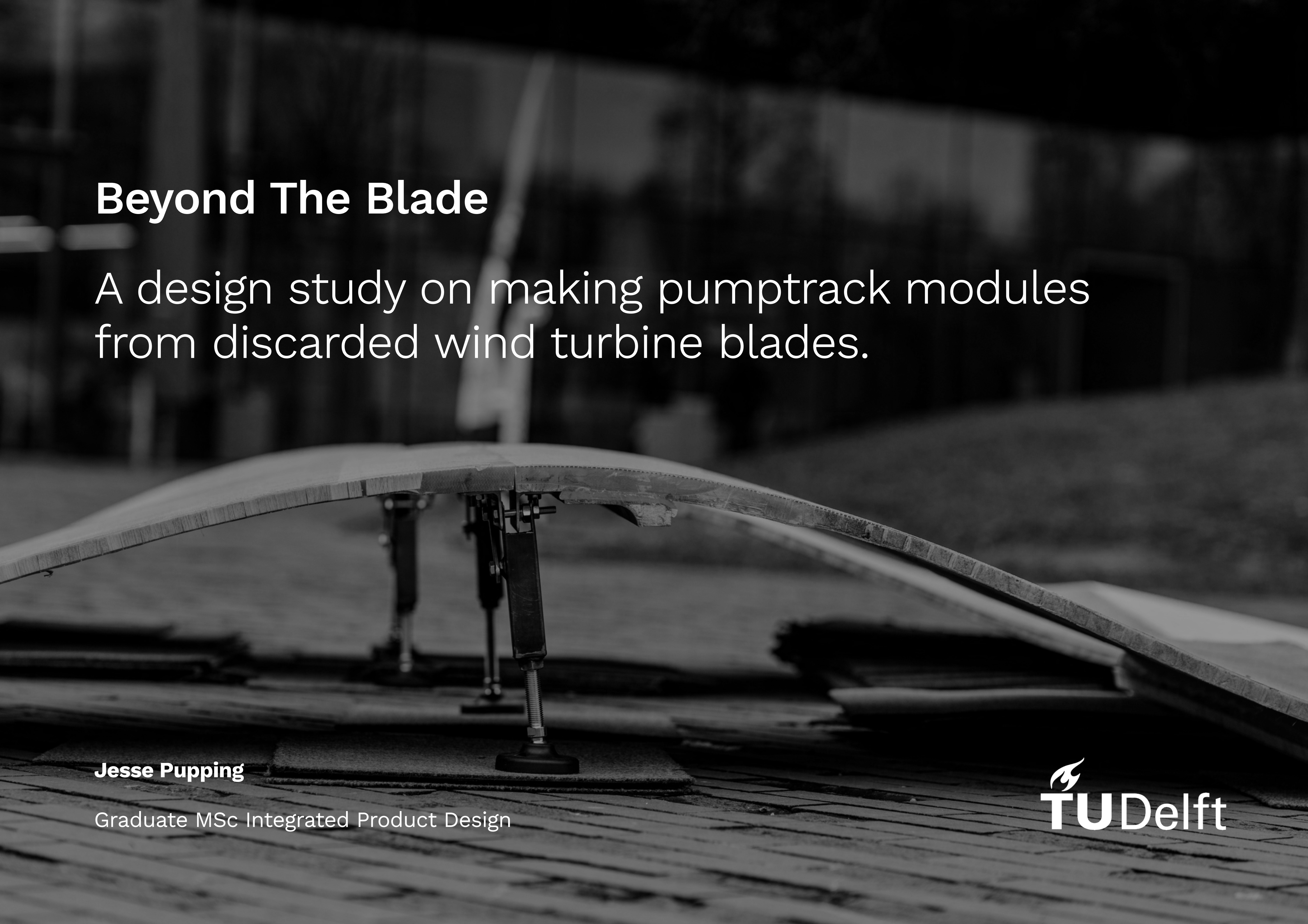

Beyond The Blade

A design study on making pumptrack modules from discarded wind turbine blades.

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Preface

We live on a planet with a growing population, consuming vast amounts of energy and resources. This increasing demand takes a toll on our environment and the world we inhabit.

As we navigate the ongoing energy transition, wind turbines have been one of the early manifestations of renewable energy. While they offer a sustainable way to generate power, their production requires significant resources and energy. If not designed with material conservation in mind, these materials eventually become what many refer to as "waste." This mindset needs to shift, products should be designed with their end-of-life in mind, ready for the next life cycle and if this is not possible, they should not be designed in the first place. This is the core principle of the circular economy.

As a designer, critical thinker, and environmentalist, I sometimes struggle to feel truly impactful. This is why I chose to focus my studies on sustainable design engineering, circular design, and prototyping sustainability transitions.

When I discovered the Reuse by Design project, I was immediately intrigued. Initially, I wanted to prevent this waste from occurring in the first place, but the reality is that we are already facing the challenge of dealing with existing wind farms reaching the end of their life-cycle. This project seemed to perfectly align with my prototyping and analytical skills, offering an opportunity to make a real impact.

By choosing this project, I aimed not only to learn but also to contribute to solving an urgent problem.

Enjoy reading!

Jesse

Credit: Patrick Wetzels

Credit: Patrick Wetzels

Acknowledgements

This thesis project has been a great journey overall. But it wouldn't have been possible without the help of some amazing people!

Wieger Hilgersom and I started our graduation almost on the same day, and throughout the process, we have been reflecting every other Friday to stay on track, keep up the good work, and improve where we were lacking. Thanks for the support!

Writing a report was a tough challenge for me. I went through many different iterations, but putting everything down in a clear and structured way was difficult. Therefore, I want to thank Gabriela Farias for proofreading and checking my report.

I am also very grateful to Fraunhofer for generously providing us with sample materials and available CAD models to experiment with.

The test event was a great success, but it wouldn't have been possible without the help of 'The Pump Factory', Wieger and Kees Dik for assisting in building the track, all the student assistants who contributed during the event, and the Communication-IO team for spreading publicity about the project, which has been a valuable addition and impactful for the industry of reusing composite material.

A special thanks to my mentor Caroline Kroon for being critical about the project and guiding me through the process.

I also want to express my appreciation to Jelle Joustra for being so involved in the project, always being open to questions, and responding so quickly to emails.

This graduation would, of course, not have been possible without all the previous years of studying, and I want to thank my family for supporting me throughout all these years.

Thanks for this wonderful ending to a great learning journey!

Abstract

The rapid expansion of wind energy over the last 40 years is leading to an increasing number of discarded wind turbine blades as they reach their end of their life. Current solutions are low- grade recycling options in which the material loses its value. With that,

this research presents a case study on the structural reuse of wind turbine blades, using an iterative design research approach to explore processes and outcomes.

Previous research has investigated various reuse cases but has been unable to develop a proof of concept for the reuse of curved material. In this case study, the research explores the potential of utilizing the blade material's unique geometric and material properties by developing a demonstrator prototype to show its feasibility.

This case study researches the process of matching wind turbine blade (WTB) pieces to create a modular pumptrack. This will be done by calculating the material's strength and finding ways to connect the modules, ensuring form continuity and sufficient tolerances.

In addition, the project ends with the conceptualisation of prototypes and the validation of the geometric and material properties to ensure their suitability for modular pumptrack modules. These modules are designed to be safe for BMX pumptrack events while considering their limitations and opportunities.

To showcase the experiential qualities of the material—such as its aesthetic attributes and associations—to both the industry and the public, the prototypes were presented through a demo pumptrack event hosted within the Delft University of Technology (TU Delft) community.

The final section summarizes the outcomes and riding experience of the pumptrack modules, providing insights into reusing wind turbine blade material specific for this use case and other cases.

Glossary

Berm: a steep corner that is made to ride with high speeds

Crest & trough: “The wave has troughs and crests. If you draw a horizontal through your rollers at the midpoint of the rollers’heights, everything above the line is a crest. Everything below the line is a trough” (McCormack, 2019).

Composite: a material made out of multiple different materials or components. Iterative design process: A process in which you go through multiple iterative cycles by validating prototypes.

Decommissioned: to take equipment out of use.

Design puzzle: A metaphor I created to describe this thesis project. The puzzle is finding the ‘puzzle pieces’; the offcuts from a wind turbine blade. And design a puzzle in this case a pumptrack.

Glass Fibre-Reinforced Polymer (GFRP): which is a composite material made by combining fine glass fibers with a polymer resin matrix.

Pumptrack: bike track which is rideable by making a pump-like motion.

Sinus wave: A periodic wave which waveform (shape) is the trigonometric sine function.

Roller: Straight part of a pumptrack with a sinus wave shape.

Research through Design (RtD): ‘*Research through design (RtD) is an approach to scientific inquiry that takes advantage of the unique insights gained through design practice to provide a better understanding of complex and future-oriented issues in the design field’* (Godin & Zahedi, 2014)

Root: The part of the blade that is closest to the mount of the turbine with the stem.

SolidWorks: Computer aided design software used to make technical drawings and models to match the blade material.

Structural reuse (by design): More interesting, and specific way of recycling for composites, is structural recycling. This preserves material quality with relatively little effort (Asmatulu et al., 2014), for example by resizing and repurposing composite parts in such a way that their unique properties as determined by the combination of material composition and structural design is maintained (Jensen & Skelton, 2018).

Off-cut: A leftover or excess piece of material that remains after a larger piece has been cut or shaped for a specific use. In the context of pumptracks. Off-cuts refer to sections of decommissioned wind turbine blades or other materials that are not used in the main construction but can still be repurposed. These pieces may have irregular shapes and require precise measurement and cutting to be effectively integrated into a new design.

Abbreviations

(GFRP)	Glass Fibre-Reinforced Polymer
WTB	Wind Turbine Blade
CiG	Civil Engineering and Geosciences
IDE	Industrial Design Engineering TU Delft
Inria	National Institute for Research in Digital Science and Technology
CMC	Sheet Moulding Compound
PVC	polyvinyl chloride
SAN	Styrene Acrylonitrile
PET	Polyethylene terephthalate
PU	Polyurethane
LCA	Life Cycle Assesment
RtD	Research Through Design
CAD	Computer Aided Design
CNC	Computer numerical control
WAS	Warenwetbesluit attractie- en speeltoestellen
MPa	Mega Pascal

Figures

All figures are author's own except stating otherwise. The credits to the owner is stated in the figure title.

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01 Introduction

The rapid expansion of wind energy is leading to an increasing number of discarded wind turbine blades: an estimated 350 tonnes (onshore blades) are expected in Europe by 2030 (Spini & Bettini, 2024). These blades, primarily constructed from composite materials, are often replaced due to diminished economic value and the introduction of newer, more efficient models (Chen et al., 2019). Currently, these decommissioned[1] blades are destined for incineration (Europe) or landfills (Figure 1) (USA & China) (Mativenga et al., 2017), contributing to large-scale waste.

With my expertise as a designer, I aim to contribute to solving this problem by developing a demonstrative product that makes full use of the structural properties and unique form of discarded blades. This project experiments with reusing wind turbine blade material in BMX pumptrack design. The idea of building mountain bike obstacles and jumps originated from a previous project within the Structural Reuse by Design initiative: a research group led by Mariana Popescu (CGs)[2], Jelle Joustra (IDE)[3] and Adrien Bousseau (Inria)[4]. Among the potential outcomes identified by van der Vinne (2024) are bike jumps, since the material scored high on efficient and structural use of the material. This posed a potentially scalable outcome that needs to be further researched. Figure 2 shares the initial concept.

The basic material tests, design and research outcome by S. van der Vinne (2024) (Figure 3), are not enough to guarantee this specific use case would be feasible. Therefore, I will research if the challenges within this use case can be solved.

Figure 3 : *Initial material tests pulling strength (Source: Van Der Vinne, 2024)*

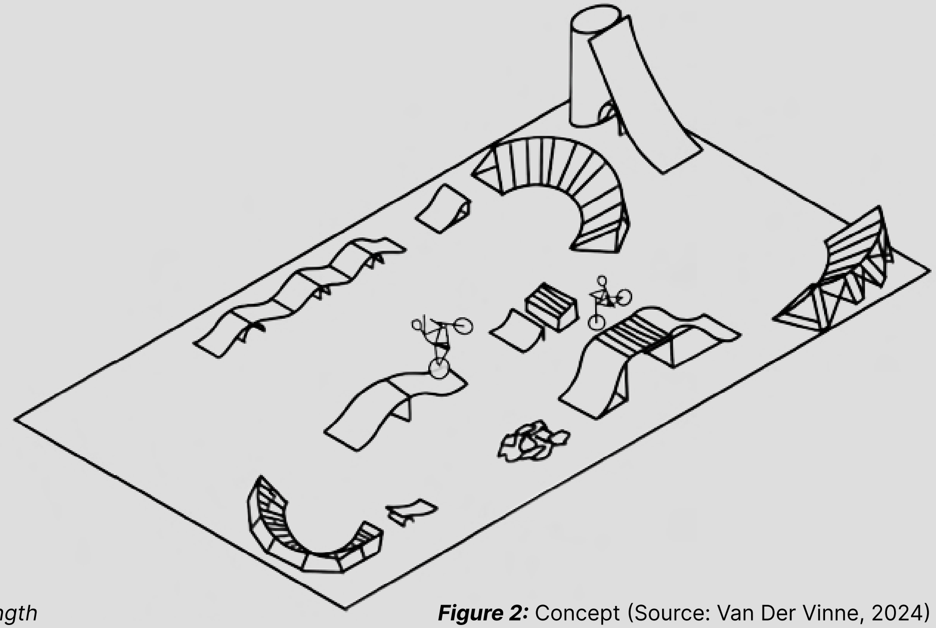


Figure 2: Concept (Source: Van Der Vinne, 2024)

Figure 1: *Windturbine graveyard USA (Wyoming) Photographer: Benjamin Rasmussen for Bloomberg Green*

[1] Decommissioning a windmill blade refers to the process of removing and retiring the blade from service
[2] Civil Engineering and Geosciences TU Delft
[3] Industrial Design Engineering TU Delft
[4] National Institute for Research in Digital Science and Technology

Figure 4 : *Fraunhofer 30m (sectioned) research blade top view(Source: Fraunhofer)*

In order to find out if a pumptrack is a feasible and viable use case as a demonstrator product, this design study elaborates on necessary details including: defining the user requirements, developing the track's flow, matching curvatures to available blade sections, embodying the design, detailing joints between blade parts, as well as track segments, 3D modelling of surface geometries, ensure user safety and environmental stability (wear, degradation, etc.) cutting patterns. Leading to the driving research questions, mentioned on page 12 & 13.

In collaboration with Fraunhofer IWES[5], a German research institute, I was provided a CAD model and the opportunity to retrieve sample WTB materials from one of their 30-meter research blades (Figure 4). This made it possible to build a full-scale prototype and validate the design.

With these parameters in mind, this project explores the potential of creating a modular pumptrack, demonstrating how this material can be reused in new ways. By showcasing the material's potential, I hope to encourage industries to recognize its value and adopt it as a cost-effective, sustainable resource in the future to their benefit in a secondary application.

[5] IWES: Institute for Wind energy Systems https://www.iwes.fraunhofer.de/en.html

02 Project brief

The project brief is therefore as follows:
Design a mobile pumptrack based on a selection of parts harvested from a wind turbine blade that is:

- Using parts harvested from a wind turbine blade, using their curvature and structural properties
- Modular, allowing dis- and re-assembly, as well as reconfiguring the track layout
- Offering a smooth ride, ensuring compatibility at the joining edges
- Safe to use, move and adapt

This led to the following research goal:

Designing a modular pumptrack to demonstrate the potential of reusing wind turbine blade material by using its form and structural properties.

Phase I - **Initial Research**

a) What is a pumptrack?

b) Why build a pumptrack?

c) How to build a pumptrack?

d) What are the important pumptrack design criteria?

e) What are the material's characteristics?

- o What is the material made of?
- o Why use this material?

f) Is the blade a potentially strong enough replacement material for pumptracks?

Phase II - **Explorative research**

a) Do the curvatures of a pumptrack match the wind turbine wing foil shapes?

b) Do the geometrical characteristics of the blade limit the potential of the pumptrack modules?

c) How to select the right curvatures in CAD?

d) How much blade material can be reused in a track?

e) How to cut the windmill blades?

f) how to select the right curvatures regarding an off-cut selection?

Phase III- **Embodiment**

a) What will the rollers look like?
b) How to connect the WTB material?
c) How to make the system modular
d) What will the support system look like?
e) What coating can be applied?

Phase IV - **Validation**

a) Does the connection system meet the safety criteria?
b) What is the impact of the design project?
c) Is there form/curve similarities in other blades?

Phase V - **Finalization**

a) How to summarize the conclusions?
b) What could be improved?
c) What needs to be further researched?

03 Project approach

Limited design research on the topic of wind turbine blade reuse has been completed, therefore there is no predefined method yet.

When explaining the project, I refer to it as a 'design puzzle'. In a typical design process, a suitable material is selected according to the product. In this project: the process is reversed. This also required a different approach than usual.

I used my previous experience using the Material Driven Design method (Elvin et al., 2015) to frame this project. In combination with an iterative design process and the Research through Design method (RtD Conference & Zoë Sadokierski, 2019), this formed the backbone of my approach for this project.

This design research project consisted of 5 phases: initial research, explorative research, embodiment, validation and finalization-phase.

Phases 1-4 of this design process are iterative, in which each cycle answers a sub research question using: literature reviews, site visits, interviews, prototyping and material simulations as means to achieve giving context for reaching the research goal.

Completing multiple design iterations helped to overcome the challenges and find opportunities for the material. For a visualization of the process, see Figure 5.

Each phase of research starts with a series of sub-questions and ends with a prototype or conclusion on the research question, these cycles are documented using the format from RtD and can be found in Appendix 03-13.

The Finalization phase 5 contains conclusion and outcomes to summarized and finalize the design and form a recommendation about the project.

In Figure 5, the line on the bottom represents the design process (Maier et al., 2018) and the above shows the phases milestones reached along the research path. This is reference, often used in design methodology, was representative of my journey.

Project stages

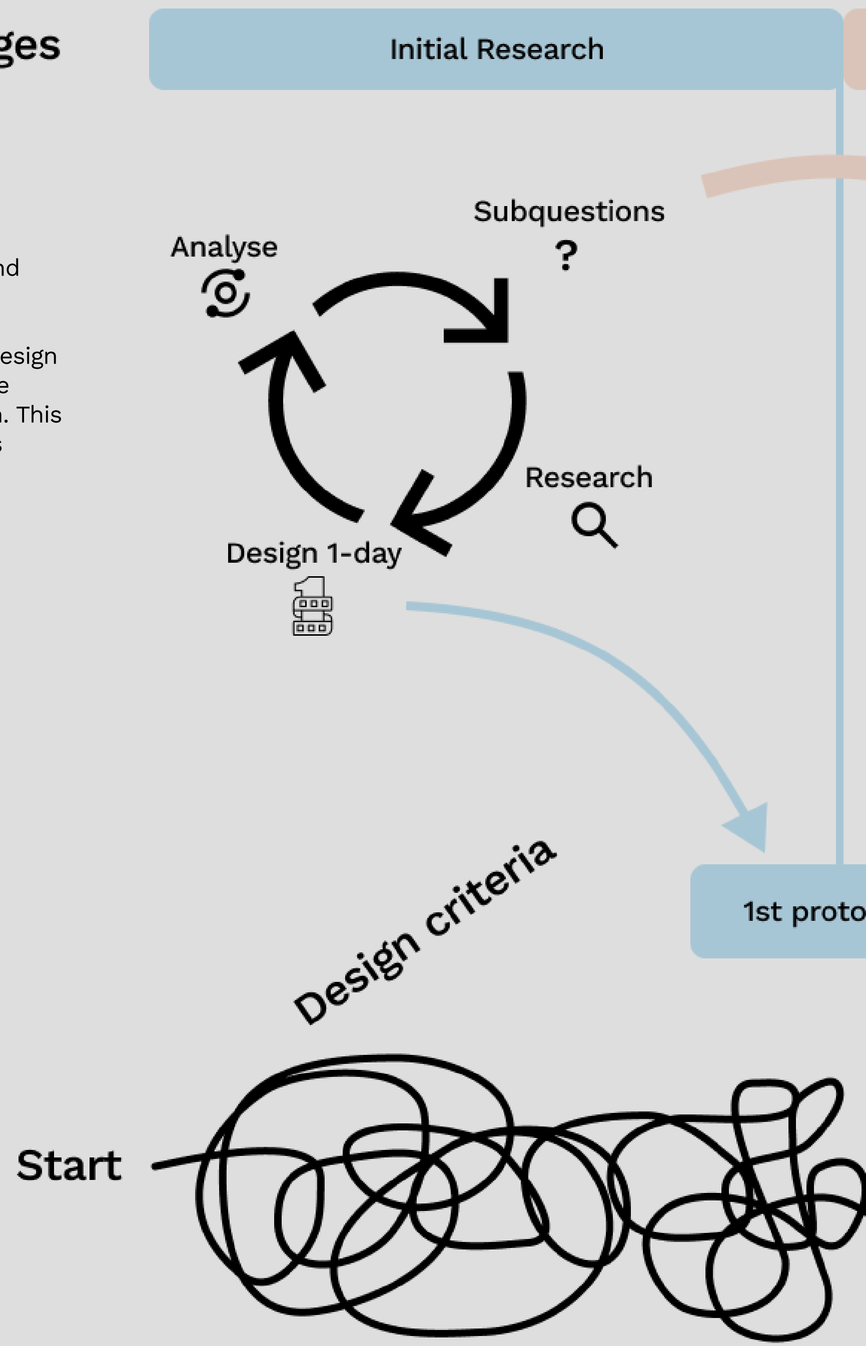
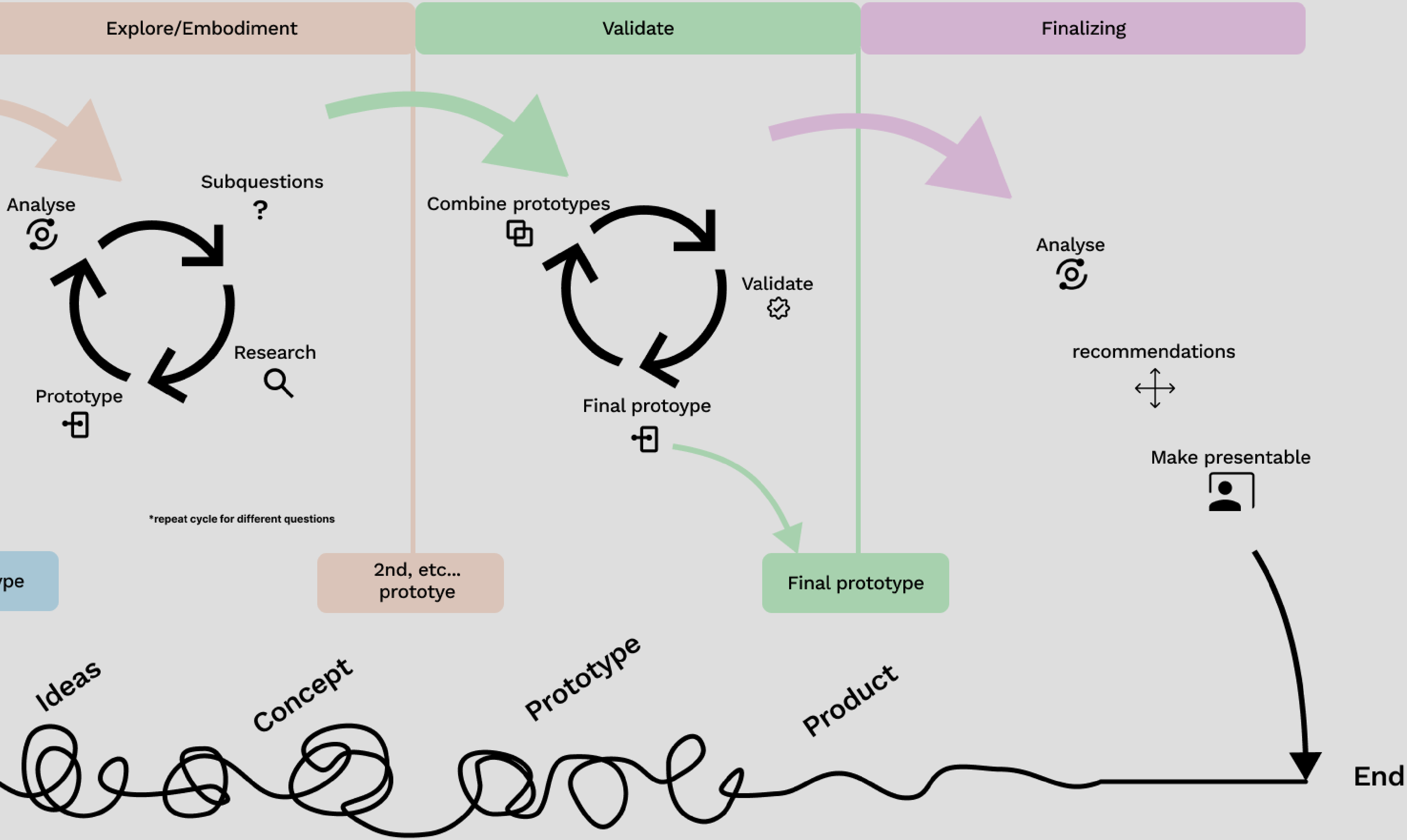


Figure 5: Design process


Explore/Embodiment
Validate
Finalizing
Analyse
Subquestions
Research
Prototype
*repeat cycle for different questions
ype
2nd, etc...
prototye
Combine prototypes
Validate
Final protoype
Final prototype
Analyse
recommendations
Make presentable
Ideas
Concept
Prototype
Product
End

04 Background

Project background

This project is situated within the context of the circular economy, where the aim is to extend the lifecycle of products and materials. By applying the principles of circular economy via the circularity ladder diagram (Figure 6), the primary focus is to prolong (R0-R2) the use of wind turbine blades to reduce them as 'waste'. Secondly is reuse (R3), then repair (R4)/refurbish (R5)/ remanufacture (R6)/repurpose (R7), and at last recycling (R8). The goal is to retain the energy, material, labour and capital costs that are embedded in the product (Bakker et al., 2018).

The primary stakeholders in this system include: wind energy companies, composite material manufacturers, sustainability advocates, governments, researchers and decommissioning companies. Each of these stakeholders has a vested interest in finding an opportunity to reuse the material in an efficient and economically viable way. The opportunity lies in finding structural reuse[6] applications for the decommissioned blades to prevent the loss of high-quality material.

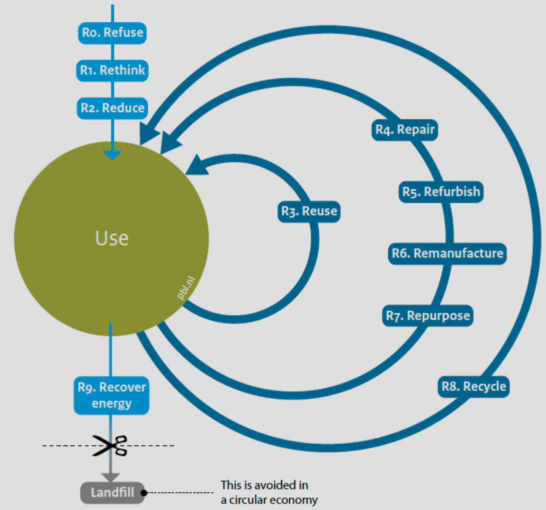


Figure 6: *The principle of circular ladder (Predan, 2020) (Credit: PBL)*

While many research efforts and conceptual ideas have explored the repurposing of discarded wind turbine blades (Figure 7), limited practical examples have succeeded to keep the material's integrity and properties to demonstrate its full potential. One notable example is Bladebridge by Re-Wind Network: a company repurposing these decommission blades for other infrastructure (Bladebridge, 2024). Other reuse cases are: the blade made playground (Studio Superuse, 2008) and a bike shelter (designboom, 2021) shown in Figure 7, however these examples are often one-offs and have not yet been proven to be scalable.

6 ***Structural reuse:*** *More interesting, and specific way of recycling for composites, is structural recycling. This preserves material quality with relatively little effort (Asmatulu et al., 2014), for example by resizing and repurposing composite parts in such a way that their unique properties as determined by the combination of material composition and structural design is maintained (Jensen & Skelton, 2018)*

Figure 7: *Bike shelter, 2021 (Source: Chris yelland), Blade-Made playground, 2008 (Source: Denis Guzzo), BladeBridge (2023)*

Material background

End of Design Life: Although the blades go through multiple maintenance and repairs during their life, wind turbine blades typically have a design life of around 20-25 years (Lauritsen et al., 2016). After this period, the structural integrity of the blades can degrade due to continuous exposure to environmental stresses like wind, UV radiation, and temperature fluctuations, making them less efficient and more prone to failure (Lund, 2024).

Technological Obsolescence: As wind energy technology advances, newer blades with more efficient designs are introduced. These newer blades can generate more energy due to improved aerodynamics, materials, and sizes, making older turbines less competitive and prompting operators to replace them even if they are not structurally compromised (Tayebi et al., 2024).

Damage and Fatigue: Blades are subject to fatigue from constant mechanical stress. Over time, this stress can cause cracks or delamination in the composite materials, especially at the tips of the blades where forces are greatest. Significant damage can make repair impractical, leading to decommissioning (Lund, 2024).

Operational Efficiency: As turbines age, their maintenance and operational costs increase. The financial costs of maintaining older blades or turbines may outweigh the benefits of continuing to operate them, especially when new, more efficient turbines are available (Tayebi et al., 2024). In some cases, operators choose to upgrade entire wind farms with larger, more powerful turbines. This process, known as repowering, leads to the decommissioning of still-functional blades to make way for more advanced systems (Tayebi et al., 2024).

Options for improvement
The most holistic solution to minimize waste would be by making better policies to prolong the blade lifetime or to redesign the blades for better repairability. One example is blades made from renewable material like wood, lowering their Co2 emissions by 78% and creating better maintenance opportunities.

However, a solution for the waste that has already been made and will continue to accumulate is still needed. In 2021 and 2022, the world had to deal with 15,000 and 50,000 tonnes of waste, respectively. In the coming years, more waste will be released, predicting that if growth continues and the industry does not change by 2050, we will have between 21.4 mega tonnes and 69.4 mega tonnes worldwide. Europe will face the problem first, since they were the earliest adopters of wind turbines. Ultimately, China will have the largest waste inventory (P. Liu & Barlow, 2017).

‘’Why are WTB currently decommissioned?’’

Source: *Vattenfall | Windpark Moerdijk*

Phase I - Initial Research

The first part of this chapter will investigate the context of pumptracks and try to create a better understanding of the research questions:
What is a pumptrack’
Why build a pumptrack’, ‘How to build a pumptrack
What are the important pumptrack design criteria?

During this phase, the main tools are:

> Literature review
> Interview with experts from ‘The Pump Factory

The following section will analyse the ‘blade material’ trying to understand:

What are the material’s characteristics?
What is the material made of?

The last portion of this chapter will give insight into the potential of replacing current material with wind blade material, answering the questions:

Why use this material?

Is the blade a potentially strong enough replacement material for pumptracks?

05 Pumptrack Background

A pumptrack is a track that can be ridden without pedalling. Instead, users ‘pump’ their way through the track. When people master the motion, they can reach speeds up to 30 mph. (McCormack, 2019)

5.1 Why a pumptrack?

Pumptracks are gaining popularity in the domain of outdoor urban environments. It is more accessible than most skateparks and a cheaper, more inclusive alternative (Riding the Waves, 2024).

5.1.1 History

Pumptracks have originated in BMX culture where people started modelling tracks from dirt to ride downhill. “The first pumptracks were probably the dense BMX trails of the ‘70s and ‘80s. The modern pumptrack revolution traces to Australian downhill bikers” (McCormack, 2019, page 6). Below, Figure 8 shows the pumping movement of a pumptrack.

Rowing through a trough; Drive hips and hands together. This absorbs the frontside and generates lots of pump power.

Anti-Rowing across a crest; Push your hands and hips apart. This keeps you balanced and gets you ready for the next row.

Figure 8 : *Pumping movement (Source: McCormack, 2019)*

5.1.2 Cultural aspect

Next to being a fun and accessible form of exercise, riding pumptracks can enhance the motor development of users. It can bring people together since it is accessible for any skill level from beginner to advanced. It also encourages coming together and collaborative learning (Schoemaker, 2023).
In modern society, 67% of children in the Netherlands do not meet their daily dose of activity (CBS, 2023). Therefore, it's important to stimulate kids to do physical activity. Pumptracks can encourage children to play more outdoors by making it more accessible to exercise and easy to host events for them to learn and get to play outside (Figure 9).

Figure 10 : *Stationary pumptrack in Elst, NL (Source: The Pump Factory, 2023)*

Figure 9 : *kids riding together (Source: McCormack, 2019)*

5.1.3 Market aspect

In the Netherlands, The Pump Factory B.V. is currently the one of the few pumptrack builders that make modular pumptracks. They host about 180 events a year with their modular pumptrack and create fixed pumptracks over the NL. The market is rapidly growing since BMX recently became an Olympic sport and municipalities get inspired by one another to build tracks. In addition, modular pumptracks are an affordable fit within the urban environment. The cost per square meter tor pumptracks is €80/m² (Pumptrackinfo.nl, 2024), regardless of the total surface area. Conversely, the cost per square meter for skateparks varies significantly, ranging from €200/m² for smaller parks to €320/m² for larger (NRC, 2023). Figure 10 shows pumptrack in a park.

The European market leader, Pumptrack.eu, has done more than 100 builds in Europe over the last 10 years, varying from modular pumptracks to stationary. When looking at the worldwide level, Velosolutions completed the construction of 534 pumptracks between 2012 and 2022 over 50 countries including Armenia, Rwanda, Nepal, Israel and Kenya (Velosolutions, 2022). These companies have helped spread the fun, making cycling and action sports more accessible for people around the world.

5.2 Building a pumptrack

Building a pumptrack can be as simple as piling up bumps of dirt in a backyard or a carefully designed modular outdoor pumptrack such as a 'speed ring' (Figure 11). Simpler tracks do not have to be less fun or ridable: there are no 'real rules' when it comes to building a track (McCormack, 2019).

***Figure 11 :** Speed ring modular pumptrack (Source: The Pump Factory, 2023)*

***Figure 13 :** Stationary asphalt pumptrack(Source: The Pump Factory, 2023)*

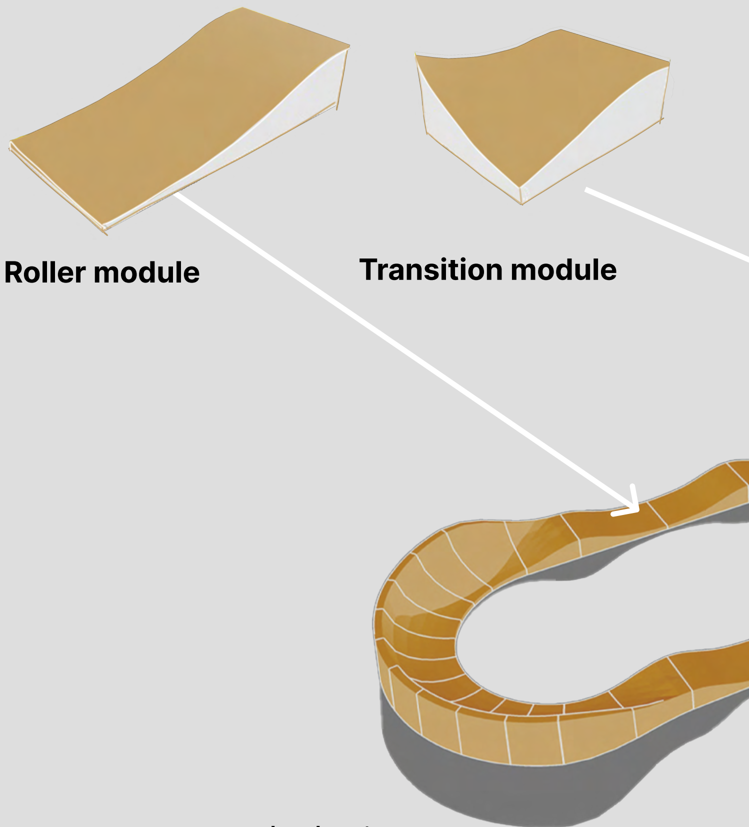
5.2.1 Pumptrack variations

Pumptracks can be categorized into 2 types: fixed pumptracks and modular pumptracks (can be build up for events), as seen in (Figure 11). Each category has many variations in layout, building quality and material (Figure 12 & 13). Their material anatomy varies from concrete, glass fibre, Polyethylene Composite, (phenolic) wood, asphalt and Sheet Moulding Compound (SMC) (pumptrackEU, 2024).

Modular pumptracks consist of various standardized modules that can be connected into a continuous loop. Making it standardized decreases the initial costs for moulds and designing.

When building a stationary track builders are less restricted by the initial cost of investments and therefore can make the track consist of variety of shapes making it less standardized.

***Figure 12:** Left Concrete track (Source: PARKITECT®) & right dirt pumptrack (Source: McCormack, 2019)*



5.2.2 Pumptrack design

A pumptrack consists of three types of sections. Rollers are the straight, wavy 'bumps' in a track. The corners (berms) can vary from 45, 90 or 180 degrees. The 'transition piece' connects the rollers with the corners, as seen in Figure 14.

There is not one perfect way of designing a pumptrack. Each pumptrack has its own characteristics, but the general rule as communicated in my interview with The Pump Factory: 'If it looks smooth and wavy it is probably ridable' (The Pump Factory pumptrack, personal communication, 10 October 2024). I created a list of guidelines on how to create a good and smooth ridable pumptrack, with guidance from the book Welcome to Pump Nation (McCormack, 2019) , the website of Parkitect (2024) and an interview with The Pump Factory (Personal communication, 10 October 2024).

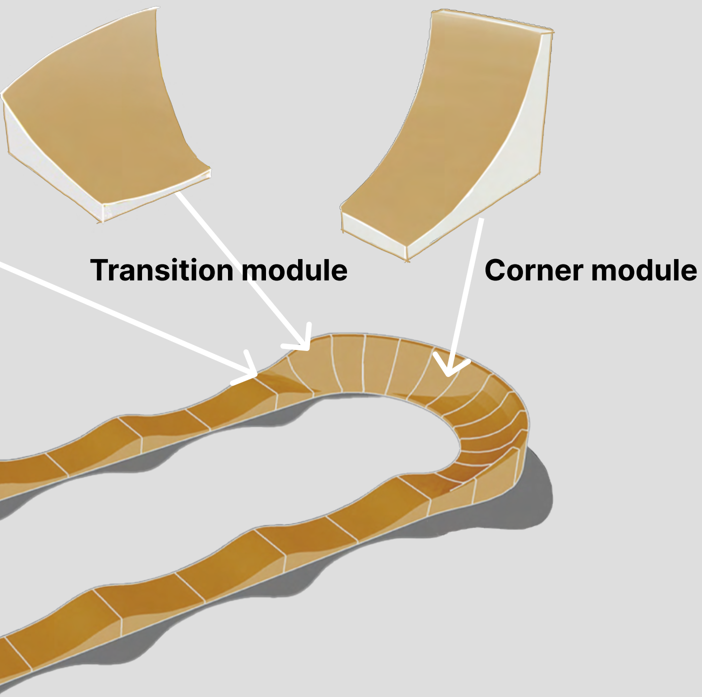


Figure 14 : Track parts explanation (Source: Bambutec, 2025)

Roller curvatures

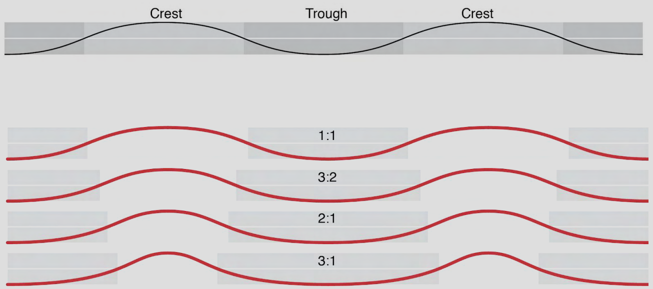


Figure 19: *Typical crest trough ratios (Source: McCormack, 2019)*

Figure 16: *Advisable height:length ratio (Source: McCormack, 2019)*

Figure 18: *Jumpable rollers (Source: McCormack, 2019)*

Figure 17: *Berm radi side and top view (Source: McCormack, 2019)*

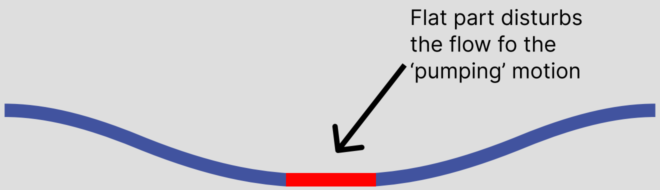


Figure 15: *Bad example of flat part in a track*

General:

- **Rule of thumb:** The wider the track the easier to stay on the track for beginners.
- **Width:** Make the track at least 1m wide and preferably 1,25m >.
- **No flat parts,** see Figure 15.
- **Wavy rollers,** corresponding with the waves from Figure 16.

Berms:

- **Rule of thumb:** The steeper the berm the faster you can pump through it.
- **Make the berms 1.2m - 1.8m wide (Parkitect, 2024).**
- **Berm radius:** The distance from its centre point to the outside of its riding line, as viewed from above in (Figure 17) . This needs to be a constant radius.
- **Radius:** 10-12 feet is an all-around radius for pumptrack corners.
  - **You can go tighter if the riders are advanced and the berms are very steep.**
  - **You can go wider if the track is very fast.**
- **Angle α for a 180 berm:** 3 feet tall – bank of 60-70 degrees (Figure 17) .
- **Angle α for a 90° berm:** 18-24 inches tall and bank of 45 degrees.

Rollers:

- **Rule of thumb:** Rollers that are close together make it easy to generate speed, but hard to maintain speed. Rollers that are far apart make it hard to generate speed, but easy to maintain speed.
- Aim for a 10- to 12-foot spacing between rollers, see Figure 16.
- **Crest:trough ratio's** (Figure 19) define the characteristics and make the rollers pointy or flat.
- **Your straight roller parts don't have to be straight.** Feel free to make slight turns using rollers. This is a flexible, easy alternative to building berms or corners.
- **Standard roller height to length ratio is 1:10 feet.**
- **Jumpable rollers** are **steeper** and have **ratio** closer to **1:5-1:8**, see Figure 18.

5.2.4 Modular Pumptrack

The modular track comes with more design challenges than stationary tracks because of the size, form and weight limitations due to transportation. There is a limited form freedom because the modules should be able to attach in a certain way and need to comply with the dimensions of, for example, a trailer or container used for transport to an event location (Figure 20).

Figure 20: *Pump Factory trailer & container boost with dimensions (Source: Pumptrack.nl)*

With these parameters in mind, the connections of the modules should be reversible and easy to assemble and dissemble. In addition, the weight of the modules should stay as low as possible to make the modules manoeuvrable without using a lift and to stay within the limits of the load capacity of for example a trailer. The mass of the premium outdoor roller modules with dimensions 2000 x 1000 x 380 mm are about 62 kg (Parkitect, 2024)(Figure 21).

Figure 21: *Premium outdoor roller (Source: Parkitekt, 2024)*

5.2.5 Construction of modules

Pumptrack modules come in a variety of shapes and materials. They often consist of:

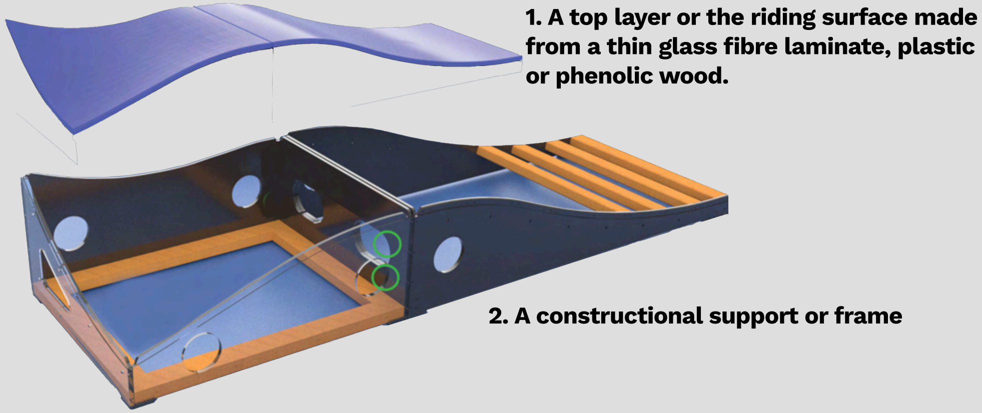


Figure 22 : *Visual of pumptrack composition (Source: Pumptrack.EU, 2024)*

Since there is currently not a norm specifically for pumptracks. The structure needs to be strong enough to comply with the safety rules according to the NEN14974 norm for skateparks and with the NEN-EN 1176 for playground equipment and surfacing.

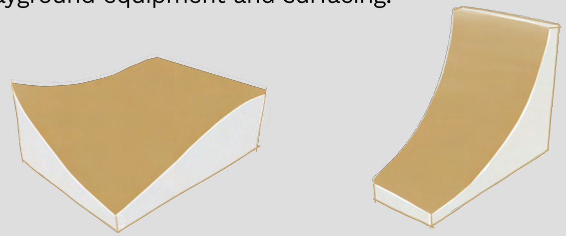


Figure 23 : *Transition piece & corner piece*

The corner modules and transition pieces that connect to the straight roller parts (Figure 23), are made using a mould designed with 3D-modelling software like SolidWorks. Using a Computer Numeric Controlled (CNC) machine to cut the right form, then vacuum forming or laminating glass fibre, the complex curvature with an epoxy can be recreated. This will be supported by an additional construction from wood or metal (Figure 25).

5.2.6 Twist in conventional tracks

Although most modular pumptrack consist of straight rollers, a transitions piece and corner modules, some variants have a slight twist in the rollers (Figure 24) to create a more organic track which riding characteristics closer to the tracks made from dirt (Figure 24). According to the McCormack (2019), a twist in rollers can make the track more fun. It is important that the twist doesn't change directions, so the rule of thumb is to not alternate the twist too much. This will make the track feel wobbly and less enjoyable to ride. Lean the twist in the direction of the following corner.

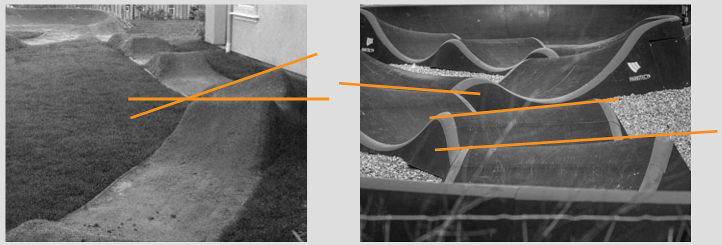


Figure 24: *Twist in dirt track and modular track (Source: McCormack, 2019 & Parkitekt, 2024)*

***Figure 25 :** Additional structures pumptrack (Source: Parkitekt, Pumptrack.nl, Pumptrack.EU)*

5.2.7 Pumptrack coatings

Coatings are there to protect the blade from wear and tear by weather. For a pumptrack, the coating requirements are different then for wind turbine blades. Since it will be exposed to friction of wheels from BMX bicycles, skateboards, scooters, etc., it will not be exposed to the same forces and weather conditions as a functional wind turbines. However, this depends on the frequency of use.

According to (NEN14974), the track surface cannot be slippery as to prevent people from falling in wet riding conditions.

Currently, pumptrack coatings are made from non-slip textured fiberglass and structured epoxy coating (Figure 26) (Parkitect, 2024).

The blade-made playground in Rotterdam, NL (Studio Superuse, 2008) used a technique similar to powder anti-skid coating on the BadeMade playground in Rotterdam (Figure 27). The durability of this coating is about 5-10 years according to the supervisor of the playground (Kipa, 2024, personal communication), and the intensity of use is almost every day. For the pumptrack, this coating needs to be anti-skid to prevent slipping in wet riding conditions.

***Figure 26 :** Surface coating (Source: Parkitect)*

***Figure 27 :** Surface coating on the blade-made playground*

5.2.8 Alternative track layouts

The modules come in different sizes based on the length of the curvature and the cut-out location of the blade. Corners are also standardized and splitable in 90 & 45 degree corners, enabling many track layouts. Connecting different size and shape modules changes the track its riding characteristics. When combining smaller sized rollers after each other, the track becomes more jumpable and faster according to McCormack (2019).

There is also pumptrack variations that are not continuous loops, such as the dual straight track from The Pump Factory, see Figure 28 .

Each track layout has its own riding characteristics. There is no such thing as a ‘perfect pumptrack’ layout. You really know when a pumptrack is enjoyable when test riding it for the first time.

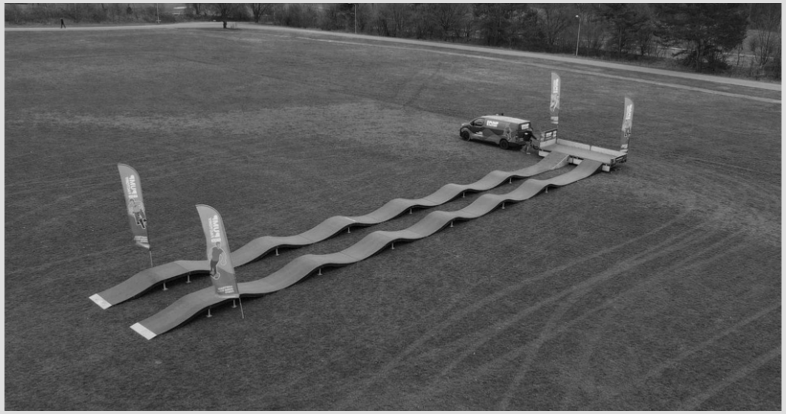


***Figure 28 :** Dual straight pumptrack (Source: The Pump Factory)*

5.3 Conclusion

Answering the research questions:

> ‘What is a pumptrack?’

A pumptrack is a looped track for bikes, skateboards, and scooters, where riders generate speed by "pumping" over rollers and through banked turns. Originating from BMX culture, modern pumptracks use materials like concrete, asphalt, or modular composites, making them versatile and accessible. Pumptracks are a trend in the urban environment making it a potentially scalable option.

> ‘Why build a pumptrack?’

They offer an affordable, low-maintenance alternative to skateparks, promoting outdoor activity and skill development for all ages and skill levels. With the rising popularity of BMX and urban recreation, pumptracks are becoming key features in public spaces.

> ‘How to build a pumptrack?’

Use the building guidelines (page 23) criteria as reference for the pumptrack design make standardized modules which make it easy to create a continuous looped track. The occurring twist in a track can make pumptrack more organic and playful. Rollers are the easiest modules to create because of their single (2D) curve.

> ‘What are the important pumptrack design requirements?’

The most important pumptrack design related requirements:

G1) Track > 1m wide. (The Pump Factory, personal communication, 10 October 2024)

G2) Gap clearance <5 mm between joining edges. NEN14974 (skateparks norm) (Appendix 19 for extensive list of safety requirements)

G3) Corners should have a constant radius in a turn which is 10-12 feet. (McCormack, 2019, page 40)

G6) Height of the corner modules is at least 85cm (Parkitect, 2024).

G7) Height of roller should be between 30-38 cm. (Chapter 5.2)

G8) Length of rollers 1500 -2000 mm and a ratio of -> 1:10 (height:length)

G9) Apply Anti-skid coating (grain between 0,6-1,6 mm) NEN1176

G10) No flat parts in the track (The Pump Factory, personal communication, 10 October 2024)

06 Blade Material Analysis

Wind turbine blades (WTB) come in different sizes and forms. Blade designs have become more efficient and bigger over the years. But the basic lay-up and material remains the same. This chapter gives a basic understanding of the geometrical and constructional characteristics of WTB.

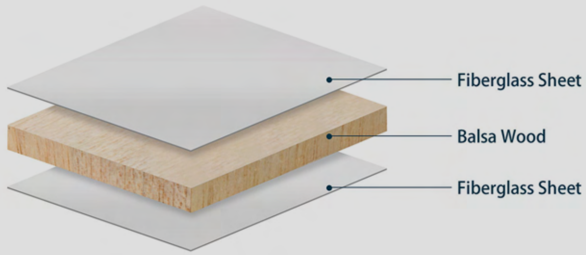


Figure 29: *GFRP-Balsa -core sandwich structure (Source: Topolo-panel.com)*

6.1.1 WTB material basics

A typical wind turbine blade is manufactured using polymer matrix composite materials in combination of monolithic (single skin) and sandwich composites. Present day designs are mainly based on Glass Fibre-Reinforced Composites (GFRP) (Thomsen, 2009). This type of material is also used in the blade of this project's prototype and is currently the most common blade material, since the turbine blades that are currently decommissioned from 25 years ago are constructed from a complex hybrid sandwich material mainly fibreglass, Balsa wood or foam (Figure 29).

As seen in Figure 30, certain sections of the WTB have a sandwich structure (sandwich shell) with a core material, typically a PVC, SAN, PET or PU or Balsa-wood core (Fathi et al., 2013; H. Liu et al., 2023). Other forms such as the spar cap, leading and trailing edge are monolithic: epoxy resin with glass fibre (shell panel). The parts used for the pumptrack rollers prototype in this project are cut from the pressure side of the wing, which is mainly sandwich structures.

Currently modular pumptracks are made from three different materials: Non-woven E-class fibreglass and epoxy resin used with sheet moulding compound (SMC) with a coating of silica and sand ('Faberland.hu', 2024) at least 5mm thick. Phenolic plywood 9mm (7-layers) ('The Pump Factory Pumptrack.nl', 2024).

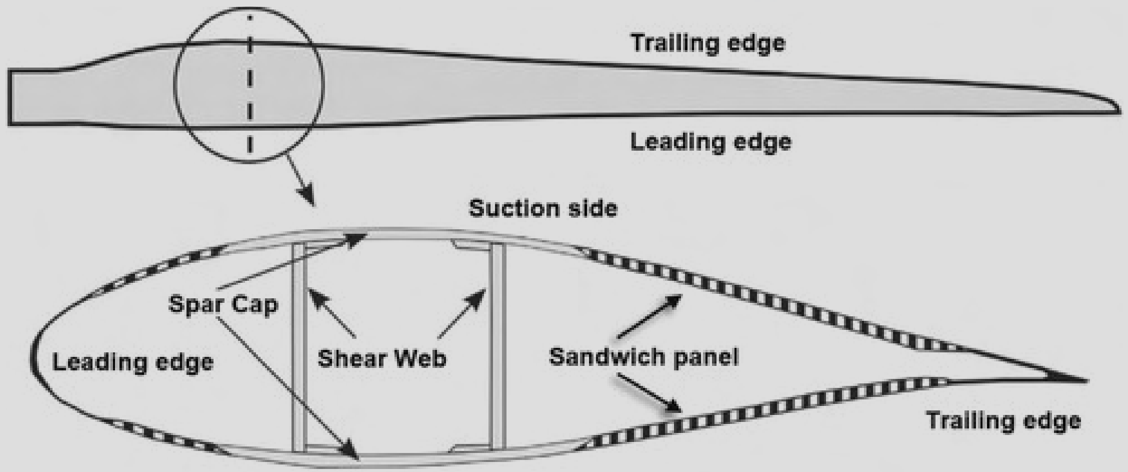


Figure 30 : *Different parts of the blade(Source: Lee, 2021)*

6.1.2 WTB Coatings

Wind turbine blades are usually coated with elastomeric coatings to protect the epoxy skin of the sandwich material and extend the lifetime of the blade. Coatings protect the turbine blades from wear and tear like rain, wind, sandstorms, UV etc. *"Conventional elastomeric coating layers consist of PU or EP. In general, PU in liquid form or in the form of a paste is used for the subsequent coating components, since it is characterised by good UV light resistance"* (Rosemeier & Krimmer, 2023, page 195). *"Unfortunately elastomeric coatings are currently used for erosion resistance, yet the life of such coatings cannot be predicted accurately"* (Slot et al., 2015, page 837).

Sometimes the decommissioned blade material can be heavily damaged and even worn down completely through this coating, as seen in (Figure 31). The leading edge is the part that wears down most.

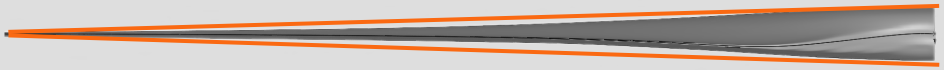


Figure 34 : *blade's tapered characteristic viewing at the trailing edge*

6.1.3 Blade geometric characteristics

A wind turbine blade is designed like an airfoil. It is optimized based on aerodynamics, load distribution, energy capture optimization and manufacturability. To make it as efficient as possible, there are a few characteristics that are important when understanding the material (Wicaksono et al., 2024).

A turbine blade's length can vary from 7,5m for the early models from 1985 (Rosemeier & Krimmer, 2023), up to an expected 145m in the near future (Hagenbeek et al., 2022) (Figure 32).

The airfoil profiles (Figure 33) might vary over the length of the blade to ensure the best aerodynamic properties, as well as a twist along the length of the blade (Figure 33). For strength properties the blade tapers towards the tip of the blade (Figure 34). These design choices create make that the variables such as material thicknesses and airfoil sizes change per blade and also within one specific blade-design to ensure sufficient strength and stiffness properties.

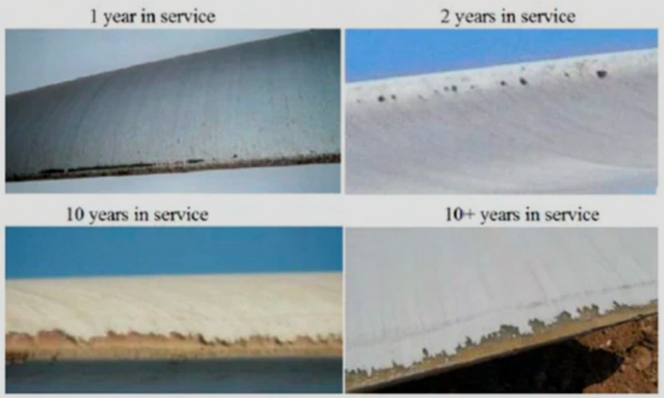


Figure 31 : *Leading edge eroded blade material (Source: Cortés et al., 2017)*

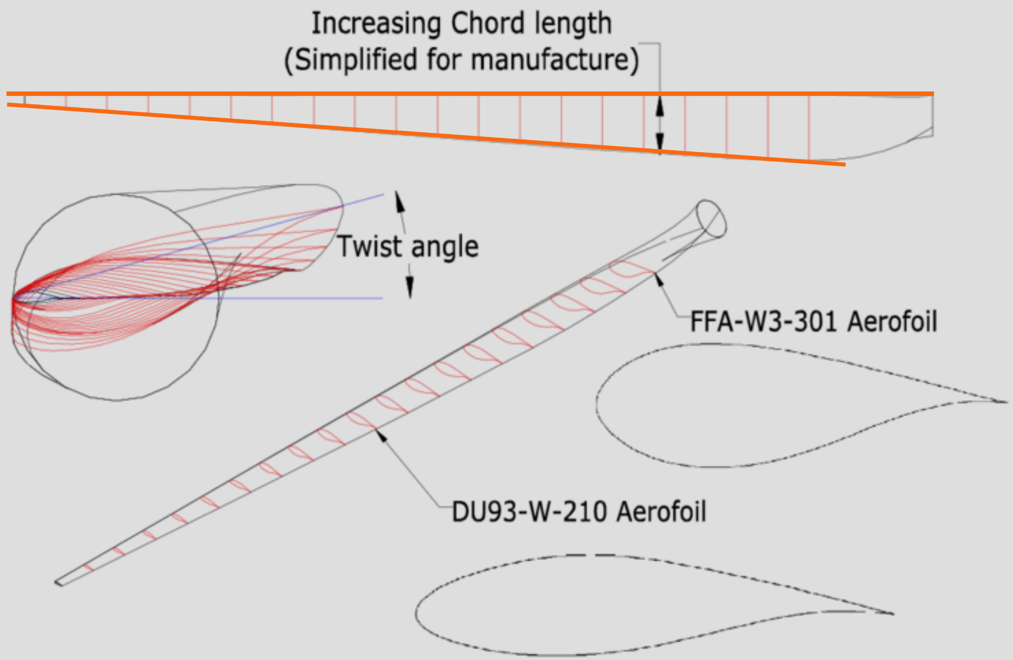


Figure 33 : *Typical modern HAWT blade with multiple aerofoil profiles, twist and linear chord length increase (Source: Schubel & Crossley, 2012)*

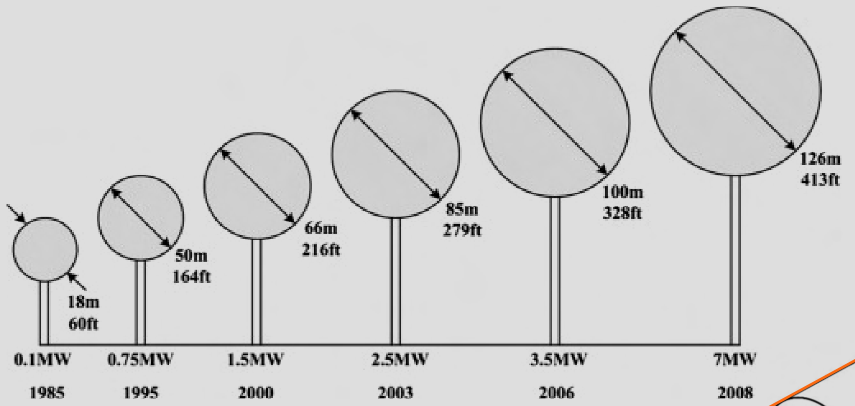


Figure 32: *Blade size (Yang & Sun, 2013)*

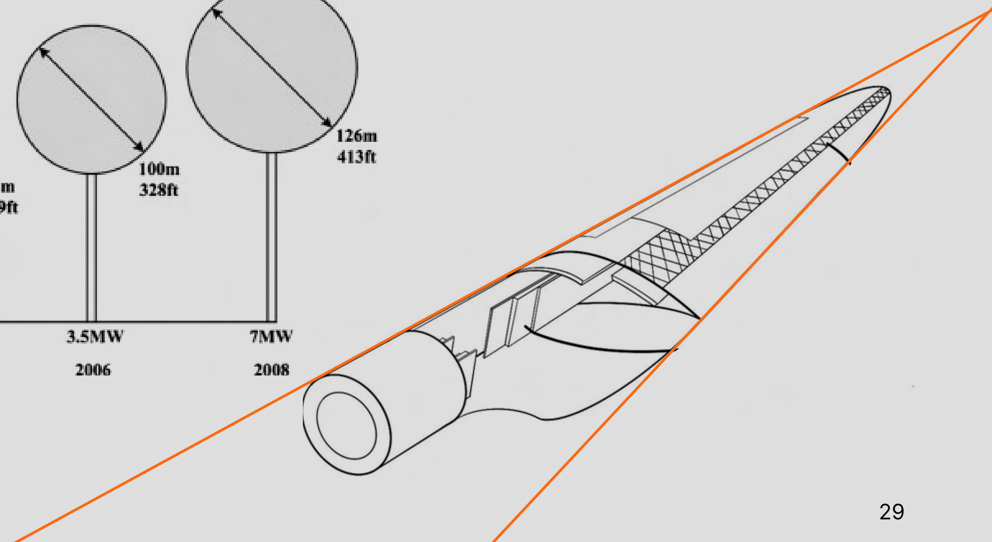


***Figure 35 :** 30m blade (Source: Fraunhofer)*

6.1.4 Reference blade

In collaboration with Fraunhofer, the ‘Structural Reuse By Design’ research group acquired a 30-meter research blade, (Figure 35) typically used for experimental purposes, as the reference blade for this study. This blade was specifically designed for research applications, allowing access to detailed design data, including a 3D model, build data, and material specifications.

Five blades of this typical model (Figure 35) were originally manufactured for studies on issues such as manufacturing defects. One of these blades was segmented into sections of approximately 1.5 meters (Figure 36) in length to verify the centre of gravity. Therefore, the blade is not coated.

For this research, these segments were selected based on their suitability for the intended study and made available for use. Subsequently, the selected blade segments were transported to Delft for further research.

***Figure 36 : T**ransportable pieces (Source: Fraunhofer)*

6.2 Conclusion

Answering the research questions:

>'What are the material's characteristics?'

When utilizing blade material, several key variables influence the overall design. These include the blade length, which determines the length of the airfoil profiles, as well as the material thickness. Additionally, the design of elements such as the twist, spar cap, and shear web play a crucial role in structural integrity.

>'What is the material made of?'

In turbine construction, both sandwich materials and solid glass fibre reinforced polymer (GFRP) components are used, each affecting the material's strength and weight properties. When repurposing blade material for secondary applications, it is essential to identify the specific type of blade and obtain relevant technical data to ensure suitability for the intended use.

For surface protection, polyurethane (PU) and epoxy (EP) coatings offer strong resistance to UV radiation and weathering, which may be particularly relevant for applications such as for pumptrack coatings.

07 Material Potential

The objective of this chapter is to explain the wind turbine blade material characteristics in more detail and its potential to replace current materials used in pumptracks.

7.1.1 Strength potential

The sandwich panel, particularly with a Balsa wood core, demonstrates superior strength-to-weight ratio of 0.325 MPa/(kg/m³) and impact resistance, as evidenced by comparisons in GRANTA (see Appendix 04). In comparison with GFRP (material 1 and 2) ranging from 0.107 to 0.138 MPa/(kg/m³), (Figure 37), these properties suggest that it could potentially reduce the weight and reliance on additional structural reinforcements, offering both performance and material efficiency advantages for use in the pumptrack design.

Further research should explore safety and constructional benefits to validate this potential of using the material without additional constructional elements. See chapter 14 Safety & 15 Impact.

Material	Density (kg/m³)	Flexural Strength (MPa)	Yield Strength (MPa)	Strength-to-Weight Ratio (MPa/(kg/m³))
Material 1: 2 layers of 1 mm E-glass biaxial	1860	199	440	0.107
Material 2: 3 layers of 1 mm E-glass biaxial	1860	199	440	0.107
Material 3: 1.5 mm face sheet, 19 mm balsa core	323	105	15.9	0.325
Material 4: Epoxy resin woven quasi-isotropic	1950	269	269	0.138
Material 5: Plywood (perpendicular to face layer)	800	55	9.9	0.069
Material 6: Plywood (parallel to face layer)	800	75	42.1	0.094

Figure 37 : *GRANTA Material table (GRANTA, 2024)*

7.1.2 Weight analysis of blade material

Although the strength to weight ratio of the sandwich panel is better than monolithic composite materials, it does not mean that it has to be lightweight. Because of the size of the blade and its manufacturing process, the blade cannot be made of sandwich panels only. The two shells, shear web and spar cap must be glued together, as seen in Figure 38 . "The spar cap is a main blade structural member that carries most of the load acting on the blade" (Lee & Shin, 2022, page 2061). Therefore, spar caps are fully made out of resin and carbon/glass fibre, creating a strong connector that is able to withstand those loads. This makes it a relatively heavy part of the blade. The total weight of the spar caps combined is accounted for approximately 30% of the weight. Followed by the skins (outer layers of the sandwich panels) which are approximately 22% of total weight (Figure 39). These percentages are according to simulations based on a 5MW 40.1 meter blade (Lee & Shin, 2022).

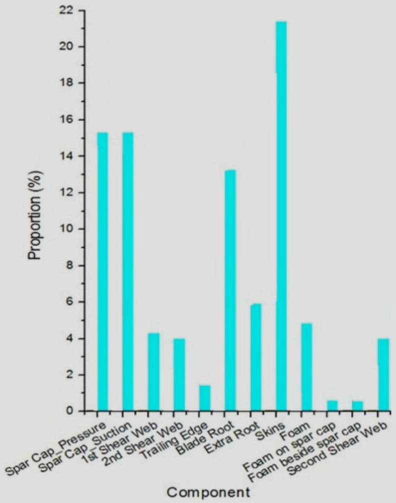


Figure 39 : *Weight distribution (Source: Lee & Shin, 2022)*

Spar cap

Glue

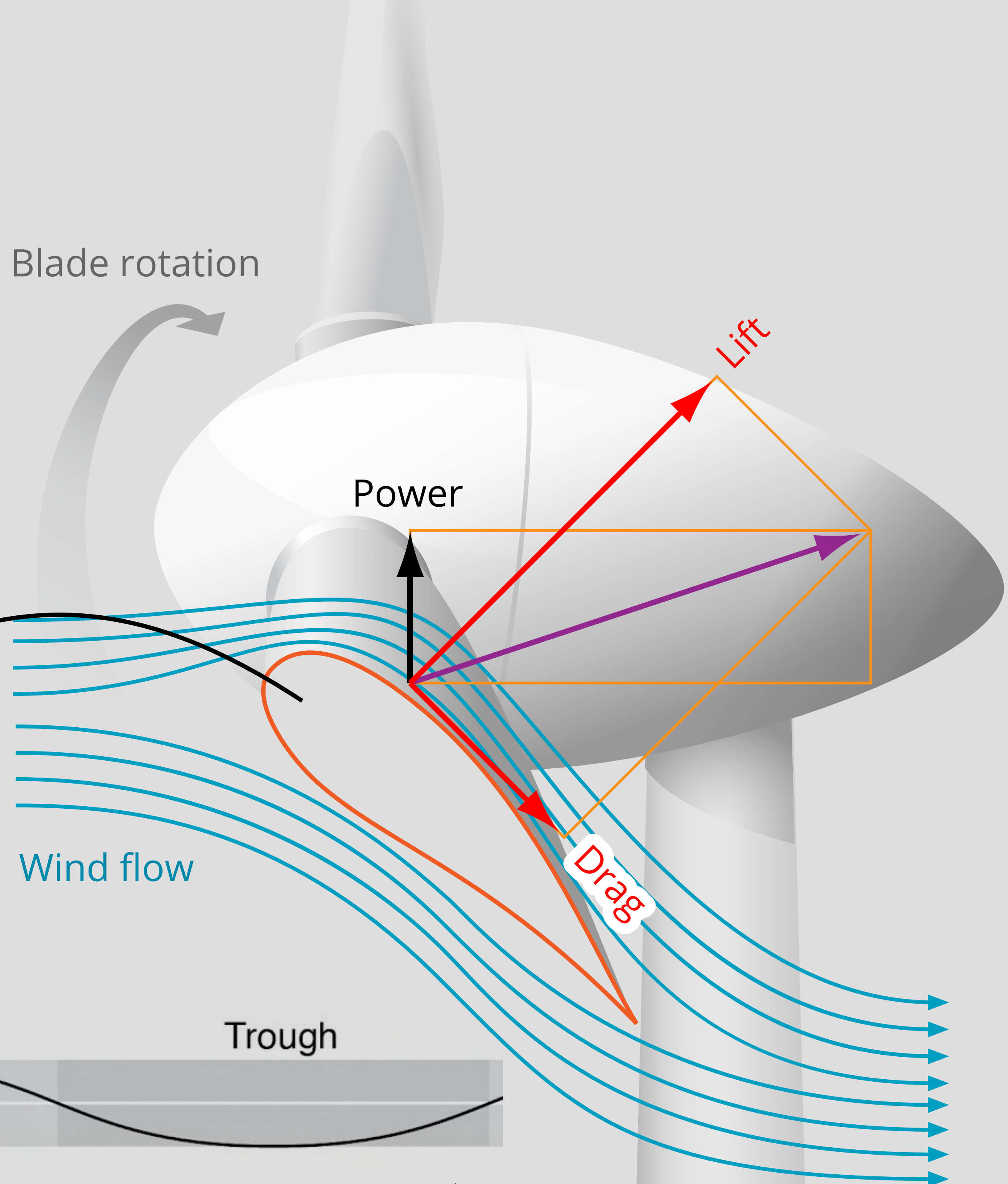
Shear web

Sandwich material

Figure 38: *spar cap glued to sandwich*

7.1.3 Geometric potential

The form of WTB is the same as a series of twisting airfoil shapes (Figure 40). This creates a lift-force which makes the wind turbine rotor spin (Figure 42). These shapes are quite close to the sinus formed shape of the rollers of a pumptrack (Figure 41).



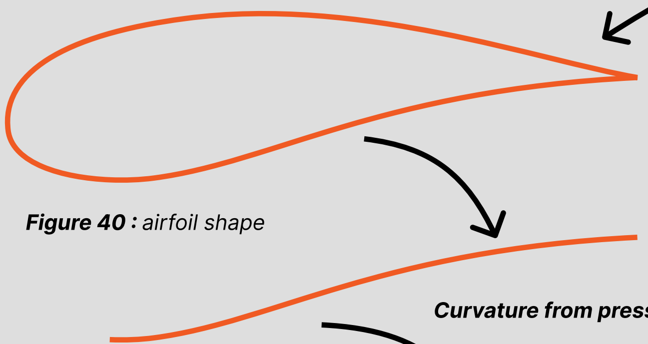


Figure 40 : *airfoil shape*

Curvature from pressure side

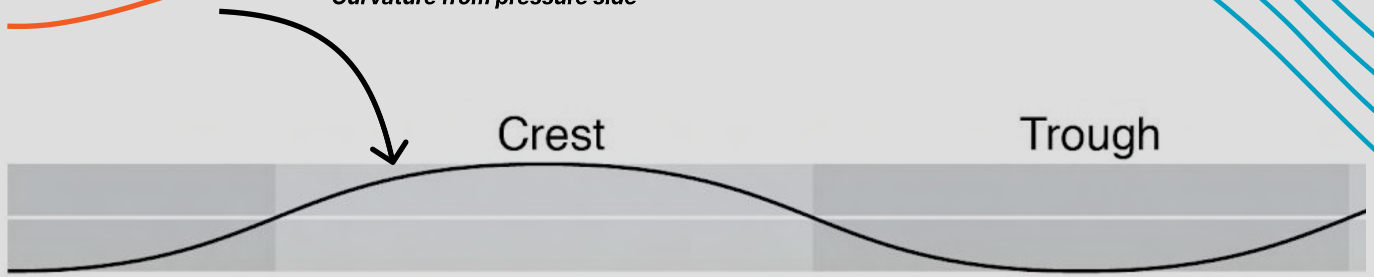


Figure 41: *Pumptrack roller (Source: McCormack, 2019)*

Figure 42 : *Wind turbine principle (Source: Encyclopedia.com, 2024)*

7.2 Conclusion

Answering the research questions:

> ‘Is the blade a potentially strong enough replacement material for pumptracks?’

The analysis of wind turbine blade (WTB) material characteristics suggests that turbine blade sandwich panels present a promising alternative to conventional pumptrack modules. With a strength-to-weight ratio of 0.325 MPa/(kg/m^3), sandwich panels, particularly those with a Balsa wood core, outperform traditional GFRP materials (which range from 0.107 to 0.138 MPa/(kg/m^3) in terms of structural efficiency.

> ‘Why use this material?’

This superior mechanical performance suggests that sandwich panels could potentially reduce the need for additional reinforcements, enhancing both material efficiency and structural integrity in pumptrack applications.

However, despite their advantages, structural support remains necessary to ensure stability and proper assembly. The spar cap, which accounts for approximately 30% of the total blade weight, is composed of resin and carbon/glass fibre. Given that these components add significant mass, it is advisable to not integrate the spar cap into modular pumptrack design.

Furthermore, the geometric shape of WTB materials, which resembles a twisted airfoil, aligns closely with the sinus profile of pumptrack rollers. This similarity suggests a potential structural and functional match, making the WTB sandwich panels a viable material choice.

However, this form similarity should be further researched and modules require an adjustable support to maintain a consistent elevation from the ground to the crest of the roller to ensure a good riding experience.

The next chapter will investigate cutting, connection methods, and handling techniques to facilitate the practical application of WTB materials in modular pumptrack construction.

Phase II - Explorative research phase

The last phase of research gave insight into the context of pumptracks, the blade material and the potential benefits and challenges of using certain blade material. This chapter will further research the remaining challenges by using sketching, drawings and prototyping as a means of research, answering some of the remaining questions.

The first section looks into the specific blade parts of a 30m research blade and gives insights in:

> Do the curvatures of a pumptrack match the wind turbine wing foil shapes in 2D & 3D?

>Do the geometrical characteristics of the blade limit the potential of the pumptrack modules?

>How to select the right curvatures in CAD?

It also gives a grasp about:

>How much blade material can be used in a pumptrack?

The final section of this chapter gives insights into:

>How to cut the windmill blades?
>How to select the right curvatures regarding an off-cut selection?

This chapter ends with a set of requirements to conclude the research phase.

08 Curvature matching

8.1 Curvature matching

One of the main challenges of the project is to match the curvatures of the blade material to the curvatures of the pumptrack. Because of the material characteristics, like tapering and twist, every blade section has a different geometry. Therefore, it is necessary to match the off-cuts to find out if and which parts are similar to pumptrack curvatures.

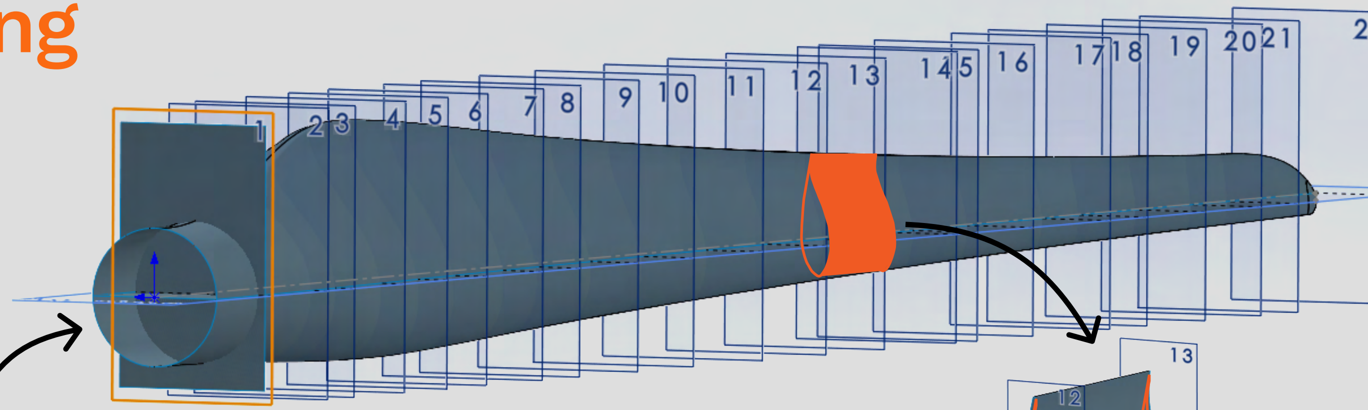
8.1.1 Converting reference blade to CAD

The material's size and complexity required a reconstruction of the blade segments in CAD (Figure 43), details can be found in Appendix 02, to facilitate their use in the full-scale prototype. The blade was sectioned in 22 sections with a width ranging from 1,0 - 1,9m.

8.1.2 Matching 2D

In order to determine whether the geometry of the airfoils aligns with the form of pumptrack roller waves, the two shapes need to be matched. The simplest and fastest way to find if this works is to look into the 2D matching.

The cross section of a blade, can be seen in Figure 44. When doing the same for the reference geometry of the pumptrack rollers, see Figure 45. Then, both geometries can be compared. It is important to use the same scale I advise (1:20) so it fits on an A4. Printing both geometries on A4 paper and cutting out the contours, you can find out if there are any similarities (Figure 46). See Appendix 03, for a more detailed description of this process.



Root

Figure 43: *Detailed blade in CAD*

The method showed that contiguous ‘piece’—specifically the 8th and 9th cut as seen in Figure 46, have similar curvatures, because the amount of twist and tapering is similar. With those matches, I found I can create sinus like rollers that potentially work for building a pumptrack.

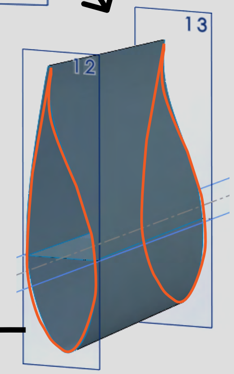


Figure 44: *Cross section 12*

Convert section 12 to 2D

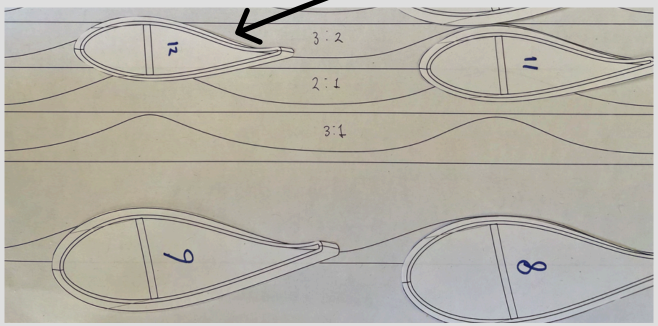


Figure 45: *Matching with pumptrack rollers*

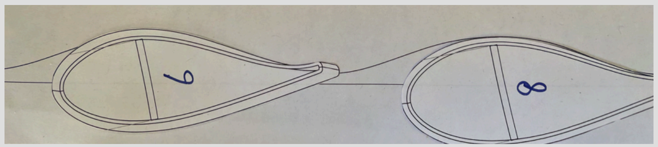
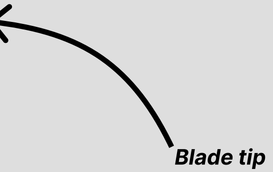


Figure 46: *Piece 8 & 9 similar curvature matching the 1:10 crest:trough ratio*

The method showed that contiguous ‘section’, for example the 8th and 9th cut (Figure 46), have similar curvatures, because the amount of twist and tapering is similar. With those matches, it is possible to create sinus like rollers that potentially work for building a pumptrack.

Closer to the top root of the blade, the curvatures align with the 1:10 height to length ratio of a common used pumptrack roller, from the building guide by (McCormack, 2019) in which the crest to through ratio is equal. Closer to the tip the curvatures match with the ‘jumpy’ or steep rollers (Figure 47), since the width of the blade decreases. See Appendix 03, for more details on the matching process of the curvatures.

Roller sizes



Another insight of this 2D matching is the different roller sizes. Since the blade is tapered, the width of the curvature varies from wide at the root of the blade, to narrow at the tip. In order to create a looped pumptrack, the modules cannot all be a different length.

Since the blade geometry changes along the length of the blade the airfoil-profiles will be longer towards the 'root' and smaller towards the tip.

For this 30m blade, it is most efficient to divide the cutting pattern in three parts. Part 1 (Figure 48) for the L-size rollers, part 2 for the M-sized rollers and part 3 for the S-size roller. This allows for building rollers with an equal length. But also takes into account efficient use of the blade material.

As seen in (Figure 49) depicting roller length: when applying it to the available pieces of the pre-cut 30m reference blade. The pieces 4-7 are L-sized, 8-11 are M-size and 12-15 S-size, with the roller height-length ratio ranging between 1:10 for a L-sized roller and 1:7 for an S-sized roller.

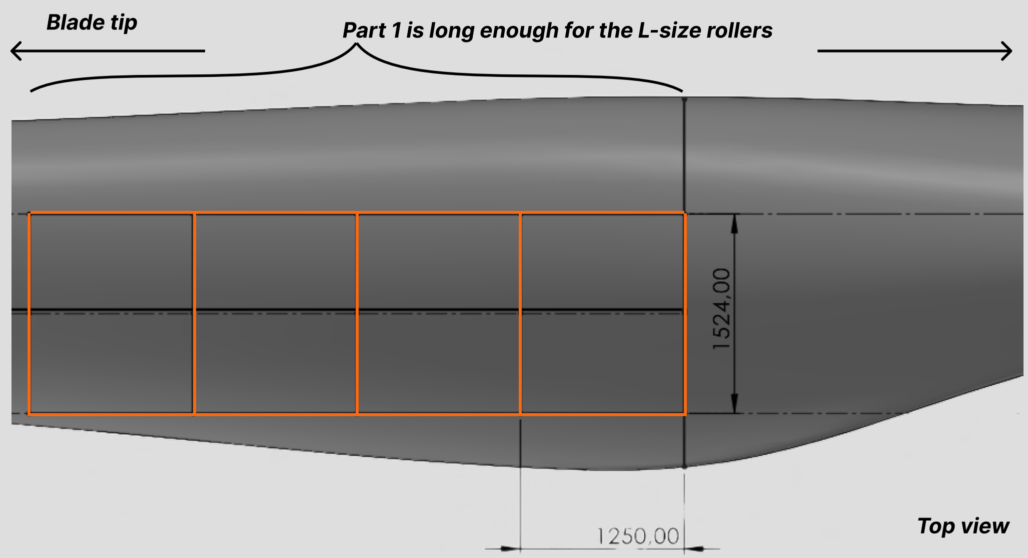


Figure 48: *Cutting pattern 4 L sized rollers, mapped on a blade*

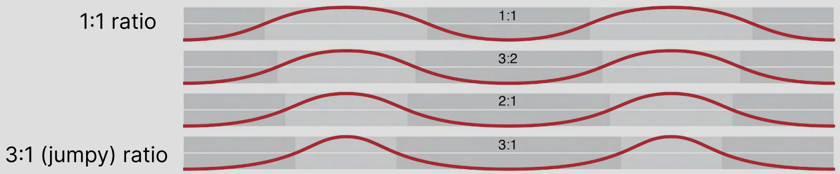


Figure 47: *Pumptrack roller different crest : trough ratios*

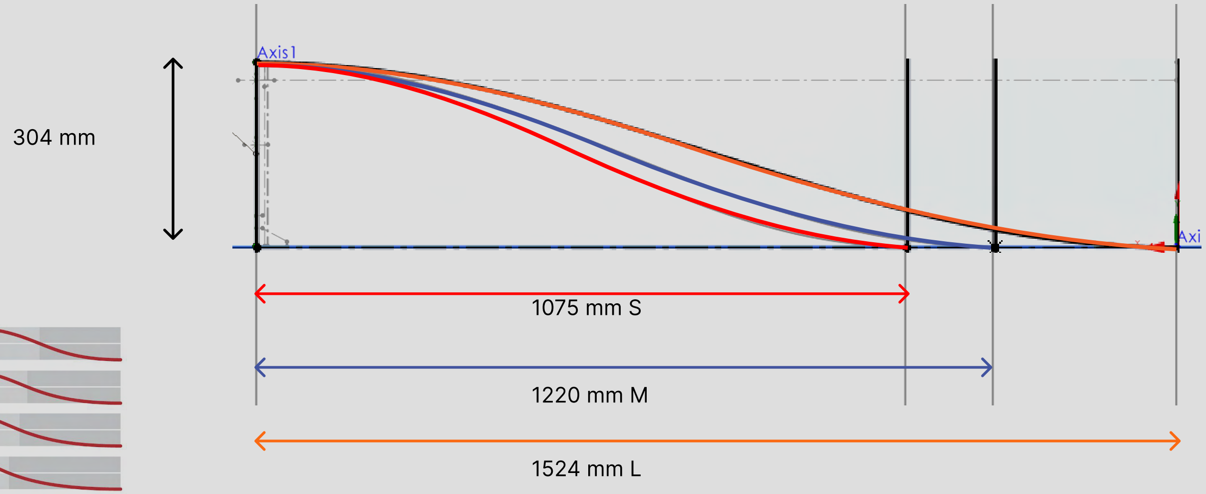


Figure 49: *Different sized rollers*

8.1.3 Curvature matching

During one of the design iterations (Appendix 05 ‘Design in one day’) the first track layout (Figure 50) has been created from 3D printed pieces. This mimics the process of mapping the cutting pattern, eventually cutting ‘the blade’ material by hand. This gave the first insights into the feasibility of the matching in 3D regarding: the alignment of the different rollers, the amount of blade material reused in a track and which part of the blade it is harvested from. This experience makes it easier to model and match the pieces in computer.

Corner:
The corner pieces could be harvested from the suction side of the blade (Figure 51) . The suction side of the blade contains less twist and taper making it a relatively flat panel when harvested. These panels can be joined together making a segmented corner (Figure 52). Whilst normally pumptracks corner modules have 3D curves, these panels are 2D curved. Making the transition between modules less gradually. This corner is not ideal since it is less smooth than a 3D curved corner. For bikes, this is less of a problem, but for skateboards or scooters this can be an issue while riding. It requires further research to understand if the effects the rideability of the track too much.

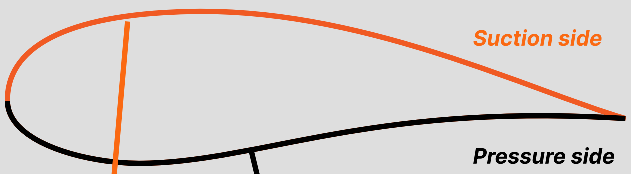


Figure 51: *airfoil suction & pressure*

Rollers:
The roller material can be harvested from the pressure-side (Figure 51) of the wind turbine blade. The rollers seem to align properly and by attaching all the harvested parts, a total of 6 rollers could be created. From the sections 4 - 16 of the 30m research blade.

Transition:
The transition piece is a complicated form, and therefore cannot be harvested from a blade. This is the only part that should be created from different material to make a continuous looped pumptrack.

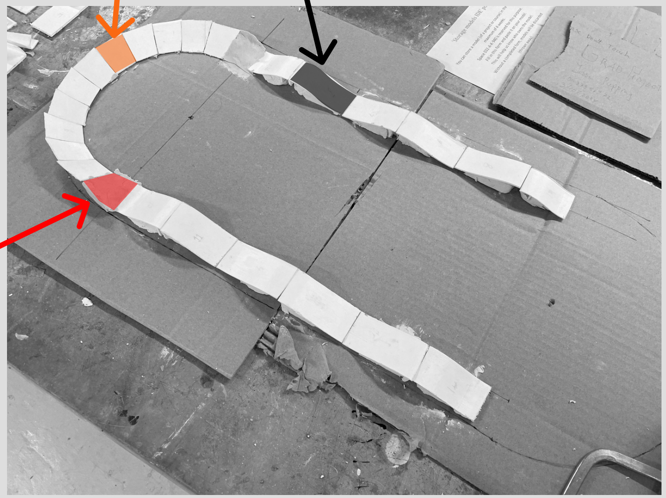


Figure 50 : *segmented corner prototype*

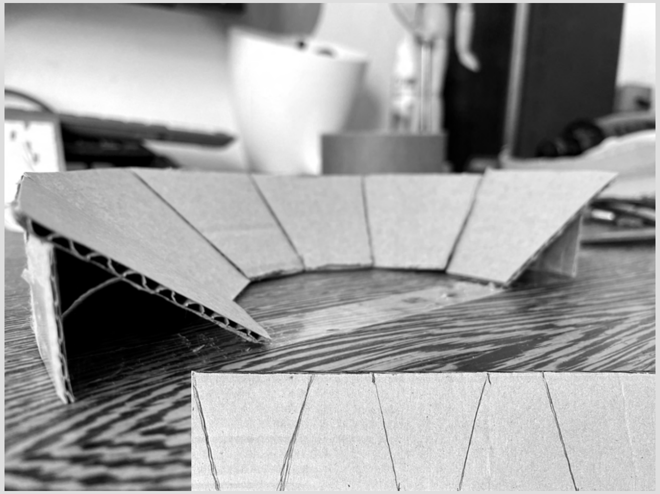


Figure 52: *Scale prototype*

8.1.4 Matching by CAD

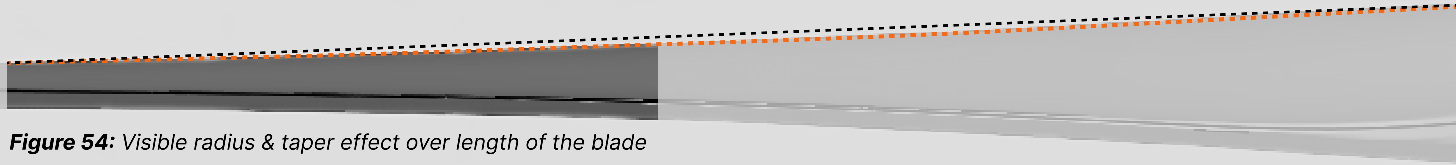


Figure 54: Visible radius & taper effect over length of the blade

In order to see the feasibility and alignment of the blade, it was key to find a more precise method. Using the existing 3D model provided by Fraunhofer the alignment of multiple modules could be simulated (Figure 53) . In this way the gap clearance and alignment could be precisely measured. Giving an insight in the compatibility at **joining edges**.

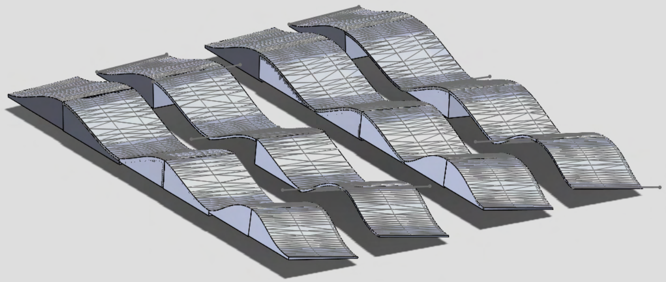


***Figure 53:** Overview of a series of (4)modules in CAD to see the difference in twist between 4 cutting techniques*

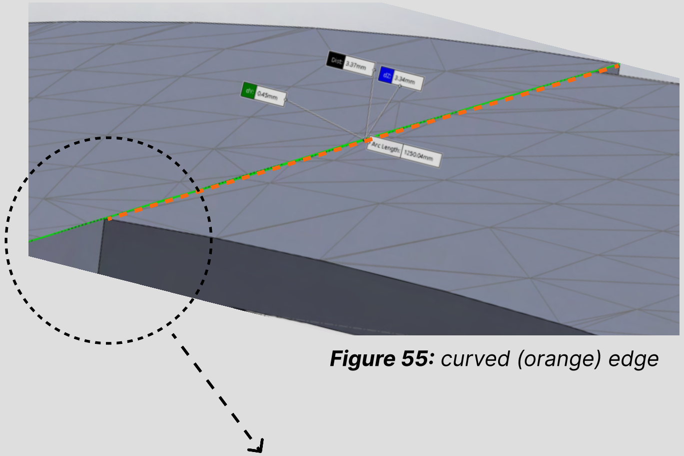


***Figure 55:** curved (orange) edge*

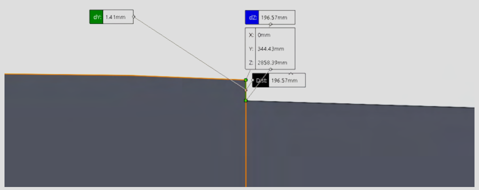


***Figure 56:** Gap clearance edges (side view)*

Gap clearance: When looking at the trailing edge of the blade (Figure 54) it is visible that the dotted (straight line) black line and the dotted orange line (follows the curve of the blade) are not overlapping 100% this is because the blade material has a slight curve.
When cutting sections each module will have a slightly curved edge (Figure 55). This creates gaps (Figure 56) when aligning. According to the NEN14974; as long as the gap clearance is lower than 5mm, this is no problem. When aligning 3 rollers in SolidWorks, I identified this clearance will not exceed 3mm for each of the cutting methods used in the research, as seen in Appendix 7. When a blade is bigger the radius on the blade material itself is bigger so the gaps will be smaller. This also highly depends on which part of the section is harvested, since some parts are more curvy than others.

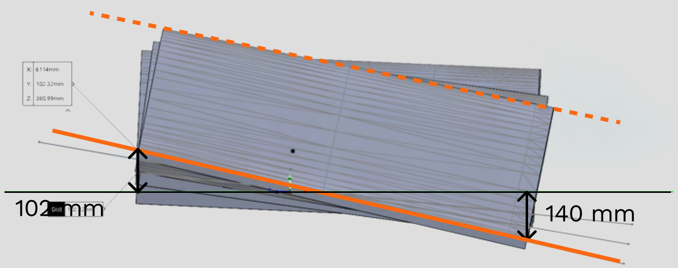


***Figure 57:** Twist in track due to tapering effect in blade material*

Tapering: The tapering in the blade translates to misalignment in the edge at the top of a pumptrack roller (crest) and the bottom of the roller (trough) (Figure 57). This effect will cause an offset of approximately ten centimetres at the end of the track (Figure 57) when using one of each size roller. The angle of this offset is about 2,2° per module. This closely corresponds with the tapering angle of the blade material, see Appendix 12.

Regarding the offcuts from the 30M reference blade, 6 rollers is the maximum amount that can be efficiently harvested from the blade material. The surface area adds up to 20 m2, analysing the 6 rollers account for a surface of 18% of the total blade surface. This could increase when using the suction side of the blade to harvest the corner modules. It could also be improved if the sections are cut more efficiently, see Chapter 11.2.

8.1.5 Matching automation software

3D matching using CAD software is a time consuming process and requires specific knowledge. Within the Structural Reuse by Design Research group, there is a team from Institute for Research in Digital Science and Technology (INRIA) under supervision of Adrien Bousseau working on the process of matching wind blade material. They succeeded in making a model that matches pieces from a certain 3D shape to another desired 3D model.

Bousseau and his team will use the case of matching pumptrack curvatures as an example to apply and improve the computer model. Doing this will make future matching processes easier.

8.2 The prototype blade

8.2.1 Blade material analysis

From the parts that were transported to Delft for research, see Appendix 17. Four sections were suitable to be used for prototyping. These pieces were later analysed on weight, arc length and other dimensions (Figure 58).

In Chapter 7, the blade analysis concluded that the spar cap is a relatively heavy part to be implemented in the modular pumptrack rollers. But it is also important to cut the optimal curve that matches the curve of the pumptrack rollers. When measuring the available blade material from Fraunhofer, it became clear that the rollers cannot solely be made from sandwich material and will contain parts of the spar cap to ensure the form similarity with the reference curves.

This is because the length of the sandwich material is shorter than the desired arc length needed for the rollers (Figure 60).

In addition, the arc position also determines the shape of the roller meaning that even if the arc length of the spar cab material is long enough sometimes it is not the desired curvature. Deviating from reference curve might make the pumptrack less smooth to ride. Figure 58.1 shows that only Section 9 of the roller can be fully made from sandwich material since the reference arc length stays withing the length of the sandwich material on both sides of the section. This is not a problem but it will mean that the roller modules become relatively heavy. This will be evaluated to see if it exceeds the preferred 64kg roller mass in Chapter 11.2.

Section	Desired arc length	Arc length sandwich material [cm]	Arc length sandwich Short side [cm]	Sandwich material Tickness [mm]	Core material	Sparcab width [cm]
9	M (126cm)	155	128	23	balsa	43
10 (section)	M (126 cm)	125	123			43
11.1	M (126 cm)	124	101	23	balsa	43
12.1	S (112 cm)	90	76	25	PET	43
12.2	S (112 cm)	109	96	25	PET	43
20	-	-	-	-	-	43

Figure 58.1: *table material analysis measurments*

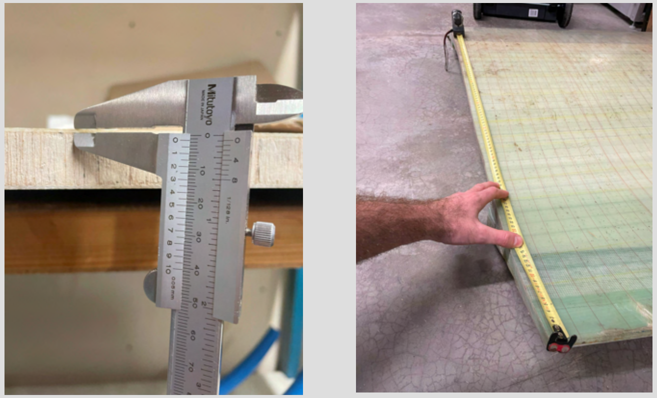


Figure 58: *Material analysis (arc length, sandwich material thickness)*

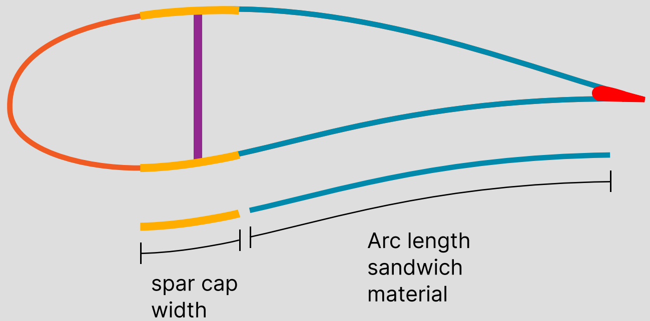


Figure 59: *Explanation Spar cap width & arc length*

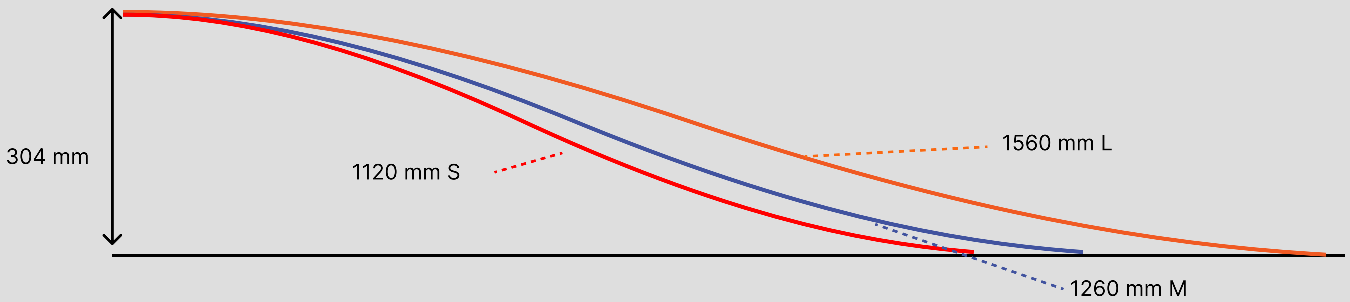


Figure 60: *Desired arc lengths S/M/L*

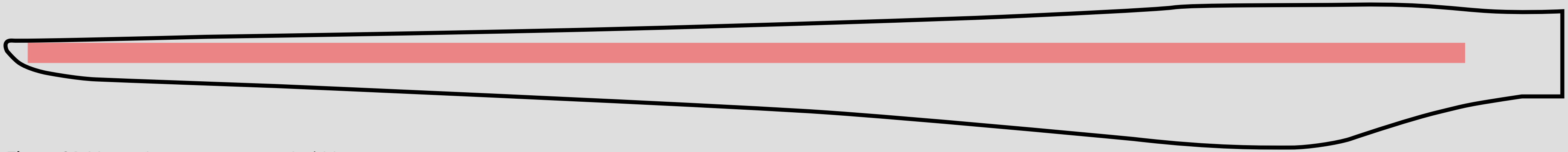


Figure 61: *Mapped out spar cap equal width*

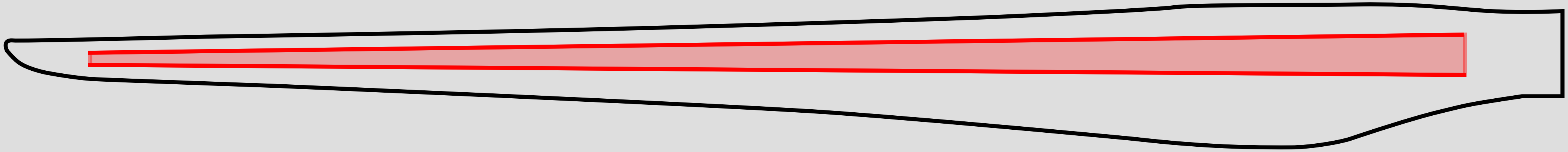


Figure 62: *Spar cap tapered design*

4.2.2 Point of reference

Because of the geometry of a blade (tapering and twist effect) there is no straight surface material. Except from the shear web inside of the blade's shell. When a blade is decommissioned, details like: length, type of blade, width and other details might not be available. When repurposing a decommissioned blade, it is important to have a point of reference, for example to map out the cutting pattern.

The spar caps and the shear web are the only relatively straight parts in the wind turbine blade and can be used as a point of reference to create a cutting pattern or as a point of reference to measure the blade's details like (arc) length and overall width.

For some blade types, the spar cap width may taper towards the tip (Figure 62) to optimize the weight of the blade, while other concepts keeps the width constant (Figure 61) (Rosemeier & Bätge, 2014), therefore making it perfect as a reference point along the length of the blade.
For the research blade, the width of the spar cap is equal over the full length of the blade (see Appendix 15), therefore it is suitable to use a reference point mapping out the cutting pattern. Since this blade was not coated, the spar cap is visible through the skins, which is very convenient. This is not the case when using a coated blade.

8.3 Conclusion

Answering the research questions:

>'Do the curvatures of a pumptrack match the turbine blade material?'

During the explorative research, it became clear that the transition piece cannot be harvested from the blade and instead separately fabricated to ensure a continuous track. The corner modules have the limitation of being 2D curved instead of the conventional 3D modules. For bikes, this is less of a problem, but for skateboards or scooters this can be an issue while riding. It requires further research to understand if the effects the rideability of the track too much.

>'How much blade material can be used in a pumptrack?'

For a 30m blade using non optimized off-cuts, 20 m^2 - equivalent to 18% of the total surface - can be repurposed as roller modules. To maximize material efficiency while maintaining a standardized roller size, the rollers should be divided into 3 lengths ranging from S-1075mm, M-1220mm & L-1524 m long.

>'Are the blades tapering and twist a problem when using the material as pumptrack modules?'

CAD simulations reveal that when connecting three differently sized rollers, the track experiences a cumulative twist offset of approximately 20 cm, corresponding to a 3-degree angle per module. Therefore, the support system must be adjustable to compensate for the material's inherent twist, maintaining structural integrity and rideability.

>'How to select the right curvatures in CAD?'

To match the right sections from a WTB with the desired form, it is important to determine the maximum arc length of the airfoil profiles of the blade. This will define the max length of the rollers. For a 30m blade this results in slightly shorter rollers (between 1075 and 1524 mm) than mentioned in the building guidelines. This might not be a problem when keeping in mind the 1:20 height to length ratio to being a more driving rule.

09 Cutting blade material

Cutting WTB material can be difficult, mainly because of the toughness of the material, the shape and the irritative and highly toxic dust that releases when cutting the material (Asmatulu et al., 2018).

9.1 Cutting Techniques

Although there are several methods for cutting, blade material manually each with their own benefits (Figure 63). A Jig/reciprocal saw for organic shapes, circular saw for long & straight cuts. Angle grinder for deeper cuts and Diamond blade chainsaw (water cooled) for rough sectioning by hand.

Jig saw (Source: Neuman, 2024)

Angle grinder (Source: buildequip.com)

Circular saw (Source: Fraunhofer)

Chain saw (Source: icsdiamondtools.com)

Figure 63: *Manual methods*

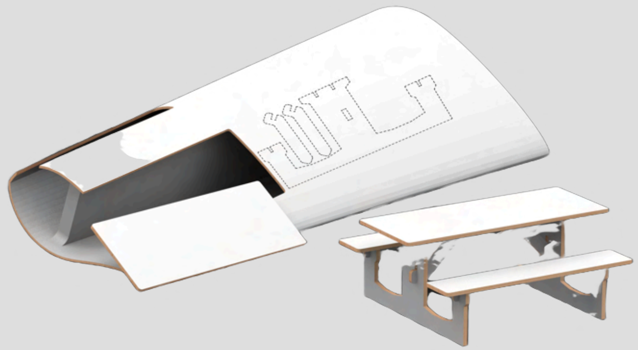


Figure 64: ***C****utting pattern picnic table (Source: Joustra, 20121)*

Sections cutting techniques:

Sectioning blade material is a rough process and requires more specialized techniques such as using a grinding belt, a diamond circular saw, or Waterjet rails cutter. For the context using a 360 rotation Diamond (1.4m diameter) circular saw blade on a excavator, the time to cut a 78m blade into 2 x1 m pieces will be approximately 3 days.

Other experimental ways like the diamond wire machine by (Evan Wright, 2021) takes about 17 min to cut through a section towards the tip of the blade (Figure 65).

These methods are still in development and can be more efficient when research specifically targets cutting of blade material. To cut precise patterns waterjet cutting on a flatbed machine can be a good option, an example of a use-case being a picnic table (Joustra, 2021) (Figure 64).

Sectioning techniques

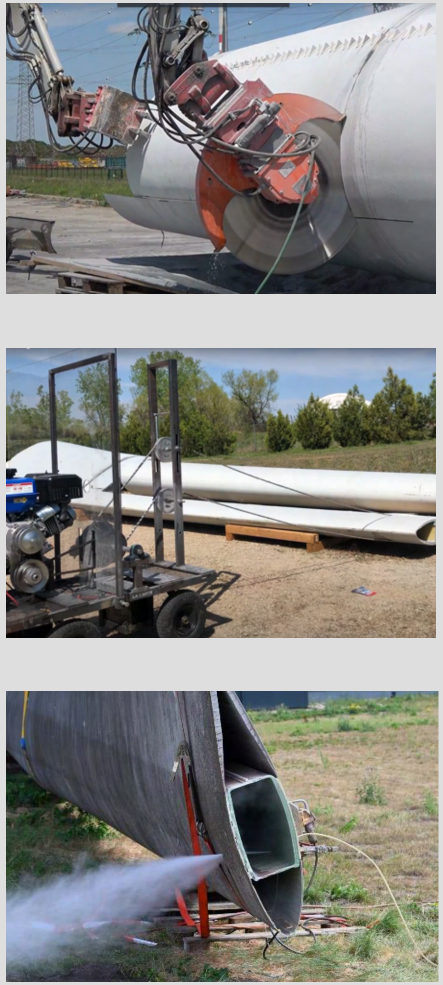


Figure 65: *Echidna Diamond Saw (Source: Echidna.com.au), Diamond wire cutting (Source: Evan Wright, 2021), Waterjet cutting (Source: TNO),*

9.2 Waterjet Cutting roller prototype

When handling or machining blade material it is necessary to take safety precautions, as identified in Appendix 14. With typical methods in mind, as well as safety concerns, this chapter expands on the process of cutting the reference WTB in this project.

Among the available options, waterjet cutting is one of the cleanest and most precise methods, with machine tolerances ranging from 0.05 mm to 0.025 mm (Schlick, 2022). It also generates the least dust, as particles bind to the water. When performed in a closed, controlled environment, these particles can be filtered out, making the process relatively clean and safe.

Considering the lack of a well-ventilated room available to master's students at TU Delft facilities and considering the project's timeframe: 2D flatbed waterjet cutting emerged as a suitable option for this project.

Fraunhofer IWES already cut out the downwind panels from the blade sections manually, so the blade was flat enough to be cut in a flatbed waterjet cutter. Van Nobelen Delft[7] was the best local resource to do this type of work within the time frame of the project.

9.3 Selecting the right curvatures

The biggest challenge during the cutting process is to create the right cutting angles and alignment with the reference lines which is found to be (Chapter 8.2) the 'spar cap'.

To accurately select the appropriate curvature for a blade section, a jig (Figure 69 & 70) can be utilized to represent both the desired curve and arc length of the roller. The optimal position for cutting can be determined by comparing the natural curvature of the blade with the predefined curvature of the jig (Figure 68). Once alignment is achieved, the start and end points of the roller section should be precisely marked (Figure 66). Subsequently, the distance from the spar cap serves as a reference to draw an accurate cutting line, ensuring precision in shaping the roller section (Figure 67). Appendix 16 gives more detailed info about the jig and matching process.

This can later be used as reference lines to set up in a flatbed waterjet machine or as cutting lines when using hand tools e.g. a circular saw.

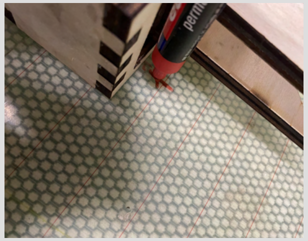


Figure 66: *Marking the reference line on blade material*

7 Van Nobelen Delft is a specialist in producing machinery, metal working and constructional building projects. They do waterjet cutting on project base.

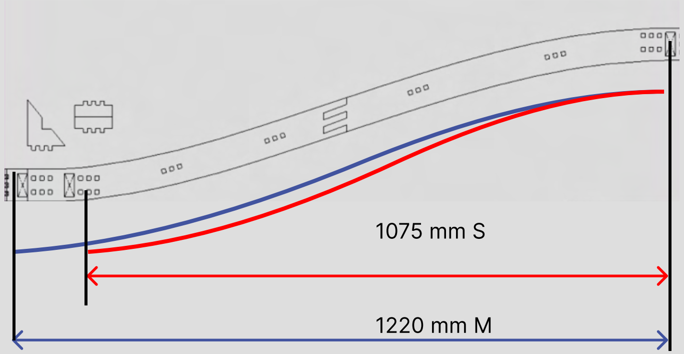


Figure 69: *JIG design for S & M curve*

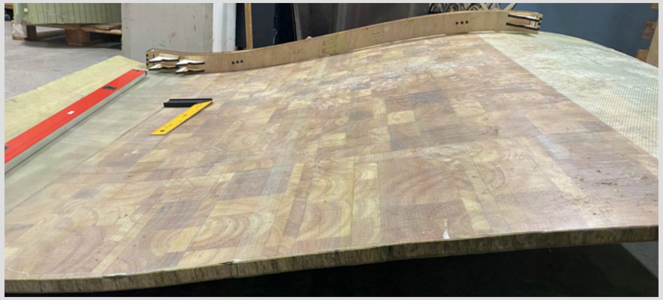


Figure 68: *Matching the reference jig curve with the blade curve*

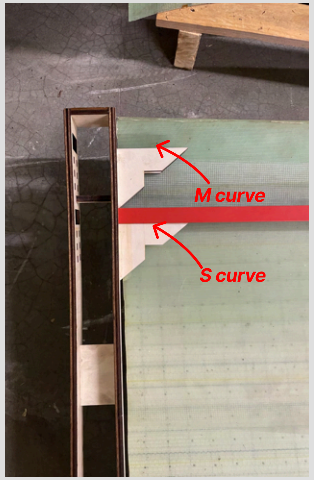


Figure 70: *Jig slots to mark S & M curve (top view)*

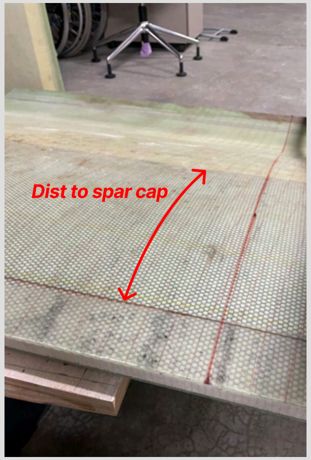


Figure 67: *Distance to sparcap*

When cutting the blade material the angle of the blade has influence on the gaps that will occur between joining edges. With respect to the top surface, a perpendicular cut results in a perfectly joining edge. A cutting angle larger than 90° creates a 'sharp' angle at the top, creating a gap at the bottom of the surface material. This allows for minor misalignments without creating a gab at the riding surface (Figure 71). It is preferred to cut edges with a slightly too sharp angle.

Therefore it is important the blade material is positioned and waterjet head or saw blade is at the right angle (Figure 72). In the case of a flatbed water cut machine it is necessary to elevate the panel so aligns with the waterjet head (Figure 72) since the head itself cannot rotate and only move up and down.

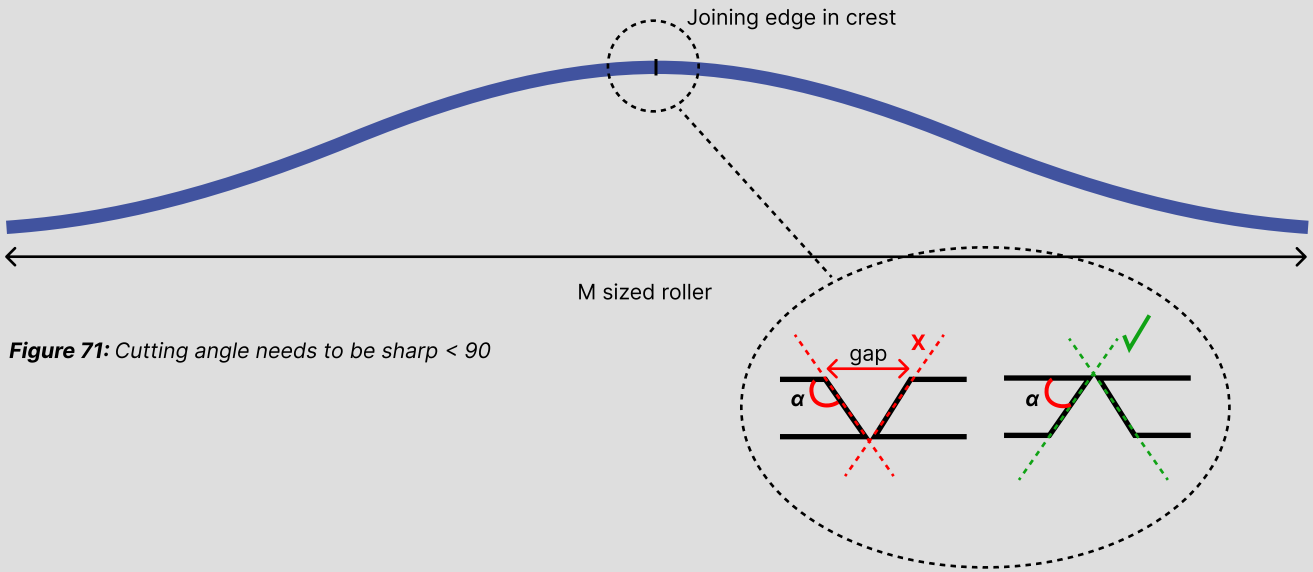
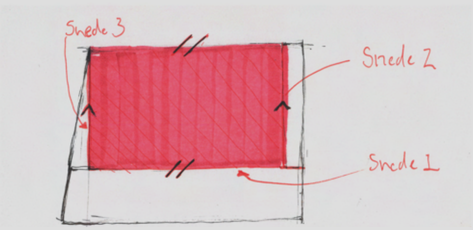


Figure 71: *Cutting angle needs to be sharp < 90*



Top view

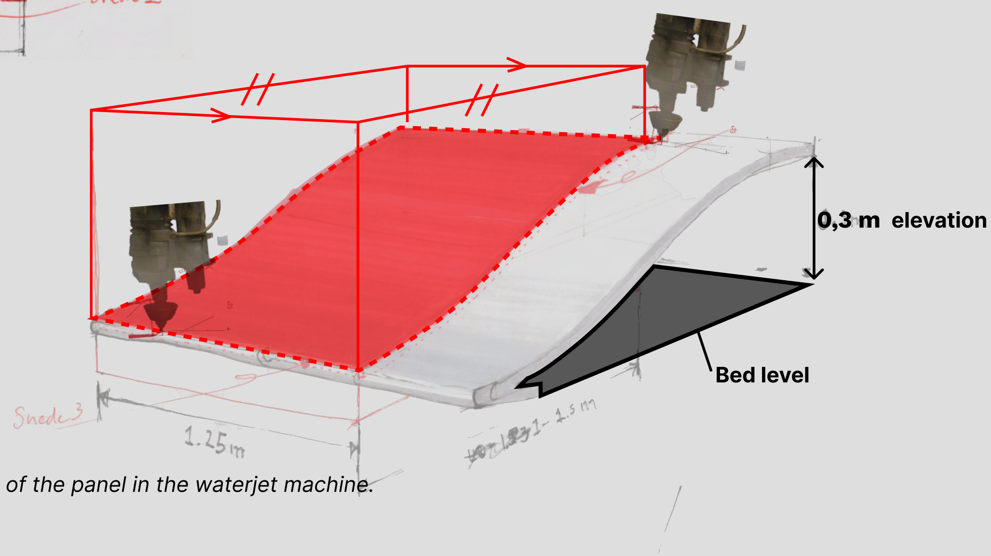


Figure 72: *schematic of the panel in the waterjet machine.*

9.4 Ideal Cutting method

Ideally, the WTB pumptrack sections would be directly cut into the right width, saving post-processing time and minimizing material off-cuts.
In this study, assuming the airfoil profiles of the turbine blade and the height of the rollers match those of the roller shapes from the book by (McCormack, 2019), the roller lengths can be mapped from the top view. This will give an optimized cutting pattern where the variables can be roller-length, arc length and shape and track width (Figure 73). This could then be used as input for a computer-controlled waterjet machine in the case of an off-site cutting scenario[8].

For an onsite scenario[9], sectioning using a rail-guided waterjet machine (Figure 74) or other automated methods may be considered. However, while waterjet cutting offers high precision, this method is less suitable due to excessive noise levels and the requirement to operate at an isolated location.

To maximize efficiency, it is preferable to cut large sections of material. This minimizes te time to set up the machine and maximizes the number of mapped blade parts in a single operation. Currently, no dedicated infrastructure exists for CNC cutting of blade material. To illustrate the potential, the largest CNC waterjet cutting machine can process materials up to 20 meters long and 5 meters wide, with sufficient pressure to cut through 400mm thickness (Largest Waterjet Cutting Machine, 2017). This capability would enable the processing of an 20-meter blade section in a single operation, reducing costs and improving efficiency compared to manually matching curvatures with a jig, as described in Chapter 9.2. However, a key technological limitation is the need for an adjustable cutting angle that remains perpendicular to the riding surface during cutting. And the extensive costs of machining.

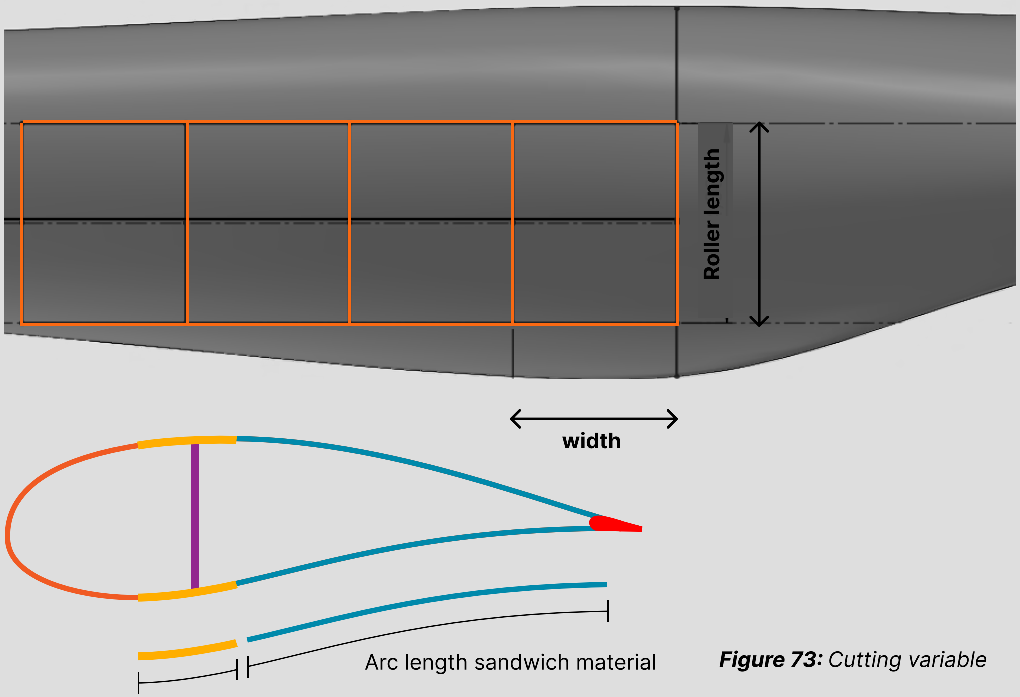


Figure 73: *Cutting variable*

[8] *Offsite cutting scenario where the blade or part of the blade is transported to watercut machine.*

[9] *Onsite cutting scenario where the blade is cut into the right pieces at the same spot where it is decommissioned*

Figure 74: *Rail guided water jet machine*

9.5 Conclusion

Answering the research questions:

>'How to cut the windmill blades?'

To ensure smooth transitions, it is preferred to cut edges at a slightly sharper angle, allowing the joined edges to align seamlessly at the top of the riding surface.
When cutting blades into sections the shear web is not accessible. It requires specialized equipment such as a Grinding Belt rough sections, Diamond Rock Saw for deep and precise cuts, or a Waterjet Rails Cutter for automated, high-precision sectioning.

When cutting more specific shapes and patterns from sections its sufficient to use cutting equipment with saw blades or grinding discs. Although it requires protective measures, including proper ventilation, dust extraction, safeguard tools and in some cases cooling of sawblades.

>'How to select the right curvatures regarding when using an off-cut blade section?'

A jig helps align the blade's natural curvature to the desired arc length & curvature, ensuring a precise form similarity with the track design. The spar cap serves as a reference for marking start for drawing straight cutting lines. To minimize gaps, a slightly sharper cutting angle minimizing gaps at the joining edges.

10 Design Requirements

Requirements

This research led to a list of requirements acting as the backbone of this design project. The list consists of the desires from the structural reuse by design research group, advice from current pumptrack builders, the NEN-norms and requirements which are specific to geometrical and other material properties of sandwich materials as building material. As well as the conclusions from the previous initial and explorative research chapters.

With this extensive list of requirements as the foundation, the next phase of this report focuses on integrating these criteria into the design, validating them through prototyping, and analysing the material properties.

General for pumptracks:

- G1) Track > 1m wide. (The Pump Factory, personal communication, 10 October 2024)
- G2) Gap clearance <5 mm between joining edges. NEN14974 (skateparks norm) (Appendix 19 for extensive list of safety requirements)
- G3) Corners should have a constant radius in a turn which is 10-12 feet. (McCormack, 2019, page 40)
- G6) Height of the corner modules is at least 85cm (Parkitect, 2024).
- G7) Height of roller should be between 30-38 cm. (Chapter 5.2)
- G8) Ratio heigh length 1:10
- G9) Apply Anti-skid coating (grain between 0,6-1,6 mm) NEN1176
- G10) No flat parts in the track (The Pump Factory, personal communication, 10 October 2024)

Blade Material specific requirements:

- B1) Withstand compressive strength of 2,8Mpa. NEN14974
- B2) Material withstands a uniformly distributed load of 3500N/m. NEN14974
- B3) Material withstands a point load of 7500 on 50x50mm surface. NEN14974
- B4) The curvatures of the blade material need to match sinus-like waves of the pumptrack. (Chapter 9.1)
- B5) Modules need to be adjustable in height between 25– 45 cm. because of the twist. (Chapter 9.1)
- B6) Support system should absorb the twist in the track, therefore be adjustable in angle between -13° and 13° for 3 rollers and 2,3° for every extra roller. (Chapter 9.1)

Project wishes (client & researcher):

- W1) Keep it simple and cost effective don’t make the design over complicated.
- W2) Rollers do not contain spar cap and/or glue material.
- W3) The weight of modules does not exceed 65kg.
- W4) The design should not limit the options of following life cycles.
- W5) Modules should be stackable for transport and storage. (Client requirement)
- W6) The modules should fit on the biggest size trailer (2,55x12m) or in a (8ft)container (client requirement)
- W7) Pumptrack modules are as durable as current modules (client requirement)
- W8) Ridable for scooter, bike and skateboards. (Client requirement)
- W9) The track tells the story about the origin of the material (Personal/client requirement)
- W10) Prototype roller should fit with current The Pump Factory pumptrack module ‘’1.25m’’ wide. (The Pump Factory, personal communication, 10 October 2024)
- W11) Fasteners should be reversible and removable with minimal tools e.g. hex-key, screwdriver. (Client requirement)
- W12) Length of roller around 2m

Phase III - Embodiment

With a comprehensive understanding of the requirements to build a pumptrack and the limitations of the blade material, the next phase explores the Embodiment Design. Creating design drawings and models to later validate on form and usability and operation in the next part of this report.

This chapter answers the questions on:

> What will the rollers look like?

> How to connect the WTB material?

> How can you make the system modular?

> What will the support system looks like?

> What coating can be applied?

It also gives insights into the challenges when building pumptrack modules from wind turbine blades. In conclusion, the remaining challenges and limitations of the material are discussed.

Credit: Patrick Wetzels

11 Roller design

This chapter gives insights into the embodiment of the roller design in a context where the track would be solely made out of blade modules. It also gives context into the prototypes that fit with the track of The Pump factory which are later evaluated in the validation phase IV.

11.1 Roller Prototypes

For this prototype the track width is 1.25m in order to fit with the existing track of 'The Pump Factory'.
With the material available it was possible to create 4 modules, 2 medium sized rollers and 2 small sized rollers (Figure 75).

The blade material has a few important variables when it comes to fastening and aligning multiple panels. Material thicknesses, material composition and mass (Figure 75.1).

After cutting the panels into the desired shape (Figure 75), the average weight of the 4 modules including hardware and fasteners is 57 kilograms, which is below the weight of conventional pumptrack modules. The weights of the sections ranged between 33 - 64 kg, the variation due to the ratio spar-cap/sandwich material. Typically, pumptrack roller modules are 2000 mm long, while the WTB prototype modules range between 1075-1554 mm. So the relative weight of the WTB sections is heavier than current pumptrack design modules. Therefore, the ratio (height:length) of the track modules ranges between 1:10,2 for 2 L-sized rollers and 1:7 for two S-sized rollers. The smaller ratio might affect the rideability of the track, this will be evaluated in Chapter 16.

Figure 75: *picture of prototype*

Section	Desired arc length	Arc length sandwich material [cm]	Arc length sandwich Short side [cm]	Mass offcut [kg]	Sandwich material Tickness [mm]	Core material	Arclength after waterjet cutting [cm]	Sparcab width [cm]
9	M (126cm)	155	128	33,6	23	balsa	134	43
10 (section)	M (126 cm)	125	123	-				43
11.1	M (126 cm)	124	101	65	23	balsa	149	43
12.1	S (112 cm)	90	76	64	25	PET	120	43
12.2	S (112 cm)	109	96	64	25	PET	132	43
20	-	-	-	-	-	-	-	43

Figure 75.1: *Overview of material properties*

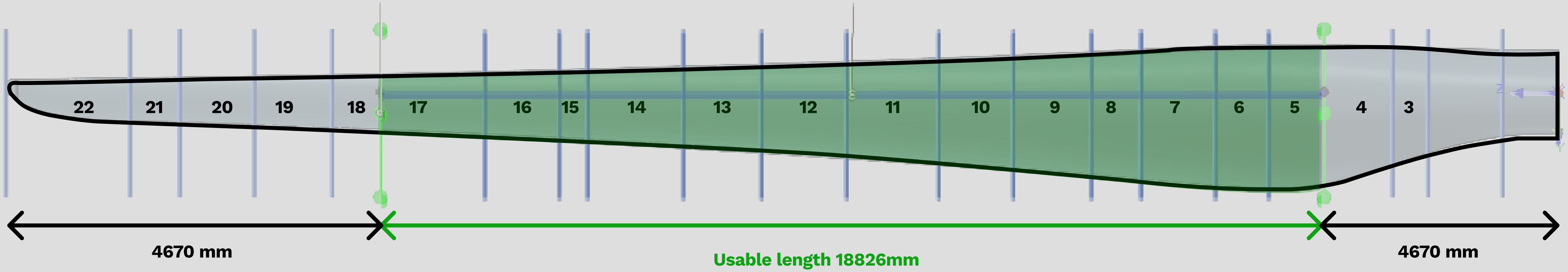


Figure 76: *inefficient sectioning*

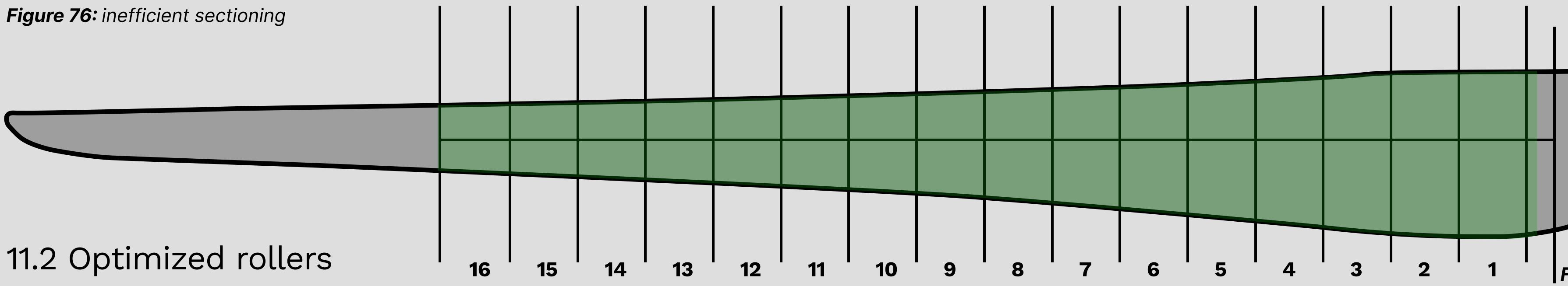


Figure 77: *Optimized sectioning*

11.2 Optimized rollers

In order to get the most efficient pattern from the wind turbine blade the rollers have three sizes: small, medium, and large.

Ideally, the track width is over 1m and preferably over 1,25m. In the case of the blade modules a wider track results in less sections that can be harvested from one blade. To get the most panels out of the blade but not give in on riding comfort, it is desired to have a smaller track width of 1,10m wide. This increases the amount of harvested modules from 12 (using the inefficient sectioning) (Figure 76) to 16 modules using optimized sectioning of 1100mm wide (Figure 77). Making it possible to create 8 roller modules instead of 6. It also means that for a 30m blade the offset per module will decrease, 6mm per module when accounting for a 2,2° offset angle ***α*,** as seen in Figure 78.

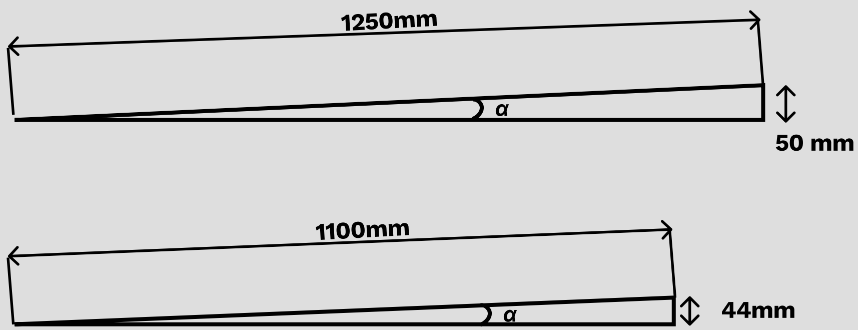
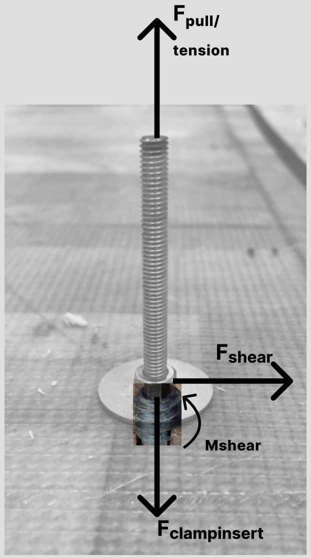


Figure 78: *Off-set minimize for a smaller roller width*

12 Connecting modules

This part of the report gives an insight in the analysing the connection methods of blade material and the embodiment of the support system specifically made for modular pumptracks.



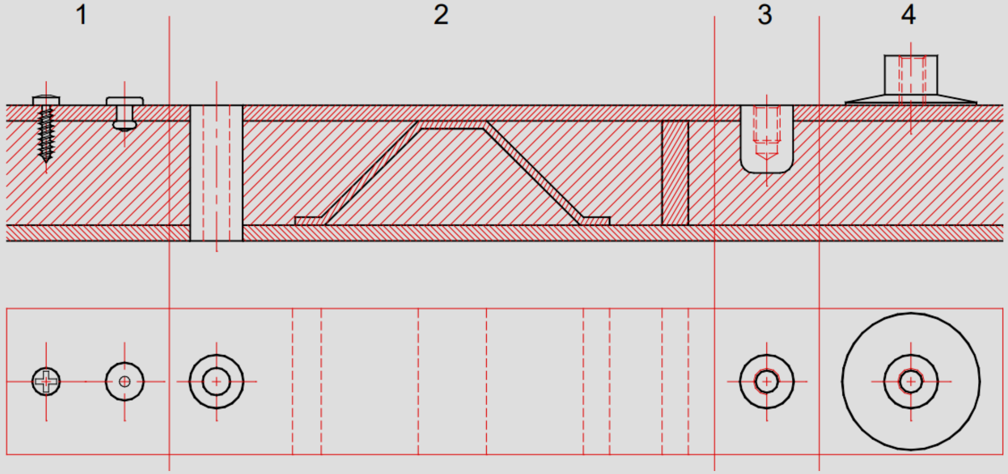


Figure 79: *Connection types (replace image) The categories are: 1: Self tapping screws and rivets, affecting one face sheet. 2: Through-the-thickness inserts (cylindrical, skin tie, diaphragm), affecting both face sheets and core. 3: Partial inserts, directly affecting only one face sheet and the core. 4: Flared cylinder (top hat) bonded onto one face sheet*

Figure 79.1*: Free body diagram*

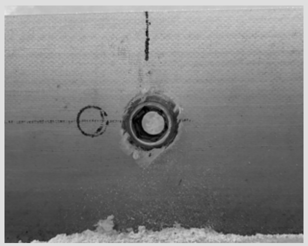
12.1 Fasteners

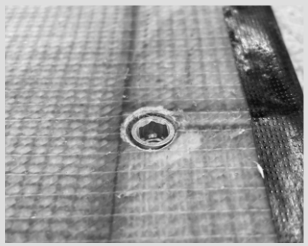
Without a standard established for fastening wind turbine material, I researched existing standards and guides for sandwich panels (e.g. Zenkert, 1997). The recommendations in the book gave good insight into the 'do's and don'ts' regarding inserts and fasteners in sandwich panels (Figure 79).

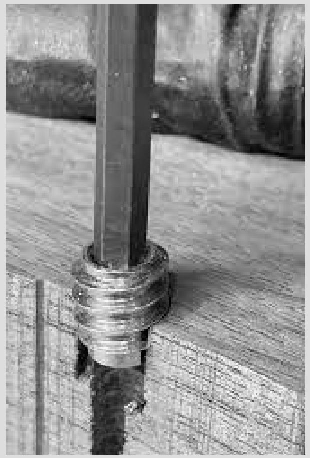
The force applying on the fasteners will be mostly shear force and tension (Figure 79.1). According to NEN14974, the fasteners cannot obstruct the riding surface, and therefore must stay below the surface of the material. The best option is to use a partial insert, this form of fasteners is often used in wood projects to create a reversible joint. Using partial inserts (Figure 81) in combination with threaded rod, washers and nuts allows the connections to be dismountable. So the material can be used in a another life-cycle phase without contamination of metal. As mentioned in the wishes (W7 & W11) from Chapter 10.

Partial inserts however do not perform well when applying a momentum to it since the core is made from soft foam or wood (Zenkert, 1997). This could be improved by clamping a washer or flange between the surface material and the bolt (Figure 82). This enlarges the surface area the momentum acts on. This principle has been tested with a sample Balsa-GFRP (Figure 82).

Figure 80: *Shear force & tension*







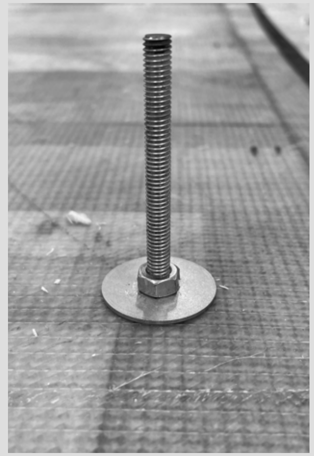


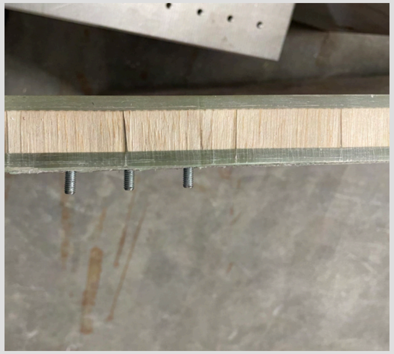
Figure 82: *Picture of the connection in sandwich material including washer*

Figure 81: *Partial insert in sandwich material & spar cap material & section view partial insert*

12.2 Module Connections

The connection between different modules is crucial to ensuring modularity and the safety of riders. Several key requirements specifically relate to these connections, full list of requirements on Chapter 10.
The support and connection system design is based on the outcome of a drawing study and a study on commonly used connection methods (drawings in Appendix 13). These are examples of conventional pumptrack designs and connections to inspire and get a feeling of the options that are out there. In the end connecting concept 3 got the best outcome of the harris profile and therefore this is used in the prototype to later validate on strength and convinience.

Each modules is connected using two L-profiles (50x50x3mm) clamped together on the outside of a (40x40x3) square tube which is part of the 'adjustable legs' by using an M10 bolt. Each L-profile is connected to the material by using partial inserts (M8), threaded rod (M8) and washers to clamp the profile against the bottom of the riding surface (Figure 85).
The holes for the M10 bolt are drilled into the flange side perpendicular to riding surface. The distance between the riding surface and the M10 bolt hole is 45mm (D1) (Figure 83) for the each module securing a 'flush' connection between modules (Figure 84). Since the edge material thickness can vary between 30,5mm and 34mm, the holes that align with the M10 bolt connection also vary in relative position to the top of the L-profile. This to compensate for the material thickness deviation.



Partial inserts with M8 threaded rod

L-profile mounted on threaded rods

Nuts clamping everything in place

Figure 85: *Connection steps*

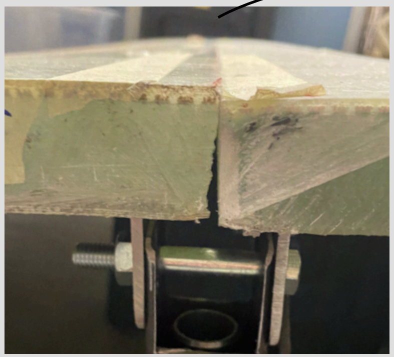


Figure 84: *Flush connection between modules*

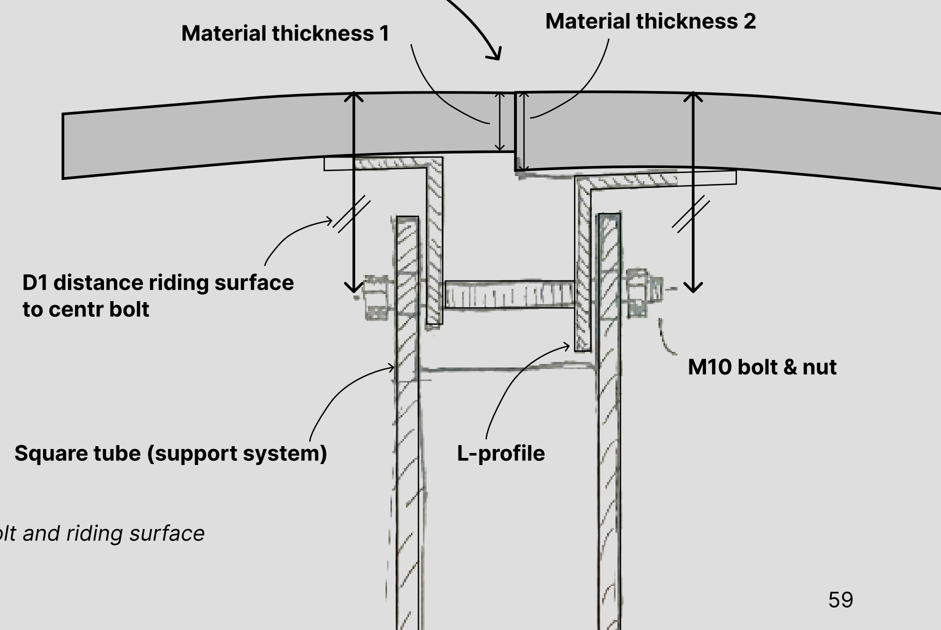


Figure 83: *Sketch drawing of distance between bolt and riding surface*

12.3 Support adjustability

During the RtD 5 research (Appendix 07), it became clear there was going to be an offset in the track because of the tapered and twisted properties of the blade (Figure 86). Therefore, the rollers also have a small twist in them. According to McCormack (2019), this is no problem but rather more fun and exciting to ride.
For a modular pumptrack, this means each module needs to be adjustable in height ranging from 15 cm to absorb the offset created by the twist in the track. This allows the track surface height to vary from 174 to 526 cm.

In RtD 8 explored in appendix 11 & 12, it is determined that the rollers will have an offset of maximum 14cm. This means the track must be elevated 14cm from ground to compensate for this offset. This also means each module needs to have height adjustable feet that can also absorb the twist of maximum 13 degrees and equal to a delta offset of 226 cm between highest and lowest point (Figure 87).

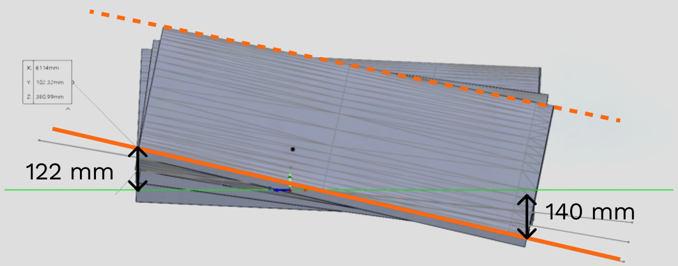


Figure 86: *Max offset retrieved from research RtD5*

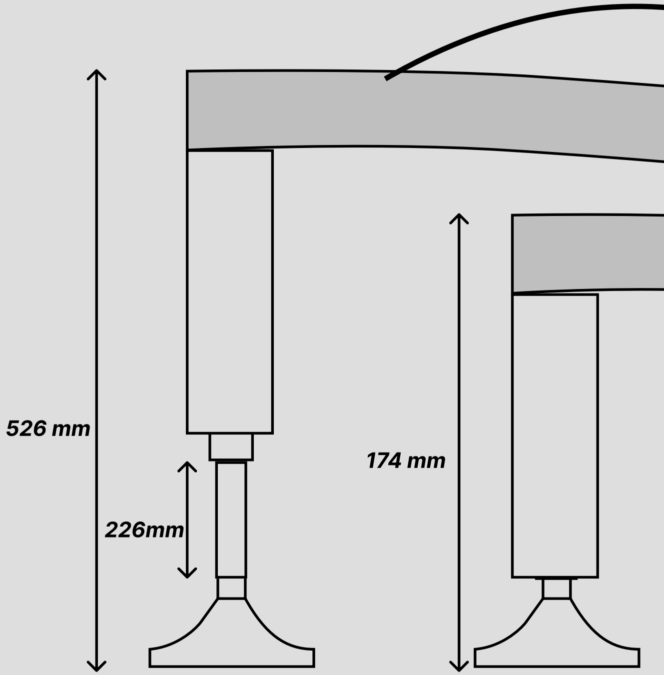


Figure 87: *Height adjustability support system*

Figure 89: *Support system*

By using four individual adjustable ball bearing feet in combination with a bolt connection at the top (Figure 89), the modules become sufficiently adjustable in height.
When connecting multiple roller modules, the twist becomes noticeable and the legs tend to bend outward (Figure 87). This is compensated by the adjustability of the angle. By applying a cross bar that connects the leg and the L-profile on the bottom of the riding surface, a slotted bolt connection makes it possible to change the angle and align the legs perpendicular to the ground surface (Figure 88).

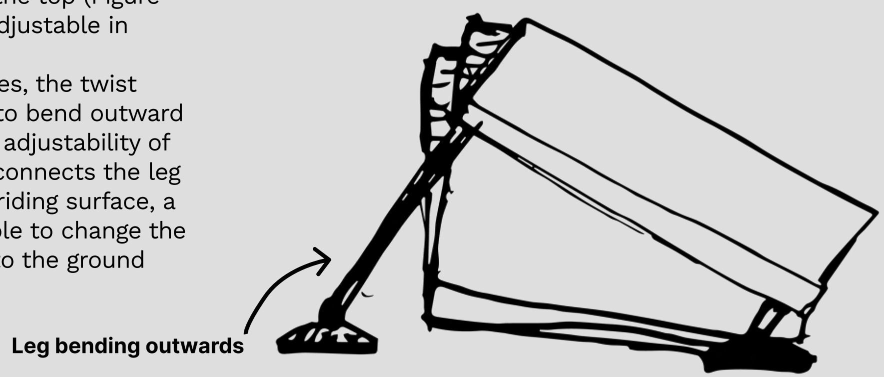


Figure 87: *Exaggerated principle of legs bending outward*

Figure 88: *Angle adjustability prototype 2*

13 Coatings

According to requirement (G9), the track surface cannot be slippery to prevent people falls in wet riding conditions.

For the modular WTB pumptrack prototype (Figure 90), I used an Quarts SiO2 antiskid granulate from (PolyesterShoppen, 2025) which is normally used for industrial flooring. The grain is fine ranging between 0,2-0,63 mm. This is less fine than conventional pumptracks with a coarse grain ranging between 1-1,6mm. The granulate should not be too course as this can cause severe shred wounds when falling on the track (The Pump Factory, 2024, personal communication).

The binder which sets the granulate is an 80% biobased outdoor coating ‘arboreabio coating’ (icaspa.com,2019) (Figure 91). When applying the coating, it is important to apply an extra thick layer in order for the granulate to stick to the coating.

Apart from coating the riding surface, it is also important to coat the exposed core material. This is a relatively soft material and might be extra prone to rotting or degrading. The same coating without granulate could be applied in this case.

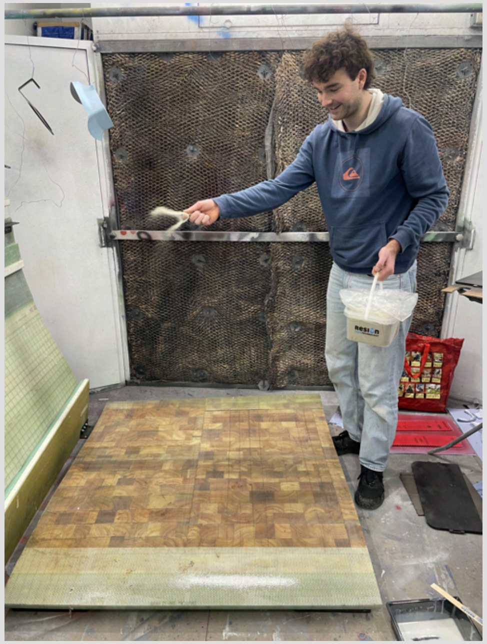


Figure 90: *Applying antiskid granulate*

Figure 90.1: *Applying bio based coating*

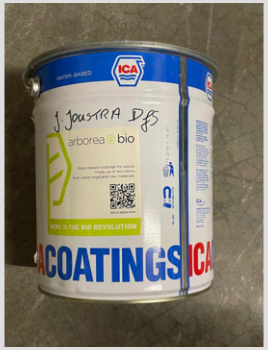


Figure 91: *bio based coating*

Figure X: *surface details of antiskid coating*

Phase IV - Validation

After completing an embodiment design, it is crucial to validate the prototypes and intended design. Therefore, this chapter will validate if the material is safe to be used without the need of additional constructional elements. It answers the research questions:

Does the connection system meet the safety criteria?

This phase also gives insights into,

What is the impact of the design project?

and identifies the scalability of this specific use case by answering:

Is there form/curve similarities in other blades?

Credit: Patrick Wetzels

14 Safety

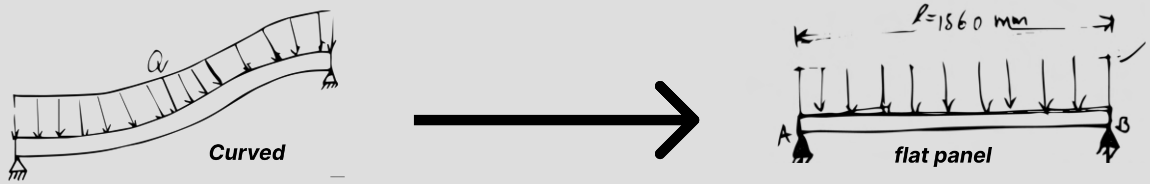


Figure 93: Simplification of distributed load on module

As discussed in Chapter 7, the sandwich panels have a superior specific strength to conventional pumptrack surface materials. Therefore, the material can potentially be used without any additional constructional reinforcements. To validate this, a series of calculations needed to be done to see if the material meets the NEN14974, the safety requirements can be found Appendix 19.

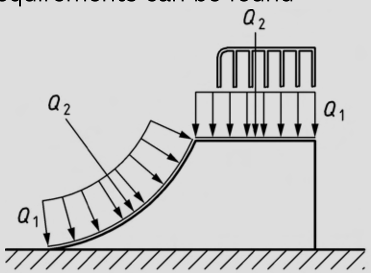


Figure 92: *load Q1 and Q2 (Source: NEN-14974)*

14.1 Material stress tests

According to the NEN14974 norm visualized in Figure 92, the material should be able to withstand a uniformly distributed load of 3,5kN/m (Q1) and a point load of 7,5kN (Q2) on a 50x50mm surface.

For this series of calculations, the material thickness is kept constant throughout all the calculations. To find out if the material is strong enough, the maximum stresses from a three-point bending failure test (Somsen et al., 2024) are compared to the stresses calculated under the loads of the NEN14974 norm.

To simplify the stress and deflection calculations, the sinus shape roller (Figure 93) is now regarded a flat panel. The length 'L' of the panel is equal to the arc length of the largest pumptrack module. The width 'b' is 1,25m of the track equal to a wide pumptrack (Figure 94). If the highest stress values are acceptable, then the smaller rollers will also be sufficient, as their shorter moment arms reduce the stress on the material.

When using the approximate theory for bending sandwich panels from the book *Mechanics of Materials* (Goodno et al, 2020, page 557), the normal forces in the core can be neglected. This is because the face materials, which have a much higher elastic modulus than the core, carry the majority of the load. This is confirmed by the material tests in the thesis report from (Somsen et al., 2024) and (Weijermars, 2016), who concluded the predominant failure mechanism is compression in the up facing (top) skin of the sandwich material when tested in a three-point bending test.

Core material parameters:
Manufacturers commonly utilize core materials such as polyvinyl chloride (PVC), styrene-acrylonitrile (SAN), polyethylene terephthalate (PET), polyurethane (PU), or Balsa wood (Fathi et al., 2013; Liu et al., 2023).

In this study, the blade material primarily consists mainly of a Balsa core with a thickness ranging from 23 mm - 25 mm.

For reference, the material strength data of three core types PET (65 kg/m³), SAN (85 kg/m³), and Balsa (155 kg/m³) are used as reference for the calculations. Figure 96 shows the outcome values for maximum bending moment (Mmax), the flexural (σflex) and compressive strength (σtop) at fact-sheet (1) (Figure 95) according to the three point bending test results from (Weijermars, 2016) using a core thickness (h_c)of 25.4 mm and a total thickness (h) of 30.2 mm (Figure 95) which are close to material used in this research.

Core Type	M_{max} (Nm)	σ_{flex} (MPa)	σ_{top} (MPa)
PET Core	177.56	38.62	77.24
SAN Core	94.65	20.60	41.20
Balsa Core	405.49	88.10	176.20

Figure 96: *Outcomes of a 3 point bending test sandwich material material.*

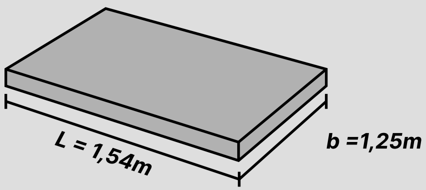


Figure 94: *Dimensions simplified panel*

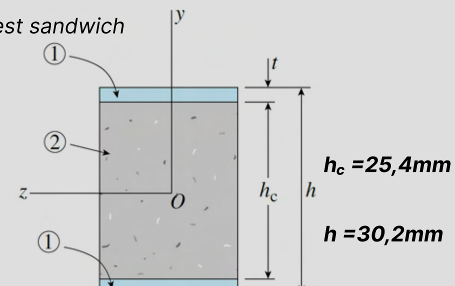


Figure 95: *Core dimensions (Source: Goodno, 2020)*

14.2 Flexural stresses

To compare the flexural stresses in the material, both flexural and normal stresses are analysed, as these are the most critical stress components identified during a three-point bending test (Somsen et al., 2024; Weijermars, 2016). These values are then compared to the theoretically occurring stresses in the material when subjected to loads Q1 and Q2 required by NEN14974.

Load Q1

The following formulas are used to calculate the flexural stresses that occur in the pumptrack roller when applying load Q1.

$$\sigma_{\text{flex}} = \frac{M_{\text{max}} \cdot c}{I_{\text{total}}}$$

$$I_{\text{total}} = \frac{b}{12} \cdot (h^3 - h_c^3) \qquad M_{\text{max}} = \frac{w \cdot L^2}{8}$$

And maximum normal stress in the material:

$$\sigma_{\text{top}} = \frac{M_{\text{max}} \cdot c}{2 \cdot I_{\text{total}}}$$

These formulas are obtained from Mechanics of Materials (Goodno et al, 2020, page 557)

Parameters:

- Distributed loads w= Q1 = 3,5 [kN/m²]
- Width of panel b = 1.25 [m]
- Thickness of material t = 0.0302 [m]
- Core thickness: 0.0254 [m]
- Distance between supports L = 1.5[m]
- c = t/2=0.0302/2= 0.0151m

When filling in the formula, it results in a maximum flexural stress of σflex = 16.0MPa. The results of the maximum compressive stress is σtop = 16.0MPa. According to the calculations, the least strong material with a SAN-core will fail at σflex= 20.6 MPa and σtop 41.20 MPa.

The leaving an 4 Mpa margin before material fails. This is equivalent to 25% of the total total flexural stress. SAN is the 'weakest' core material making it enough to assume that this and the panels with the other core materials are suitable in terms of flexural and compressive strength properties under the load of Q1.
For reference, the required load Q1 equals 8 people (85kg) standing on the modules (Figure 96).

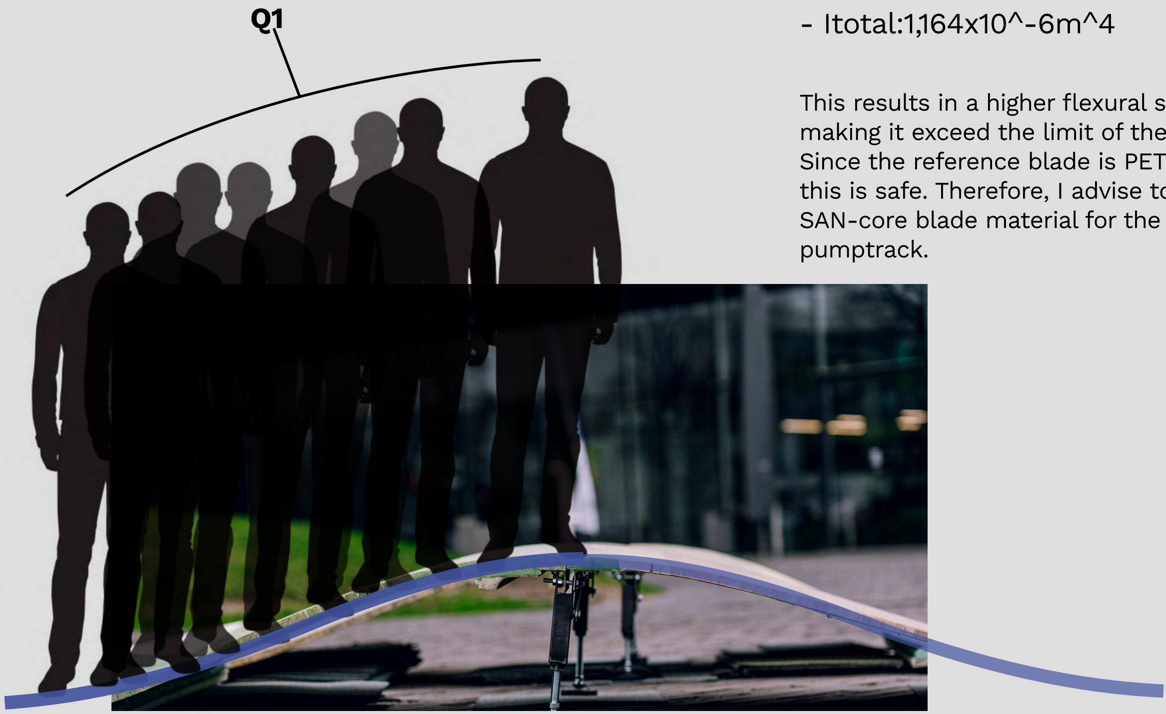


Figure 96: *mass 3,5Kn/m² equal to 8 people*

Load Q2

The flexural stress for Q2 requires a different approach. Since it is a point load the stress is more localised and the formulas to simulate this are different than a distributed load. Therefore, a different formula for Mmax is used:

$$M_{\text{max}} = \frac{Q_2 L}{4} \qquad \sigma_{\text{flexural}} = \frac{M_{\text{max}} \cdot c}{I_{\text{total}}}$$

Parameters:

- Q2: 7Kn
- Width of panel b = 1.25 [m]
- Thickness of material t = 0.0302 [m]
- Core thickness: 0.0254 [m]
- Distance between supports L = 1.5[m]
- Emodulus: 26,4 GPa
- Itotal:1,164x10^-6m^4

This results in a higher flexural stress Fflex = 34.05MPa making it exceed the limit of the San-core material. Since the reference blade is PET-core and Balsa-core this is safe. Therefore, I advise to reconsider the reuse of SAN-core blade material for the use case of a pumptrack.

14.3 Deflection

Deflection is another important factor to consider regarding safety. Too little deflection is undesirable, as it indicates that the connections and legs are absorbing most of the force. Excessive deflection can cause misalignment at the joining edges and lead to wear, as the constant movement of the panels may create friction and degrade the material over time.

The following formula (Figure 97) is used to calculate the maximum deflection under the loads of Q1 & Q2 on two sides of the panel. The long side (Figure 100) is perpendicular to the X-axis and the short side (Figure 101) is perpendicular to the Y-axis (Figure 98).

Based on the maximum ratios of computed deflection to span L (1,5m and 1,25 m) for beams and slabs according to the ACI 318 building code (ACI, 2019). An estimation for the case of a pumptrack involving human interaction, deflection should typically not exceed L/360 equivalent to a max deflection of 41,6 mm for Ix and 34,7mm for Iy. This is to ensure comfort, prevent excessive bending and maintain integrity. According to the calculations in appendix 20, all deflections stay within acceptable limits (Figure 99), ensuring a safe riding surface.

	Calculation	Value (mm)
1	Deflection (Q1, I_x)	-10.0
2	Deflection (Q1, I_y)	-4.0
3	Deflection (Q2, I_x)	-23.0
4	Deflection (Q2, I_y)	-11.0

Figure 99: *deflection calculation results*

For distributed load Q_1:

$$\delta_{\max} = \frac{5Q_1L^4}{384EI}$$

- Once for I_x (deflection along the **long** side)
- Once for I_y (deflection along the **short** side)

For point load Q_2:

$$\delta_{\max} = \frac{Q_2L^3}{48EI}$$

Figure 97: *Deflection formulas*

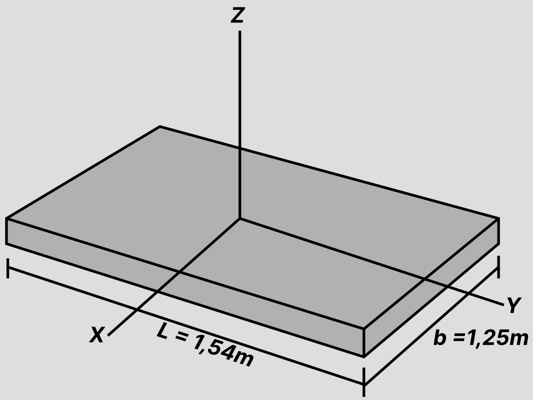


Figure 98: *Deflection schematic*

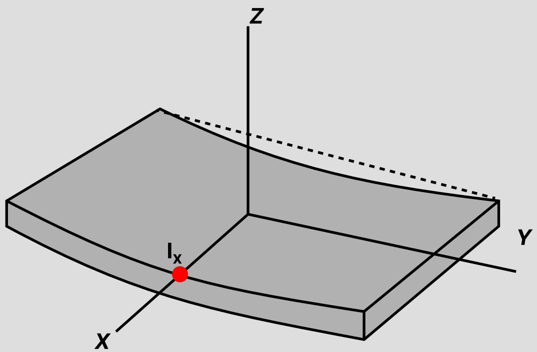


Figure 100: *Deflection along the long side of the panel*

14.4 Compressive strength

The compressive strength provides insight into how much impact the blade material can withstand. For example, in the event of a crash, a bike handlebar could drop onto the material's surface. Although no standard test exists specifically for pumptracks, the point load Q2 over a 50x50mm area serves as an indicator of the material's compressive strength. Under the most critical load Q2 (Figure 102), the calculated compressive stress is 3 MPa.
According to the GRANTA database, the compressive strength of commonly used foams varies with density. However, the compressive strength of the sandwich panel does not depend solely on the foam. The skin material, epoxy glass fibre, typically exhibits a compressive strength between 516 and 688 MPa (GRANTA, 2024). Combining those materials result in a material which has a compressive strength between 138–204 MPa (van Rossum et al., 2024) obtained from the GRANTA database. This suggests that the compressive strength properties are sufficient for this use case.

$$\sigma_{\text{compressive}} = \frac{Q_2}{A}$$

Figure 102: *Formula compressive strength*

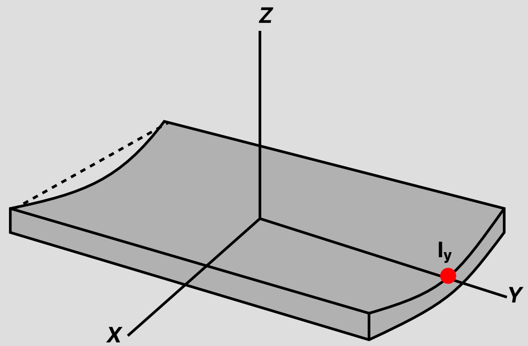


Figure 101: *Deflection along the long side of the panel*

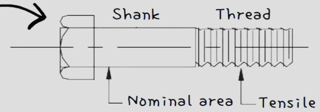
14.5 Safety of support system

To ensure safety of the support system, the same hardware has been applied to the new support system as used in the conventional modules from Chapter 5.2.4. The most force is acting on the bolts used to connect the legs with the material panel's interface, as seen Figure 103.

Ultimate tensile strength

$$\boxed{\text{shear capacity} = \frac{0.6 \times F_{ub} \times A}{\gamma_{M2}}}$$

Partial safety factor 1.25



Diameter mm	12	16	20	22	24
Tensile area	84.3	157	245	303	353

Figure 105: *Formula to calculate shear force*

Figure 104: *Takes 17 people to break one M10 bolt*

14.6 Shear force

The weakest link in the support system is the bolt connection between the flange and the material. The primary force acting on these bolts is shear force, although clamping force also plays a role in the connection. The presence of clamping force may reduce the overall shear force experienced by the bolts.
To ensure a conservative assessment, this calculation (Figure 105) considers the worst-case scenario, in which the entire force is absorbed as shear force in the bolt. The following calculation provides an indication of the strength margin of the bolt connection under extreme conditions, where all applied force acts solely as shear force (Figure 103).

According to the DIN 931 standard, steel bolts with a Hex Head Bolt have a minimum tensile strength of 500 N/mm2. According to the calculation, the bolt should be able to withstand 13.92kN (M10). This is equal to 17 people standing on the WTB module and all the shear force acts on one M10 bolt 104 (Figure 104). In the case of the pumptrack, it should be able to withstand a force equal to 8 people.

According to the NEN norm, the track should withstand a distributed load of 3,5kN/m2. For the largest panel, that is:
F = 1,5 [m] x 1,25 [m] * 3,5 [kN/m2] =6,56kN
This is equal to 656 kg and approximately 8 people of 85 kg.

This margin between 6,56 kN and 13.92 kN is enough to ensure a safe connection, as well as the fact that the load will be distributed over two of M10 bolts.

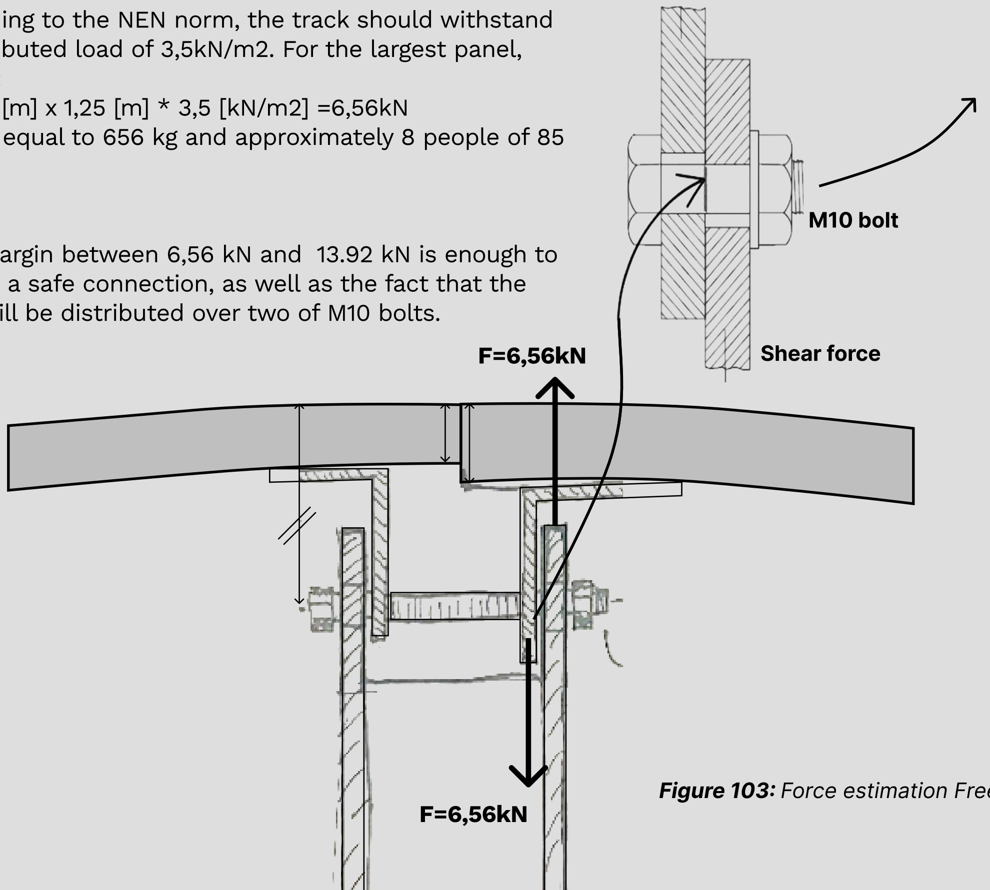


Figure 103: *Force estimation Free body diagram*

14.6 Conclusion

To answer the question:

‘Does the connection system meet the safety criteria?’

It seems that for all the safety calculations, the sandwich material with Balsa wood is the safest to use while the other materials like PET and SAN foam core should be carefully reconsidered. The less favourable compressive properties of these foams make it perform less well on the compressive strength test. These foams should be further researched as this is outside the bounds of this project.

In comparison to the results for flexural and max compressive stress at point of failure, the flexural (σ= 15.99MPa) and maximum compressive stress (σ_{top} = 15.98MPa) stay within the limits of the three different sandwich panels. For the distributed load, for the max flexural strength in the material will exceed the SAN-core panel’s flexural limit, but this is an extreme case and the other tested stress values stay within the given safety limit according to the NEN14974.
Therefore, the material is a safe and sufficient replacement for a pumptrack roller according to the norm and materials tests.

‘Is all blade material safe to be used in pumptracks?’

Since every WTB blade has different core material, density and face sheet thicknesses, this should be alculation should be adjusted to the specific parameters of the blade material. Regarding this specific blade using a PET and Balsa core (Ttotal =30,2mm and Tcore=25,4mm) the material is regarded safe for the use-case of a pumptrack.

To asses other type of blade material the parameters **Ttotal, Tcore, span width (L) and width (b)** should be adjusted to the corresponding material.

15 Impact

15.1 Material savings

Currently, the straight roller parts can be harvestedfrom the blade are making up 18% of the blade's outer surface. Taking into account 6 rollers. That percentage will become more when using the rest of the material for the segmented corner panels. When looking at the optimized cutting pattern, 8 rollers can be harvested from the 30m blade, increasing the harvested surface area from 20 to 24 m². As a result, using WTB material can save the same amount of material in wood or virgin epoxy material.

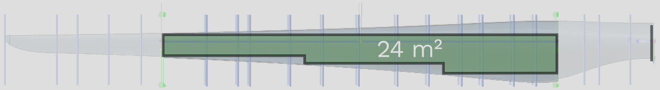


***Figure 106:** Harvested blade parts*

15.2 Changing the Industry

In order to change the industry, infrastructure should be ready to process the material. To make it economically viable there should be enough interest in using the material. For the acceptance of 'waste' materials, in this case WTB materials, it is important that people get exposed to the experiential qualities (e.g., aesthetic attributes, their associations, etc.) of innovations (Karana et al., 2018). Therefore, one of the goals of this project is to host an event to 'test' the new material and expose people to a different use case of this material, which is further elaborated on in Chapter 16.

15.3 An opinion from an industry

In my interview with The Pump Factory, we discussed the potential of the blade material in the use case of a pumptrack. This conversation led to a few advantages and disadvantages of the material (The Pump Factory, personal communication, 10 October 2024):

Disadvantages:
- Limited availability due to insufficient infrastructure.
- Uncertain strength and material properties, requiring further research and testing.
- Pre-shaped material constrains design flexibility, particularly for corner configurations.

Advantages:
- Potential to reduce initial material costs.
- Strong narrative appeal, enhancing the material's marketability.
- Aligns with the growing demand for circular and sustainable pumptrack construction.

Pump Factory has identified an increasing demand from municipalities for sustainability reports and circularity assessments when commissioning pumptracks. Given the advantages outlined above, the material appears to have significant potential in this context.
Ultimately, The Pump Factory specializes in the construction of fixed pumptracks. A key advantage of this approach is that they are not reliant on specific manufacturers, as they produce the track components in-house. This flexibility facilitates the adoption of new building materials. Since fixed pumptracks hold a larger market share compared to modular pumptracks, there is greater potential for integrating this material in combination with concrete and asphalt in fixed pumptrack construction.

15.4 Scalability pumptrack

To ensure scalability, processing the maximum possible amount of blade material at a time is essential to minimize machinery costs and other investments. This project uses 18% of the blade material's surface for 6 rollers only (30m blade).

It is important to note that this research is based on a specific blade, meaning the design is not necessarily replicable in a 1:1 manner for other blades. However, when applying the CAD matching method (Chapter 8.1) to a 60m blade, results indicate that roller sizes can be scaled up proportionally. The airfoil geometries in wind turbine blades are often identical in shape but vary in size, ensuring that curvature similarity remains consistent. For instance, when analysing a 60m 5MW NREL blade (Figure 107) using the 2D matching method from Chapter 8.1, the same height-to-length ratio was found to be applicable, with rollers increasing in size accordingly. Instead of a 1:10 ft comparison, rollers can be manufactured with lengths of up to 20 ft, particularly in sections near the root of the blade. This suggests that despite differences in overall dimensions, the scaling principles remain valid, supporting the feasibility of adapting the process to larger blades with minor modifications. This can potentially increase the amount of material harvested.

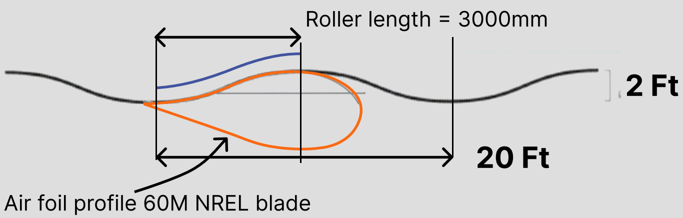


***Figure 107:** 1:10 ratio also applicable to the NREL 5MW 60m blade*

15.5 Scaling up blade material usage

Automated matching process

As previously mentioned, the research group from Inria is looking to automate matching of blade materials to other objects. This research can act as a practical example to compare the results of the computer model. When this model evolves, it can be used to optimize the mapping of cutting patterns and function as a matching tool to for example curvatures for pumptracks or other applications like soundwall, shelters, roofing bridges etc.

Automate cutting process

Since (Voodin, 2024) is already producing blades ranging from 60–80m using laminated wood and a CNC machine (Figure 108), the same recycling technology can be applied to blades by utilizing similar methods for sectioning and cutting. Once the industry develops sufficient interest in automated cutting processes, recycling companies can invest in computer-controlled cutting technologies for wind turbine blades, similar to those used by Voodin in their production. By integrating these two processes, the blade material will become more accessible for various industries, increasing its market value and establishing it as a high-quality alternative to other materials with similar properties.

Figure 108: *CNC mill shaping a wooden WTB (Voodin, 2024) (Source: balticwind.EU)*

16 Test event

The objective of the test event was to raise awareness of alternatives for discarded wind turbine blades and to assess whether the roller prototypes provide sufficient riding quality and if the setup functions effectively. The event set-up included the 4 prototype modules connected to The Pump Factory's track (Figure 109) and a ramp to secure a good ride-out i.e. exit from pumptrack. See Appendix 18 for the 'ride-out' design. Some of the other research project prototypes and posters (Figure 110) were also displayed.

Figure 109: *Test set-up with 4 prototype modules (Credit: Patrick Wetzels)*

Figure 110: *Info banner (Credit: Tudelft, 2023)*

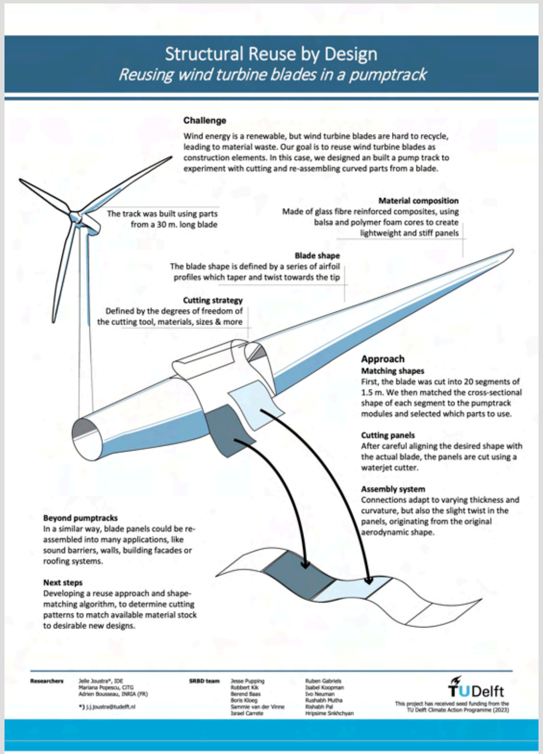


Figure 110: *Info poster during event (Jelle Joustra, 2025)*

Figure 111: *Overview of test event (Credit: New Media Centre)*

16.1 Test Set-up

Results:

About 50 participants entered the track (Figure 111) of which 14 participants filled out the survey. I could ask 5 people about their experience during the test event. Next to that there was a constant flow of people walking in & out of the building getting exposed to the track and the other informative blade research demonstrators like the blade picnic table, speaker and the informative project poster.

Expert view:

Observations from the test event indicate that the modules performed as expected under repeated loading from various riders. According to ‘The Pump Factory’, who managed the event, the modules "held up perfectly," demonstrating structural integrity and resistance to impact forces. This suggests that the material composition including the foam core and epoxy glass fibre skin provided sufficient compressive strength and resilience to dynamic loads, in alignment with the calculations in Chapter 14.
Furthermore, no significant deformation, delamination, or surface degradation was observed after use.

Setting up: v

Setting up the event went smoothly. The WTB roller modules took longer to set up because of the bolt connections between each module. In comparison, The Pump Factory modules slotted into place, making them faster to put together than the WTB roller modules. Therefore the overall build-up of the blade modules felt a bit slow and inconvenient. Although both methods require at least 2 people to assemble the track.

Connection:

All the connections of the support system kept the track together sufficiently during the event without any issues. The system and hardware remained flush for the duration of the event creating good tolerances in the track surface between joining edges (Figure 112).

Rollers:

The height of the WTB rollers were set-up to the height of the rollers from The Pump Factory track. In the initial design, the WTB rollers were supposed to be 30cm high, but The Pump Factory rollers were closer to 38cm , resulting in a ratio (height:length) ranging between 1:6 (S)– 1:7 (M sized roller), making it steeper than the initial reference curvatures from Chapter 8.1.

Spar cap:

For one of the roller connections, it was not possible to mount the L-profiles far enough inwards because the excessive shear web glue is in the way, as seen in Figure 112 and 113. This is important thing to consider during the matching of the curvatures and cutting the material.

Glue obstructing L-profile

Figure 112: *excessive shear web glue obstructing the positioning of the L-profile*

16.2 Antiskid coating

During the test event, rainfall occurred at one point, providing an opportunity to assess the grip performance of the anti-skid coating under wet conditions. Post-event survey feedback from a skateboard rider indicated that "the modules became slippery in rainy conditions." Although this is based on just a singular opinion. It suggests that the fine-grit (0,6-1mm) skid layer might be insufficient for maintaining traction in wet environments. To further evaluate this, future tests should incorporate a medium-grit coating under similar conditions to determine whether it enhances surface grip and rider safety.

Figure 113: *good tolerances in the track surface between joining edges*

16.3 Test survey

In addition to material performance, the riding experience was assessed based on qualitative feedback from users and industry experts. The participants were asked to compare the riding of the conventional modules with the blade modules.

The general response was positive about the event was positive, with The Pump Factory mentioning "a fun, sustainable alternative to current modules." However, one key observation regarding the track feel emerged from the test event:

"When placing too many of these relatively short rollers in series, the track could feel a bit stiff."

Rideability is a broad term and subjective, dependent on a user's skill level and experience. To test the riding experience of the prototype, it is therefore necessary to get information about the perception of the participants by means of a survey.

In the survey (N=14) both negative and positive terms are used to describe the perception of the track to cancel any biases towards negative or positive answering see Appendix 22 for extensive survey results.

Of the 15 participants that filled out the survey. To overall outcome of the prototype modules was good, it being perceived as sturdy, stable, safe and grippy (Figure 115). Next to that 70% experienced the last rollers to be steep in comparison with the track from The Pump Factory.

During the test-event the rollers were set-up slightly too high giving them it a 'jumpy' and slightly 'pointy' characteristic (Figure 114). This could clarify the outcome of the survey to be perceived as steep. Riding these rollers requires a faster pumping motion and greater skill, especially when placed at the end of the track, where riders have already gained significant forward speed.

This suggests that the frequency and amplitude of the rollers influence the overall ride dynamics. The relatively short roller length may result in less fluid transitions between elements, which could affect the natural flow and momentum retention of the track. Future iterations should consider optimizing roller spacing and curvature transitions to enhance rider comfort and performance consistency.

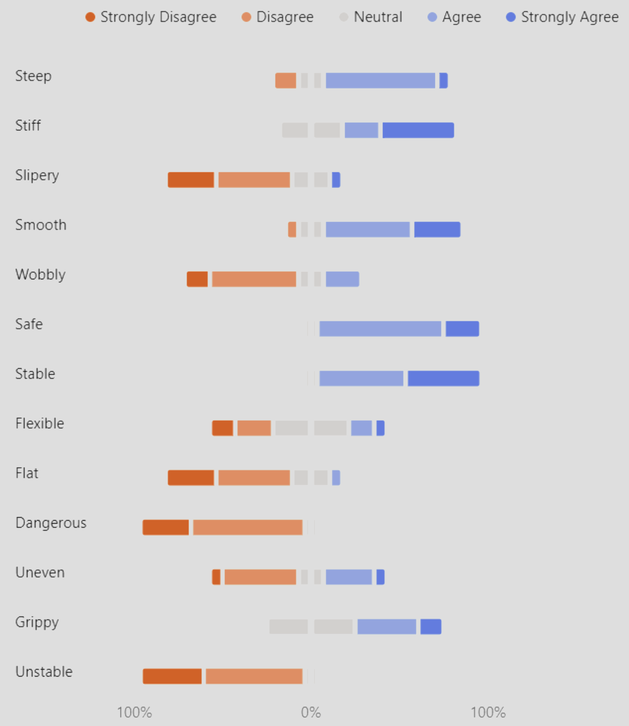


Figure 115: *Survey results*

Jumpable rollers: straight ratio, say 1:5-1:8 instead of the standard 1:10.

Figure 114: *Pointy roller & shorter 'jumpable' rollers (Source: McCormack, 2019)*

16.4 Conclusion

The test event provided valuable insights into the structural performance, ride quality, and practical usability of the wind turbine blade (WTB) roller modules. Overall, the results indicate that the modules successfully withstood repeated dynamic loading and maintained structural integrity throughout the event. The connections between modules and the support system functioned as intended, with minimal gaps (<5mm), improving upon the existing track by The Pump Factory, which had gap clearances exceeding 5mm. Feedback from riders and industry experts suggests that the WTB modules offer a viable and sustainable alternative to conventional pumptrack components.

However, several areas for improvement and optimization were identified:

• The roller height-to-length ratio was steeper than expected, with values ranging from 1:6 (S) to 1:7 (M) compared to the original design reference. This made the track feel steeper, requiring a faster pumping motion. Future iterations should refine these proportions to enhance flow and rideability.

• The support system adjustability range should be increased from 24 cm to 52 cm to better accommodate track curvature and height variations.

• Additional support in the troughs of the rollers is necessary to improve overall stability.

• The setup process took longer than conventional modules, primarily due to bolt connections. The Pump Factory modules, which use a slot-in system, were faster to assemble, highlighting a need for a more efficient connection system in future designs.

• The anti-skid coating performed well in dry conditions but became slippery when wet, particularly for skateboard riders. Feedback indicated that the fine-grit (0.6–1 mm) coating might be insufficient for wet conditions, suggesting that future tests should evaluate a medium-grit (0.63–1 mm) coating for improved grip.

• Riders noted that when testing roller prototypes, placing modules in series rather than parallel would provide a more continuous riding experience, allowing participants to better assess the track's flow and dynamics.

• The twist in the track was not a significant issue, but skateboard riders could feel a slight deviation while riding. Minor adjustments could further optimize smooth transitions, particularly for skateboarding.

• The lightweight nature of the sandwich panels suggests that they could potentially be set up by a single person, making them more practical for transport and assembly.

The test event validated the technical feasibility and structural durability of the WTB roller modules while highlighting key areas for design refinement and rider experience enhancement. These insights will guide further design improvements for optimized modular pumptrack performance.

Phase V - Finilization

This phase concludes the project and gives recommendations and adaptations to the current design based on the outcomes of the test event. It highlights challenges and opportunities for future research in the field of structural reuse by design in general and specifically for the use case of a pumptrack. Giving the leverage points to continue the further development of matching processes and the development of WTB constructions and connections.

Credit: Patrick Wetzels

17 Conclusion

This research explores the feasibility of repurposing decommissioned wind turbine blade (WTB) material for modular pumptrack design. The findings based on a 30m research blade, demonstrate that WTB material can serve as a safe and structurally sufficient alternative when properly processed and adapted, offering a sustainable approach to material reuse. However, several key factors must be considered to ensure optimal performance and efficient implementation.

17.1 Material safety

Among the evaluated sandwich materials, Balsa wood core panels exhibited the highest safety margins, outperforming PET and SAN foam cores in compressive strength. While flexural and compressive stress values remained within acceptable limits for all three materials, SAN-core panels exceeded their flexural limit under extreme point loads.

Both sandwich materials and solid Glass Fibre-Reinforced Polymer (GFRP) components can differ in thickness, density and material. This needs to be considered when doing safety calculations for another type of blade.

17.2 Manufacturing and Assembly

A adjustable leg at the bottom is required to support the offset in the trough of the track.
Setting up the track requires at least two people. Bolt connections extend the assembly time compared to pre-assembled systems like The Pump Factory track, but they increase safety and decrease gap clearances. Panels composed mostly of sandwich materials could potentially be assembled by a single person, improving modularity and installation efficiency.
The 4 roller prototypes should be tested in series in 1 track rather than in two parallel tracks. That makes it easier to analyse the track's rideability.

17.3 Material Processing and Cutting Considerations

The cutting angle in reference to the riding surface impacts the gap clearance at the joining edges. A perpendicular cut results in a perfect edge while a cutting angle greater than 90° creates a sharp top angle, allowing for minor misalignments without affecting the riding surface continuity.

Sectioning blade material is not possible manually and requires specialized equipment, like belt grinder, large diamond saw or a rails waterjet cutting machine. Waterjet cutting is only viable in remote outdoor areas or in controlled environments due to noise and safety concerns. Proper ventilation, dust extraction, and protective gear are essential when using saw-based cutting methods to protect both workers and the environment.

Efficiently sectioning the blade minimizes material processing costs and off-cuts while efficiently using the blade material. Therefore, it is advised to be involved in the early stage of decommissioning to advise proper sectioning of the WTB material.
The spar cap or shear web serves as the most reliable reference point for cutting and alignment.

17.4 Material Utilization Efficiency

Approximately 18% (20 m²) of a 30m WTB can be repurposed as roller modules resulting in a series of 12 modules creating 6 rollers. Roller lengths should be standardized to optimize blade usage while ensuring modularity and possible continuous track designs.
The transition module between corner and roller modules cannot be harvested from the blade and must be separately fabricated to maintain track continuity.
Corner modules can be harvested from the blade, however more research on the feasibility and rideability of segmented corner modules from WTB material is necessary.

17.5 Structural and Design Considerations

Adjustability of the support system should be increased to a range from 24 to 52 cm to accommodate the twist in the track for a combination of three rollers in a series. CAD simulations revealed a 14 cm cumulative twist offset when connecting the 3 differently sized rollers, corresponding to an average tapering angle of ~2.3° per module corresponding closely with the horizontal tapering angle of the blade. The twist in the track from the WTB roller was not a significant issue. However, one skater who used the track communicated their perception of a slight wobble

Partial inserts, preferably with hex sockets, provide a reliable option for connecting hardware to the WTB. When used with proper drill tolerances, they can securely fasten reversible connections between sandwich panels and spar cap material. To ensure structural integrity, the inserts connection should be tested on shear and pull/tensional forces. The primary limitation for a future material cycle of the material is the remaining holes in the surface.

17.6 Surface Protection

Polyurethane (PU) and epoxy (EP) coatings provide effective resistance against UV exposure and weathering, making them suitable for pumptrack applications in combination with adding an anti-skid granulate with grit-size 0.63-1 mm being sufficient for all use cases. Coatings should be reapplied every 7-10 years depending on the use frequency.

18 Recommendations

This chapter outlines key design considerations and recommendations for optimizing blade constructions and specifically considerations for the building of a pumptrack form blade material.

Spar cap reference

Unfortunately, not all blades have visible spar caps from the outside of the blade. This makes it harder to indentify length and width properties. So for future projects I would recommend to us the shear web as point of reference or section the blade and indentify the spar cap trough the cutting face of the section. This can help to do the blade mapping and manually draw patterns and reference points.

Positioning of rollers in a track

Given that the blade track contains different size rollers and shorter rollers being perceived as steep. I recommend placing shorter rollers at the beginning of each track or at the end of slower sections, such as after a corner. When the initial speed is low, it is easier to perform the rowing and anti-rowing movements over shorter rollers, as the required motion is slower and more controlled at lower speeds.

Perfect wave 1:10 ratio

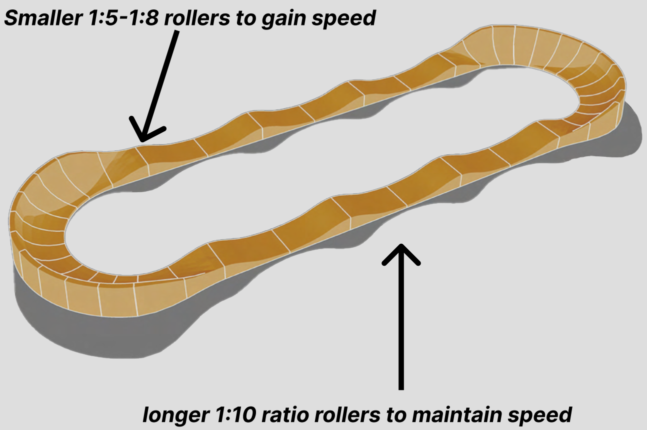
Pointy 3:1 crest:trough ratio

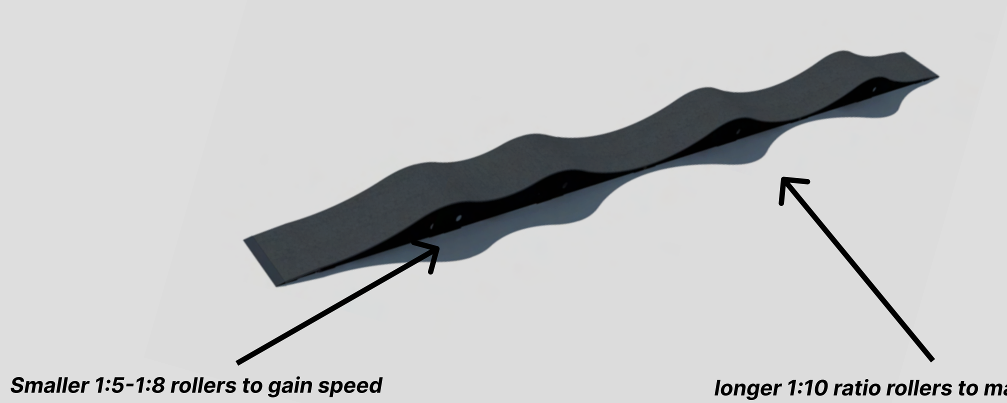
Short and Jumpable 1:5-1:8 ratio (height:length)

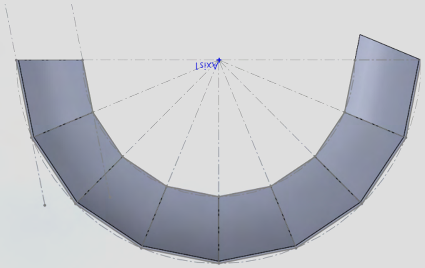
Corner modules

The corner modules made from WTB-material are a potentially suitable replacement for current corner modules. Although within the time-frame of this project it was not possible to validate this on a 1:1 scale with the actual material.

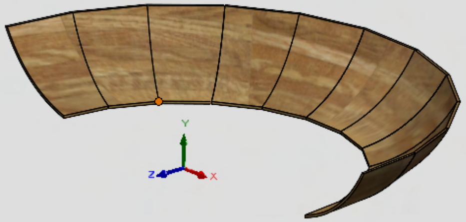
According to the scaled cardboard prototypes and the 3d printed prototypes from Appendix 05, the downwind side of the material can be used to create relatively flat panels. However, this approach results in a less gradual transitions between modules, than conventional tracks, which may limit the track's rideability. I advise to make between 9 and 12 sections depending on the material availability the more panels the more graduate the transitions between modules will be.

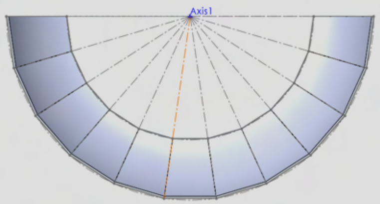






8 sections

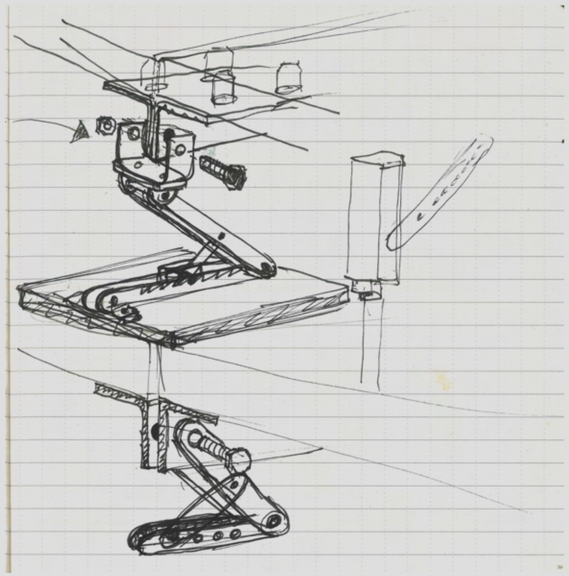




More segments make the transitions smoother depending on availability 12 segments could be harvested from the blade material. According to the the 1st RtD3 prototype this is possible to make one 180 ° corner.

Bottom support

For the bottom connection there is a need of a mechanism that folds flat but can also be adjusted easily to the required height. Similar mechanisms are used in the folding beds and roofing.



Support system

In the case of aligning the panels and making it a flush fit, it is important to design for micro adjustment allowance. In the case of my final prototype, I drilled all the holes to a custom height which was a time intensive and secure process. By creating a more standard support system and allowing micro adjustments, the production time and therefore costs can be decreased.

What mechanisms work:
o ratchet support bracket
o jack mechanism
o adjustable feet
o individual feet vs combined
o multiple slots on the leg

19 Final Implications and Future Research

This study confirms that WTB material can be successfully repurposed into modular pumptrack rollers, promoting circular economy initiatives in composite recycling. However, given the variability in blade material properties, future research should focus on developing standardized methodologies for material selection, computer controlled cutting techniques, and structural optimization. Additionally, further testing on larger blades is necessary to expand the applicability of this approach.

The test methods used for testing partial-insert-strength in sandwich materials and spar cap material were not quantified and should be further tested.

Currently, there is no fully validated proof of concept for the corner modules. Further prototyping and testing are required to assess their feasibility. Additionally, to determine whether this concept provides a truly sustainable solution for repurposing wind turbine blade material, a life cycle assessment (LCA) should be conducted.

The medium-sized grid coating, as well as the coating for the sides of the material, could be tested to evaluate their effectiveness. Moreover, the impact of the recommended design adaptations on the assembly process should be examined to assess whether they improve the efficiency and ease of track construction. Further testing of the inserts, specifically in terms of pull-out strength and shear force, is necessary to ensure the safety and reliability of these connections.

Although wind turbine blade material is currently considered waste and thus remains low in cost, a more detailed analysis of the total expenses involved in acquiring and processing the material is needed. This would provide a clearer understanding of the cost efficiency of blade track modules.

By refining processing methods and establishing guidelines for parameter adjustments, researchers and industry professionals can replicate and enhance this process, paving the way for scaling up future, sustainable structural reuse projects.

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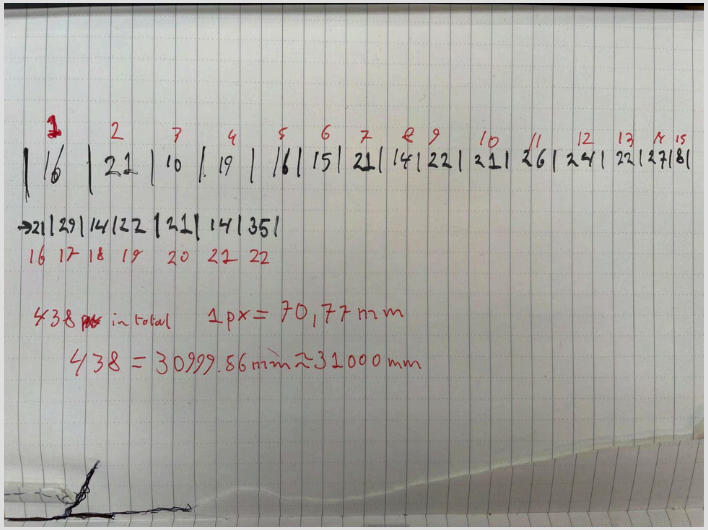
Appendix Table of contents

The appendix consist of the Research through Design methods 1-9 (RtD) and chapters with additional information necessary to give more context to the research I did in this design study.

01 Mapping blade

Notes calculations



Mapping the blade

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1132mm	1486mm	708mm	1344mm	1132mm	1062mm	1486mm	991mm	1557mm	1486mm	1840mm	1699mm	1557mm	1911mm	566mm	1486mm	2053mm	991mm	1557mm	1486mm	991mm	2477mm

Piece 5,6 are potentially too small for a 1,25m track
But could be usefull in a 1m track

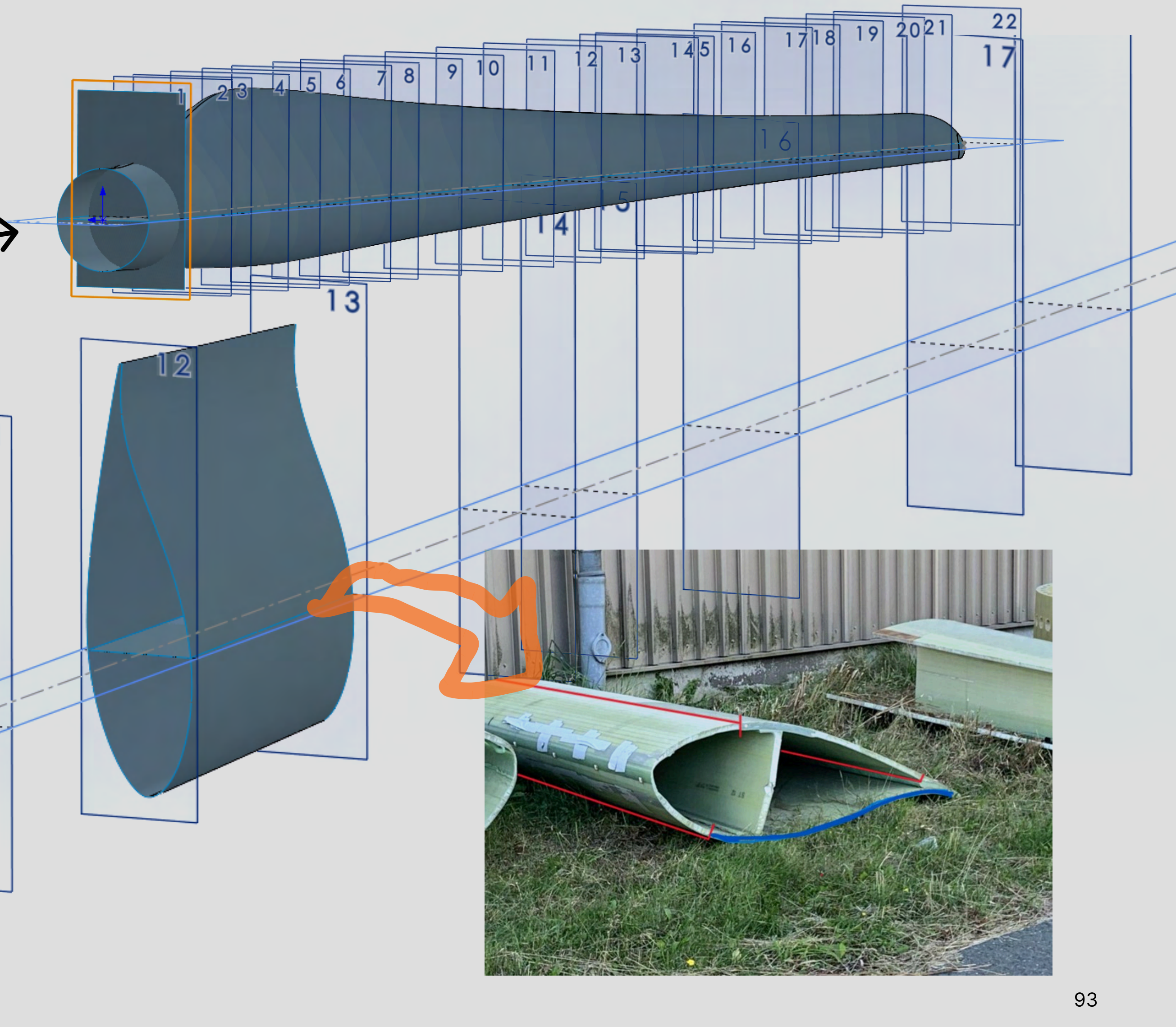
15/16 Combined?

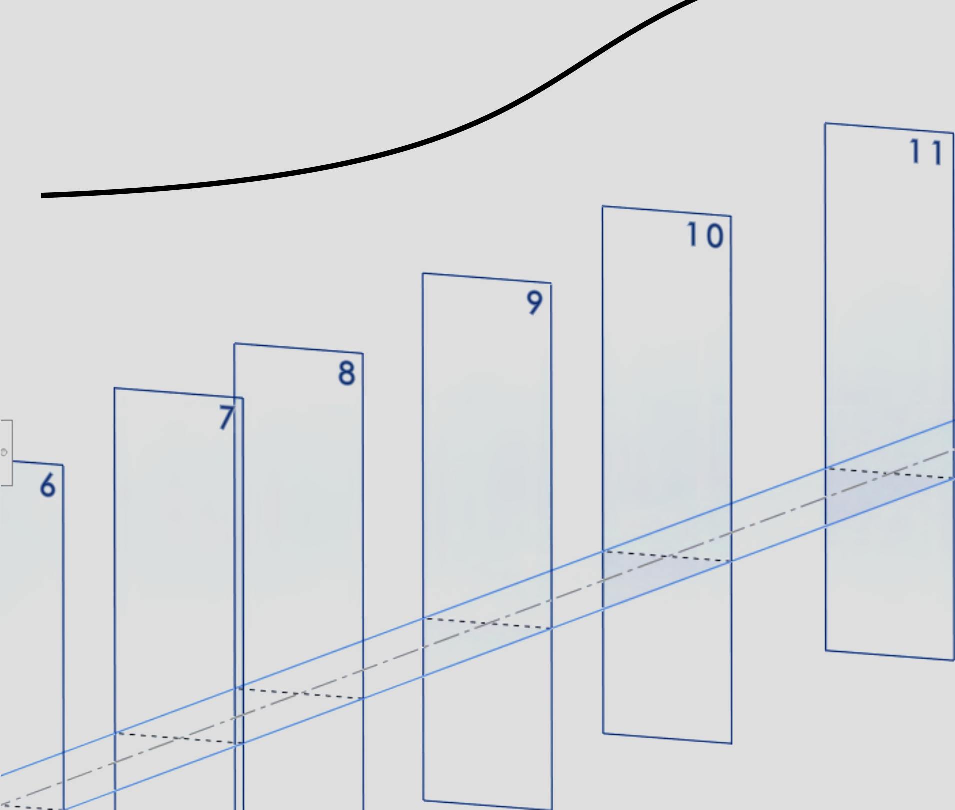
8 is too small for a roller but could be used for a corner piece

02 Transfer to CAD

In order to start with the research I needed to create a cad model which represents the actual parts from the chopped up blade. So I mapped out the pieces in the picture and estimated the length of the individual pieces by counting the distance in pixels between each part, since the full length of the blade was known, I could translate the ratio of the pixels to the actual length, see Figure X.

I recreated this in the computer by using the cad model provided by Fraunhofer. When creating a plane for each cut it was easy to chop up the "blade shell" into 22 pieces just like in the picture.
Now there is a 1:1 model (Figure X) of each of the pieces, these models are used in further research.



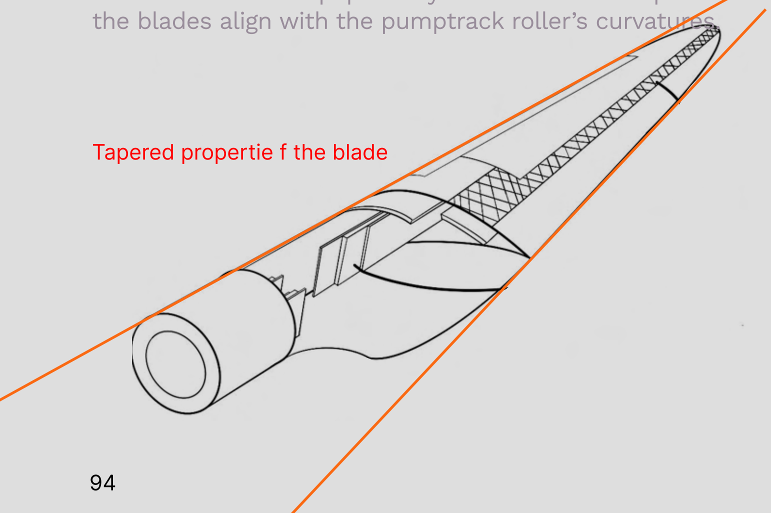


03 RtD 1 Matching curves

Aim:
Is the curvature of the turbine blades suitable for a pumptrack?

Context:
In order to validate if the project is feasible and the curvatures align it seems like the first step to find out if the blade has potential. Within the context of this project this is a first time for this type of research. I don't think this has been done by any previous people expect from this research from France that's uses a computer algorithm to match shapes of windmill blades with other objects, in 3D. I'm applying it by hand in 2D.

Method:
1. Create CAD file ''Mootjes'' LABEL ALL THE PARTS
2. Print ''Mootjes'' in from the frontal view 2D on paper first iteration (LABEL THE PAPERS)
3. Print multiple of the same A4-size papers with the frequently used curvatures in pumptracks from PumptrackNation (McCormack, 2019).
4. Alligne 2d blade curvatures with the sinus waves 1 by 1 and trace them on paper so you can see which parts of the blades align with the pumptrack roller's curvatures.



Tapered propertie f the blade

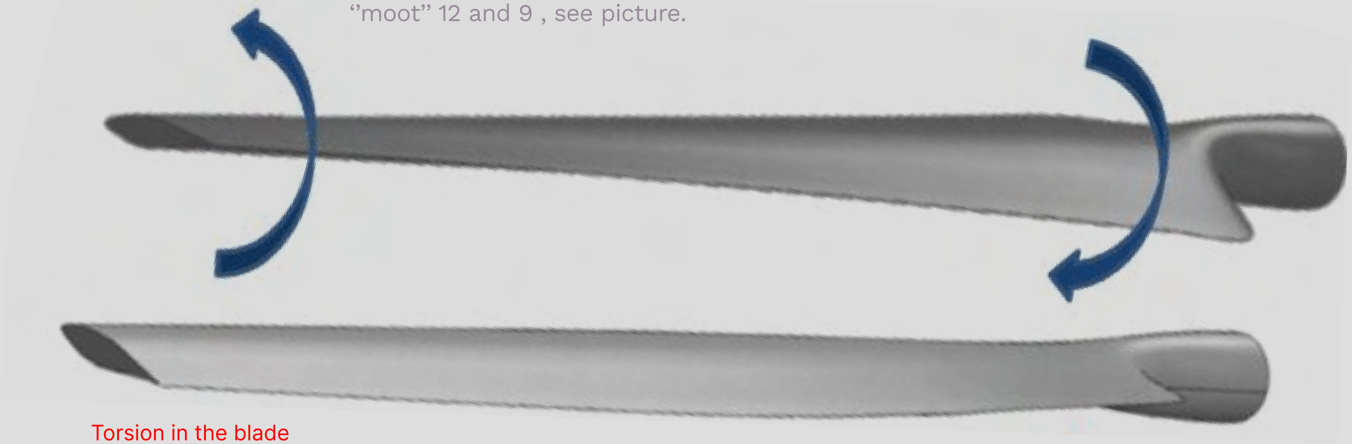
Reflection on action:
I expected to find fewer matches in the blade curves than I happened to find during the research. It was easy to get lost in all the different blades. Because the blades seem to have such a specific curvature, what's interesting to find out
I would have created more of a system in matching and tracing. I kind of intuitively traced the blade parts that matched the rollers. Although it worked out fine this is not very secure method.
Improvement: So start with 1 ''moot'' and try and match it with all the different rollers, so in my case you would end up with 21 papers (for every mootje) to see which curvature it matches.

Validation:
• Contiguous ''mootjes'' so e.g. the 4th and 5th cut have similar curvatures, therefore form a match. With those matches you can create even sinus like rollers that potentially work for building a pumptrack!
• The waves
1. Closer to the top root of the blade the curvatures align more with the 1:10 hight length ratio, from (McCormack, 2019) in which the crest:through ratio is equal. This creates a sinus wave on 1:20 scale, see moot 6 & 7.
2. If you want to create a jumpable wave roller-set you can combine a piece of blade that's closer to the root and skip a view pieces to combine for example. The combination of ''moot'' 12 and 9 , see picture.

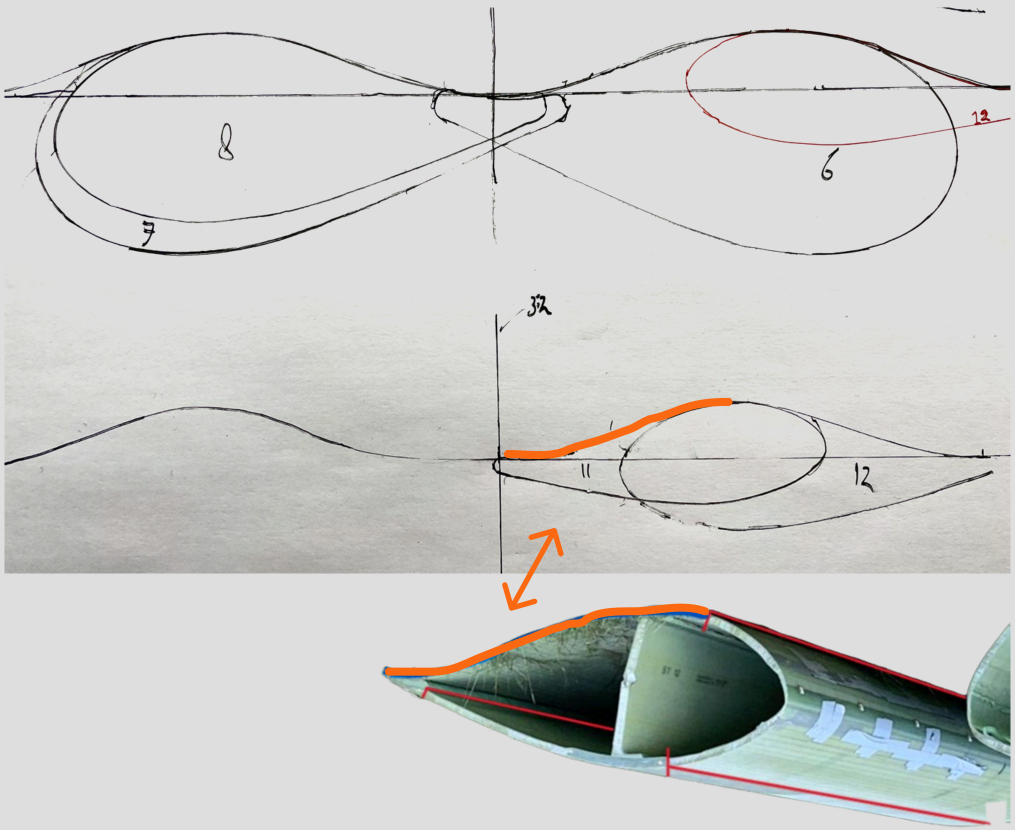
Take aways:

Contiguous '''pieces'' so e.g. the 4th and 5th cut have similar curvatures, because the tapered properties of the blade are similar if ''pieces'' are cut out closer to each other. With those matches you can create even sinus like rollers that potentially work for building a pumptrack!

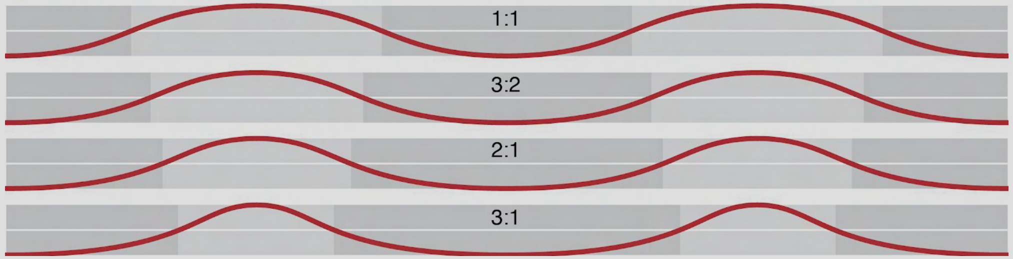
If you want to create a jumpable wave roller-set you can combine a piece of blade that's closer to the root and skip a view pieces to combine for example. The combination of ''moot'' 12 and 9 , see picture.



Torsion in the blade



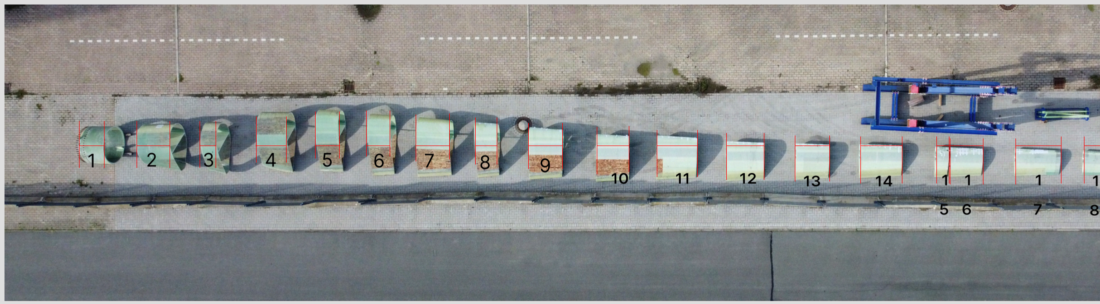
Roller trough:crest ratios



Insight X Closer to the top root of the blade the curvatures align more with the 1:10 hight length ratio, from (McCormack, 2019) in which the crest:through ratio is equal. This creates a sinus wave on 1:20 scale, see moot 6 & 7.

What's next:

To proceed in order to find out if this also works in 3D I needed to create a scale model in 3D which I tried in the next chapter, Design in 1-day. Another thing to find out is; if this curvatures are represented in other blades so that I can prove the material wouldn't just work for this 1 specific blade type.



04 Rtd 2 Granta & Material study

The objective of this chapter is to validate that the wind turbine blade is a suitable replacement for the current materials ''Betonplex'' and Sheet moulding compound (SMC) used by current manufactures like pumptrack.eu and Boost Pumptracks.

As you can see in the pictures figure x * figure x the name of the different parts of the blade.

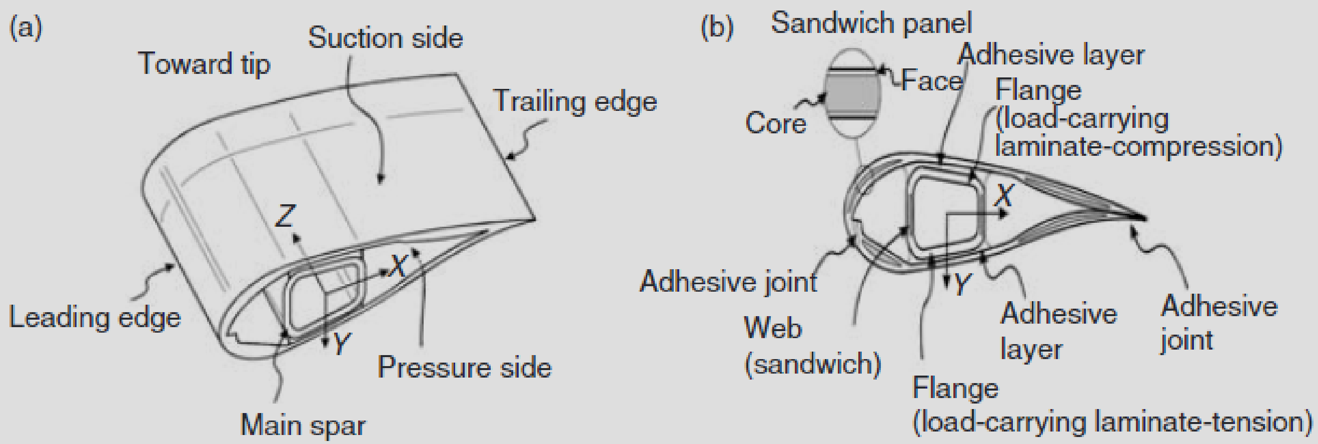


Figure Blade parts

A typical wind turbine blade is manufactured using polymer matrix composite materials, in a combination of monolithic (single skin) and sandwich composites. Present day designs are mainly based on glass fibre-reinforced composites (GFRP" (Thomsen, 2009). This type of material is also used in the blade that I'm using for my prototype later on and is the currently the most common blade material, since the turbine blades from 25 years ago were made with this technique.

As you can see in figure X, Certain sections of the wind turbine blade have a sandwich structure (sandwich shell) with a foam based or wooden core other are just monolithic so just epoxy resin with glass fibre(shell panel). The parts that I use for the pumptrack rollers are cut from the pressure side of the wing which is mainly sandwich structures.

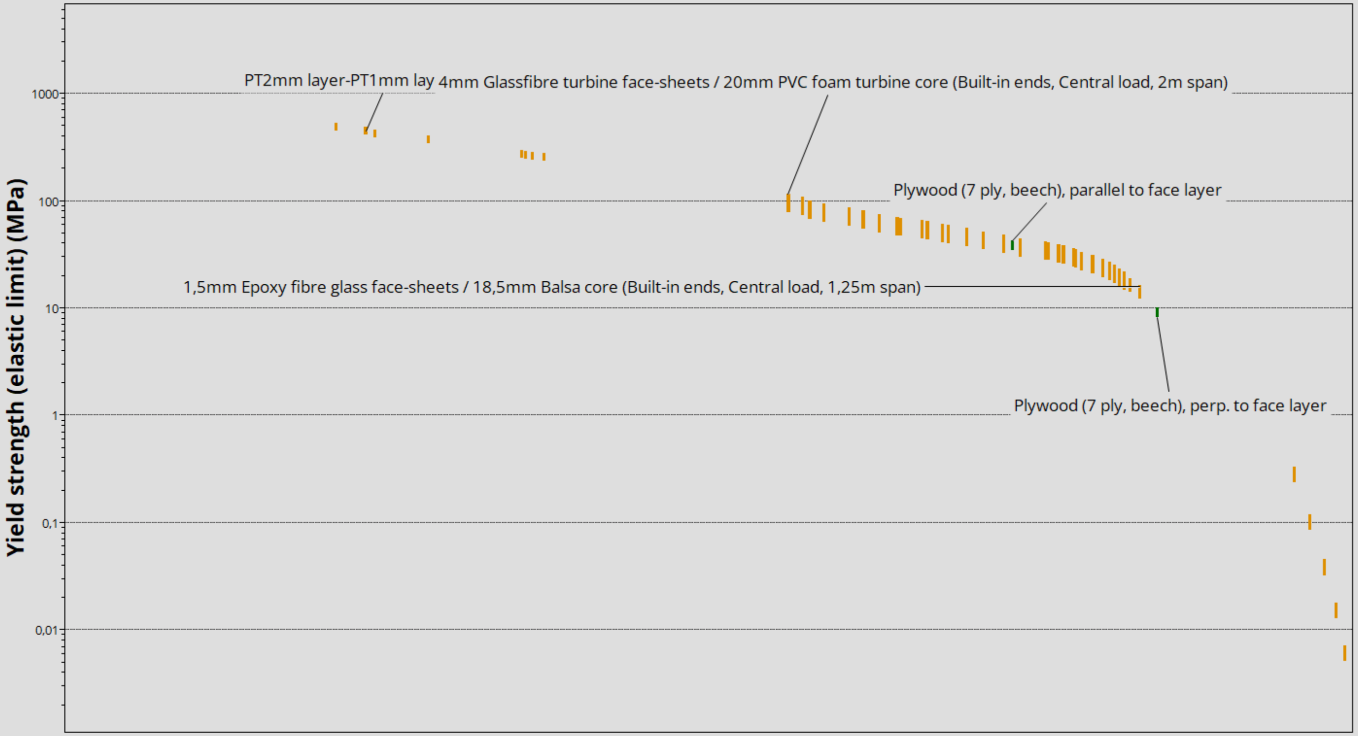


Figure granta table comparing strength of different materials

	Plywood (7 ply, beech), perp. to face layer	Plywood (7 ply, beech), parallel to face layer	PT2mm layer-PT1mm layer (1 / 1) mm	Epoxy resin / E glass pumptrack woven (Quasi-isotropic Composite) - 46%vf	1,5mm Epoxy fibre glass face-sheets / 18,5mm Balsa core (Built-in ends, Central load, 1,25m span)
Composition overview					
Material family	Composite (natural)	Composite (natural)			
Base material	Wood (composite)	Wood (composite)			
Renewable content (%)	100	100	0	0	0
Composition detail (polymers and natural materials)					
Wood (%)	100	100	0	0	0
Price					
Price (EUR/kg)	0,505 - 0,56	0,505 - 0,56	32,5	1,91 - 3,79	24,2 - 28,9
Price per unit volume (EUR/m^3)	354 - 448	354 - 448			
Physical properties					
Density (kg/m^3)	700 - 800	700 - 800	1860	1770 - 1950	328 - 363
Mechanical properties					
Young's modulus (GPa)	3,8 - 5,7	4,5 - 6,5	26,4	17,9 - 20,9	5,49 - 5,83
Specific stiffness (MN.m/kg)	5,04 - 7,68	5,96 - 8,77			
Yield strength (elastic limit) (MPa)	8,1 - 9,9	34,4 - 42,1	440	243 - 269	12,2 - 16,1
Tensile strength (MPa)	35 - 55	40 - 65		249 - 278	
Specific strength (kN.m/kg)	10,6 - 13,5	45,1 - 57,3			
Elongation (% strain)	2,49 - 3,04	2,4 - 2,93			
Compressive strength (MPa)	21 - 31	20 - 35		516 - 668	
Flexural modulus (GPa)	3,8 - 5,2	6 - 9	27	17,9 - 20,9	10,2 - 10,5
Flexural strength (modulus of rupture) (MPa)	35 - 55	50 - 75	199	243 - 269	87,2 - 107
Shear modulus (GPa)	0,2 - 0,3	0,2 - 0,3		9,67 - 11,5	
Shear strength (MPa)	3 - 5	3 - 5			
Bulk modulus (GPa)	1,78 - 2,66	1,78 - 2,66		21,9 - 25,2	
Poisson's ratio	0,2 - 0,3	0,2 - 0,3		0,308 - 0,325	
Shape factor	6	5			
Hardness - Brinell (HB)	26,4 - 32,3	26,4 - 32,3			
Elastic stored energy (springs) (kJ/m^3)	6,58 - 11,3	104 - 173			
Fatigue strength at 10^7 cycles (MPa)	11,8 - 14,5	16,5 - 20,2			
Differential shrinkage (radial) (%)	0,01 - 0,03	0,01 - 0,03			
Differential shrinkage (tangential) (%)	0,2 - 0,4	0,2 - 0,4			
Work to maximum strength (kJ/m^3)	50,6 - 61,9	58,6 - 71,6			
Impact & fracture properties					
Fracture toughness (MPa.m^0.5)	0,5 - 1	0,5 - 1			
Toughness (G) (kJ/m^2)	0,0578 - 0,2	0,0499 - 0,171			

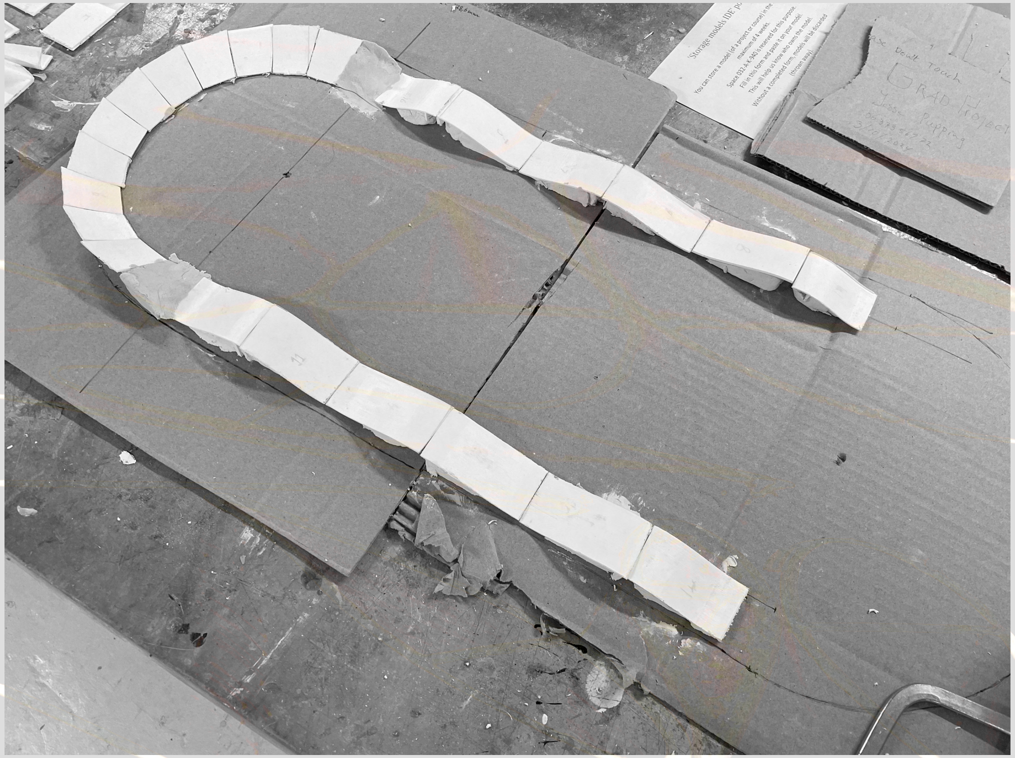
Ganta material synthesize table

To get a rough estimate of the material strength in comparison to the conventional materials I did a comparison between ultimate strength in GRANTA, see figure X & X.

Whats next:
The material tests by Sammie on impact and point load gave a convincing indication to the material's strength. When showing to the pump track builders they emphasised that I should be more worried about the toughness when applying an impact point load to the material. I can validate based on the graphs and simulations that the wind blades are strong to compete with wooden alternatives, the impact resistance and the material test for the NEN14974 norm Req X are tested in chapter, see Material test page X.

05 Rtd 3 Design in 1 day

Aim:
Find out if the 2d shapes from design in 1-day are also applicable in 3D.
Context:
Using prototypes to validate is a method I've been doing throughout my studies. This specific prototype will validate if the 3D shapes are compatible and gives me the first insides in how to connect parts. It will also give me insides in how much of a blade I can use and which track design is suitable for the specific amount of blade material. As a reference I used the ''tiny speed ring'' track, see Figure X.
Method:
1. Print the 3D 'mootjes'
2. Make a track layout preferably start simple and small. I based it on the 'Speed ring' layout with 3 rollers on each side and two 180 deg corners.
3. Use the matched 2d forms from Rtd1 to map out were the rollers need to be places
4. Cut the 3D parts in to the right shapes based on the outlines traced in 2D.
5. Based on the amount of rollers you have draw a 1:20 scale track model on a piece of cardboard.
6. Use modelling clay and cardboard and the 3D pieces to create a 1:20 scale pumptrack
7. Analyse the track!



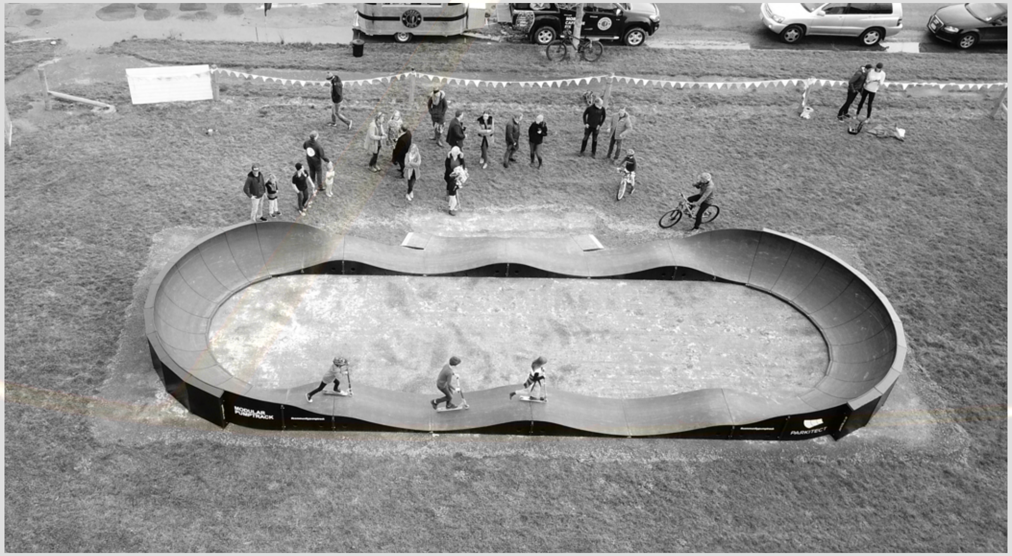


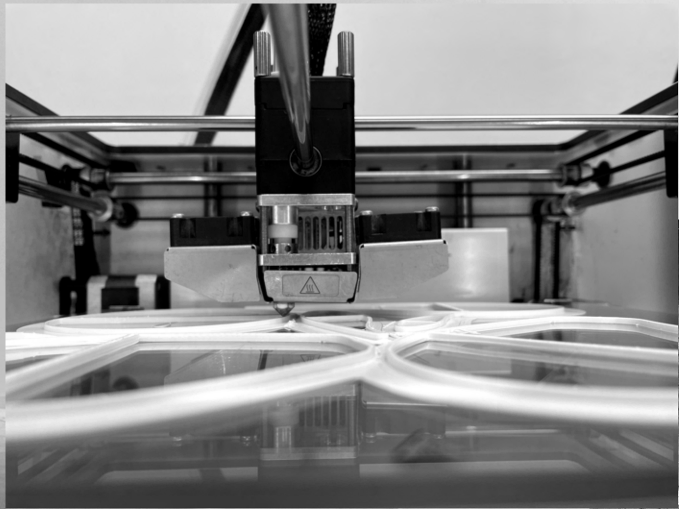
Figure x Speed ring

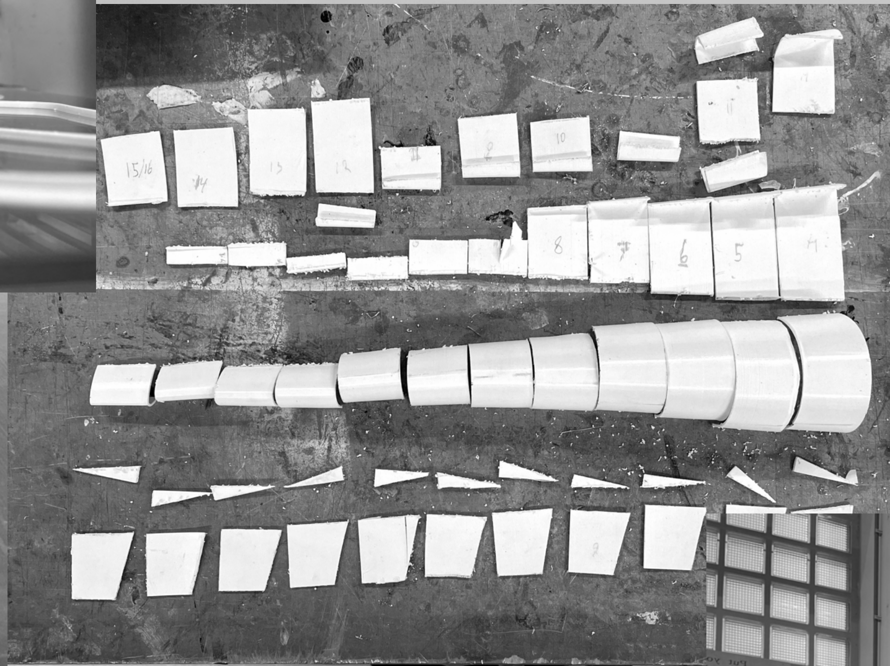
Reflection on action:

I expected to find out that it was going to be hard to have enough pieces it made me feel insecure about the project realisation. But when doing it and cutting all the 3d printed pieces it actually came together quite nicely and there is many options of using blade parts for the corner and the straight parts. So that gave me some more confidence in the viability of this project.
Improvement:
The method works quite well since working with physical prototypes and material makes you understand the material better. Although it's hard to work precise and therefore I would include cutting lines or just 3D-print the specific cuts

Validation:

This research turned out to have a positive result, the model showed that the specific pieces retrieved from the 2d mapping could be cut out of the blades with a metal saw. As you can see in the picture X the specific parts do align without to big of a gap and the offset of the blades doesn't seem to influence the track.
The amount of blade material used is to be calculated but is definitely enough for the speed ring track I used in this research.
Pump Factory was quite positive about the way the roller looked on the scale model and highlighted that the gaps between the modules can't be more than 5mm.
They were positive and advised to continue building to test it in real life.





What's next:

Test if it's possible to get double curves corners out of the 2d curved and straight panels, Rtd 4

Rtd 5 Eliminate the insecure cutting and create a cad version of the track so I can calculate the surface area and the percentage of blade material used in this specific track.

06 RtD 4 Corner modules

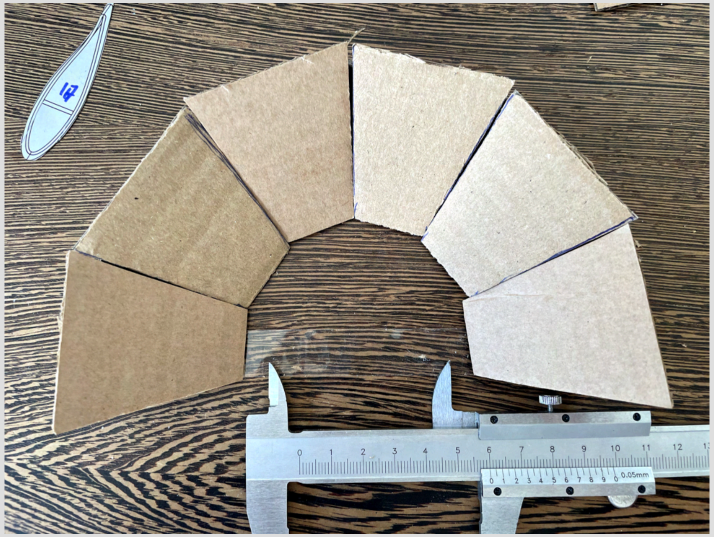
Aim:
Find out if residual blade material can be used for a 3D double curved corner.

Context:
This research will determine the viability of making a 180 deg corner from the blade material that's left after cutting out the 'roller' parts from the material. There are a few requirements regarding corners:
• A constant radius 10-feet radius is good for beginners
• The angle need to be around 60-80 deg
• The steeper the better, but also the steeper the less suitable for beginners.
• The corner is smooth so there is no loss of energy and no discomfort
For this research we are using the same track layout as RtD2. SolidWorks is used to determine the corner design and amount of modules.

Method:
For this research we are using the same track layout as RtD2. SolidWorks is used to determine the corner design, amount of modules and cutting angles. Later I applied the same angles to the residual blade material, see Figure x. Prior to diving into SolidWorks I started doing a lofi-prototype to get a feeling of the shape and form, see Figure X. for more details see appendix X

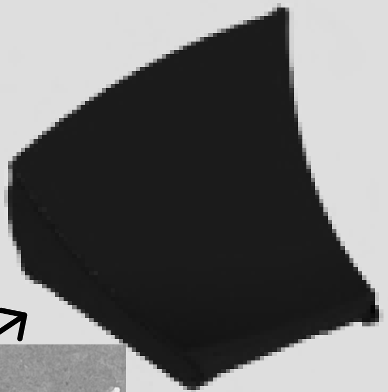
Figure x Speed ring

1. Use the leftover 3D printed 1:20 scale material from RtD 2 'mootjes'. See picture X for specific mootjes
2. Determine the amount of modules that need to go into the corner by measuring the width of the blade and the preferred radius (10-feet). See picture X SolidWorks mapping.
3. If capable create a representation of one of the blade cut-outs and try to retrieve the angle that the straight pieces need to have to fit them flush with each other. (the more parts the smoother the transitions between each module)
4. Cut the 2D shaped pieces out of the material.
5. Cut of the residual material that makes it possible to lay the parts flush.
6. Use clay to stick the pieces to the track.
7. Analyse the process and see reflect on the process.



Method:

For this research we are using the same track lay-out as RtD2. SolidWorks is used to determine the corner design, amount of modules and cutting angles. Later I applied the same angles to the residual blade material, see figure x. Prior to diving into SolidWorks I started doing a lofi prototype with cardboard to get a feeling of the shape.



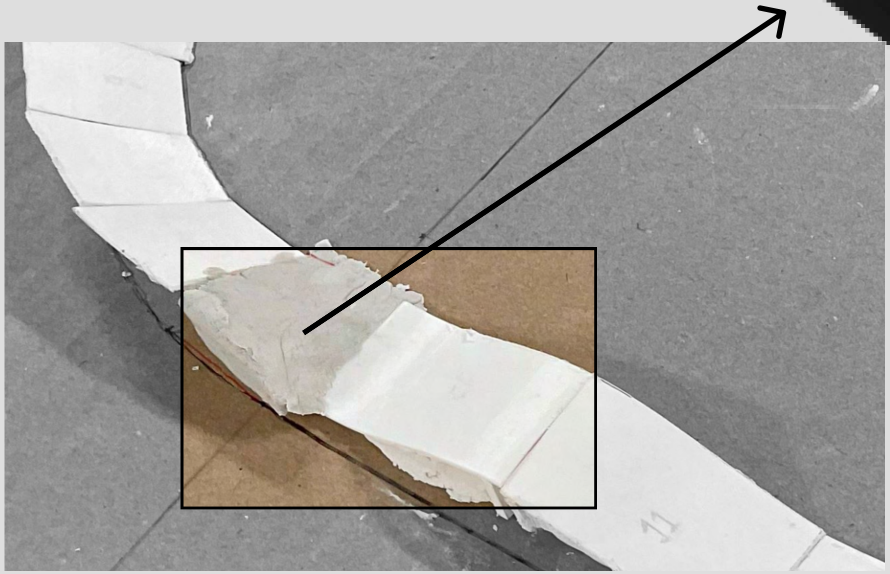


figure x Visual Transitions piece

Reflection on action:

As I ran out of time according to my planning I felt a bit rushed during this RtD phase. This made me rush the cutting of the parts and made it less precise. Although I could finish this phase before the weekend it made the result a bit less precise.
Improvement:
I would use a different method to cut the the 3D printed plastic parts, since the metal saw left some rough edges. Since the saw is quite flexible it made bended saw lines. Therefore the result is less useful. A preferred method is using a hot wire cutter to kind of melt the plastic.
In general I would redo the process digitally and print it again for a more precise outcome.

Validation:

This research validates that it is definitely possible to make a corner out of the 2d curved corners. I would have hoped to validate that the shapes will align good enough but due to the precisions this couldn't be determined.

During the research it became clear the transition module that connects the corner to the last roller, has a shape that's unsuitable to retrieve from the wind turbine blades.
see
As boost pumpfactory advised, you can make the corners but it will probably less secure and therefore the track might become less suitable for smaller wheels.

What's next:

- Base the corners on the specific design from parkitekt (boost uses this one)
- Print it so that it represents the cutted parts
- Create a method on how to cut precisely for the actual 1:1 prototype
- Find a way to smoothen the transitions between corner modules.

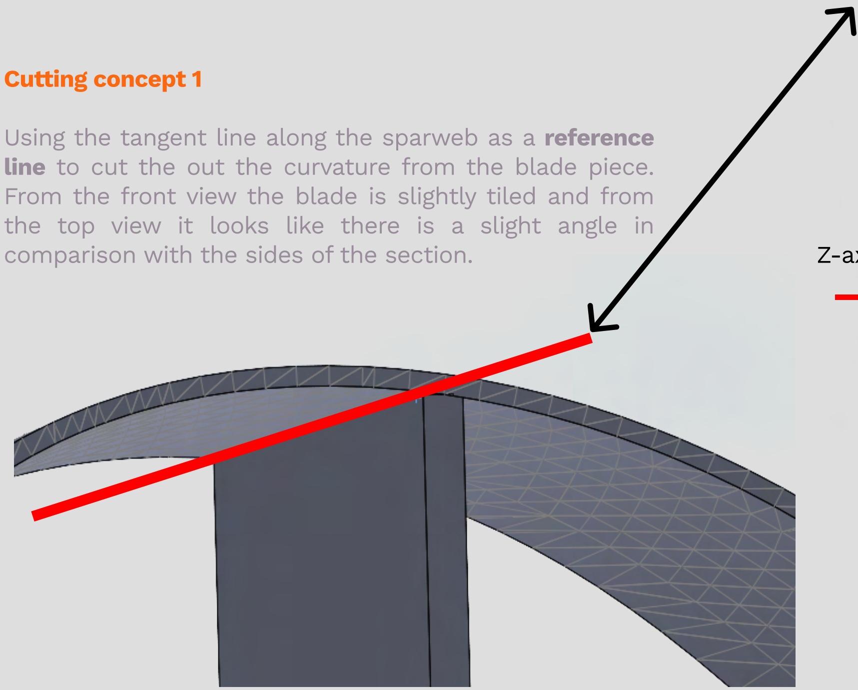
07 Rtd 5 Cutting methods

Is the torsion in the blades a problem for the connection of the modules?

Until now I found out that the curves are suitable, the material is strong enough, there is enough material in the blade available for the rollers plus 1 corner. In order to enable the creation of a full scale prototype I need to know more details. Since I don't have the actual blade material available yet I will recreate a Track in CAD to investigate the potential. Therefore this is the 2nd track iteration. For the cutting of the blade I found that there is 2 ways how to approach the cutting. Both cutting concepts required quite some prelaminar work in cad software, this is explained in appendix X.

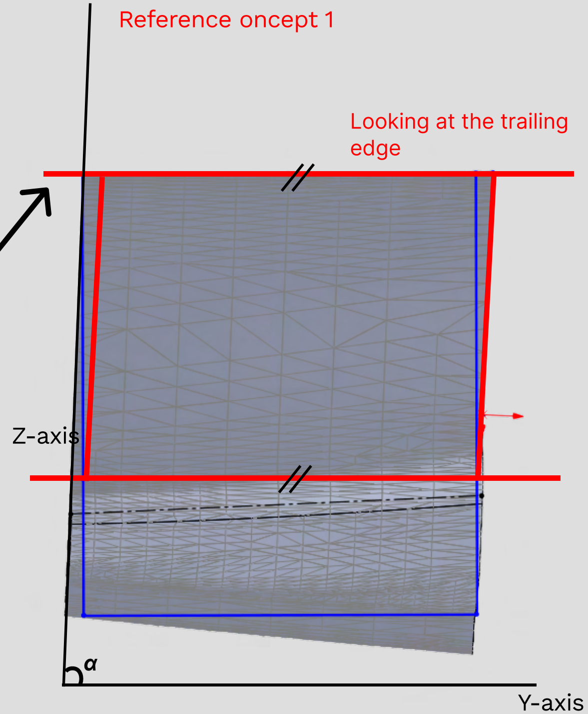
Cutting concept 1

Using the tangent line along the sparweb as a **reference line** to cut the out the curvature from the blade piece. From the front view the blade is slightly tiled and from the top view it looks like there is a slight angle in comparison with the sides of the section.

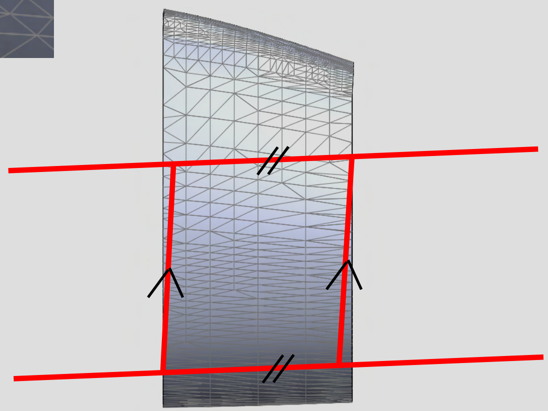


Side section view

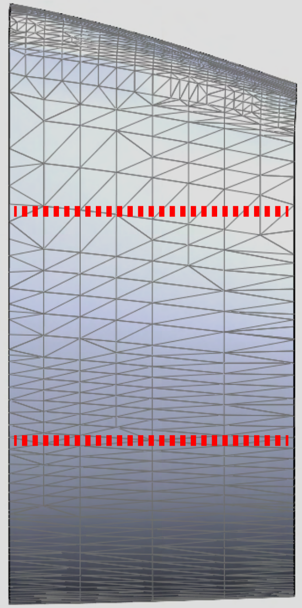
Reference line is perpendicular with the zx-face



Slight angle due to the reference line following the curve of the blade



top view blade



top view blade

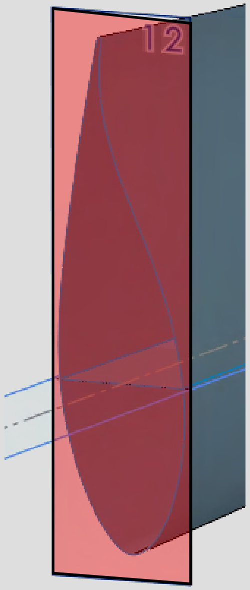


Figure x Reference face
cuting concept 2

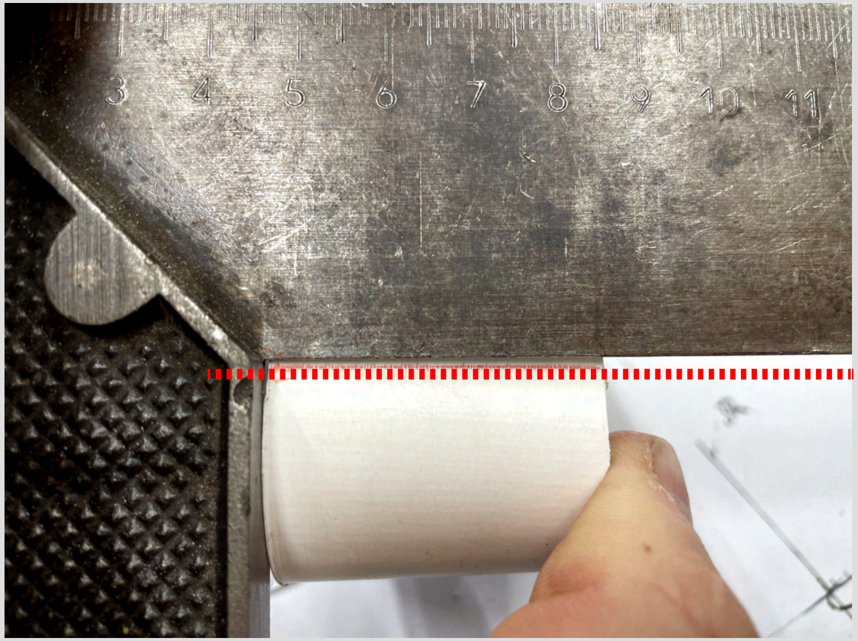
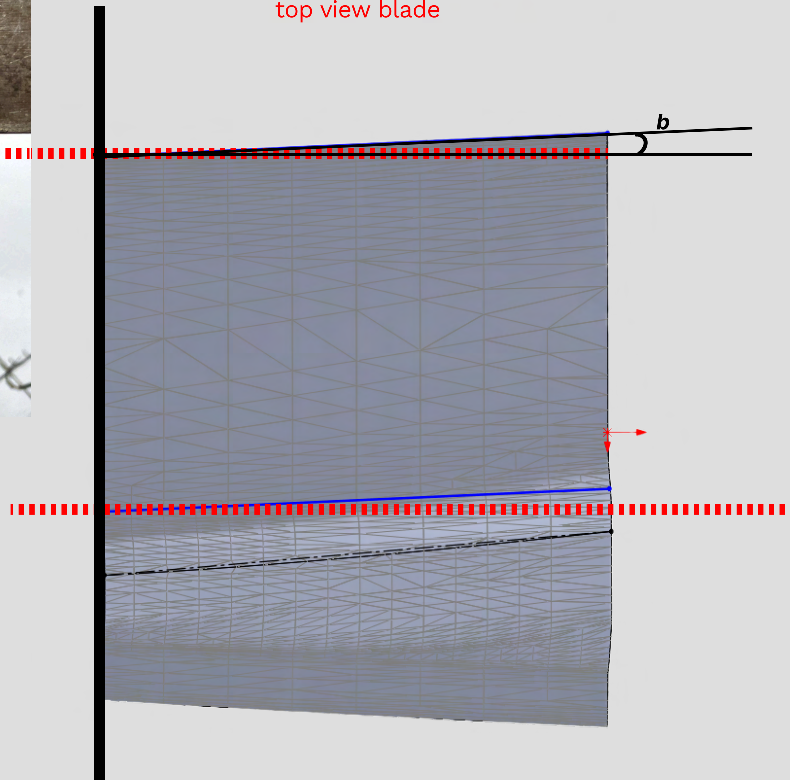


Figure x Scale model
reference line

Cutting concept 2

Or use utting concept 2. Prior to cutting outthe curvatures the blade need to be cutted into pieces, the saw blade creates a face. In cutting concept two this face is used as a reference to draw the cutting line, see figure x for the way I drew the line on the 3D printed pieces.



Looking at the trailing
edge

08 Validation RtD 5

Validation in cad:

During the matching of the roller curves I found out that it is convenient to use three different lengths for the rollers S/M/L . Since every blade piece has slightly different dimensions the length of the curve varies a lot, by dividing the modules into 3 different lengths S/M/L you create uniformity within the curvatures. See figure x

S/M/L visual drawing style, top view with sm/l indication, Mootjes align with s or m curveShow or reference to picture of RtD 1 tapered design

By measuring the alignment in SolidWorks after aligning the track I figured that The top of the rollers are aligning very smoothly with gabs of between 0-1mm.

Concept 1:

Using this method you normilize the curve and create a more straight and homogeneous roller surface. Since you cancel out the torsion by angleing the blade piece.

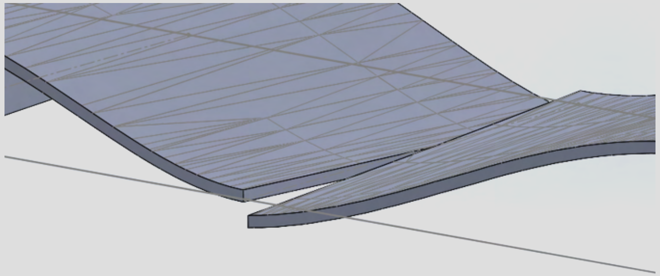


Figure x Misalignment in trough due to torsion in curvatures

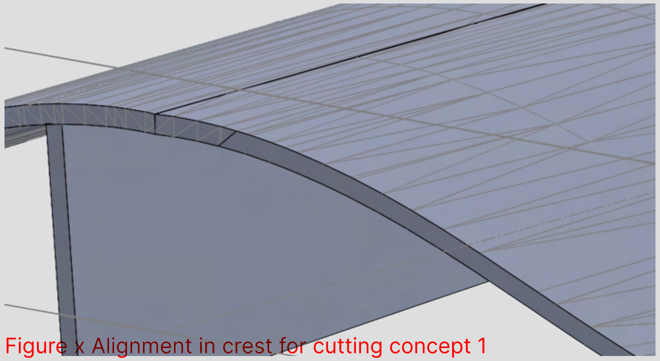
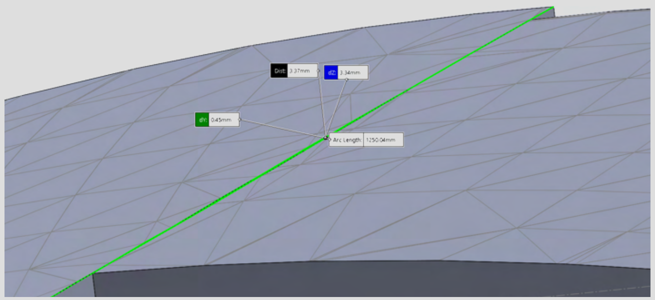


Figure x Alignment in crest for cutting concept 1



Concept 2 :

Unfortunately I found out that cutting concept 2 created a big torsion in the track, therefore the track becomes very wobbly.

This can be solved in two ways:

1. Create a connection piece in between the through parts.
2. Align the through parts, creating a track that is not straight and has a lot of torsion. Therefore there need to be a connection part that connects the wobbly track with the corner pieces x2.

Figure of torsion, show piece of connection piece in between crest

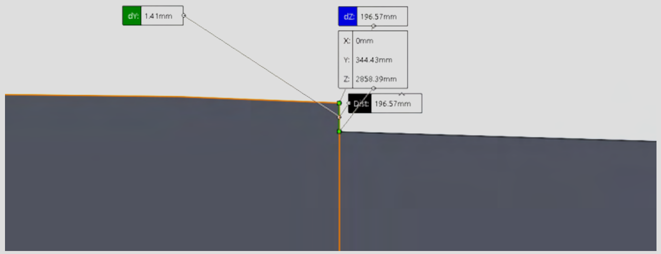


Figure x Biggest gab measured in CAD

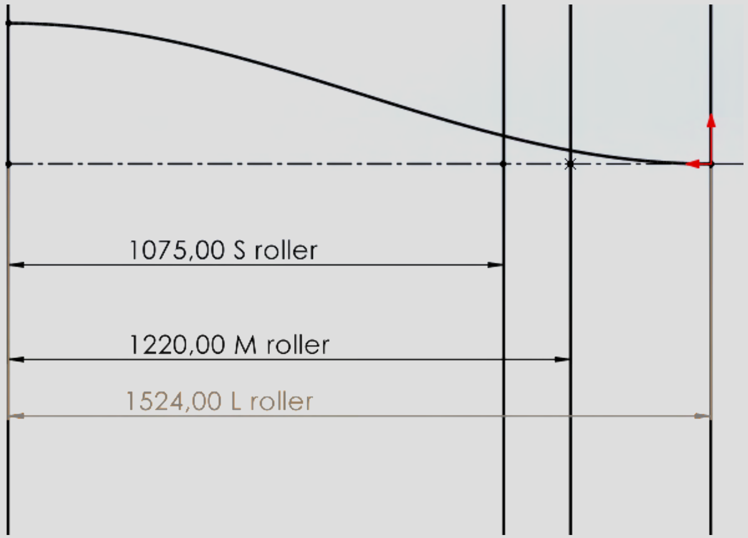


Figure x Length of diffeent rolle sizes

Conclusions:
- The least torsion and better alignment between the modules occurred when cutting the track by using cutting method 2
- It’s better to have two transition pieces at each end of the track instead of between each module.
- The S/M/L modules align better than in the first iteration
- Cutting concept 2 creates less torsion, but seems harder to execute when doing the cuts in real life versus in cad software.

What’s next
- Creating a jig to be able to do cutting method 2 in real-life
- Since the torsion in the track is not ideal try to find a way to eliminate the torsions. RtD 6 Inversed curves
- Find a way to automate the curvature and matching of the blade material to the specific needs of a track, see scaling up

Validation in 3D

Since it was very time consuming to validate the torsion and difference in cutting concepts I created representative 3D files for both cutting methods and created a track from 3D printed parts.
Then I could measure the torsion at the beginning and end of each straight part of the track.
See figure top view and measure of the track’s torsion.

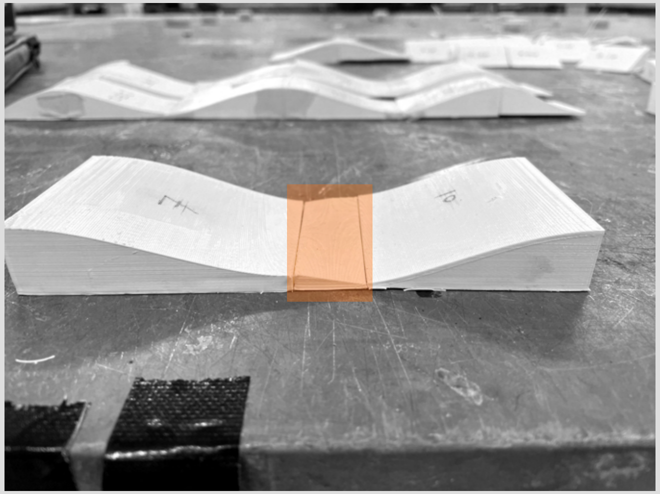


Figure x Connection piece

09 RtD 6 Inversed curves 3th track iteration

How can you eliminate the torsion in the track?

Context:

Since the torsion in the blade gradually decreases over the length and the curves taper down gradually over length. Potentially the curvatures cancel one another out when using the inside of the blade and have a inversion of the curve, See figure X.

Method:

Basically you can just extrude the other side of the surface and you have the inverted curvature. In order to cancel out the track you need to alternate the pieces between and inverted piece and a ''normal'' piece, see figure X lay out.

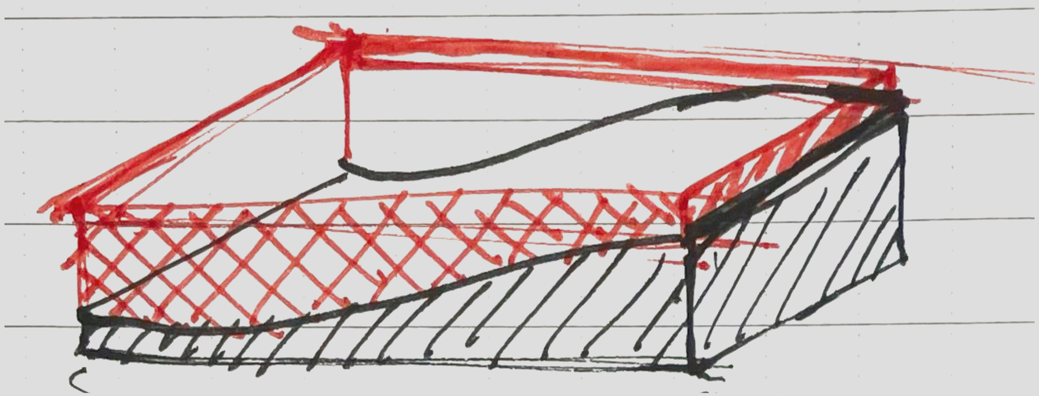


Figure X flip side of the curve

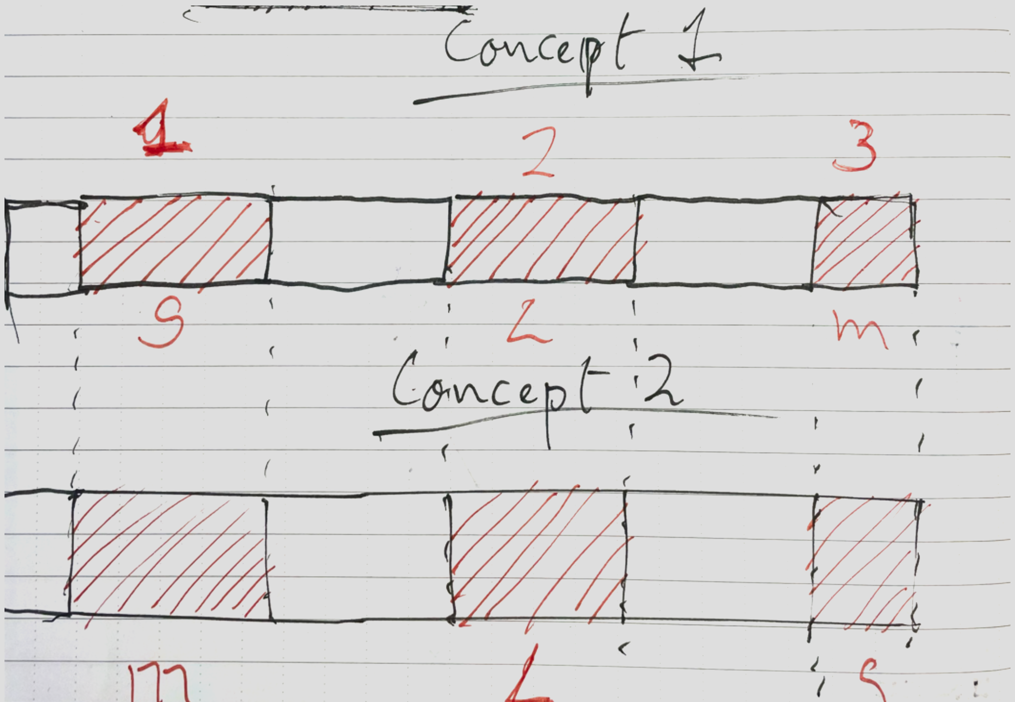


Figure X lay out.

Validation:

- Preferable use cutting technique 2 since it creates the least wobble in the track
- Inversed curves create less torsion but they are less smooth in the transitioning from in the crest part

What's next:

- Prototype a way to level the modules and connect them, see chapter module connections
- See if the curvatures are still suitable in the inverted state

Figure X Lowest torsion measured

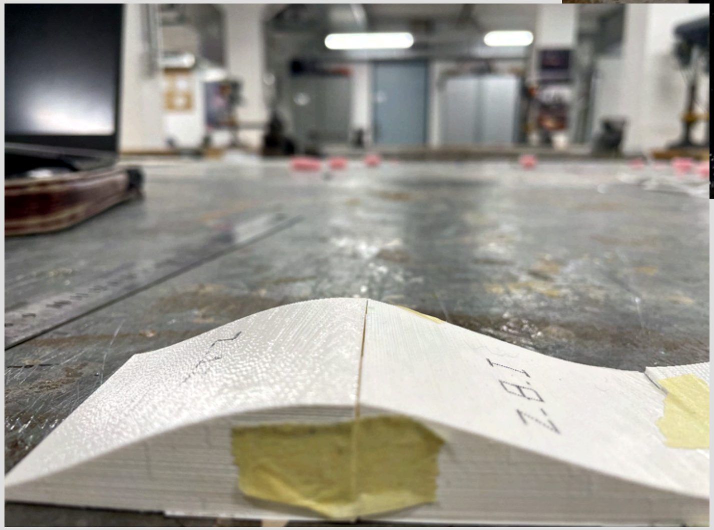


Figure X Picture of steep crest, transition in crest

10 RtD 7 Curved corners

How to best cut the blade to make suitable corners from the residual blade material?

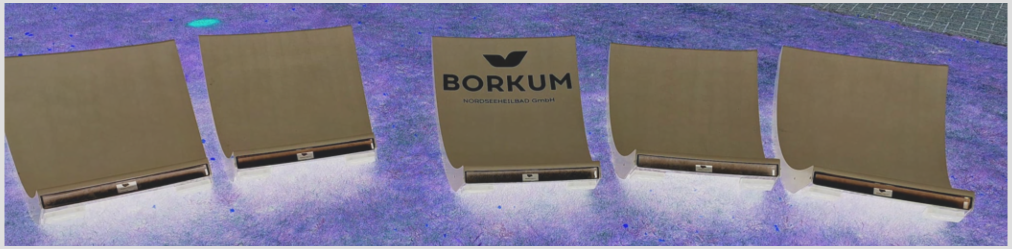


Figure X Corner modules

Context:

The corner modules from current tracks use double curved modules, see figure. Unfortunately the turbine blade material is not perfectly shaped for the corners, therefore the alternative is to use single curved or "flat" parts, like in RtD4 page X to create corner modules.

After cutting out the curvatures for the rollers modules. There will be a lot of material left for the corner pieces. Ideally the 180 deg corner is divided in modules that cover 15 deg per module of which the first and the last two pieces are transition pieces resulting in a 8 modules per corner, see figure X .

Method:

By keeping the opposite side of the curvature in cat software, you end up with all the "left over" material. You can recut this material into straight panels and align them in a different assembly. Since this is a very time intensive process. First its better to just try and do this on scale with the left over 3d print material. I've tried it for 1 piece and it didn't work out in cad since you don't have any references, so this is to be continued........

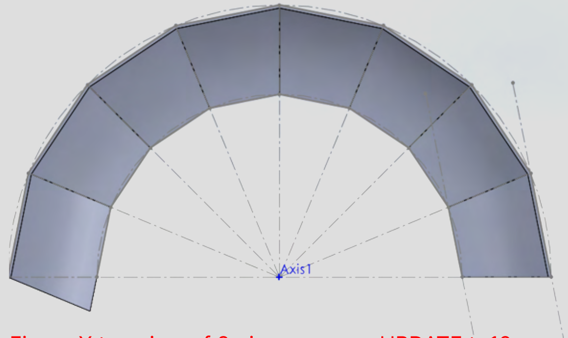


Figure X top view of 8 pieces corner UPDATE to12

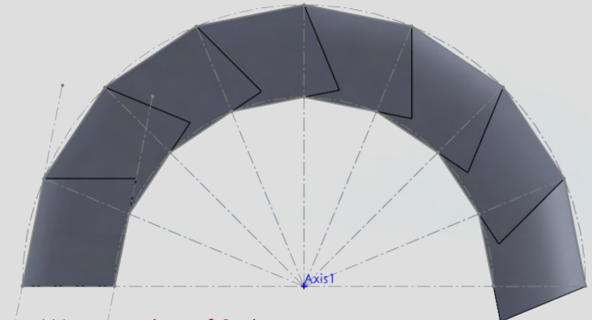


Figure X bottom view of 8 pieces

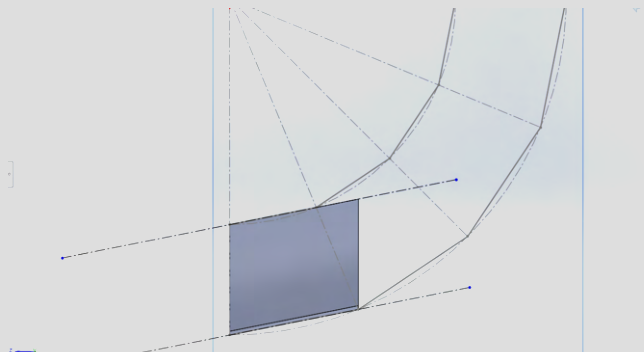


Figure X Uncutted corner curvature top view

Validation:

If you create a lay out from top view and use those measurements to create a cutting patter from the front view it doesn't work. The pieces will have too different curvatures to match it without creating too big of a gap between the modules.

What's next:

- **Base the corners on the specific design from parkitekt (boost uses this one)**
- **Print it so that it represents the cutted parts**
- **Create a method on how to cut precisely for the actual 1:1 prototype**
- **Find a way to smoothen the transitions between corner modules.**

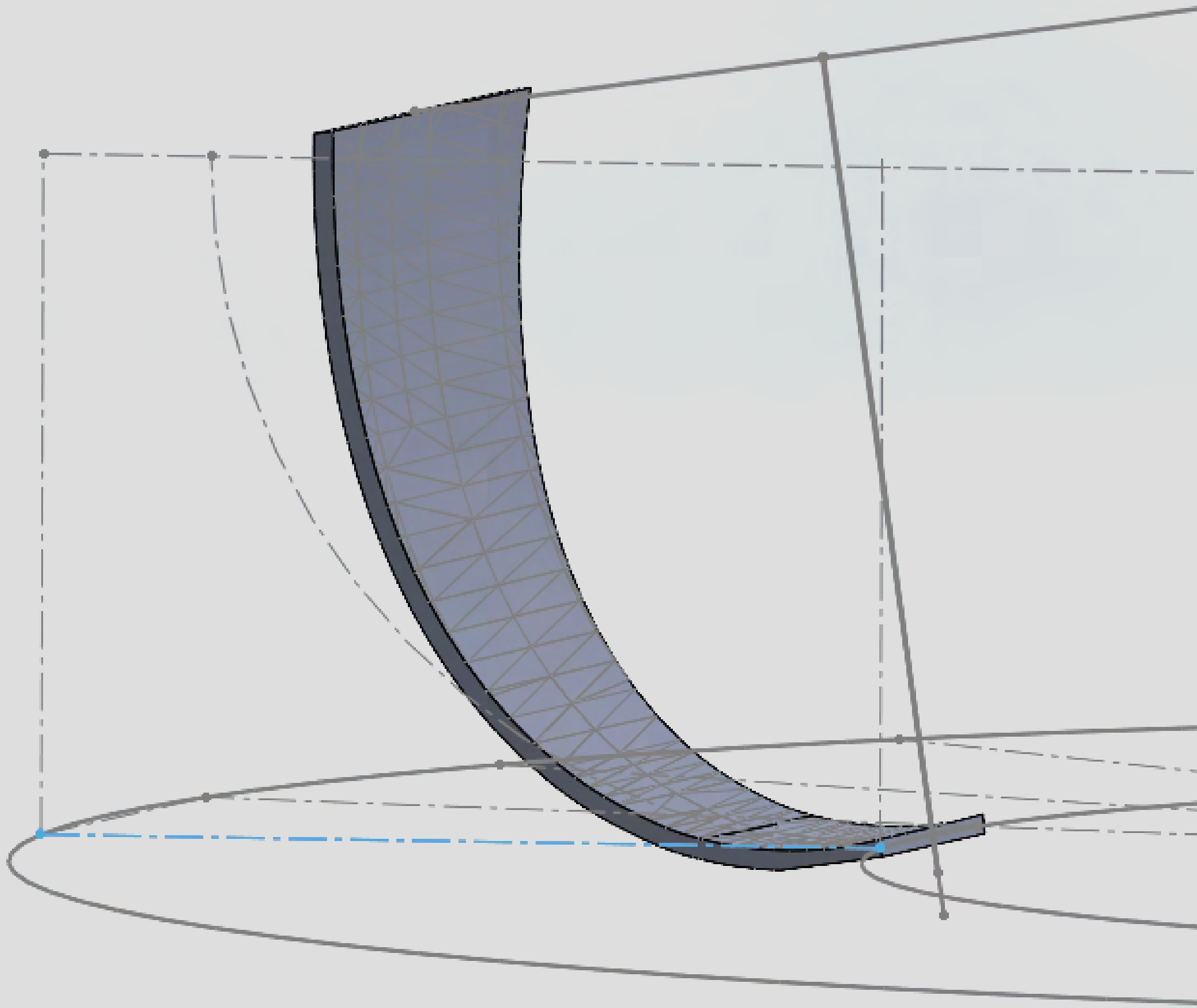


Figure XCorner module curvature

11 Rtd 8: The offset of 3 rollers

Aim: Find out what precisely is the difference in twist between the different cutting methods?

Context:
In RtD 5 I discovered different ways of cutting, it was hard to precisely determine what the angle in the curvatures would be. This angle occurs due to the twist in the blade material. By creating a solidworks assembly and place the modules in a track, the angle and gaps can be measured within the SolidWorks environment.

Method:
1. Create similar track layouts, 1 track per cutting method (2) and one for each inverted version.
2. Allign the first roller with the ground plane, now there is a reference which is needed to measure the offset and angle at the end of the track.
3. Measure the angle in the front plane, see picture and the biggest gap between the models.
Figure X: Method offset

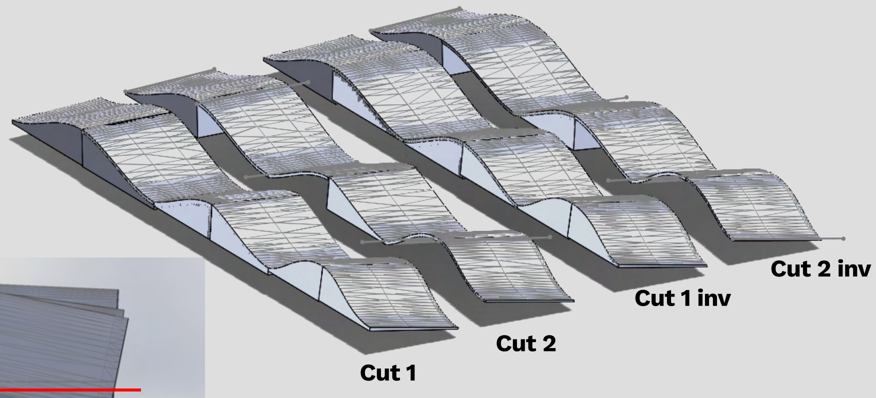
Reflection on action:
During the process I got quite frustrated since it is hard to work with non-standard parts. Creating references and mating the modules in SolidWorks is very time consuming, but it was necessary to proof the point, so in the end I felt relieved that it's done. And I can base my next steps on actual measurements!

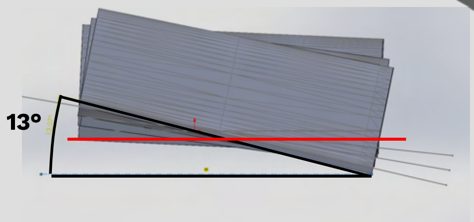
Improvement:
The process is very time consuming in SolidWorks, I might have been able to proof the point with less rollers saving some time.

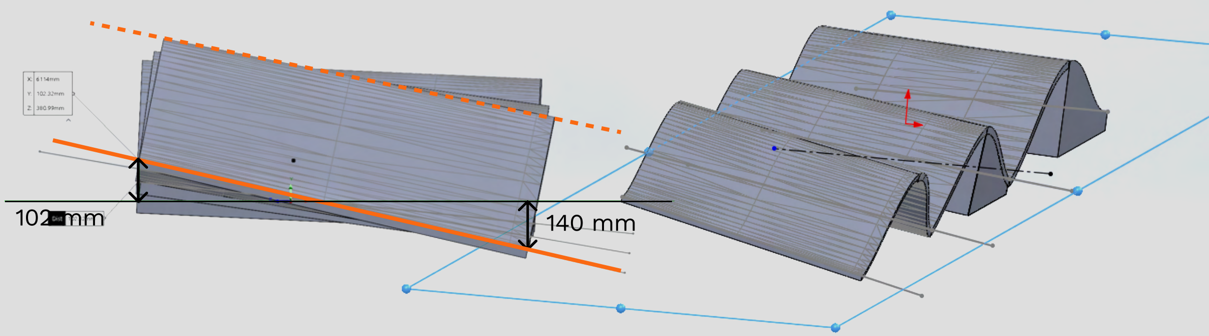
Validation:
So according to the measurements the cutting method 1, has the least gap clearance and the least offset due to twist.
This is great since the cutting method is most suitable for manual cutting.

What's next:
- Creating a 3D cad model of the complete track (from with blade material) to show how everything connects.
- Cutting the actual material samples by using cutting method 1

Cutting and lay-out for the three roller types				
	Cut 1 [mm]	Cut 2 [mm]	Cut 1 Inverted [mm]	Cut 2 Inverted [mm]
Angle	13,07 deg	13,43 deg	13,13 deg	13,15 deg
Offset Left	102	114	106	106
Offset Right	124	118	121	121
Delta	226	232	227	227
Biggest Gab	1 mm	1mm	3mm	3mm







12 Tapering effect & Angle offset

When looking at the overall tapering effect to the side of the blade towards the trailing edge. The tapering at the top difference for 30m blade and a 60m NREL 5MW blade.

Difference in angle of the taper:

30M Blade: 1-15m 0,8° and 15-30m 2,3°
60m Blade: 1-30m 0,7° and 30-60m 2.2°

Based on these two measurements there is an offset angle difference of 0,1 deg this might not be enough to conclude any significant differences between the two blade designs.

It does mean that there is a significant difference in the angle between the first and second half. This means that the angle in the blade material and therefore the twist in the blade from the pieces closer to the tip should be less. Than closer to the root.
In appendix 'offset 3 rollers' the relative twist angle is about 13°. When dividing it by 6 (from the 6 modules forming the rollers) the angle per module is 2.16°. The parts analysed are from the region of the blade between the 15-30 m part. The this closely corresponds with the angle of 2,3 degrees measured in the offset of the blade after cutting the rollers in CAD. The differences in the angles can be cause by the twist in the blade.

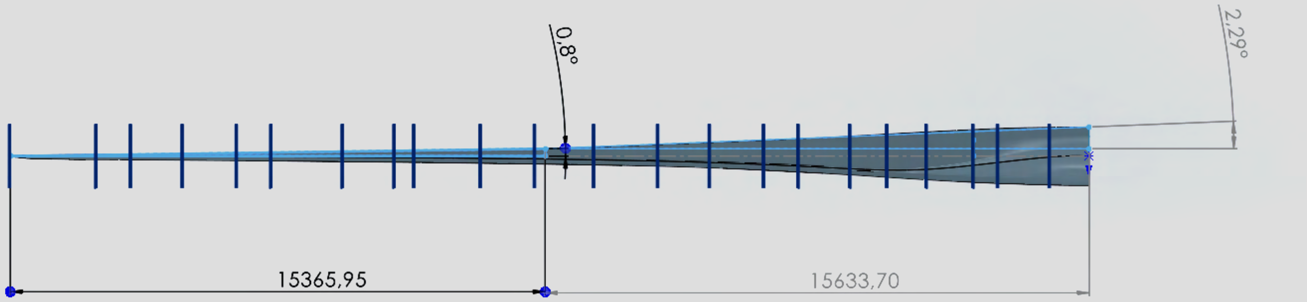


Figure: angle 30m

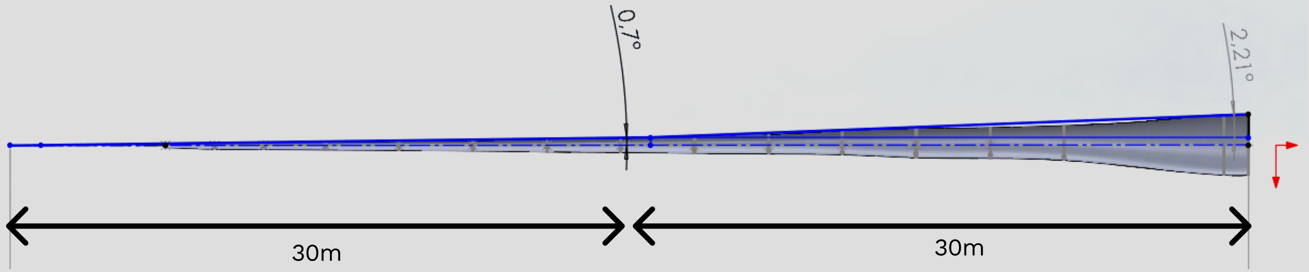


Figure: angle 60m

13 RtD 9 Roller support and connections

Aim: What is the best way to connect the rollers and to make it fit with current pumptracks?
Context:
In order to secure the:
- Top alignment
- Bottom alignment
- Adjustability per roller
- Fasteners and sandwich material

There needs to be a structure supporting the curvatures and securing a strong and precise connection. The main challenges are supporting the:

- Difference in material thickness
- Twist offset in the bottom
- Weight support
- Easy assembly

Method:
1. The first step is ''Analysing the current connection methods of modular pumptracks'' My approach I visited a pumptrack builder and did photo research,
2. After having grasped some of the current supporting systems, I moved into the ideation phase where I used DESIGN SKETCHING as a means to explore different options.
3. I Figured out the how to make the support system adjustable in height, by using a variation of the support system of THE PUMP FACTORY, therefore I could already build the base parts the ''legs'' from steel. See FIGURE X.

4. To validate if the insert would work I used the advice from THE HANDBOOK OF SANDWICH MATERIALS (Zenkert, 1997) and tested those in the material, see PICTURE X INSERT.
5. With the validated connection method I could move into the detailed solutions phase, by prototyping. I created multiple iteration of prototypes by using the real dimensions of the track but with 5mm plywood to work faster .
6. The last step is calculating if the bolts and material can withstand the force from the NEN-norm refer to chapter X.

Reflection on action:
In general the research was very stretched because I started thinking about it already from the start, I like how I used different iterations and was not afraid to rethink the way it should be done.

Improvement:
I would have liked to start prototyping with cardboard first since it is a faster and more insightful way of working than drawing for me.

Validation
The 1:1 prototype should validate the if the support system actually works. But through prototyping and calculating

FIGURE X PUMPTRACK DETAILS.

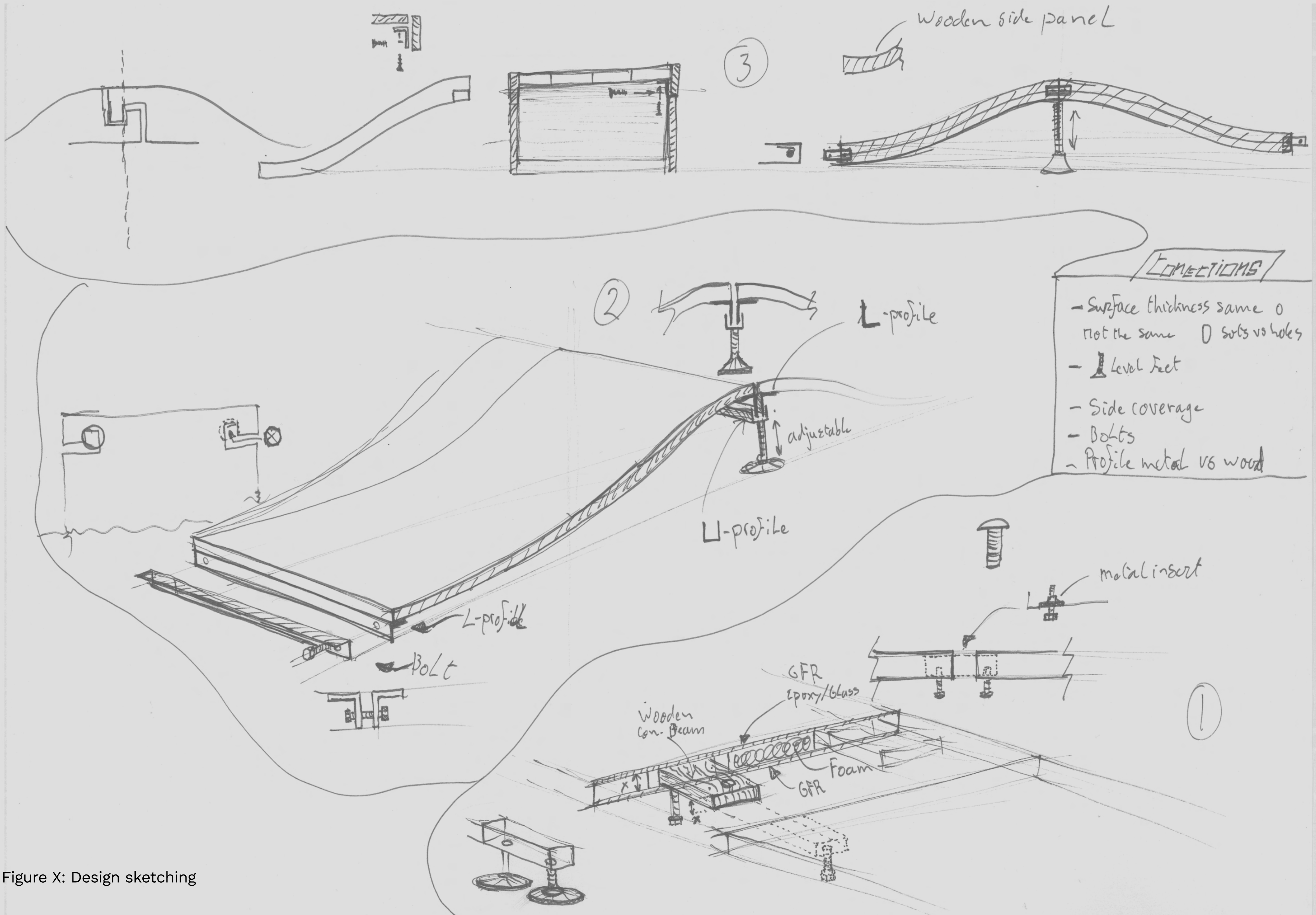


Figure X: Design sketching

14 Cutting plan

Communication and material selection

Before pick up the blade material needed to be ready for transport. Because of limited transport and storage options. We had to choose only a few options based on availability (some pieces were used for other projects), weight, geometry and size.
Fraunhofer cut the blade into transportable pieces without losing the necessary form requirements. Down here some pictures of the blad material.

Analyse the blade material

After picking up the blade material at Fraunhofer. The material needed to be analysed since the CAD model was just a representation of the real material therefore difference from reality.

Due to transport and availability of the parts at Fraunhofer, two complete sections (piece 10 & 20), four pre-cut curvatures (12.1, 12.2, 11.1 and 9), one leading edge and a few shear web parts have been transported to the IDE Faculty for further research. This project prioritises to analyse the 4 curvatures and piece 10 (complete section). Since these pieces together can make two rollers, therefore fit into a conventional track for testing.
These parts were suitable to make an S and M sized roller. Unfortunately the parts closer to the root were not available anymore.

Section	Desired arc length	Arc length sandwich material [cm]	Arc length sandwich Short side [cm]
9	M (126cm)	155	128
10 (section)	M (126 cm)	125	123
11.1	M (126 cm)	124	101
12.1	S (112 cm)	90	76
12.2	S (112 cm)	109	96
20	-	-	-
			gemiddelde:

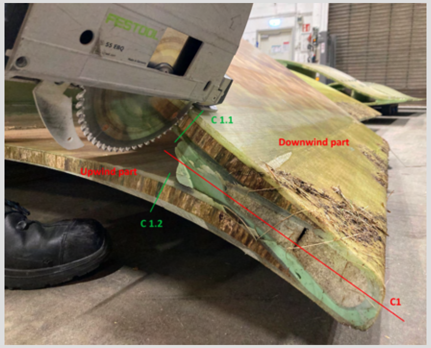


Figure: communication about cutting

Analyse surface material

The blade surface area and the roller surface area are obtained from the cad-model in SolidWorks. In the calculation there is a total of 12 modules creating 6 rollers. This amount could be increased when using the left over material for corner panels .

Tooling
The researchers from Fraunhofer provided us with practicalities about the cutting process. It is possible to cut through most parts of the blades with basic tools and the right blades (Figure X). Tools selection: a hacksaw, jigsaw, circular saw or an angle grinder. But each tool has their advantage.
Cutting advise:
- Circular saw for longer & straight cuts.
- Jig saw for precision
- Hacksaw for thicker parts

In addition to that it’s very important to have proper safety measures, including dust collection system; closed of room with a vacuum cleaner type 2 filter and an adapter to connect another vacuum cleaner to the tools, this prevents dust release in the first place. And makes it less dangerous for your health.

For protection it’s necessary to use a overall and full mask with FP3 filter. When cutting big surfaces and harder parts, it’s necessary to also apply gas-filters for the toxic fumes that occur when heating up the material with the friction of the blade.

surface area	mm^2	# used in	srfc area m^2	% of total srfc area	combined%
Shell entire blade	112497030				
L curve	1962209,3	4	7,8	7,0	
M curve	1585879	4	6,3	5,6	18
S curve	1417000	4	5,7	5,0	
Total			**20**		

Figure X: tooling blades and dust extraction

15 Reference blade material analysis

To answer some of the research questions it was necessary to analyze the actual blade material, based on arc length, mass and geometric properties.

The inverted curve is not possible when the roller surface includes the spar cap, since the shear web connection to the spar cap contains a lot of glue (Figure X). Removing this is a very difficult procedure and will cause damage the riding surface and makes the inverted roller unsuitable for the use in the pumptrack.

Spar cap width of the 9th section and the 20th section are the same, between 10 meter and 26 meter. Making the spar cap a good reference point to draw the cutting pattern.

Large amount of glue

The largest possible arc length turned out larger than the specific arc length

Section	Desired arc length	Arc length sandwich material [cm]	Arc length sandwich Short side [cm]	Mass offcut [kg]	Sandwich material Tickness [mm]	Core material	Arclength after waterjet cutting [cm]	Sparcab width [cm]
9	M (126cm)	155	128	33,6	23	balsa	134	43
10 (section)	M (126 cm)	125	123	-				43
11.1	M (126 cm)	124	101	65	23	balsa	149	43
12.1	S (112 cm)	90	76	64	25	PET	120	43
12.2	S (112 cm)	109	96	64	25	PET	132	43
20	-	-	-	-	-	-	-	43
			gemiddelde:	**57**				

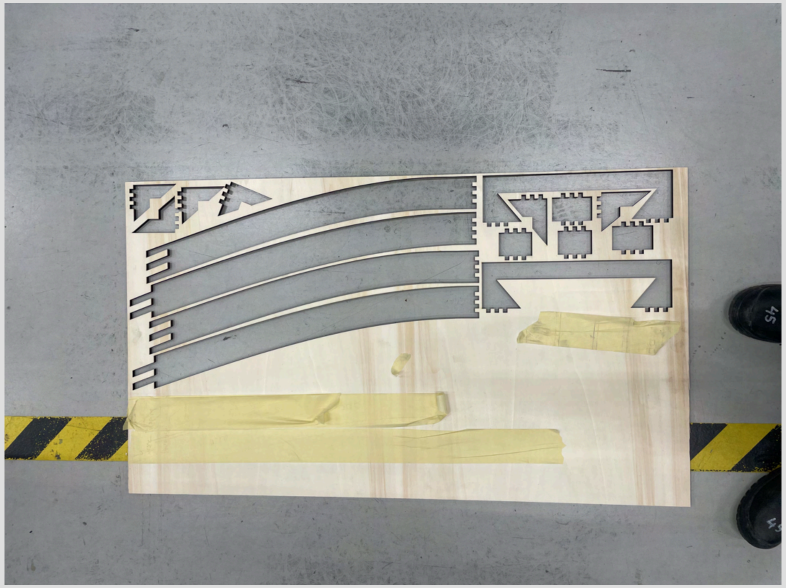
FIGURE X PUMPTRACK DETAILS.

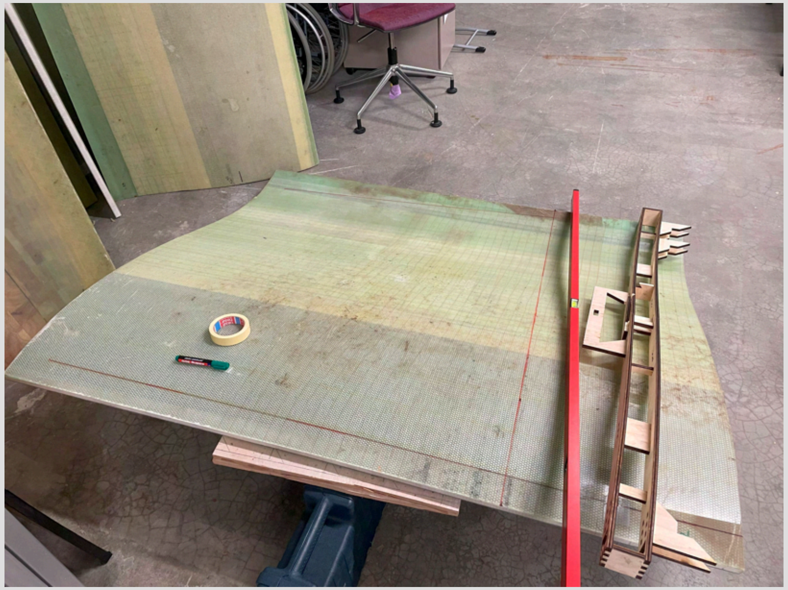
Width of spar cap is equal between section 20 and 9

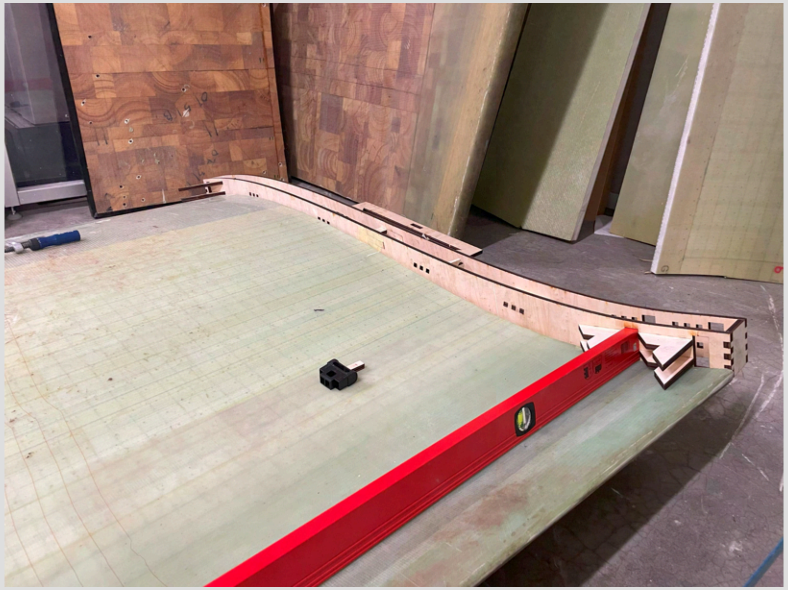
16 Jig

In order to make accurate cutting pattern, I build a jig. The jig's shape is a representation of the roller sizes, S and M. It is used to mark the arc length for an S and M size roller on the blade material surface.
By holding the jig next to the blade material's curvature it is possible to find the best match with the 'ideal' sinus curvature. The 'match' is determined by eye in this case.

This specific jig fits an leveller which creates a 90° angle with the jig and therefore the cutting line will be perpendicular to the side edge of the blade material.
During the process I found out that the sparcap is a better point of reference and therefore the jig was only used as a template to measure the desired arc lengths.



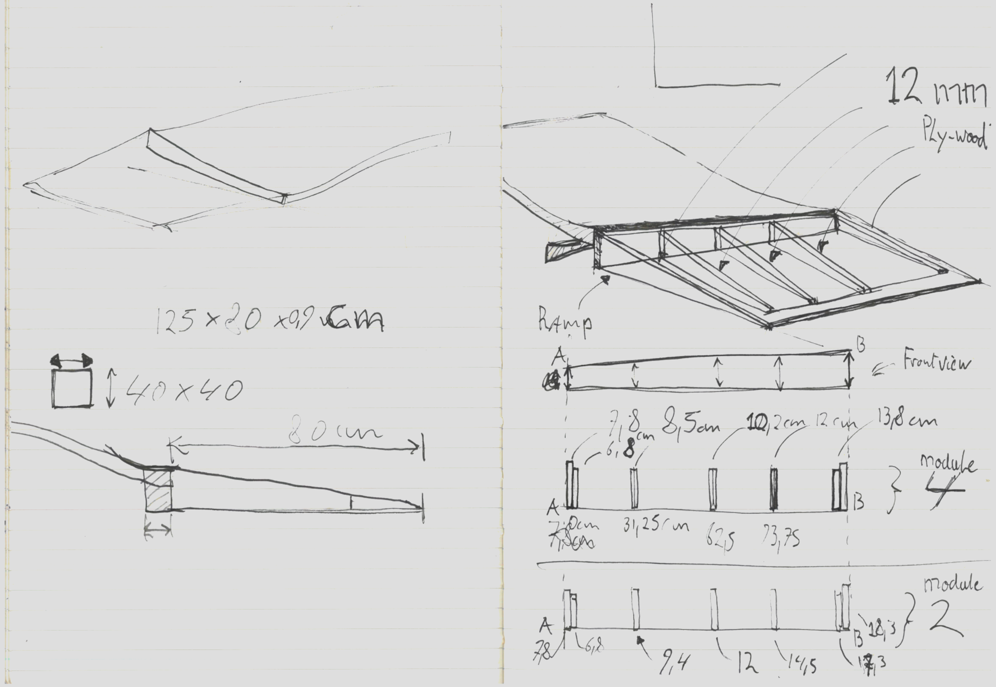




17 Blade Transport

It was not an easy task transporting and carrying around the blade material. The sections are only movable with help of a fork lift, the panels can be transported using a simple card.

18 Ride-out


12 mm
Ply-wood
125 x 20 x 9,9 cm
40 x 40
80 cm
Ramp
Front view
module 4
module 2

19 NEN14974 Safety requirements

The track needs to comply with the European safety standards for skateparks and with the European standard for skateparks. The pumptrack builders The Pump Factory advised me to look at the NEN14974 norm. The most important requirements being req X and req 5, req coating.

ReqX All externally accessible edges shall be rounded with a radius of at least 3 mm or chamfered by a minimum of (3 × 3) mm.

Req X The difference between a horizontal rolling surface and the toe of the foot plate shall not exceed 5 mm (see Figure 1). The foot plate shall be tangential with the inclined rolling surface. A transition shall not meet the ground with its foot plate at an angle greater than 15°

Req X Skate elements shall be designed and constructed with sufficient stability. They shall not tilt, dent or wobble. Skate elements shall be firmly fixed to the ground or be secured against displacement or toppling over either by their own weight or by anchoring.

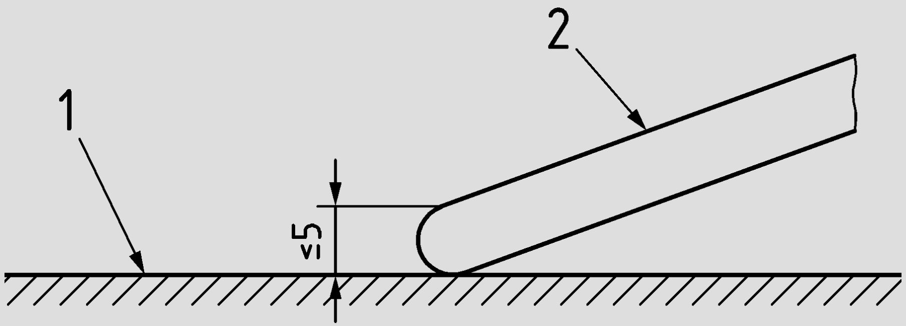
Req X All skate elements and rolling surfaces shall be able to withstand a distributed load Q1 of 3,5 kN/m2 applied perpendicularly to the tangent of the rolling surface (according to Figure 3).

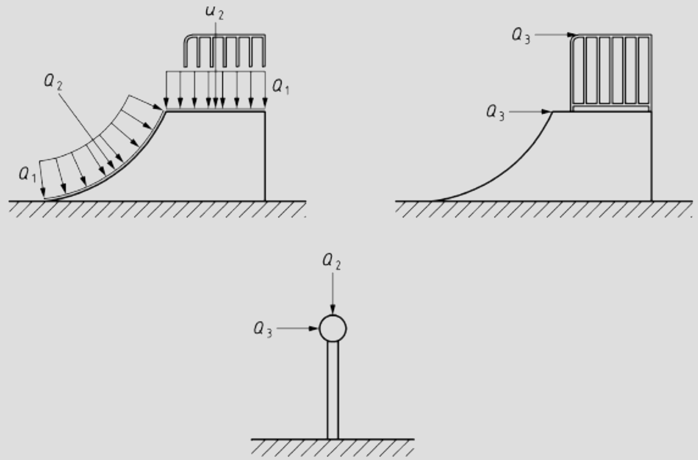
Req X Additionally, the skate elements and rolling surfaces shall withstand a point load Q2 of 7,0 kN, distributed over an area 50 mm × 50 mm at any point.

Req X Drain covers shall be able to be rolled over. Holes in the drain cover shall not exceed 8 mm × 8 mm in size.

Req X The rolling surface shall be even, smooth and closed. Mounting parts shall not project into it. Specific attention shall be given to the transition from the skate element to the flat, especially to asphalt surfaces. Any possible irregularities in height, e.g. stones, holes, or due to misalignment of edges or joints, shall not exceed 3 mm. 6.1.4 and 6.2.3 are an exception to this. Where the rolling surface consists of multiple layers of various materials, the layers shall not become detached from each other. The width of open joints shall not exceed 5 mm. A rolling surface can be cut off by a gap from another non-loose material. The requirements of the rolling surface do not apply here.

Req X For safety when using with harder type wheels, like a skateboard its necessary to apply a coating. In my interview with The Pump Factorypumptrack they say the grain on the pumptrack.eu is to course and the anti-slip betonplex .





Key

Q_1 distributed load
Q_2 point load
Q_3 line load

20 **Safety calculations**

16.1 Parameters used in Deflection & compressive strength calculations

Among the evaluated sandwich materials, Balsa wood core panels exhibited the highest safety margins, outperforming PET and SAN foam cores in compressive strength. While flexural and compressive stress values remained within acceptable limits for all three materials, SAN-core panels exceeded their flexural limit under extreme point loads.

Both sandwich materials and solid glass fibre-reinforced polymer (GFRP) components can differ in thickness, density and material. This needs to be considered when doing safety calculations for another type of blade.

Young's modulus:
The material synthesizer in GRANTA gave a value for young's modulus of E= 20,7 Gpa E-glass/epoxy skins. When looking at the GRANTA synthesizer table (Figure X). The E-grade glass fibre epoxy matrix for the skins gives a Young's modulus of 17,9 - 20,9 Gpa.
This E-modulus this is in the same order of magnitude as the values used in a 'Thesis on mechanical properties' used as a reference (Weijermars, 2016) (Figure X) and the thesis report on 'material test of wind turbine blade' (Somsen et al., 2024), see Figure X . The skin layers 15.28 - 22.9 Gpa.
For deflection calculations use the average values for the Face sheet material since this is the best approximation for the calculation according to (Goodno, 2020).
Resulting in an average (Weijermars , 2016, 20,7GPa) + (GRANTA, average of 19,4GPa) + (somsen etal, 2024, 19,09 GPa) gives 19,73 GPa.
For the formulas of the stress and deflection calculations are retrieved from the book on Mechanics of materials (Goodno, 2020) Chapter 6. The material strength.
The compressive strength of the sandwich material is between 138 and 204 MPa (van Rossum et al., 2024) obtained from GRANTA database.

Bending Test reference:

Figure 3 shows the results for a cyclic test on an AG sample. The cycles can roughly be divided into two parts: the first part, where the maximum stress takes values up to 80 MPa, and the second part where the stresses are significantly lower. The transition between these two parts is the failure by compression of the upper layer, in this case the thin one. Once the upper layer of GFRP is compressed, the wood below it is also gravely compressed- see Figure 3. This leads to failure of the material. ***This means that the predominant failure mechanism is compression, since this occurs before breaking of the fibres on the bottom due to tension.*** (Somsen et al., 2024)

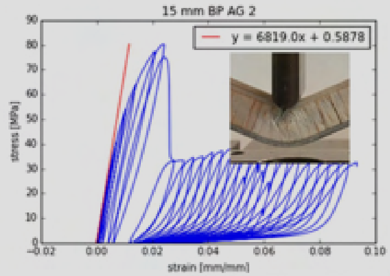


Fig. 3: Stress-strain curve of 15 mm BP AG 2, cyclic load, thin side up, and failed sample

Penetration test reference:

The specimens are cut into pieces of 150 mm x 100 mm with a thickness of 30.2 mm as shown in Figure 0.10. The specimens are subjected to an impact force of 3.4 m/s with a weight of 5.895 kg, from a height of 60 cm, resulting in 34.7J impact energy.

Figure 0.10: Impact-affected zones of the SAN foam (a), PET foam (b) and Balsa (c) cored specimens.

A BMX weighs around 15kg on average (Krivec, 2024) so its equal to 1/3th of the BMX weight falling from 0,6m with all the mass above with point of impact. I assume that in a scenario where the pack drops on the surface it would probably damage the surface but not brake it since the force of impact is almost never in one direction and will be absorbed also absorb by sliding and friction.

16.2 Three point bending values calculations

I retrieved the following values from the thesis on Mechanics of sandwich materials by (Weijermars, 2016) this values are results from a 3 point bending test according to the test standard ASTM C393/C393M for sandwich panels. I took the averages force of failure for each material.

Values:

- L = 150 mm;

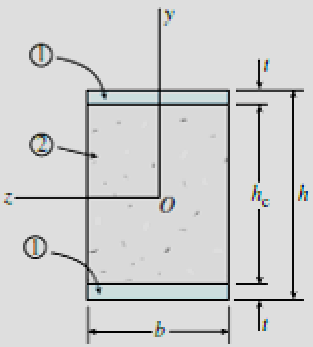
Step-by-Step Recalculation:

1. Moment of Inertia (I_{total}):

$$I_{\text{total}} = \frac{b}{12} \cdot (h^3 - h_c^3)$$

Where:

- $h = 30.2\,\text{mm} = 0.0302\,\text{m}$



$10^{-5} = 1.11 \times 10^{-5}\,\text{m}^3$

$\times 10^{-8}\,\text{m}^4$

- b = 75mm width
- h = 30.2mm
- hc = 25.4mm
- PET Core: Ffailure, PET=4735 N
- SAN Core: Ffailure, SAN=2524
- Balsa Core: Ffailure, Balsa=10813 N

According to the Approximate theory of bending sandwich materials and the

How These Compare in Sandwich Panels:

Stress Type	Relevance	Material Property to Compare Against
Flexural Stress	Bending stress (tension/compression in faces). Critical in 3-point bending tests.	Flexural strength
Tensile Stress	Stress in the tension face under bending.	Tensile strength
Compressive Stress	Stress in the compression face under bending.	Compressive strength
Shear Stress	Shear in the core, usually caused by transverse loads in 3-point bending tests.	Shear strength
Normal Stress	Combination of tensile and compressive stresses in bending.	Compare with tensile and compressive limits.

standard formula's for moment of inertia and flexural strength and Max Bending moment retrieved from the book by

3. Flexural Stress (σ_{flex}):

$$\sigma_{\text{flex}} = \frac{M_{\max} \cdot c}{I_{\text{total}}}$$

For each core:

- PET Core: $\sigma_{\text{flex, PET}} = \frac{177.56 \cdot 0.0151}{6.94 \times 10^{-8}} = 38.62\,\text{MPa}$
- SAN Core: $\sigma_{\text{flex, SAN}} = \frac{94.65 \cdot 0.0151}{6.94 \times 10^{-8}} = 20.60\,\text{MPa}$
- Balsa Core: $\sigma_{\text{flex, Balsa}} = \frac{405.49 \cdot 0.0151}{6.94 \times 10^{-8}} = 88.10\,\text{MPa}$

(Goodno, 2020).

4. Compressive Stress at the Top (σ_{top}):

2. Maximum Bending Moment ($M_{\max}$):

$$M_{\max} = \frac{F_{\text{failure}} \cdot L}{4}$$

For each core:

- PET Core: $M_{\text{max, PET}} = \frac{4735 \cdot 0.15}{4} = 177.56\,\text{Nm}$
- SAN Core: $M_{\text{max, SAN}} = \frac{2524 \cdot 0.15}{4} = 94.65\,\text{Nm}$
- Balsa Core: $M_{\text{max, Balsa}} = \frac{10813 \cdot 0.15}{4} = 405.49\,\text{Nm}$

3. Flexural Stress (σ_{flex}):

$$\sigma_{\text{flex}} = \frac{M_{\max} \cdot c}{I_{\text{total}}}$$

For each core:

- PET Core: $\sigma_{\text{flex, PET}} = \frac{177.56 \cdot 0.0151}{6.94 \times 10^{-8}} = 38.62\,\text{MPa}$
- SAN Core: $\sigma_{\text{flex, SAN}} = \frac{94.65 \cdot 0.0151}{6.94 \times 10^{-8}} = 20.60\,\text{MPa}$
- Balsa Core: $\sigma_{\text{flex, Balsa}} = \frac{405.49 \cdot 0.0151}{6.94 \times 10^{-8}} = 88.10\,\text{MPa}$

16.3 Flexural stress calculations Q1

Step 1: Total load per unit

The total load per unit length of the panel is:

*w = q x b =3500N/ m²x 1.25 =**4375 N***

Step 2: Maximum bending moment (M_{max})

For a simply supported panel under a uniform load, the maximum bending moment is:

$$M_{\max} = \frac{wL^2}{8}$$

$$M_{\max} = \frac{4375 \cdot 1.5^2}{8}$$

$$M_{\max} = \frac{4375 \cdot 2.25}{8} = 1232.81\,\text{Nm}$$

Step 3: Moment of inertia (I)

$$I_{\text{total}} = \frac{b}{12} \cdot (h^3 - h_c^3)$$

$$h^3 = 0.0302^3 = 0.000027564, \quad h_c^3 = 0.0254^3 = 0.000016382$$

$$h^3 - h_c^3 = 0.000027564 - 0.000016382 = 0.000011182$$

$$I_{\text{total}} = \frac{1.25}{12} \cdot 0.000011182$$

$$I_{\text{total}} = 0.000001165\,\text{m}^4$$

Step 4: Flexural stress (σ)

$$\sigma = \frac{M_{\max} \cdot c}{I_{\text{total}}}$$

$$\sigma = \frac{1232.81 \cdot 0.0151}{0.000001165}$$

$$\sigma = \frac{18.623431}{0.000001165} = 15,993,448\,\text{Pa} = 15.99\,\text{MPa}$$

Reference to people

Cording to the NEN norm the track should withstand a distributed load of 3,5kN/m² which for the largest panel is:

F = 1,5 [m] x 1,25 [m] * 3,5 [kN/m] =6,56kN

This is equal to approx. 656 kg and approximately 8 persons of 85 kg.

According to the calculations the least strong material with a SAN-core will fail at 20.6 MPa

When reversing the calculation and calculate the max distributed load for this flexural strength with the largest panel of 1,25x1,5m it results in a load of 5,641 N/m so for a 1,25 m wide panel 7051N which is 705 kg of weight equals, 8,3 people (85kg)

16.4 Deflection calculations

Since it is a relatively small panel we approach this case as a sandwich beam. Using the formula of a simply supported beam to calculate the deflection on the long side x and the short side y.

Using the formulas for moment of inertia:

For I_x (Deflection Along Long Side)

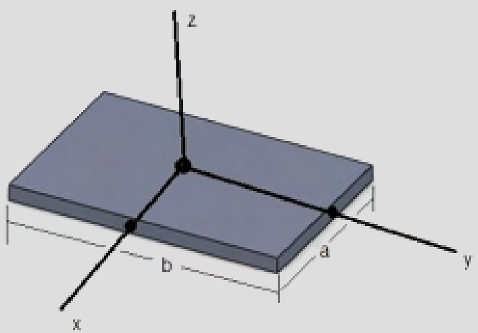
$$I_x = \frac{b}{12}(h_{core}^2 - h^3)$$

- Here, b **refers to the panel width (1.25 m)**, as the deflection is considered along the long span L.

For I_y (Deflection Along Short Side)

$$I_y = \frac{L}{12}(h_{core}^2 - h^3)$$

- Here, L **replaces** b, because we swap the length and width to calculate deflection along the short span.



Us the following formulas:

For distributed load Q_1:

$$\delta_{\max} = \frac{5Q_1L^4}{384EI}$$

- Once for I_x (deflection along the **long** side)
- Once for I_y (deflection along the **short** side)

For point load Q_2:

$$\delta_{\max} = \frac{Q_2L^3}{48EI}$$

Example 1: Deflection for Distributed Load (Q_1) in I_x

Formula:

$$\delta_{\max} = \frac{5Q_1L^4}{384EI_x}$$

Given Values:

- $Q_1 = 3500$ N/m
- $L = 1.5$ m
- $E = 19.73 \times 10^9$ Pa
- $I_x = -1.162 \times 10^{-6}$ m^4

Step-by-Step Calculation:

$$\delta_{\max} = \frac{5 \times (3500) \times (1.5)^4}{384 \times (19.73 \times 10^9) \times (-1.162 \times 10^{-6})}$$

$$= \frac{5 \times 3500 \times 5.0625}{384 \times 19.73 \times 10^9 \times -1.162 \times 10^{-6}}$$

$$= \frac{88593.75}{-8.806 \times 10^3}$$

$$\delta_{\max} = -10 \text{ mm}$$

Example 2: Deflection for Point Load (Q_2) in I_y

Formula:

$$\delta_{\max} = \frac{Q_2L^3}{48EI_y}$$

Given Values:

- $Q_2 = 7500$ N
- $L = 1.25$ m (since it's I_y)
- $E = 19.73 \times 10^9$ Pa
- $I_y = -1.395 \times 10^{-6}$ m^4

Step-by-Step Calculation:

$$\delta_{\max} = \frac{(7500) \times (1.25)^3}{48 \times (19.73 \times 10^9) \times (-1.395 \times 10^{-6})}$$

$$= \frac{7500 \times 1.953}{48 \times 19.73 \times 10^9 \times -1.395 \times 10^{-6}}$$

$$= \frac{14647.5}{-13.19 \times 10^2}$$

$$\delta_{\max} = -11 \text{ mm}$$

Rounded Deflection Calculations

	Calculation	Value (mm)
1	Deflection (Q1, I_x)	-10.0
2	Deflection (Q1, I_y)	-4.0
3	Deflection (Q2, I_x)	-23.0
4	Deflection (Q2, I_y)	-11.0

16.6 Shear force calculations M10 & M12

For **M10 Bolt**:

$$F_v = \frac{\alpha_v \cdot F_{ub} \cdot A}{\gamma_{M2}}$$

$$F_v = \frac{0.6 \cdot 500 \cdot 58}{1.25}$$

1. $0.6 \cdot 500 = 300,$
2. $300 \cdot 58 = 17,400\,\mathrm{N},$
3. $F_v = \frac{17,400}{1.25} = 13,920\,\mathrm{N} = 13.92\,\mathrm{kN}.$

For **M12 Bolt**:

$$F_v = \frac{\alpha_v \cdot F_{ub} \cdot A}{\gamma_{M2}}$$

$$F_v = \frac{0.6 \cdot 500 \cdot 84.3}{1.25}$$

1. $0.6 \cdot 500 = 300,$
2. $300 \cdot 84.3 = 25,290\,\mathrm{N},$
3. $F_v = \frac{25,290}{1.25} = 20,232\,\mathrm{N} = 20.23\,\mathrm{kN}.$

21 Inserts & Support connection

Attachment to the sandwich material

For the attachment to the sandwich material and to the epoxy parts of the sandwich material inserts are a good solution when bolting through the material is not possible.
Depending on the force requirements and material thickness inserts can be used.

Since the core material is soft, the core drilling should be done with a smaller bits then when drilling in the glass fibre and epoxy parts or the glue parts. See table for the tolerances used in this project.
It's advisable to use inserts with a hex driver slot since those can be screwed in with more force and tent to break less fast then the slotted inserts, see Figure Insert types.

Core material	Insert outer diameter [mm]	Insert thread dimension	Drill bit size [mm]
Sandwich panel (Balsa core)	15	M8	13,5
	12	M6	10,5 mm
Glass fibre composite	15	M8	14
	12	M6	11

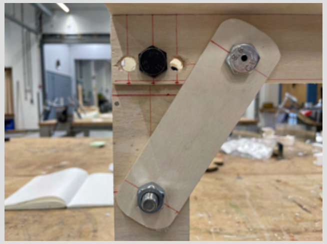
Figure: table tolerances

Figure: insert types slotted & Hex key

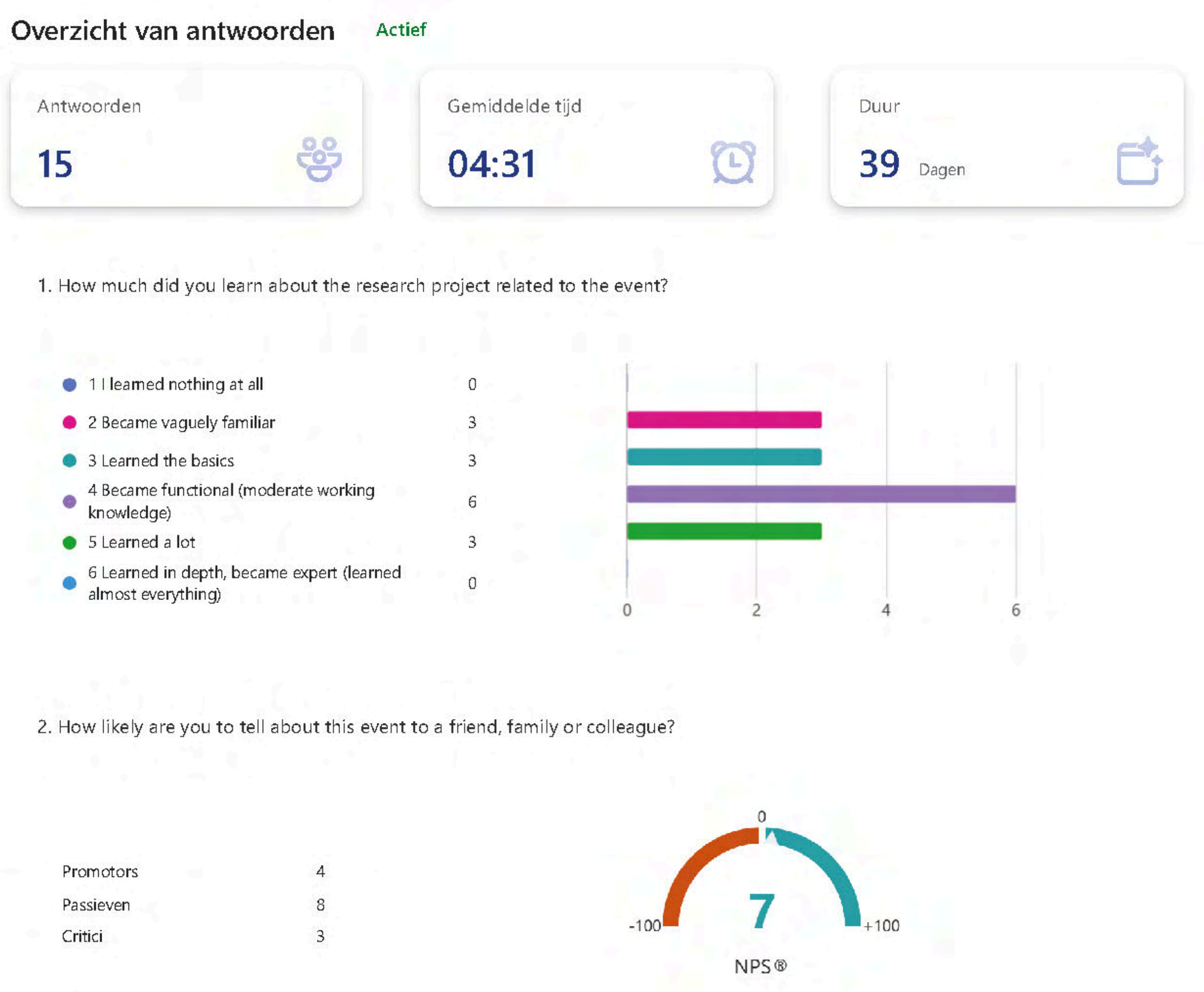
Bottom connection

For the bottom connection there is a need of a mechanism that folds flat but can also be adjusted easily to the required height. Similar mechanisms are used in the folding beds and roofing

Iterations support adjustability



22 Survey Results



3. Share with us your highlight(s) of the event.

15
Antwoorden

Meest recente antwoorden

"For me the highlight was seeing how many people turned out and were willi... "

"Was super fun to be on the bikes"

"Learning new skill, nice to do something during break, adrenaline feels gooo... "

...

5 respondenten (36%) antwoordden fun op deze vraag. Bijwerken

4. What do you think of the idea of repurposing windturbine blades?

15
Antwoorden

Meest recente antwoorden

"I think it is extremely necessary and a good way to still make use of the mat... "

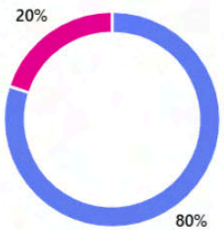
"It's necessary to deal with the waste stream"

"I really like the fact that you found a solution for a part of the windturbine. I ... "

...

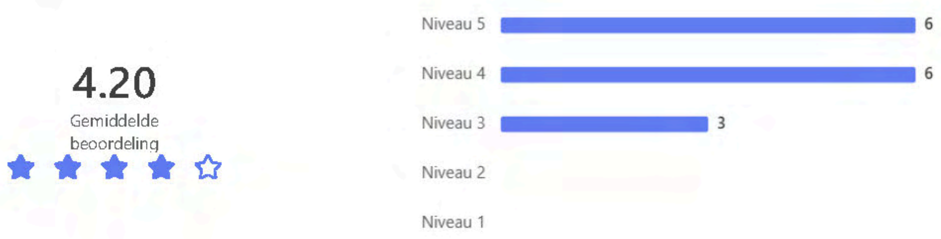
5. Did you ride the pumptrack?

Yes with BMX	12
Yes (skateboard)	3
No	0



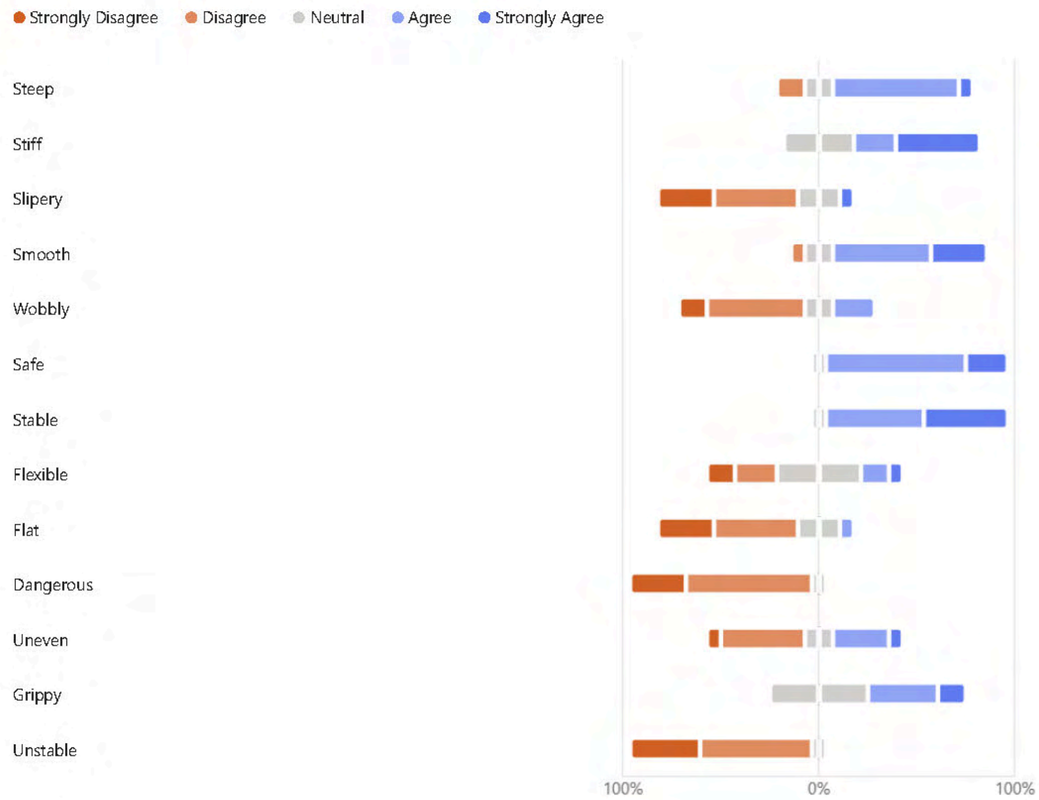
6. Did you already have experience riding a pumptrack?

7. How did you like the overall experience of riding a pumptrack?



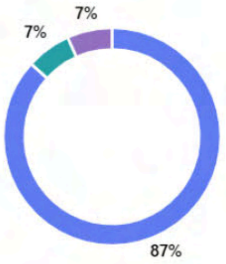
8. The following questions are about the experience of the track, which side of the track did you ride?

9. Regarding the last 'roller' or bump did you percieve it to be:



10. Did you know the last roller or bump in the track is made from a windturbine blade?

Yes	13
No	0
I just found out now!	1
Andere	1



23 Graduation 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	Pupping 7467	IDE master(s)	IPD ✓ DfI SPD
Initials	J.K.R.	2nd non-IDE master	
Given name	Jesse	Individual programme *(date of approval)*	
Student number	4875877	Medisign	
		HPM	

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

Chair	Jelle Joustra	dept./section	
mentor	Caroline Kroon	dept./section	
2nd mentor			
client:			
city:	Delft	country:	Netherlands
optional comments			

! 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)

Jelle Joustra — Digitally signed by Jelle Joustra Date: 2024.09.19 17:35:57 +02'00'

Name Jelle Joustra Date 19 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)

Robin den Braber — Digitaal ondertekend door Robin den Braber Datum: 2024.11.15 09:36:44 +01'00'

Name Robin den Braber Date 15 nov 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: 2024.11.20 09:50:03 +01'00'

Name Monique von Morgen Date 20 Nov 2024 Signature

Personal Project Brief – IDE Master Graduation Project

Name student Jesse Pupping **Student number** 4,875,877

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Repurposing windblades for the use of a modular pumptrack

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)

The rapid expansion of wind energy is leading to an increasing number of discarded wind turbine blades, an estimated 350 tons becoming available in europe by 2030 (onshore only) (Spini & Bettini, 2024). These blades, primarily made of composite materials, are often replaced due to decreased economic value as newer, more efficient models emerge. Currently, these discarded blades are destined for incineration or landfills, contributing to large-scale waste, particularly in regions like the USA.

This project is situated within the context of the circular economy, where the aim is to extend the lifecycle of products and materials. By applying the principles of the butterfly diagram, the focus is on prolonging the use of windmill blades, reusing or redistributing them, and ultimately recycling them. The primary stakeholders include wind energy companies, composite material manufacturers, and sustainability advocates, all of whom have a vested interest in reducing material waste and optimizing the value of composite materials.

The opportunity lies in finding structural reuse applications for these blades to prevent the loss of high-quality material. Building on a previous thesis from 2024, this project will explore the feasibility of repurposing wind turbine blades into modular pumptracks. The goal is to demonstrate the material's potential in new industries, focusing on a full-scale prototype to validate the concept's desirability, feasibility, and viability.

→ *space available for images / figures on next page*

introduction (continued): space for images

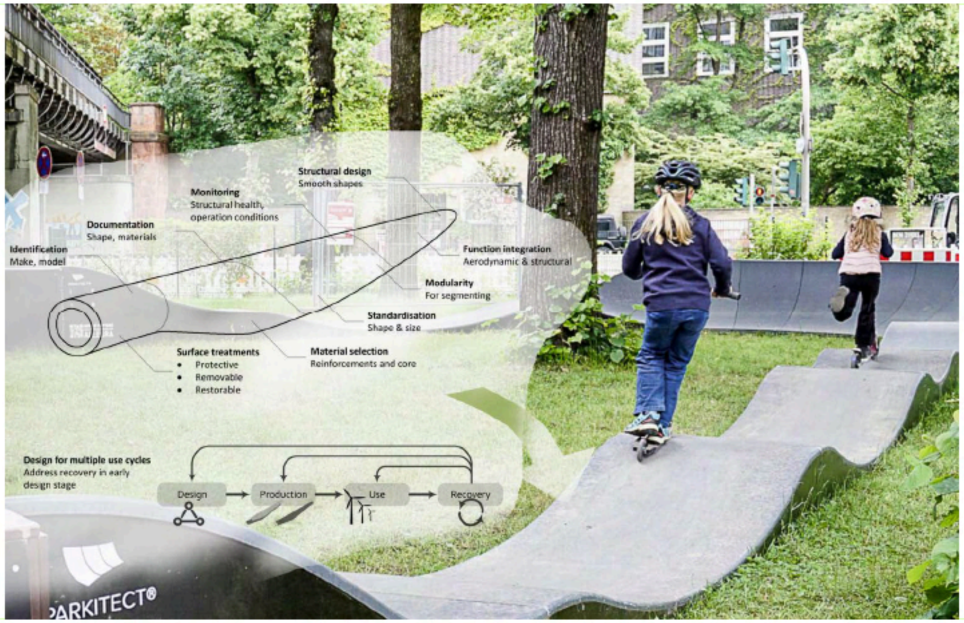


image / figure 1 Infographic "Design insights enabling structural reuse" & "pumptrack context" (Joustra, 2021)

image / figure 2 Example of products made out of windturbine blades

DESIGN FOR our future

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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)

While many research efforts and conceptual ideas have explored the repurposing of discarded wind turbine blades, see figure 1. Little practical examples succeeded to keep the material's integrity and properties to demonstrate its full potential. Though a notable exceptions are: Studio Superuse, Designboom and bladebridge which created different products, see figure 2. However, no other stakeholders in the industry have managed to launch a scalable or market-ready product using these materials.

The challenge lies in finding a product purpose that retains the strength, stiffness and durability while also providing a viable, scalable solution. The complex form of the blades and the stiff composite material makes this a challenge to reshape and cut. Many current ideas fail to maintain the high-performance properties of the composite material, leading to a loss of value when the blades are repurposed.

With my expertise, I aim to contribute to solving this problem by developing a demonstrative product that makes full use of the structural properties of discarded wind blades. This project will explore the potential of creating a modular pumptrack, demonstrating how this material can be reused in new ways. By showcasing the material's potential, I hope to encourage industries to recognize its val

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:

Design and a prototype to validate the process of repurposing windturbine blades for research and demostrative purposes in the context of modular outdoor pumptracks.

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)

To carry out the graduation project, I will use a combination of research and design methods to generate a practical solution. Field research and interviews with industry stakeholders will help gather insights and identify key challenges. I will focus on embodiement design to explore and prototype with composite materials from discarded wind blades to ensure their optimal use. Granta software will be used for material validation, assessing properties and sustainability. Surface modeling will help create digital prototypes, while physical prototyping and 3D printing will validate the design's functionality. A fast-track Life Cycle Assessment (LCA) will evaluate environmental impact. Co-creation sessions with industry partners will refine the design and encourage collaboration.

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	19 sept 2024
Mid-term evaluation	12 nov 2024
Green light meeting	21 jan 2025
Graduation ceremony	20 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	
Number of project days per week	

Comments:

Motivation and personal ambitions

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

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

Motivation and Ambition

My ambition for this project is to address sustainability challenges by repurposing discarded wind turbine blades. I aim to demonstrate the potential of this material in innovative ways while contributing to the circular economy. Through this project, I hope to make an impact in the field by developing a full-scale prototype, creating a unique analog prototyping method, and gaining publicity to inspire industries to explore new uses for composite materials.

Competencies and Learning Objectives

This project will allow me to develop key competencies and skills. I want to improve my project planning abilities, specifically using Excel for detailed tracking and management. By using reflective writing during my process through weekly diary entries, I aim to strengthen my self-awareness and adaptability. I also want to enhance my design capabilities through pump track design, surface modeling, and building a high-end prototype. Expanding my skills in digital visualization, rendering, and presenting will ensure I can communicate my ideas effectively. Additionally, I will develop expertise in fast-track Life Cycle Assessment (LCA) and Material-Driven Design, ensuring sustainability remains central to my work. Throughout the project, I aim to maintain a balanced workload while enjoying the creative process.


Pumptrack
Testevent
test ride a pumptrack
made from windturbine
blades
23 JAN
12:45 - 16:00
@ IDE SQUARE


Teaching Lab

thanks for reading
don’t hesitate to reach out to me for questions

Jesse Pupping

MSc Graduate - Integrated Product Design
Delft, March 2025