$		27,00	27,00	m/s
K		0,23	0,23	
n		0,50	0,50	
p	kans	0,02	0,02	
$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0}$		27,00	27,00	m/s
$v_m(z) = c_r(z) * c_0(z) * v_b * c_{prob}$		23,32	23,32	m/s
$c_{prob} = \left(\frac{1 - K * \ln(-\ln(1-p))}{1 - K * \ln(-\ln(0,98))}\right)^n$		1,00	1,00	
$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$		0,63	0,63	
$k_r = 0,19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0,07}$ NB: $Z_{0,II}$=0,05		0,21	0,21	
$I_v(z) = \frac{\sigma_v}{v_m(z)}$		0,24	0,24	
$\sigma_v = k_r \cdot v_b \cdot k_I$		5,65	5,65	
$q_p(z) = (1 + 7 * I_v(z)) * 0,5\rho * v_m(z)^2$	$q_p(z)$=	0,916	0,916	kN/m²

Tabel 5.1 — Berekeningsprocedures voor de bepaling van windbelastingen

Parameter	Naslag
extreme stuwdruk q_p	
basiswindsnelheid v_b	4.2 (2)P
referentiehoogte z_e	hoofdstuk 7
terreincategorie	tabel 4.1
karakteristieke extreme stuwdruk q_p	4.5 (1)
turbulentie-intensiteit I_v	4.4
gemiddelde windsnelheid v_m	4.3.1
orografiefactor $c_o(z)$	4.3.3
ruwheidcoëfficiënt $c_r(z)$	4.3.2
Winddruk, bijvoorbeeld voor bekleding, bevestigingen en constructiedelen	
uitwendige drukcoëfficiënt c_{pe}	hoofdstuk 7
inwendige drukcoëfficiënt c_{pi}	hoofdstuk 7
nettodrukcoefficiënt $c_{p,net}$	hoofdstuk 7
uitwendige winddruk $w_e = q_p\, c_{pe}$	5.2 (1)
inwendige winddruk: $w_i = q_p\, c_{pi}$	5.2 (2)
Windkrachten op constructies, bijvoorbeeld voor algemene windeffecten	
bouwwerkfactor $c_s c_d$	6
windkracht F_w berekend met krachtcoëfficiënten	5.3 (2)
windkracht F_w berekend met drukcoëfficiënten	5.3 (3)

BEREKENING C_0 (terreinorografie, art. 4.3.3)

Berekening volgens Bijlage A3

Samenvatting windbewonerszijde

Lijzijde kliffen en steile hellingen	Formule
C_0 = 1,38	(A.3)
s = 0,63	(A.7)
A = -0,35	(A.8)
B = -0,49	(A.9)
C= 0,46	(A.10)

Samenvatting windbewonerszijde

Lijzijde kliffen en steile hellingen	Formule
C_0 = 1,38	(A.3)
s = 0,63	(A.7)
A = -0,35	(A.8)
B = -0,49	(A.9)
C= 0,46	(A.10)

BEREKENING CsCd (bouwwerkfactor, art. 6.2)

$B^2 = \frac{1}{1 + \frac{3}{2} \cdot \sqrt{\left(\frac{b}{L(z_s)}\right)^2 + \left(\frac{h}{L(z_s)}\right)^2 + \left(\frac{b}{L(z_s)} \cdot \frac{h}{L(z_s)}\right)^2}}$	B2 =	0,73	0,73			
	Z =	4,00	4,00 m			
$L(z) = L_t \cdot \left(\frac{z}{z_t}\right)^\alpha$ Voorwaarde z ≥ zmin	Lt =	300	300 m			
	zt =	200	200 m			
	L(zs) =	29,89	29,89			
α = 0,67 + 0,05 * Ln(z_0)	α =	0,59	0,59			
$c_s = \frac{1 + 7 \cdot I_v(z_s) \cdot \sqrt{B^2}}{1 + 7 \cdot I_v(z_s)}$	Cs =	0,910	0,910			
	Cd =	1,05	1,05			
$c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s) \cdot \sqrt{B^2}}$	h =	4,00	4,00	**< 50m**	OK	OK
	h/b =	0,67	0,67	**< 5**	OK	OK
$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)}$	CsCd =	0,955	0,955			

WINDBELASTING PER ZONE CONFORM NEN-EN 1991-1-4

	Bewonerszijde	Wegzijde	
Windzone A	2,98	2,98	kN/m²
Windzone B	2,45	2,45	kN/m²
Windzone C	1,49	1,49	kN/m²
Windzone D	1,05	1,05	kN/m²

Appendix M

Invitation to thesis presentation at Heijmans