Assembly and Connection System for Structural Reuse of Wind Turbine Blades

By Robbert Kik 4668294

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

Chair:
Dr. Song, Y
Delft University of Technology
Department of Sustainable Design Engineering

Mentor:
Dr. Ir. Joustra, J. J.
Delft University of Technology
Department of Sustainable Design Engineering

Abstract:
This project addresses the growing environmental concern surrounding wind turbine blade waste by proposing an innovative solution for structural reuse. The primary focus is developing an adaptable assembly and connection system that effectively integrates retrieved segments into new structures. The approach involves segmentation and circular design principles, aiming to preserve the value and functionality of decommissioned wind turbine blades. This report provides a comprehensive overview of the problem context, research findings, and the ongoing development and design of the assembly and connection system. The report concludes with a design proposition for a scalable geodesic dome.

Acknowledgements

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Introduction

The construction and energy sectors are two major contributors to climate change, resource depletion and waste generation. The construction sector needs large volumes of raw materials. On the other hand, while wind energy is renewable, wind turbine blades are made of high-grade yet hard to recycle, composite materials (Joustra, 2023).

In 2020, 4.000 wind turbines in Europe were 15 years or older, representing 36 Gigawatt (GW) of energy capacity. Most of the ageing wind turbines are stationed in Germany, followed by Spain, France and Italy. Out of the 36 GW, 9 are 20-24 years old and around 1 GW are 25 years or older (Tang, 2020). Since the average lifespan of a wind turbine is 20 to 25 years, the Global Wind Energy Council predicts that for future global wind power installations a total of 16.8 million tonnes of Fibre-reinforced plastic materials will need to be disposed of or recycled by 2030 and 39.8 million tonnes by 2050. (Bank et al., 2018)

Wind turbine blades are made from a high-end composite, consisting of thermosetting resin matrix composite materials reinforced by glass fibre (GF), carbon fibre (CF) or glass/CFs hybrid, which have wide applications. However, the composites are difficult to recycle because of cross-linked thermoset polymers for their matrices, which cannot be re-melted or remoulded. This is based on their inherent nature of heterogeneity for the thermoset-based polymer composites. (Chen et al., 2019)

Since the current recycling capacity is insufficient, decommissioning leads to a lot of value and energy loss (Joustra et al., 2021). Waste managing companies used to landfill the wind turbine blades. However, this leads to the loss of all the energy and value put into the blades. While the composite waste volume will increase strongly in coming decades, landfilling the waste will soon be banned (Designing wind turbine blades that can be recycled | TNO, z.d.)

Structural reuse, also referred to as structural recycling, is an attractive alternative solution. Through segmentation, different high-accuracy construction elements can be cut from the wind turbine blade, making the blade suitable for repurposing. The advantages of repurposing are that it reuses the structure and the quality of the composite materials without requiring significant reprocessing. It extends considerably the life of the composite material and thereby reduces the environmental impact throughout the product lifecycle. (Beauson et al., 2022)

In this way, structural reuse could provide solutions for the end-of-life of wind turbine blades within the energy sector and avoid using raw resources within the construction sector (Joustra et al., 2022).

1. Problem context

1.1 Renewable Energy industry

Energy demand is increasing. Social and economic development to improve human health and welfare require more and more energy. Also, basic human needs like lighting, cooking, comfort, mobility and communication have become inseparable from energy consumption. (Edenhofer et al., 2012) While the world energy production was 17,450 Terrawatt hour in 2004, the world energy consumption is estimated to be 31,657 TWh in 2030. (International Energy Agency. & Organisation for Economic Co-operation and Development., 2003)

Nowadays, the term “climate change” is of great concern to scientists, politicians and the world as a whole. Although the earth’s climate has continuously through time, the rate of change in the past decades is one of the greatest threats the earth is currently facing. (Owusu & Asumadu-Sarkodie, 2016)

The United Nations Framework Convention on Climate Change (UNFCCC) acclaims the change of climate directly or indirectly to human activity. (Fräss-Ehrfeld, 2009) The emission of CO2 is a large contributor to climate change. (Mitchell, 1989) With coal, oil and gas still being the main source of energy (IEA, 2023), in 2021, a new record of 36.3 Gigaton of CO2 was emitted by humans for energy, with electricity and heat being responsible for the majority. (Energy Agency, 2021)

Society has become more aware of the impacts of CO2-emitting energy sources and renewable energy solutions have become more common. (Ostachowicz et al., 2016) Among solar energy, geothermal power and hydropower, there is wind energy.

The carbon footprint of wind energy, expressed in CO2 intensity, is 20-38 gCO2/kWh for on-shore and 9-13gCO2/kWh for offshore applications. This is smaller than more traditional energy sources such as coal (786-990 gCO2/kWh), natural gas (488 gCO2/kWh), nuclear power (26 gCO2/kWh) and even some renewable sources like geothermal power (15-53 gCO2/kWh) and solar energy (88 gCO2/kWh). (Post, 2011)

Mankind has been taking advantage of wind energy for centuries. Sailing ships, grinding grain or pumping water; the wind has served as a free, clean and infinite energy source. (Gary Johnson Manhattan, 2006) Although the percentage of wind energy is currently 7.33% (Statista, 2023) of all energy produced worldwide, in 2016, the International Energy Agency expected that in 2035 25% of all energy produced would be from wind. (Ostachowicz et al., 2016)

The amount of wind turbines (WT) needs to grow extensively in the coming decades to realise this growth. With the increasing number of new WT, the end-of-life (EOL) of the WT becomes a crucial question. Since WT have a lifespan between 20 and 25 years (J. J. Joustra et al., 2020), between 2026 and 2030, more than 11000 WT are expected to be decommissioned (GWEC, 2022) and this number will only keep growing.

While 94% of the mass of a WT consists of recyclable material, like steel and aluminium from the tower and the nacelle. However, the blade of the wind turbine is made from Polymer composites reinforced with glass fibre. (Woo & Whale, 2022) These composites have cross-linked thermoset polymers for their matrices, which are hard to recycle because they can’t be re-melted or remoulded due to their inherent essence of heterogeneity. (Yang et al., 2012)

Composite recycling is not only a challenge for the wind industry; multiple sectors are facing this challenge. Blade waste is estimated to represent only 10% of the total thermoset composite waste by 2025. The relatively low volumes of composite blade waste compose a challenge to realise a profitable recycling business based only on this waste stream (Schmid et al., 2020)

Although nowadays the share of the total composite waste might be relatively small, an increase in the number of WT will lead to 43 million tonnes of blade waste worldwide by 2050. (P. Liu & Barlow, 2017) Current solutions for the end-of-life of Glass Fibre-Reinforced Polymer (GFRP) include; incineration (with or without energy recovery), landfilling and mechanical grinding. End-of-life options like Pyrolysis and Solvolysis are still being researched. However, in these recovery methods, a lot of energy, value and structural properties of the composite material are partly or entirely lost. Also taking into account environmental complications, WindEurope calls for a European Union-wide ban on landfilling blade material in 2025. (WindEurope, 2020) Therefore, reuse and repurposing of the blade material is proposed. When the methods are placed on the Waste Hierarchy of the US Environmental Protection Agency, it is noticeable that reuse and repurposing are most preferred. (Leahy, 2019)

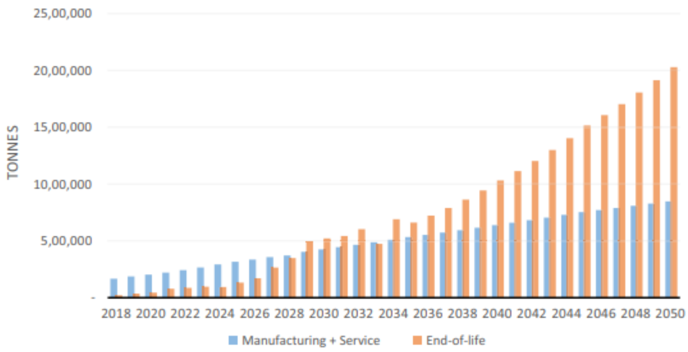


Figure 1 Global wind turbine blade waste projection up to 2050

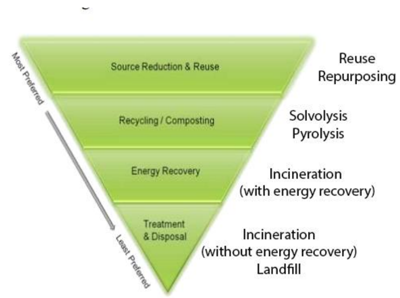


Figure 2 EOL Blade options in the context of Waste Hierarchy

1.2 Structural reuse

Reusing the blade composite material's structural and material properties could provide a more environmentally, socially and economically sustainable solution. (Leahy, 2019) Some examples of reuse applications include but are not limited to; picnic tables, (J. Joustra et al., 2021) bus shelters, (Te Lintelo, 2023) playgrounds, (Blademade, 2008) bridges, (Re-Wind, 2022) housing, (Bank et al., 2018) and even transmission poles. (Alshannaq et al., 2021) All these solutions make use of and benefit from the capacity of the material but are still hard to implement on an industrial scale. Therefore, they are called occasional solutions (Beauson & Brøndsted, 2016).

(Beauson & Brøndsted, 2016) divide how the blade material is used in these projects into two categories: "Large Sections" and "Construction Elements". "Large Sections" of the blade can be used to preserve the good quality and the structural capacity of the blade material. In this way, little re-processing is needed to extend the life of the material. On the other hand, due to the complex structure of the blade, possible applications are limited and mass production is almost impossible.

"Construction Elements" like beams, plates or curved elements can also be cut out of the blades. Cutting "Construction Elements" calls for heavier processing and the form of these elements is also restricted by the structure of the blade. Yet, standardised elements offer the possibility of more applications. Both "Large Sections" and "Construction Elements" need a reliable source of blade material to enable the industrialisation of the recycling solution.

1.3 The TU Delft Structural Reuse by Design-Project

Structural reuse of wind turbine blade material has sparked Mariana Popescu (CGs), Jelle Joustra (IDE) and Adrien Bousseau (Inria) to start the Structural Reuse by Design project. Their goal is to: "form a virtuous loop between the energy and construction sectors by exploring structural reuse of wind turbine blades as "Construction Elements." (Popescu et al., 2023)

The project aims to systematically match the availability of blade material with the intended structural reuse application. To reach this goal it is important to streamline the workflow from design to fabrication and assembly and find the most important parameters that drive the definition of the cutting patterns.

A demonstrator is proposed as a proof of concept of structural reusing the blade material and is aimed to be showcased at the Dutch Design Week in Eindhoven.

Several steps are identified: 1) The development of a preparatory computer-aided segmentation strategy, 2) the design for the demonstrator based on the material's properties and the development of a system for 3) processing and 4) assembly.

The development of the demonstrator will serve the project to explore the workflow, establish design parameters and define reuse scenarios. In addition, the demonstrator will provide a way to showcase the possibilities regarding the structural reuse of blade components in architectural applications.

I focused on the 4) assembly part of the pavilion.

1.4 Problem definition

The design and building of new structures with the use of segmentations of existing parts leads to design challenges. Not only in terms of geometry, structural properties and processing but also regarding assembly.

This Graduation Project will focus on the challenge of connecting retrieved segments into a new assembly. The main goal is to develop an assembly and connection system, which is adaptable, to ensure the system is sufficient for any curvature, thickness and material composition, and allows for dis- and reassembly, to enable transport and reconfiguration, while working together with research of the CEG faculty to evaluate structural properties and form findings.

I will be doing research and evaluating with computer-aided design software on form finding-study, in collaboration with but not dependent on the research of the CEG faculty, regarding the segmentations for the structural reuse of wind turbine blades. I will design and manufacture an assembly and connection system to enable architectural appliances with the segmented panels and evaluate whether it has reached the goals of the problem definition.

My goal is to create a proof-of-concept of the assembly and connection system for the demonstrator of the "reuse by design"-project, in collaboration with the researchers of the EEMCS and CEG faculties. During the design process, I am going to make different digital and physical prototypes of the assembly and connection system. The proof-of-concept should be able to allow for dis- and reassembly, usability for various curvatures, thicknesses and material compositions and sufficient structural use. Also, the proof-of-concept should prove it is viable, feasible and desirable.

1.5 Research questions

The research in this project is constructed to aim answering the following research questions:

Research questions

- What geometries are expected in a Wind Turbine Blade?
- What is the impact of Structural Reuse of Wind Turbine Blades?
- What existing pavilions are there?
- What existing joints are there?
- How can you assemble panels with different thicknesses?
- How can you assemble panels with different curvatures?
- How can you make a joint that allows the design of the demonstrator?
    - How can you make a joint that allows the form of the design of the demonstrator?
    - How can you make a joint that allows the strength needed for the design of the demonstrator?
- How can you make a joint that allows for assembly?
- How can you make a joint that allows for disassembly?
- How can you make a joint that allows for reassembly?

Method

During the 100 days of the Graduation project, I followed the double diamond strategy model. (British Design Council, 2005)

The first diamond is the “problem”-space, which focuses on gathering information and defining the problem definition. The second diamond is the “solution”-space, which focuses on creating ideas and carefully selecting the best solution.

The two diamonds consist of 4 phases. The first phase of the project, the "Discover"-phase, consists of exploring the problem space in further detail. The goal is to get a better understanding and gather more experience regarding the topic of the design project. This is done through deep-diving into the problem through research about the related topics, conversations with experts and stakeholders and accepting different perspectives.

In the second phase, the “Define”-phase, the problem definition will be fully defined and converged into a distinct design project using all the information and experience of the “Discover”-phase.

After, in the "Develop"-phase, diverging development of a design will take place. In this phase, by combining perspectives and cocreation, different solutions for the problem definition are explored through prototypes and iterating.

The finalising of the design is done in the “Deliver"-phase. The project converges to a final design concept that is desirable, viable and feasible through testing and selection methods.

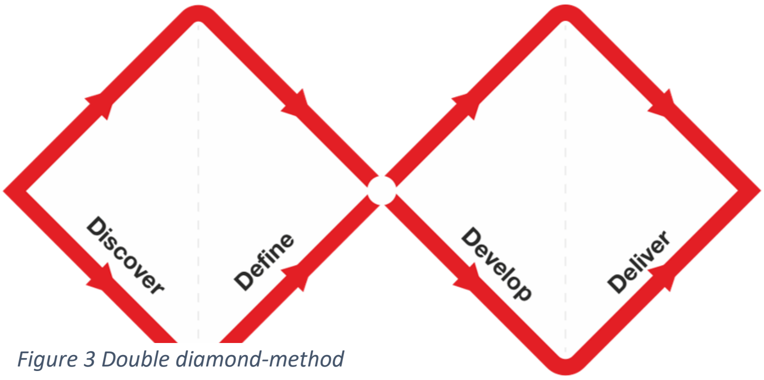


Figure 3 Double diamond-method

To structure the “Discover”-phase, the different levels of “deconstruction” of the Vision in Product – Method are used. (Hekkert & van Dijk, 2014) This method dissects the “past” of a product on three different levels. As the book of Hekkert & van Dijk (2014) says: “the deconstruction phase of ViP is more of a way of thinking about things rather than a strict method.”

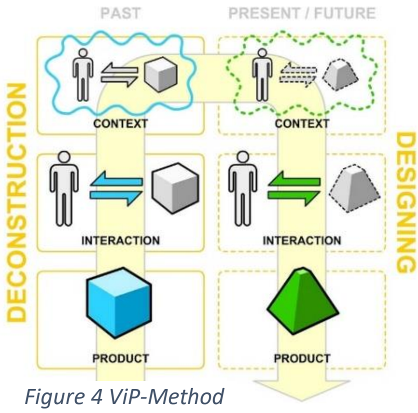


Figure 4 ViP-Method

The first step in deconstruction is the Product-level, in which I looked at all the quantitative and qualitative characteristics of the existing product(s). There are two ways the ViP method provides to value a product; Extrinsically and Intrinsically. Extrinsic values are the technical specifications of the existing products, like: material specification, dimensions or any other physical feature. Intrinsic values are intangible attributes that add value to the product like; sustainability, safety or flexibility.

The second step in deconstruction is the Interaction-level, where I analyse the relationship between the product and society. This analysis is mainly about how people are indirectly affected by the product.

The last step in deconstruction is the Context-level. In this stage, the existing space the new product will take place in was explored. The aim was to find and understand the factors of the original conditions of product, impact and its context.

Going through these steps provides a clear image of the current and past characteristics on Product-, Interaction- and Context-level.

2. Product Level: The Blade

In the Product-level step, I looked at the technical aspects of the existing product; the blade of a wind turbine. To get a more general sense of the source material for this project, thorough research on wind turbine blades was conducted.

2.1 Intrinsic values

2.1.1 The blade design

Wind turbine blades vary in shape and size, from commercial 1m blades up to 100m+. (Electrek, 2022)

For this project, a reference blade was chosen for analysis; the Sandia 61.5m-blade. (Resor, 2013) This reference blade is made for research by Sandia National Laboratories and is based on the offshore 5MW baseline wind turbine blade by the National Renewable Energy Laboratory (NREL) (Jonkman et al., 2009) and on the Dutch Offshore Wind Energy Converter (DOWEC) studies. (Lindenburg, 2003) This blade was chosen because its dimensions and specifications are publicly accessible. Also, this blade is used in many other projects and research. In this way, this project can build upon those existing studies.

The Sandia reference blade is 61.5m long and is modelled after and represents a 5MW turbine, both onshore and offshore. (Resor, 2013) The shape is defined by 7 different aerofoils in 17 different positions. J. Joustra et al., (2021) divide the blade into three main parts: inboard, midspan and outboard. The inboard is defined by 3 circles, the midspan by 5 airfoils from the TU Delft family and the last third of the blade, the outboard, by the NACA 64-series. (Resor, 2013) Airfoils, the cross-section of the blade, are the foundation of any wind turbine blade. They are streamlined geometries which are capable of generating a lot of lift and drag (OOEE&RN, 2023) and their performance determines the outer form of the blade.

Table 4: NuMAD station parameters for the Sandia 61.5m blade.

Blade span (m)	Rotor Radius (m)	Blade Section Shape; NuMAD Airfoil File	TE Type	Twist (deg)	Chord (m)	X-offset* (-)	Aero. Center* (-)
0	1.5	circular	round	13.308	3.386	0.5	0.5
0.3	1.8	circular	round	13.308	3.386	0.5	0.5
0.4	1.9	interp	round	13.308			
0.5	2	interp	round	13.308			
0.6	2.1	interp	round	13.308			
0.7	2.2	interp	round	13.308			
0.8	2.3	interp	round	13.308			
1.3667	**2.8667**	**circular**	**round**	**13.308**	**3.386**	**0.5**	**0.5**
1.5	3	interp	round	13.308			
1.6	3.1	interp	round	13.308			
4.1	**5.6**	**interp**	**round**	**13.308**			
5.5	7	interp	round	13.308			
6.8333	**8.3333**	**interp***	**flat**	**13.308**			
9	10.5	interp	flat	13.308			
10.25	**11.75**	**DU99-W-405**	**flat**	**13.308**	**4.557**	**0.4**	**0.275**
12	13.5	interp	flat				
14.35	**15.85**	**DU99-W-350**	**flat**	**11.48**	**4.652**	**0.4**	**0.275**
17	18.5	interp	flat				
18.45	**19.95**	**interp***	**flat**	**10.162**			
20.5	22	interp	flat				
22.55	**24.05**	**DU97-W-300**	**flat**	**9.011**	**4.249**	**0.4**	**0.275**
24.6	26.1	interp	flat				
26.65	**28.15**	**DU91-W-250**	**flat**	**7.795**	**4.007**	**0.4**	**0.275**
30.75	**32.25**	**DU91-W-250**	**flat**	**6.544**	**3.748**	**0.4**	**0.275**
32	33.5	interp	flat				
34.85	**36.35**	**DU93-W-210**	**flat**	**5.361**	**3.502**	**0.4**	**0.275**
37	38.5	interp	flat				
38.95	**40.45**	**DU93-W-210**	**flat**	**4.188**	**3.256**	**0.4**	**0.275**
41	42.5	interp	sharp				
42	43.5	interp	sharp				
43.05	**44.55**	**NACA-64-618**	**sharp**	**3.125**	**3.01**	**0.4**	**0.275**
45	46.5	interp	sharp				
47.15	**48.65**	**NACA-64-618**	**sharp**	**2.319**	**2.764**	**0.4**	**0.275**
51.25	**52.75**	**NACA-64-618**	**sharp**	**1.526**	**2.518**	**0.4**	**0.275**
54.6667	**56.1667**	**NACA-64-618**	**sharp**	**0.863**	**2.313**	**0.4**	**0.275**
57.4	**58.9**	**NACA-64-618**	**sharp**	**0.37**	**2.086**	**0.4**	**0.275**
60.1333	**61.6333**	**NACA-64-618**	**sharp**	**0.106**	**1.419**	**0.4**	**0.275**
61.5	63	NACA-64-618	sharp	0	1.0855*	0.4	0.275

Table 1 NuMAD station parameters for the Sandia 61.5m blade

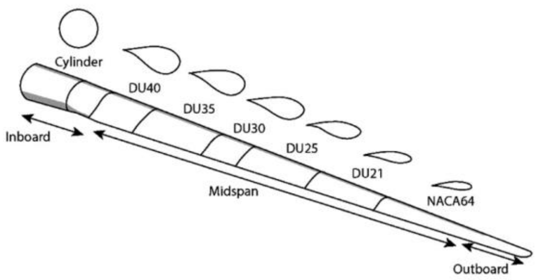


Figure 5 Airfoil through Sandia 61.5 Blade

To know what shape to work with when reusing segmented parts of a wind turbine blade, it is favourable to have a 3D model of the outer shell. This was realised by using the geometry of the TU Delft and NACA airfoils.

While aerodynamic performance determines the outer shape of the blade, structural properties define the inner shape. Accordingly, the wind turbine blade consists of two faces, joined together and stiffened by two integral shear webs linking the upper and lower parts of the blade. Aeroshells, which are made of sandwich structures, are primarily designed against elastic buckling. (Mishnaevsky et al., 2017)

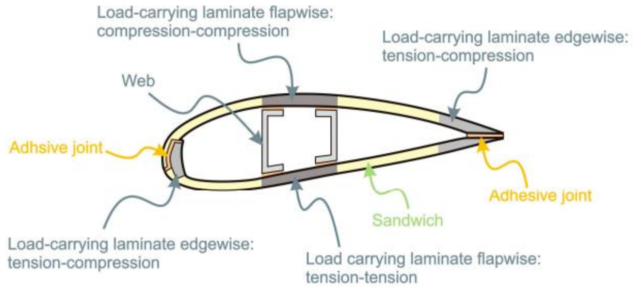


Figure 6 Schema of blade section

The load-carrying laminates at the main spar and at the leading and trailing edges are expected to have the most damage after 25-years of service. Accordingly, rain and other particulates in the air erode the leading edge by impacting at high velocities, especially at the outboard of the blade. (Mishnaevsky et al., 2017) The inboard is a cylinder with a diameter of 4 meters and 100mm thick GFRP and the adhesive bonding is poorly defined and abundantly applied, both raise challenges for recovery of the material. (J. Joustra et al., 2021) Therefore, the non-load-carrying sandwich parts from the midspan without adhesive bonding seem to be the most useful for this project.

The sandwich structure of the SNL61.5 blade is made of triaxial Glass Fibre Reinforced Plastic (GFRP) skins, a foam core, and glass and carbon fibre unidirectional reinforcements. (Resor, 2013) From research of (J. Joustra et al., 2021), segmentations from decommissioned wind turbine blades outperformed other lightweight materials for constructions loaded in bending.

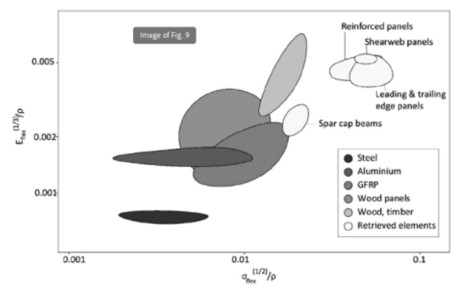


Figure 7 Stiffness vs strength conventional construction materials vs blade material

	Layer Thickness	Ex	Ey	Gxy	prxy	Dens.	UTS	UCS	Reference
	[mm]	[MPa]	[MPa]	[MPa]	[-]	[kg/m3]	[MPa]	[MPa]	
Gelcoat	0.05	3440		1380	0.3	1235	-	-	from SAND2011-3779, Sandia 100-m Blade
E-LT-5500(UD)	0.47	41,800	14,000	2630	0.28	1920	972	702	from SAND2011-3779, Sandia 100-m Blade
SNL(Triax)	0.94	27,700	13,650	7200	0.39	1850	700[iii]	-	from SAND2011-3779, Sandia 100-m Blade
Saertex(DB)	1	13,600	13,300	11,800	0.49	1780	144	213	from SAND2011-3779, Sandia 100-m Blade
FOAM[iv]	1	256	256	22	0.3	200	-	-	from SAND2011-3779, Sandia 100-m Blade
Carbon(UD)[v]	0.47	114,500	8,390	5990	0.27	1220	1546	1047	Inverse CLT starting from MSU Materials Database data: MD-P2B; [±45/(0)4C]S; 55%vf; EP; Newport NB307; carbon prepreg; 85% Uni; 15%DB

Table 2 Material properties

To get more familiar with the shape of the wind turbine blade, I created several Lo-Fi and Hi-Fi prototypes. The first prototype was made by entering the coordinates from the air foils into SolidWorks. Then, the air foils were exported to Illustrator separately and sent as a pdf to a printer and printed onto 100 gram A4-paper. To ensure a more steady mould of the air foils, the cut outs of the air foils were glued onto several layers of cardboard and cut out carefully. These moulds will provide easier rapid sketching of the existing curves in the wind turbine blade.

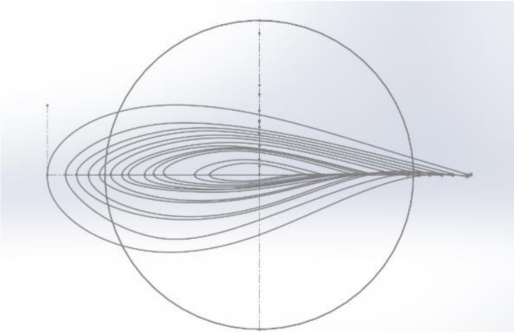


Figure 8 Cardboard molds airfoil

Figure 9 Airfoil curves comparison

To create a full scale 3D model of the wind turbine blade, the documentation from (Resor, 2013) was used. The coordinates from the air foils were added with the offsets and the twists from the NuMad parameters of the Sandia 61.5m blade. After, a loft was created through all the air foils. By drawing verticals on the chord line and connecting the midpoints of the verticals, the chamber line was found. By shelling the loft and dividing the blade over the chamber line, an upper half and lower half shell were created.

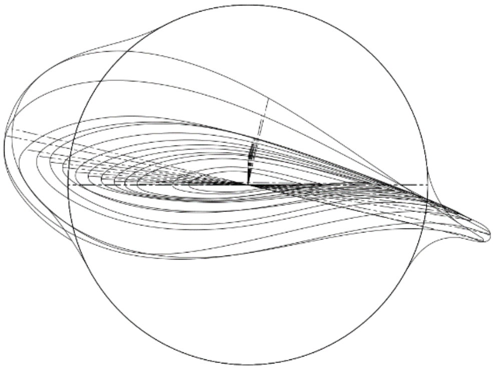


Figure 10 Dissection blade curve

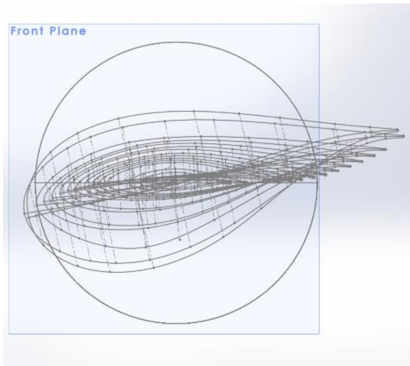


Figure 11 Construction Chamber line

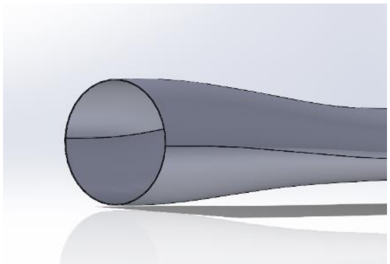


Figure 12 Upper/lower half seperation

Lastly, the upper and lower halves were separated into the intervals between two air foils. In this way, the different curves could be analysed more thorough to get a better understanding of what the forms within the wind turbine blades are. These segmentations were 3D printed to examine the contour hands on.

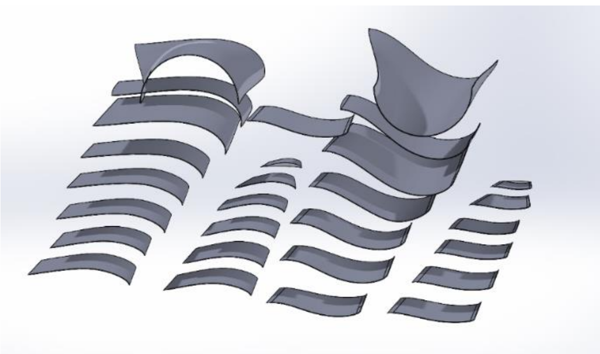


Figure 13 Segmentation upper lower half

Figure 14 Segmentations 3D print

The main lesson I learned from dissecting the blade model is that almost all of the parts are “convex” or “concave” curves. This helps when designing a construction, since these kinds of curves allow to lay them next to each other more easily to create a shell structure, as shown in Figure 16.

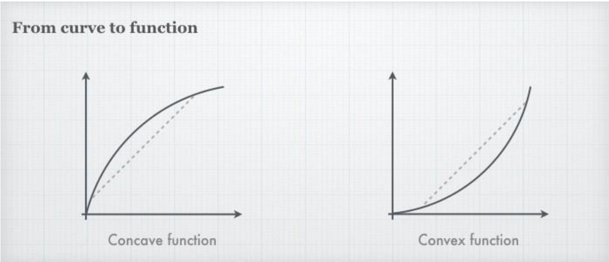


Figure 15 Concave/convex curves

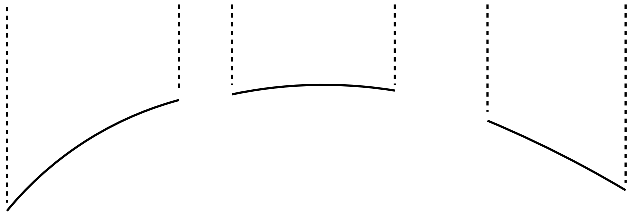


Figure 16 attached convex/concave curves

3. Interaction Level: Impact

3.1 Sustainability Impact

The need to reuse the blade material is established. However, what is the sustainability impact of structural reuse in comparison to current EOL strategies. The current EOL strategies are mainly incineration and landfill. (P. Liu et al., 2019) These two strategies are at the bottom of the Waste Framework Directive. (European Commission, 2008). In the research of (Deeney et al., 2021), they compare the EOL strategies; landfill, incineration, co processing in cement, making furniture or a bridge from the blade material. In his study, eleven qualities were derived from the United Nations Sustainable Development Goals and tested on the 5 different EOL strategies. The qualities are divided into 3 sustainability themes; Economy, Society and Environment. Through a Delphi study (a method to gather the opinion of experts with questionnaires) with 28 participants (Deeney et al., 2021) weigh the different qualities as presented in Fi.

Figure 17 Waste hierarchy

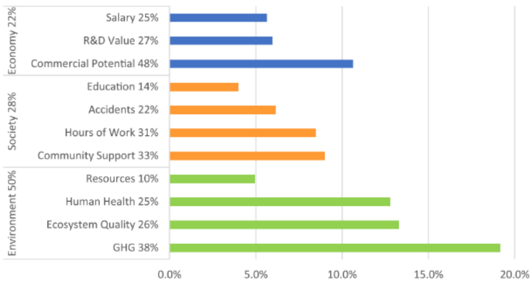


Figure 18 Delphi study

With an Analytic Hierarchy Process (AHP), a structured way to analyse complex decisions based on mathematics the positive impact of the qualities were calculated and for the negative impact the PROMETHEE-method, a preference ranking method, was calculated. The graphs shown in Figure 19 were created accordingly.

In both calculations and all qualities, reuse of the material in furniture making or bridge fabrication is the most or second most desirable. “Furniture making” had the most positive impact in the topics of Economy and Society. However, Environment was weighted more important by the Delphi study and since “Bridge fabrication” scored higher in Environment, (Deeney et al., 2021) concluded that “Bridge fabrication” had the most sustainable impact. “Furniture making” was the runner up.

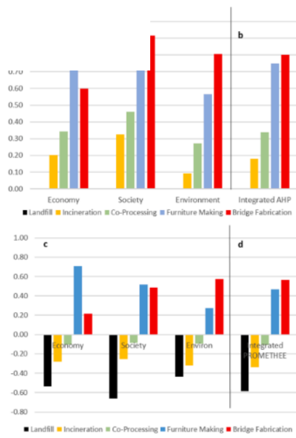


Figure 19 Analytic Hierarchy Process

I thought this was interesting, since it could be argued that creating a pavilion from blade material is a crossover between "Furniture making" and "Bridge fabrication". It has similarities with "Furniture making" since the blade is most likely to be cut down to smaller panels and it has similarities with "Bridge fabrication" since the material is going to have withstand a lot of force and is used structurally.

It has been shown that structurally reusing the material is preferable. The question how much the impact could be was calculated by (Nagle et al., 2022). This research took into account a lot of different variables that may not be relevant to this study (it is a niche study regarding Ireland), but it seems interesting to take a look at how much repurposing the blade material could benefit. A Life Cycle Analysis for three different use scenarios with the same boundaries (Figure 20) was conducted. The LCA includes the transport of the blade, the manufacturing of the substituted components and the emissions during these processes.

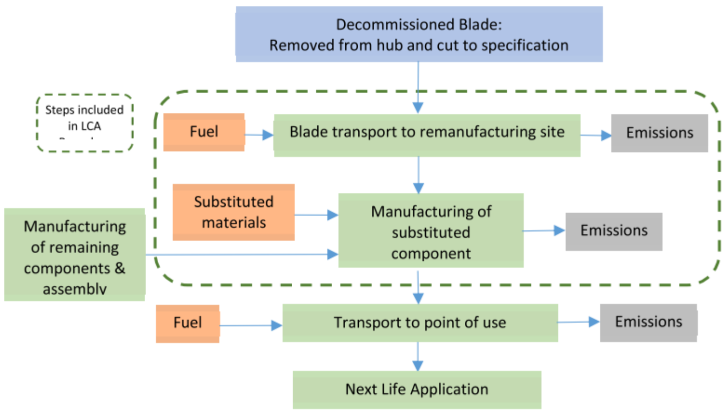


Figure 20 LCA boundaries for all three scenarios

By combining the three different scenarios, an equivalent of kg CO2 was calculated. (Nagle et al., 2022) claimed that on average 342 kg CO2 per ton blade waste could be saved. When repurposing 20% of blade material in Ireland, 135 tonnes of waste could be saved from landfill and 30780 kg CO2 emissions per year. With an equivalent of 3115km per 345 kg CO2 for an average Irish vehicle (SEAI, 2018), 280350 km could be driven for 30780 kg CO2 or 6,99 times around the circumference of the earth or 52,1 times a flight between New York and London. (Government UK DESNZ, 2020)

If these are the numbers regarding repurposing only 20% percent of waste material in Ireland, it can only be imagined what impact structural reuse could have when implemented worldwide.

3.2 Economic Impact

Not only does material reuse have impact on sustainability aspects of the life cycle of a wind turbine blade, it can also highly affect the overall investment costs of manufacturing the blade. A detailed cost model was made of the SNL-100 blade. (Bortolotti et al., 2019) I took this as a reference, since most costs equations mentioned in the paper are linear with the length of the blade.

As can been seen in Figure 21, material is by far the largest cost share of the SNL-100-03 blade. With an Overall cost of 547.723,35 dollars and Material cost being 327.375,64 dollars, Material is 59,77% of Overall cost of the blade. If we calculate this back to a blade of 61.5m long, the Overall cost would be 336.849,86 dollars and the Material cost would be 201.336,02 dollars.

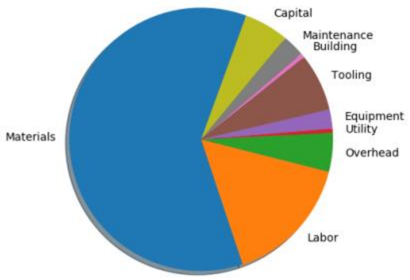


Figure 21 Shares of the overall costs of the SNL-100-03 Blade

Table 27. Total Composite, Core, and Coating Costs of the SNL-100-03 Blade

Composites and filler	Cost with waste [$]	Resin and adhesive	Cost with waste [$]	Other parts	Cost [$]	
Bx GF	7,370.97	Resin	63,027.83	Bolts	2,356.19	
UD CF	79,045.98	Hardener	18,899.57	Barrel nuts	1,130.97	
UD GF	7,214.01	Adhesive Part A	7,830.56	LPS	4,180.00	
Tx GF	45,990.11	Adhesive Part B	1,448.65	Consumables	13,449.65	
Gelcoat	5,924.00					
Balsa	19,770.06					
Foam	49,737.08					**Total**
Total	215,052.21	Total	91,206.61	Total	21,116.81	**327,375.63**

Table 3 Total composite, core and coating costs of the SNL-100-03 blade

When looking at the bill of materials for the SNL-100-03 blade, it can be calculated that the biaxial, uniaxial and triaxial Glass fibres as well as the Balsa wood and the resin (the materials in the parts that we aim to repurpose) are worth 143.372,98 dollars, which is 43.79% of the overall material cost. Taking 336.849,86 dollars as a possible overall cost for the SNL-61.5m blade and the useable material in the blade as worth 26.18% of the entire cost, the useable material for the 61.5m blade is worth 88174,38 dollars. Worth mentioning is that in the SNL-100 blade, Carbon Fibre is used for the spar caps, since this project mainly focusses on Glass fibre, this material is disregarded.

4. Context Level: Exploration

In the last step to diverge within the context of the Structural Reuse By Design (SRBD) project, the different elements of the project were explored. Firstly, in several papers other pavilions and their building techniques were examined. Secondly, the assembly connection systems in these pavilions was examined. Lastly, conversations with experts in different areas regarding elements of the SRBD-project were held. The most interesting findings are summarised in this chapter.

4.1 Pavilions

Pavilions come in all sorts and shapes and are almost a kind of art in itself. Innovative forms are realised through creative architecture, building techniques and assembly methods. (Merriam-Webster, n.d.) describes the definition of pavilion as following:

"3a. A usually open sometimes ornamental structure in a garden, park, or place of recreation that is used for entertainment or shelter.

3b. A temporary structure erected at an exposition by an individual exhibitor."

To get a better understanding of what forms or structures can be expected in creating a pavilion for the SRBD-project, an exploration on existing pavilion was conducted. Countless examples of installations can be found on the World Wide Web. By examining and grouping pictures of pavilions together (Dörfler et al., 2023), I found 2 design principles (*Unity & Variety - Aesthetics*, n.d.) that might be useful for this Graduation Project: *"Unity through repetition"* and "*Unity with varied repetition"*.

Unity through repetition

Repetition is a valuable device to achieve visual unity. By repeating colour, shape, texture, direction or angles, an aesthetic feeling is realised. In the pavilions, this is mostly done in two different ways; repetition as the entire form and repetition of an element. An example of repetition as the entire form is PAVILION in Figure 22, created by the students from the College of Architecture, Kuwait University. In this pavilion, a structure is created by the repetition of the same element and is in this way elongated. An example of repetition of elements is the BUGA Wood Pavilion in Figure 23, by the Institute for Computational Design and Construction of the University of Stuttgart. In this pavilion, different elements are repeated in a certain pattern to create a different shape.

Figure 22 PAVILION

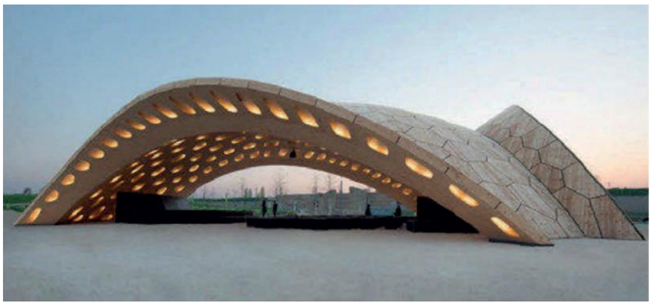


Figure 23 BUGA Wood Pavilion

Unity through varied repetition

Unity can also be achieved by varied repetition. In this design principle, we talk more about a rhythm instead of pure repetition. Colour, shape, texture, direction or angles follow each other up instead being copied. Within this design principle also two types can be distinguished; “Varying-throughout-the-entire-structure” and “varying-between-elements”.

A good example of this “varying-throughout-the-entire-structure”-principle is the pavilion created by (Hafner & Bickel, 2021). It can be noticed that each element is slightly different from the elements next to it, creating a certain rhythm throughout the pavilion.

“Varying-between-elements” can be found in the A(FIN)NE PAVILLION (Figure 25) from the University of Montréal. All the elements vary from form a lot but create a smooth curve all together.

These 4 design principles are interesting to me and will be taken into account in furthering the Graduation Project.

Worth noting is that there are two different ways to create curved surfaces within the pavilions. Curved surfaces can be realised through panels or struts. Since I aim to reuse as much wind turbine materials as possible, my focus lays on curved surfaces through panels.

Figure 24 Hafnet & Bickel

Figure 25 A(FIN)NE PAVILLION

4.2 Joints

After examining different pavilions, an exploration of existing joints was completed. In architecture there are many conventional ways to connect different parts to each other. In the assembly of pavilions, designers and architects can even be more innovative with how they connect parts to each other, since the strength of the construction is more often the second most important quality of a pavilion. The aesthetic qualities come first, which lead to interesting assembly and connection systems. Some interesting joints are summarised in this paragraph.

Interlocking structure

(Dahy, 2019) shows an interesting Biomimetic Pavilion built on the campus of the University of Stuttgart. This assembly system was really interesting to me, not only that it does not require additional materials to assemble the pavilion, but also the assembly strategy was interesting to me. The wood used is very flexible, which makes it possible to interlock all the panels on the ground and lift the entire shell by bending the two end points to each other and locking them on the ground. This assembly strategy is worth taking into further consideration.

Figure 26 Dahy (2019)

Puzzle-like panel

(Li & Knippers, 2015) is an example of puzzle-like joint between the panels. In this dome by the University of Stuttgart, the panels are constructed to fit closely together. This allows for a tight fit and a smooth curve of flat panels. The tightly fitted joints are secured with a screw to ensure for a non-moveable fit. I think it is interesting that in this project the material is almost solely adapted to the function of joining the panels together. This is done in a seemingly aesthetic way, however, the joint is the leading factor of the dome’s elements.

Figure 27 Li & Knippers (2015)

Rope as a connector

(Elmas et al., 2022) uses rope as a connection between different panels. I think this is really interesting to implement in a build, since it is not a common construction material. However, I like the fact that it is completely retrievable after disassembly. After disassembly, you have the material you connected and the rope you had before. In the picture of reuse and sustainability, I think this is an interesting quality. Assembly itself does not require any skill or tools. Also, a rope allows for some flexibility between the panels, which could be beneficial when working with panels of wind turbine blade material that have different thicknesses.

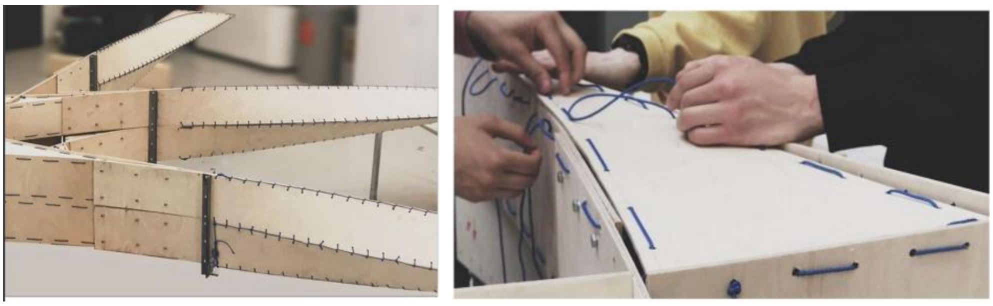


Figure 28 Elmas et al. (2022)

Twisted braided structure

(Nabaei et al., 2015) proposes a braided structure with the material. With wood, an interlacing pattern is made. This not only ensures a stronger frame, but adds a certain aesthetic quality to the pavilion as well. Although the wind turbine blade material is not flexible, like the wood that is used in this concept, I think it is an attractive way of assembly without any additional material. Which is favourable with the material reuse and sustainability aspects in mind.

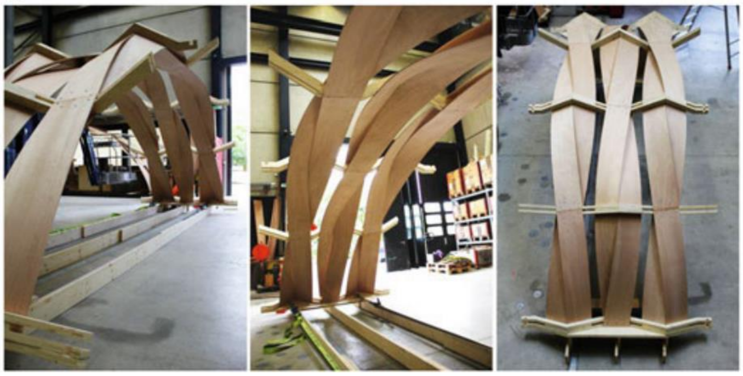


Figure 29 Nadeai et al. (2015)

Bolted structure

Lastly, (Bigas & Gardner, n.d.) propose a somewhat more commonly used connection system. The timber folded plate pavilion from the University of Barcelona is bolted with steel plates between the sides of the panels. The steel plates are pre-bend into certain degrees that make the structure of the shell dome possible with flat plates. I think it is intriguing that in this structure a quite complex structure can be created. Also I think that the steel plates could be retrieved from a different waste stream.

Figure 30 Bigas & Gardner

4.3 Experts

To learn from people who are more experienced on several topics, different meetings were held. Regarding joints, creating with the blade material, and designing architectural appliances experts were contacted to learn from their experiences. Some main take-aways, findings or interesting remarks are mentioned in this chapter.

4.3.1 Mastermate

Mastermate is a technical wholesale company that specialises in mounting materials, hinges, locks and tools. I spoke with Richard, Technical Advisor Construction, and Jaël, Sustainable Development Goals Impact Manager. The combination of construction knowledge and sustainability knowledge resulted in an interesting conversation. The conversations were held in Dutch and are translated to English.

Jaël explains: *"Mastermate is, next to a wholesale company, recycling materials from demolished buildings. After the demolition company has demounted valuable materials, it gets driven to one of the Mastermate facilities, checked, cleaned and added to the inventory system."*

In this way, Mastermate tries to add to a more sustainable and circular economy, which is an essential element of this Graduation Project.

After explaining the aim of my project, I asked what some construction tips and tricks to keep in mind while designing an assembly and connection system for a pavilion.

Richard advised me: *"There is already a lot on the market to join different parts together. Let your self be inspired by what already exists."*

"When joining different parts together you will have to look how to create flat surfaces. To make a sturdy connection, you will always have to look for or to create flat surfaces."

Richard warns me: *"Be aware of air anchors! You will not believe how many architects design things that cannot be assembled in reality."*

Lastly, Richard tells me: *"It is important to know how strong your material is. How close to the edge can you drill in it? Is it flexible or do you need to harden the material in anyway?"*

All these points were really interesting to me and were be taken into consideration during this project.

4.3.2 Blade-Made

Blade-Made is a company that designs concepts with the use of wind turbine blades. They are aiming for sustainability, awareness and innovation regarding the waste that is caused by the wind energy industry. I spoke with Jos,the co-founder of the company and an architect within the company. He specialises in designing with waste materials and created several of the Blade-Made projects.

I asked Jos what the practicalities are of reusing wind turbine blades in the Blade-Made concepts. His tips and tricks could be summarised in 3 main topics; Damage, Safety and Design.

Damage

"One main thing that you need to keep in mind is that you're designing with waste material. After the wind turbine blade has been decommissioned it is deemed waste and treated as such. When the blade arrives at the place where you want to process it for your reuse concept, it has bruises, dents or worse, next to the 20 years of use damage." Jos said.

Safety

I asked Jos how they made sure the processed material in the public concepts was cured to ensure safe spaces. *"The saw cuts were cured with extra epoxy to fix the sharp edges of the cut blade material."*

Design

I asked where Jos got the inspiration for the form finding of the concepts from. Jos explained: *"I start designing when I know exactly what blade I am given to use, including all the damage. After concluding what parts are not useable anymore and which parts are and taking the place where the concept will be placed in consideration, we start actually designing the concept."*

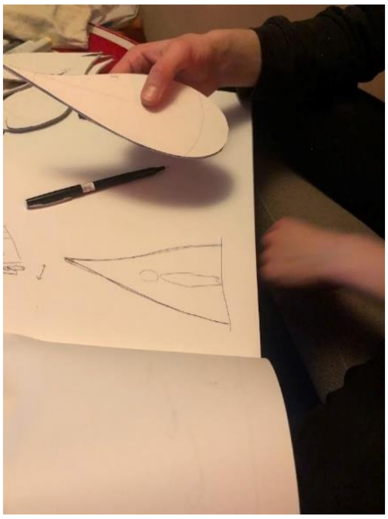
Remarks

Jos pointed me to the following: *"When designing the construction of the dome, be aware that you do not cut down the panels too small. Try to keep them as large as possible. This remains the possibility to cut down the panels even smaller and could provide for an extra End-of-life of the material."*

All these points were really interesting to me and were be taken into consideration during this project.

4.3.3 Co-creation

Since designing a connection and assembly system for a pavilion requires the design of a pavilion, I planned a co-creation session with a MSc Architecture student. The goal of the session was to get a better understanding of the form finding of a pavilion from a person who specialises in Architecture. As a preparation, moulds of the airfoils were made from cardboard, to make rapid sketching possible. These could also be used to create a physical scale model, including a person model on the same scale, to get a better understanding of the proportion of the 61.5 m blade.



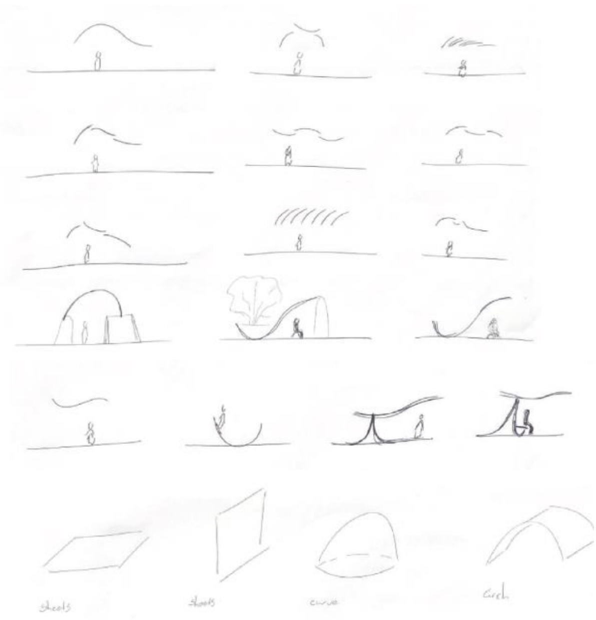


Figure 31 Co-creation session

After some rapid prototyping with the curves from the airfoils, we discussed restrictions and findings from creating 2D pavilions.

Jules: “The largest airfoils are useful because they are larger than a human. Using this part of the blade can create a lot of space. The smaller airfoils can maybe be used as walling or flooring.”

Jules: “It seems like the only way to make a dome-like structure, realistically, is to cut semi-flat panels out of the blade”.

Jules: ”There is an enormous mismatch between the scale of the blade and the scale of a small pavilion. You will not be able to use a lot of material in the pavilion.”

Jules: “I can see multiple generations of the End-of-life of the blade. The first one could be a concert stage, the next one a pavilion, then a bus stop, picnic table, planks and then ground into flakes for concrete or incineration.”

5. Design

5.1 SRBD-Project design

After exploring different fields that could be interesting for creating a pavilion and speaking with experts, I went back to the SRBD team. After experiencing that the pavilion can look like, consist of and be as large or small as anything you want, it is important to discuss with the SRBD team what they have in mind and what they expect to place on the Dutch Design Week campus. I discussed with Jelle Joustra what they deem realistic. Several wants and needs were mentioned.

- The pavilion will be a shell structure of some sort.
- The pavilion should be about 4m x 4m x 2m.
- The panels for the pavilion should fit in a delivery van (2.44m x 1.22m)
- The panels should be able to be carried by 1 to 2 persons.
- The pavilion should be able to be assembled and disassembled.

It is proposed that further exploration can be done regarding three different concepts: a hexagon structure like the one of the TUK's Digital Timber Construction group in FIGUREX, a triangular structure like the shell by ADF Robotics or a shell structure with differentiating panels.

Figure 32 Options ccepts

6. Prototyping

To get a better understanding of how the blade material is workable and how the curve of the blade affects the creation of new shapes with cut-out panels, some hands-on prototyping was done.

6.1 Rope

As discussed in Chapter 4.1, I was inspired by the pavilion of (Dahy, 2019) and (Elmas et al., 2022). The assembly method from Dahy (Figure 33), where the pavilion is constructed on the ground and lifted, struck me as valuable. The rope joint of Elmas (Figure 34) inspired me since it made it possible to retrieve the material for construction and the rope back again after disassembly. To find out if those techniques could be used in combination with wind turbine blade material, experiments were conducted.

Figure 33 Dahy (2019)

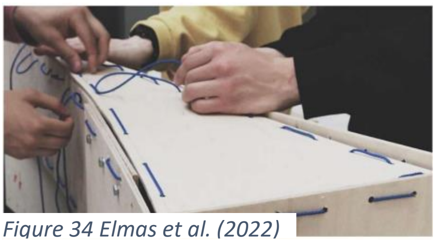


Figure 34 Elmas et al. (2022)

Using a climbing rope, a jigsaw and an electric drill, pieces of blade material were connected. Although the first connection between two panels seemed promising when expended to four, buckling arose. However, the flexibility of the rope showed some potential in connecting panels with differentiating edges and thicknesses. Also, rope provided a degree of freedom in connecting between the panels and allowed the construction to lie flat on the ground, which is an interesting feature.

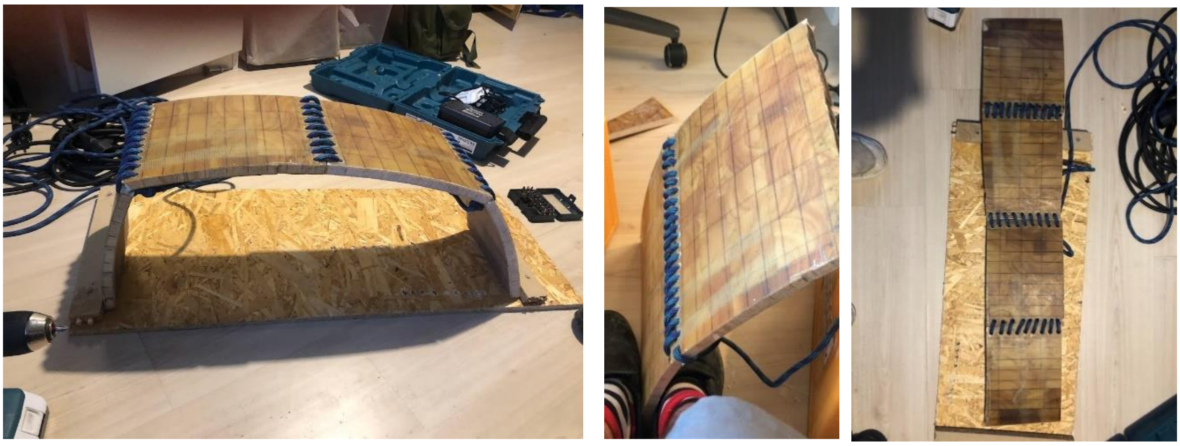


Figure 35 Rope Prototyping

The first cut in the blade material was attempted with a Makita-jigsaw. This deemed to be an ineffective technique. Since the heat of repeatedly cutting through Glass Fibre Reinforced Polymer, with a rather small sawblade, was too much for the metal saw to withstand and melted. Accordingly, burn marks on the Balsa-wood arose. Therefore, all future cuts were done with a handsaw.

Figure 36 Jigsaw experiment

6.2 Hinges

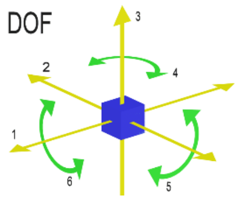


Figure 37 Degrees of Freedom

As experienced with rope as a connection technique, some flexibility could be a favourable feature for the connection method. However, the degree of freedom within the elastic rope was too much and led to buckling between the panels. Some small hinge tests were conducted keeping in mind Richard from Mastermade’s knowledge to look into existing solutions

The hinges allow for only one degrees of freedom and prevent the construction from buckling. The hinges can be placed on the outside or the inside of the arch, which both make different assembly methods possible. Both options allow to align panels with different thicknesses on either the outer edges or the inner edges to each other.

Figure 38 Hinge outside concept

When the hinges are on the outside of the arch, the construction is held up by the material of two panels putting force on each other, when forced is applied to the outsides of the arch. Due to the strong and relatively thick nature of the blade material, this allows for a sturdy build. The hinges make this concept fully foldable when no pressure is applied on the outsides of the arch.

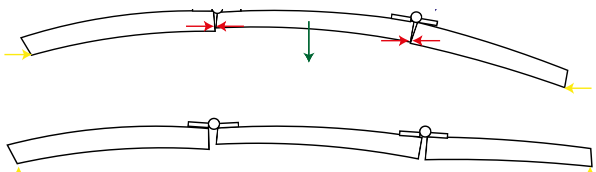


Figure 39 Schematic outside hinge

When the hinges are on the inside of the arch, there is no need to apply extra force on the outsides of the construction. The force is distributed through the sides of the panels due to the nature of the form and the freedom of movement is on the non-load bearing side.

Figure 40 Folded hinge

However, this construction is not fully foldable, because when the panels are hinged, the lower edges of the material will eventually touch each other again and will apply force again.

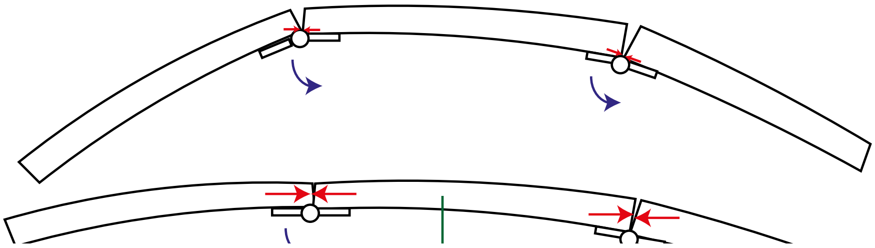


Figure 41 Schematic inside hinge

Figure 42 Inside hinge concept

To get a better understanding of how these connections would act in a double curved panel construction, rather than an arch, a quick prototype was made with outside hinges and a hanging point in the middle. Here, it can be seen that a problem arises when outside hinges are used. The gaps between the panels, that needed to make the hinges rotatable, are hard to define or assemble. They are easily too big or too small.

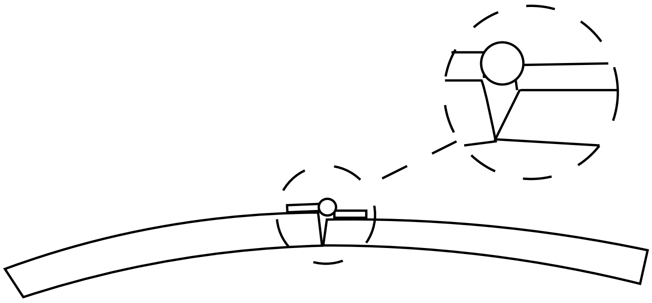


Figure 43 Fault hinge

Figure 44 4-way joint

I think the small degrees of freedom are an interesting feature since they allow for some flexibility with the material. Also, the possibility to fold the structure can bring some options for some smooth assembly methods, like the one of (Dahy, 2019). The self-standing structure sparked the most interest, since the force distribution seemed engaging.

6.3 Geodesic Dome

With the three different concepts from the SRBD-team and the self-standing arch from the rapid prototyping exploration in mind, the search for different dome-like structures started. My focus was mainly on constructions that consist of panels, to ensure extensive amounts of material reused in the creation of the pavilion.

There are countless possibilities to create such a construction. However, since this project focuses on an assembly and connection system, I was in search of a rather simple construction, but with a wide variety of use cases and a possibility to extend or complicate.

That is when I came upon the Geodesic dome. This structure was first designed by Walther Bauersfeld in 1922 as the planetarium for the German city Jena. (Gáspár, 2022) It is a hemispherical shell structure, which is based on a geodesic (meaning the shortest line between two points that lies in a surface (Cambridge Dictionary, n.d.)) polyhedron (which is a three-dimensional shape with faces, that have at least three straight edges, vertices and angles (SplashLearn, n.d.)(Oxford Learners Dictionaries, n.d.)) A simplified definition of a geodesic dome is that it is the result of the subdivision of the faces of a polyhedron projected onto a spherical surface, as shown in Figure 47 (Gáspár, 2022)

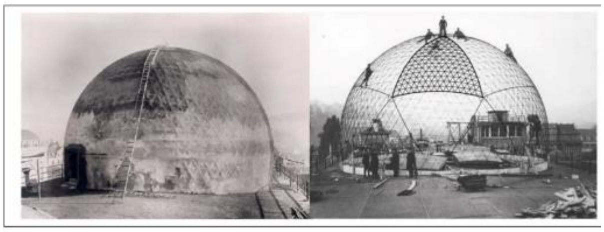


Figure 45 First planetarium of Jena

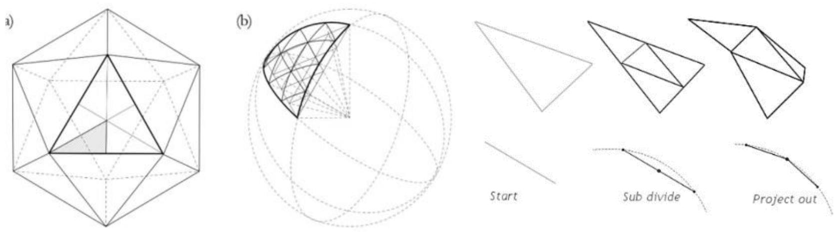


Figure 47 Subdivison polyhedron

A starting polyhedron that is used most commonly is the icosahedron, which is a twenty-sided polyhedron wildly used as a die-shape in games like Dungeons & Dragons.

Similarly to the inside-hinge-arch-prototype, the triangular elements of the dome realise a structurally rigid shell, due to Tensegrity. This a term created by Buckminster Fuller 1955 and is stands for tensional integrity. It is a definition for a network of members that are continuously in compression or tension. Creating not only a self-sustaining structure, but also a dome is able to distribute stress throughout the structure, making the geodesic dome able to withstand large loads. (Geo-dome UK, n.d.) explains how this works.

Firstly, we simplify to one triangle. In this case, 50 pounds is used as a point load, resulting in to 25 pounds of load on both points on the ground, since the load is divided evenly. Due to the chosen lever, or the length of the struts between the points, this leads to 29 pounds of load in both legs and 15 pounds of tensile load in lower strut. It can be noticed that the compressive load at the top of the triangle causes lower loads in the other struts, since it is distributed through all the sides. When used in a geodesic dome, as shown in Figure 49, this compression and tension division of throughout the entire structures. When the triangles distribute the load over even more triangles, this makes the dome able to withstand heavy loads.

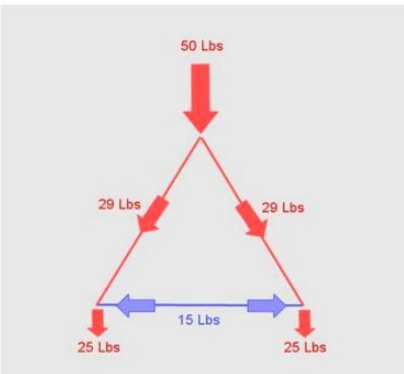


Figure 48 Triangle force division

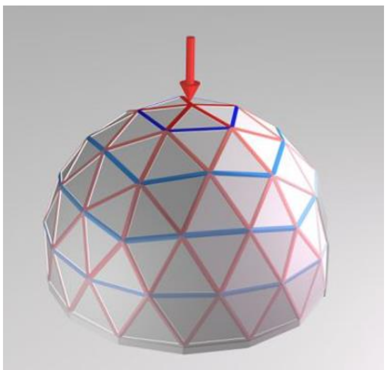


Figure 49 Structure force division

Next to being strong, geodesic domes can create large volumes of space, while using little surface area, making the dome efficient in regards of using material to realise shelter. (Buckminster Fuller Institute, n.d.)

As mentioned before, the geodesic dome is commonly made by projecting subdivisions of the faces of an icosahedron on a sphere. This can be done in different frequencies. From 1 frequency, or 1v, up to as how many subdivisions one could want. This process is called tessellation and allows for two different characteristics; more subdivisions result in a stronger and rounder structure.

When constructing higher frequency domes, more different struts and/or different panels are required. This is due to the way the tessellation is projected onto the sphere.

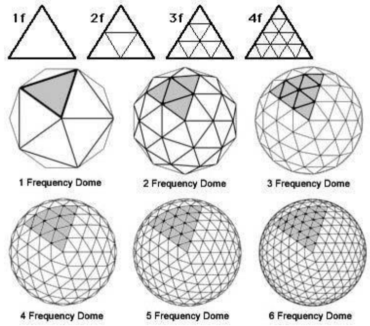


Figure 50 Frequency of domes

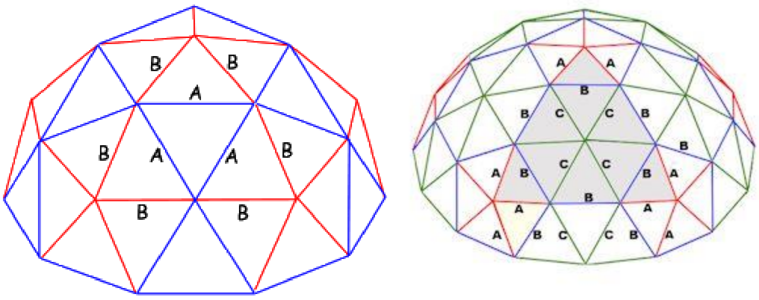


Figure 51 2v vs 3v dome

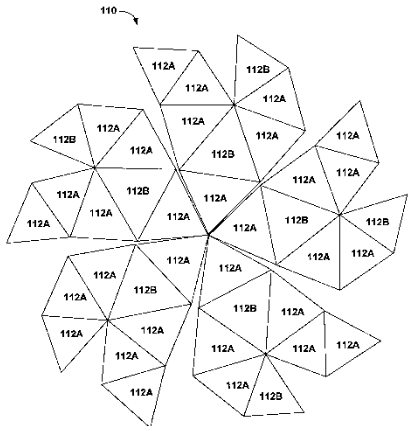


Figure 52 Triangle map 2v

(Geodome UK, n.d.) proposes, from experience, that a 2v Geodesic dome is suitable for domes up to a diameter of 4 meter. Since this graduation project is focused on the assembly and connection system for pavilion of these dimensions and the fact that a solution for either frequency would fit all frequencies, all future work will regard a 2v Geodesic dome.

Figure 52 is from a patent from (David Geiger, n.d.) and shows the map of a 2v geodesic dome made out of panels. Accordingly, Figure 53 shows that the triangles are divided along two set factors; an A and B side, which are 0.61803 x dome radius (A) and 0.54653 x dome radius(B). This allows for some easy calculating.

strut length = dome radius * strut factor

Strut	Strut factor	Dome	Sphere
A	.61803	35	60
B	.54653	30	60
4-way connectors		10	0
5-way connectors		6	12
6-way connectors		10	30

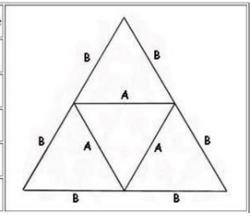


Figure 53 Overview 2v dome

To get a better understanding of the self-sustaining characteristic of the dome and get hands on experience in creating and assembling a dome, a small and rapid prototype was realised. Using rough cuts and duct tape a 2v geodesic dome was assembled following the map of the patent of (David Geiger, n.d.). This showed me 3 things; the structure is entirely self-sustaining and is able to withstand a substantial amount of load, like the sources from earlier in this chapter proved as well. Also, the duct tape allowed a similar degree of freedom as a hinge, making the panels able to rotate on each other but not move.

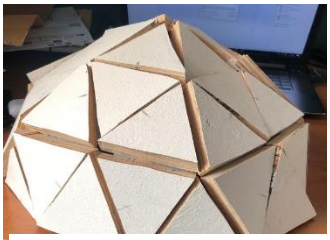
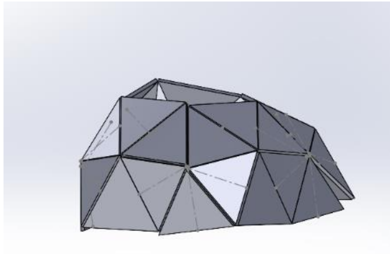


Figure 54 Rapid prototyping dome

In order to make a digital structural analysis of the 2v Geodesic, I attempted to create a 3D-model in SolidWorks. This was done in two different ways. Firstly, I tried to define the dome solely by mating the edges and the points of triangles (Figure 55.1). However, this led to over dimensioning of the structure and made the assembly “forget” previous set mates or had to break them to fulfil new ones. I thought that was due to the lack of additional geometry. As an attempt to solve this, I added a circle in the second attempt to constrain the form somewhat more (Figure 55.2). However, this still did not seem to fix the problem. At this point, I concluded that there might be an issue in forcing the dome into a 3D-model and that the stresses within the structure that make the dome self-sustaining are not easily translated into geometry.



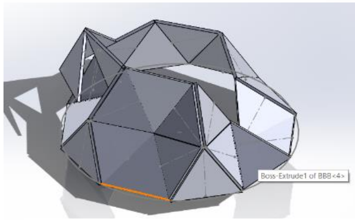
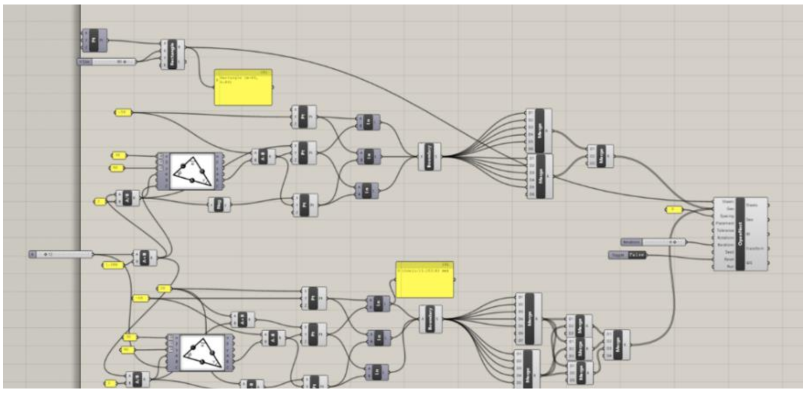


Figure 55.1 Solidworks 3D model
Figure 55.2 Solid works model with circle

6.4 Bin packing

Since I was still curious about the extent of the strength of the dome and wanted to experiment with hinges some more, a more precise prototype was created. To do so I purchased a wooden panel of 120cm x 60 cm x 8mm at the Gamma. I wanted to use as much of the material as possible and make the triangles, and thus the dome itself, as large as possible. To do is, I made a bin packing file in Grasshopper. In this file, the dimensions of the wooden panel and the A and B triangle are initiated. The triangles are copied and merged (10 times AAA and 30 times BBA). Both are inputs for Opennest, which is a Bin packing plugin. This plugin takes a sheet (the wooden panel) and geometry (the triangles) and rotates the geometry to fit it in the sheet as efficiently as possible. Due to a number slider where the triangles are depended on, the size of the triangles can be modified easily. By increasing the number slider until the geometry does not fit the sheet anymore and requires a second one to fit, in theory, the maximum size of the triangles can be found for this specific wooden panel. In this case, that is 17.03 cm for side A and 15.06 cm for side B and (strut length/strut factor = dome radius) 17.03 cm / 0.68103 = 27.56 cm radius or 55.11 cm diameter.



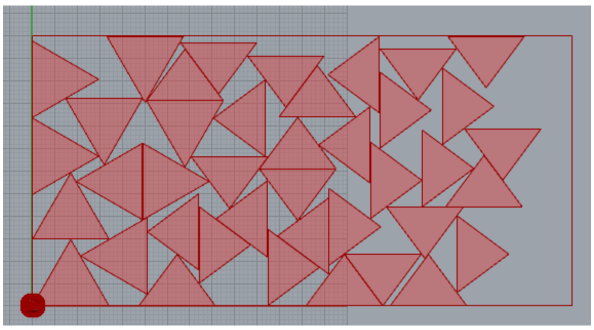


Figure 56 Binpacking Rhinoceros

When I looked at the result of the bin packing by the OpenNest algorithm, I thought that the waste material, although possible, was quite extensive to be the most efficient way to divide the wooden panel. To test this, I made an Illustrator file and inputted the triangles with the dimensions from Grasshopper. Since I was going to cut these triangles by hand, I wanted to limit the saw cuts as much as possible and overlapped as many as I could. As can been seen in Figure 57, there is an obvious empty space that can be filled by enlarging the triangles. This was done by a simple grab and pull in Illustrator, making the A side 19.99 cm, the B side 17.68 cm and the radius 32.44 cm or radius 64.69 cm, minimising the residual material.

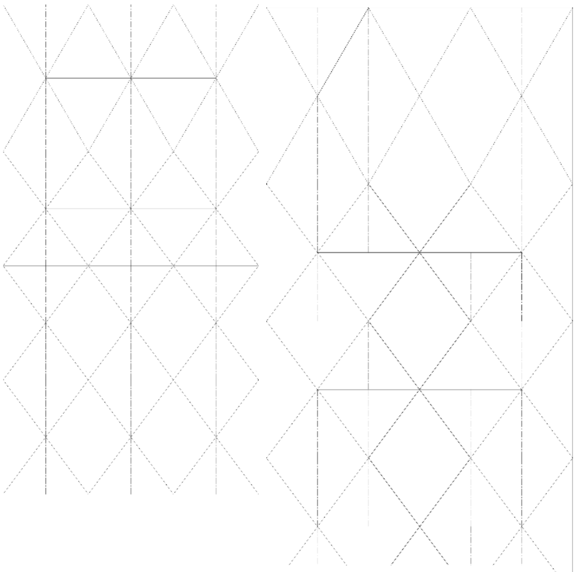


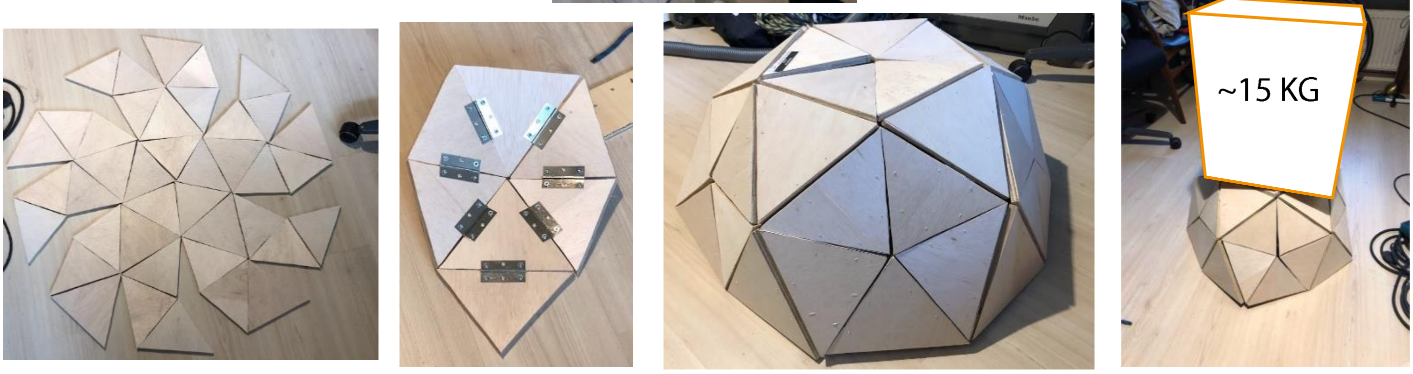
Figure 57 Tesselation binpacking dimensions vs

After defining the dimensions of the triangles and the dome, this cutting pattern was drawn on the wooden panel, cut into pieces and screwed into the geodesic dome. To realise this, 55x 66mm hinges with 2x3 screw holes and 220 1.5cm Torque screws were used.

While and after assembling the dome using screws, I learned some key lessons regarding the manufacturing.

1) When designing the assembly and connection system for the pavilion, the assembly strategy should be taken into account. Since I was working on a smaller scale, I could move the dome around. If a dome is several meters long, this will not be a realistic option anymore. So it has to be taken into account how the connections and panels are assembled when building the dome.
2) The dome assembled with hinges as a joint accomplishes a strong dome with lightweight material, while keeping some flexibility between the panels during assembly of the dome. The load is divided easily through the structure.

Figure 58 Process Geodesic dome prototype



3) Bin packing might not be the best option to determine the cutting pattern.

This last lesson asks for some additional research. When this problem was presented at one of the SRBD-workshops, Adrien Bousseau mentioned that the difference between what the OpenNest does and what I did by hand is that the algorithm is expecting random differentiating geometries to fit in the sheet. However, for the geodesic dome are mostly equal size triangles.

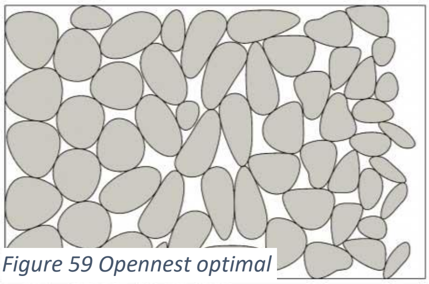


Figure 59 Opennest optimal

(Kamali et al., n.d.) shows an useful example of packing triangles in a rectangle. It can be seen that seemingly more random packing of triangles might be useful in relatively large triangles, or rather when there is limited space. When a larger amount of smaller triangles can be used, a pattern more similar to the one I made in Illustrator is more efficient in minimising material waste.

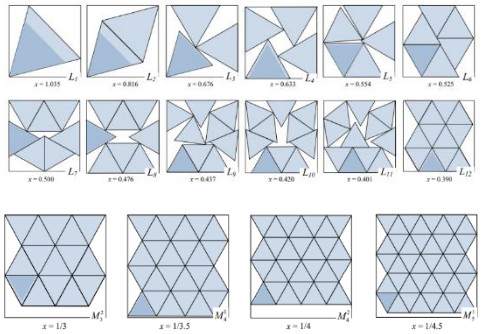


Figure 60 Tesselation triangles

This is because triangles allow for a technique called Tessellation. (Meriam Webster Dictionary, n.d.) defines it as “a covering of an infinite geometric plane without gaps or overlaps by a congruent plane figure of one type or a few types.”

With tessellation, the only waste that occurs is the parts of the sheet where the infinite pattern cannot be continued. To know if tessellation is an option for cutting the blade material into useful pieces for a geodesic dome with a diameter of 4m, it seems useful to do some calculations.

The blade has a surface area of around 476 m^2 (calculated with SolidWorks), including the part that cannot be used. Where around 224 m^2 is in the midspan of the blade (from DU99-W-405 – DU93-W-210), including the parts with bonding and spar caps.

For a dome with a diameter of 4m, the radius is 2m. (dome radius * strut factor = strut length) 2m x 0.61803 = 1.24m for side A and 2m x 0.54653 = 1.09 m for side B. The area of a triangle is ½ x width x height. Triangle AAA = ½ x 1.24m x 1.07m = 0.66 m^2 and BBA = ½ x 1.24m x 0.89m = 0.55 m^2.

30 x BBA triangles and 10 x AAA triangle = 23.10 m^2. This is 10% of the surface of the midspan, therefore I think tessellation can be used for dividing the blade.

When tessellation is used for dividing the blade into triangles, some other implications are raised.

6.5 Tessellation

Triangles are needed to construct the 2v Geodesic dome. The projection of a tessellated pattern of the wanted triangles on the wind turbine blade might be an interesting option to work with. However, it should be noted that when this pattern is projected onto the surface of the blade, some shift in the geometry will arise. When projected directly on an almost flat surface, minimal curvature can be found, but when there is a stronger curvature, a more difficult problem emerges.

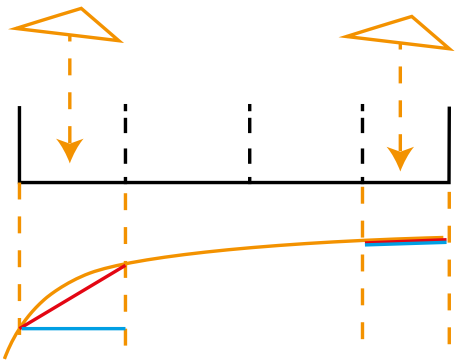


Figure 61 Curved projection

In this paragraph, I search for a solution regarding the division of the blade in useful triangles.

6.6 Projection

Until now, mostly flat panels were assumed, however, when aiming the use of as much blade material as possible, some curvature is found. To examine to what extent the difference between the target geometry and the geometry in reality occurs, I conducted a small experiment in Solidworks. By projecting target triangles onto the 3D-model of the blade and digitally measuring the resulting projected triangles. For this experiment, I chose to work with the Midspan of the NREL Research blade (Resor, 2013), which reaches from 10.25m to 38.95m of the bladespan. The largest possible inner rectangle is drawn to disregard the leading and trailing edge, which are more likely to have damage from years of service.

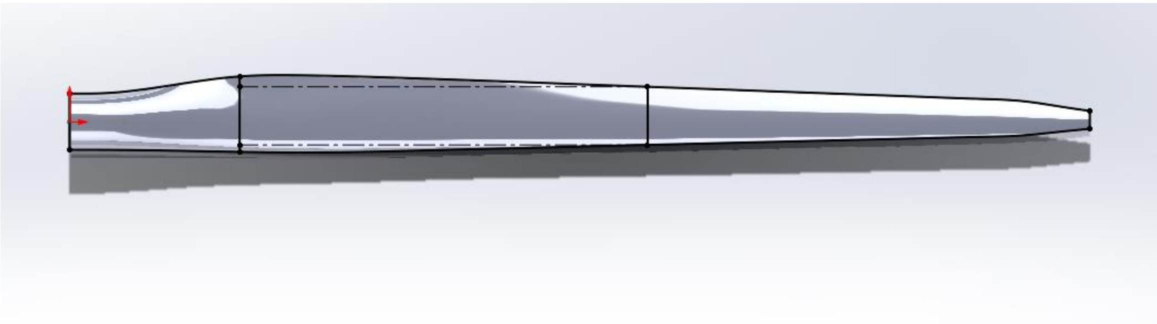
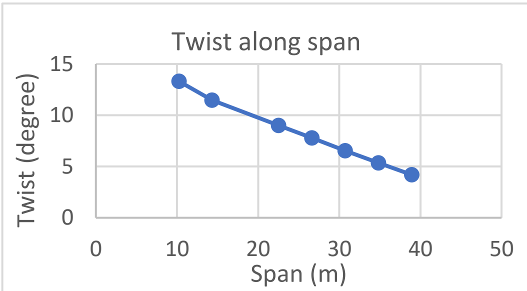


Figure 62 Midspan blade

Bladespan	Shape	Degree	Chord
10.25	DU99-W-405	13,308	4,557
14.35	DU99-W-350	11,480	4,652
22.55	DU97-W-300	9,011	4,249
26.65	DU91-W-250	7,795	4,007
30.75	DU91-W-250	6,544	3,748
34.85	DU93-W-210	5,361	3,502
38.95	DU93-W-210	4,188	3,256

Table 4 Airfoils midspan



Graph 1 Twist along span

To ensure less difference between the target triangle and the triangle in the 3D simulation, a projection plane is constructed. The projection plan should be turned along the most efficient face of the blade, to take the twist of the blade into consideration. As Table 3 shows, the twist of the blade is almost linear. Therefore, the projection plane is chosen to be perpendicular to the middle airfoil of the midspan and turned 7,795 degrees from the top plane.

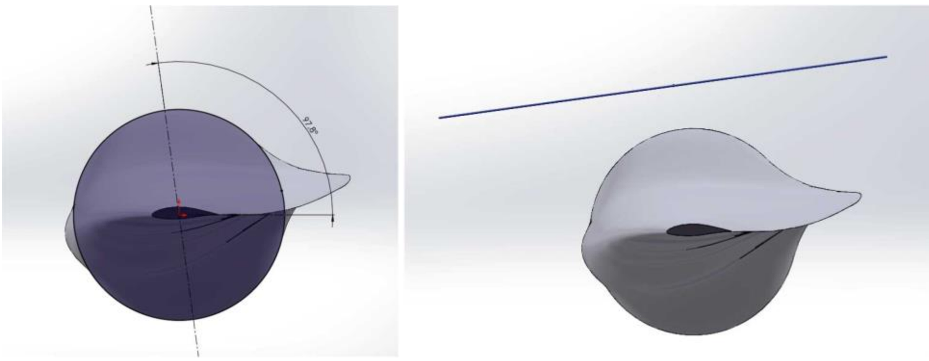


Figure 63 Projection plane

In the drawn rectangle on the projection plane, the BBA and AAA triangles with the A side at 1.24m and the B side at 1.09 m, as calculated in Chapter 6.4, are sketched. Since for a 2v geodesic dome, 10 AAA triangles and 30 BBA triangles are needed, one row of AAA triangles and 3 rows of BBA triangles are marked out through the means of tessellation. The sketch is projected onto the upper shell and the lower shell of the blade and the rows are “cut-out” separately and stored as a new part.

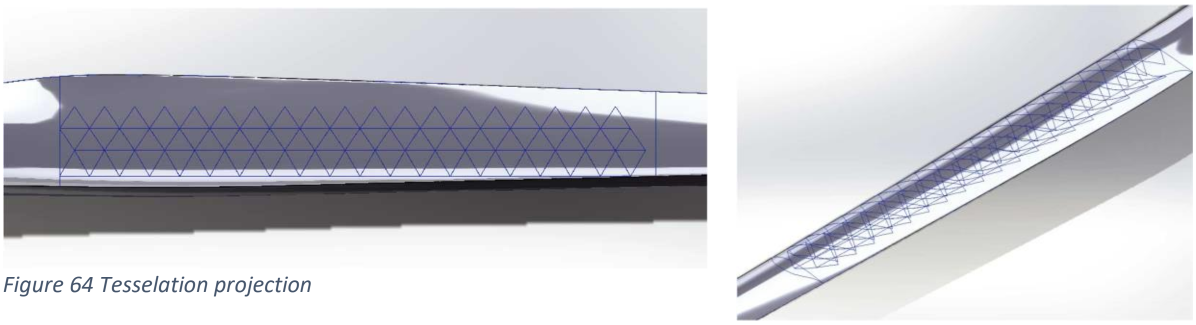


Figure 64 Tesselation projection

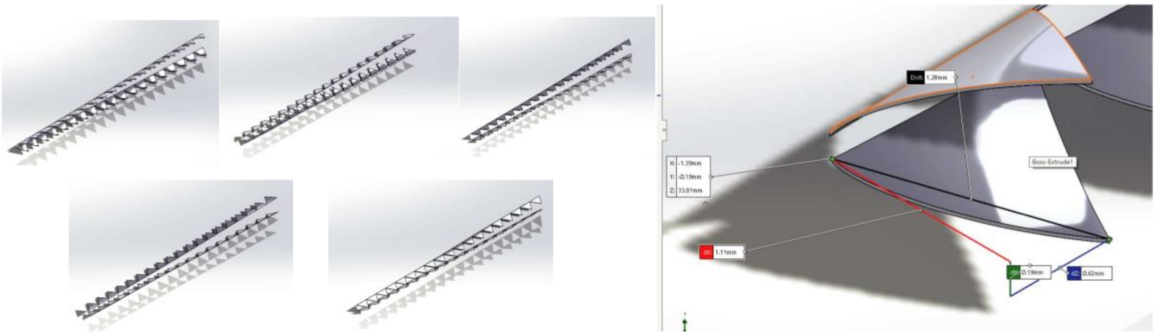
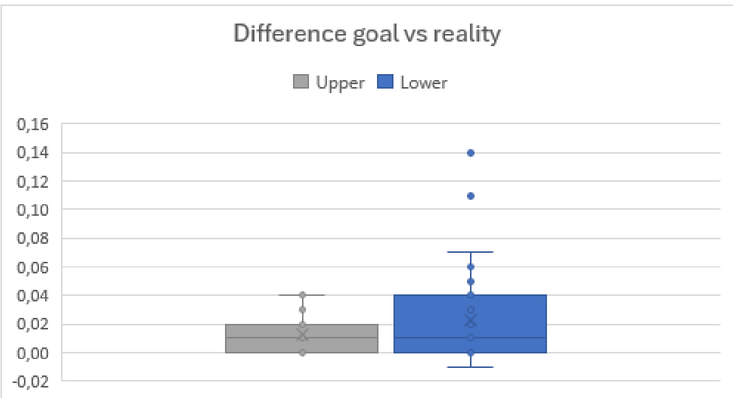


figure 65 Rows of projected triangles along blade

Using the internal measuring tool from Solidworks, the distance between the points is analysed. Ideally, this distance would resemble the length of the target triangle. To calculate the overall difference between the target and the digital model of the projected triangles, from every row the upper and lower first, middle and last triangles are measured. The measurements are compared with the target triangles and the difference is calculated. (Appendix A) In Graph 2, it is shown that the difference between the target triangle and digital reality varies between -0.01 m and 0.07 m with some outliers. The mean of the difference is 1 cm for the upper triangles and 2 cm for the lower triangles. This does not seem that much of a difference, however, when added up in a dome construction with 40 panels, this could lead to a difference of more than 40 cm overall, which is not favourable. Although these differences could be minimised by changing the projection plane, a different slicing method should be considered.



Graph 2 Difference goal vs reality

6.7 Triangulation

The curved surface of a wind turbine blade makes it complicated to use as a structural material. The experimental hinge joints, previously discussed in Chapter 6, although proven to be rigid after completing the dome structure, may lead to structural problems. When the curves of adjacent panels do not line up, a connection between the panels on the side borders might be difficult. Although a solution that can be altered to fit every single case could be a solution, this might be overcomplicating the problem. Modularity in building the dome seems a more favourable solution. This raises the question; Is it possible to force the panels into more exact geometry? When you are able to cut the panels into desired shapes, a more general fitting solution for the panel joints can be designed.

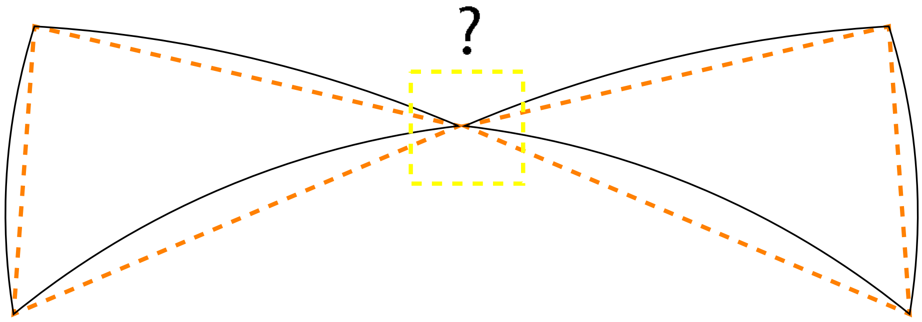


Figure 66 True curve vs geometry curve

When cutting triangles out of a mostly convex (Chapter 2) curved surface and assembling them into a structure, it might be a better solution to connect the panels at the points that the triangle consists of. In this way, you can disregard the possible curve between the points and focus on cutting out the true target curve, where the distance between the points is the triangle that is needed to construct the desired geodesic dome.

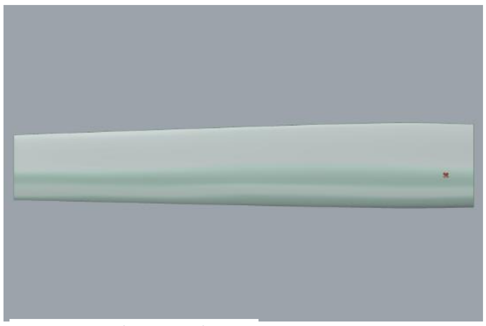


Figure 67 Rhino midspan

In Rhinoceros, using a loft model of the NREL 5MW research blade from Mariana Popescu as a base Appendix B, a scaled 1:1 digital model from the midspan is created. In Grasshopper, with the Mesh Closest Point-block, a point on the surface of the blade is created. Using this point as the midpoint, a circle is drawn with radius of 1.236 m (the A-side of a triangle) and with the Mesh-Curve Intersection-block a second point on the blade with the target distance to the first point is found. A line is drawn between those points. From this line the midpoint is taken and a second circle is drawn with the target length of 1.070 m and the intersection between the circle and the surface is taken as the third point. A triangle is drawn between the 3 points. Using this method, the distance between the points of the triangle will always be the target distance and triangles with the same distance between all 3 points can be digitally cut out of the blade.

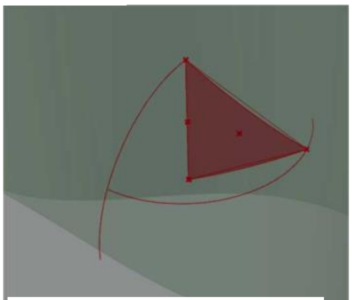


Figure 68 Triangulated triangle

To streamline the process if slicing multiple triangles out of the blade and avoid having to construct each point one-by-one, I take a look back at the measurements taken in SolidWorks. (Appendix A) In these measurements, the A and B side were drawn along the width of the blade and C was drawn along the length of the blade. As can be seen in Appendix A, in the measurements in Solidworks there was almost no difference between the target dimension and digital reality.

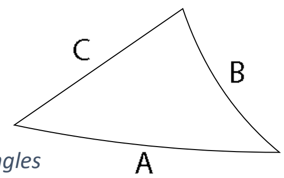


Figure 69 Side division triangles

To integrate the possibility to cut multiple triangles out of the blade, the lack of difference between target and reality is utilised. Instead of drawing each individual point, a boundary is drawn along the length of the blade. This boundary is used to compose a tessellation pattern and construct adjacent triangles.

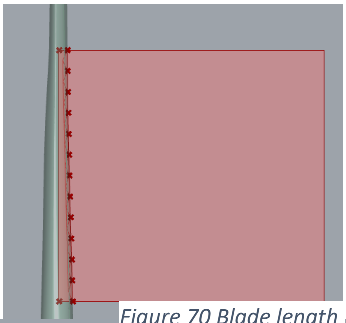


Figure 70 Blade length

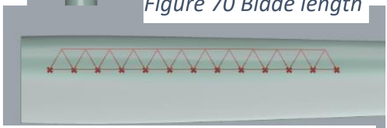
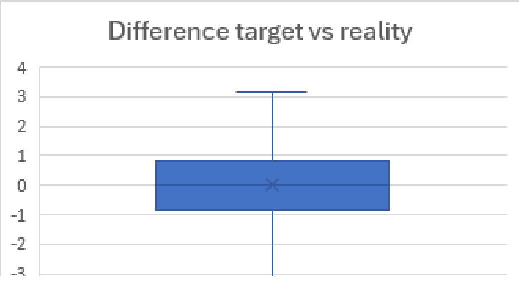


Figure 71 Projected triangulate triangles

To evaluate if this method is sufficient to obtain correct dimensions of triangles using the blade as a source geometry, the lengths of the drawn lines are exported to a document. To calculate the accuracy, the difference between 1236 mm and the given lines by Rhinoceros is computed. The results are shown in Graph 3. On average, 0 mm difference occurs, with a standard deviations in differences between 0 and 1 mm and outliers to less than 3 mm. I deem these tolerances sufficient enough to move forward with this approach.

The same method is used to construct rows along the entire width of the wind turbine blade model with 2 rows of ABB triangles. This slicing method will be used later on in the project to construct a prototype.



Graph 3 Difference vs reality triangulation

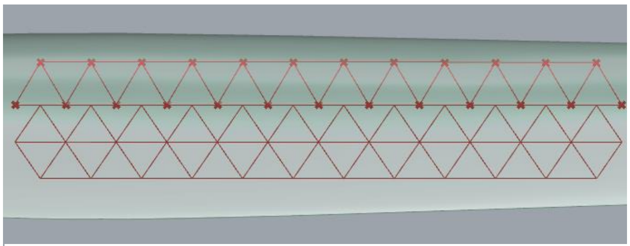


Figure 72 Rows of triangulated triangles

6.8 Joint Design

After being able to construct geometrical accurate triangles, a switch from an edge-to-edge connection (As discussed in the beginning of Chapter 6) to a nodal connection method is required. (Alpermann et al., 2010) shows an overview of different patented nodal connectors for geodesic domes, including their pros and cons. Their research shows that a plate connection system (5) is best optimised for temporary structures, which is the use case of this project. They conclude this through questioning three criteria; Modularity, fast assembly and disassembly and adaptiveness to imperfections.

(Alpermann et al., 2010) recognises one con for the plate connector, which is the geometric offset from the ideal truss node. By introducing material between the struts, the connection does not lie perfectly on the geometric node of the geodesic dome, like in a 1-bolt connection. Although this increases the stress in the connection, only some local yield peaks occur, which does not pose as a severe risk to the structural integrity of the plate connection.

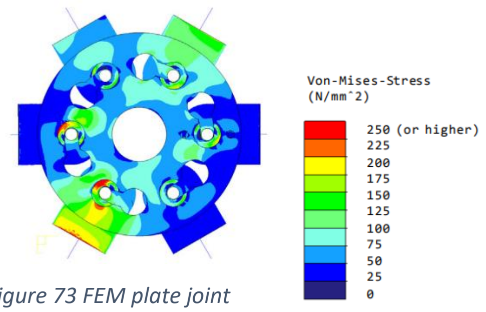


Figure 73 FEM plate joint

Type	1 (Clamp)	2 (Ring)	3 (Ball)	4 (Bolt)	5 (Plate)
Patents	US2682235, US1679758, US0226319, US0291952, US4244152	US4244152, US4297825, US5996288	US4455803, US4608790		DE202005017822U1, US4203265, US5704169, US5937589
Image	[2]	[3]	[4]	[5]	[6]
Features	Clamp: Struts are clamped together bia bolt tension between female and male parts.	Ring: Steel cylinder with slots/ holes for fixing struts.	Ball: Most popular truss connecter system. Solid steel node. Threaded bars.	1-Bolt: Simple and strong. 1 bolt system. Steel struts with pressed & drilled ends.	Plate: System in which all struts pinned or fixed to connecter plate.
Pros	Versatile node for variable angles and number of struts.	Deep node suitable for slender struts such as timber beams.	Can sustain large forces. Rigid during erection. Good for large spans.	Closely approximates idealised truss. Simple & cheap manufacture.	Facilitates fast erection and offers good level of geometric adaptability.
Cons	Unstable system during assembly. Heavy & expensive components.	Geometric offset from ideal truss node.	No variability. Each component must be geometrically correct.	1 node failure = 6 struts failure. Fast assembly / disassembly impractical.	Geometric offset from ideal truss node.
Designer / Product	Fuller node, Bauersfeld Node		MERO KK, NK, TK, ZK	Pacific Domes	System Tecture, Zendome
Applicaton	Small - large spans	Medium spans	Large - very large spans	Small - medium spans	Small - medium spans

Table 5 Typology nodal joints

Since the dome that I imagine for the SRBD-project is going to be made with panels rather than struts, the joint should be more than a node for the stuts to come together. It should allow for bolting the panel to the plate connection and, since the panels are cut in a way that the distance between the endpoints of panel is a geometrically correct flat triangle, the joint should have an angle to assemble the panels in the geodesic dome structure. According to (*Domerama*, 2012), these angles are 15.86 degrees for A struts and 18 degrees for B struts.

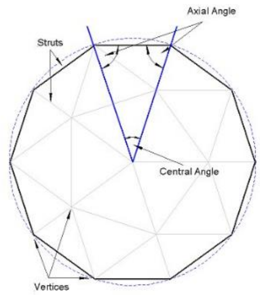


Figure 74 Axial angle

(*Geo-Dome*, 2014) explains how this is calculated. In Figure 75, a slice of a 2v geodesic dome is shown. When lines are drawn to the ends of a strut from the centre of the dome, a triangle is constructed. The angle between the strut and the triangle is called the axial angle. 90 degrees – axial angle = bend angle.

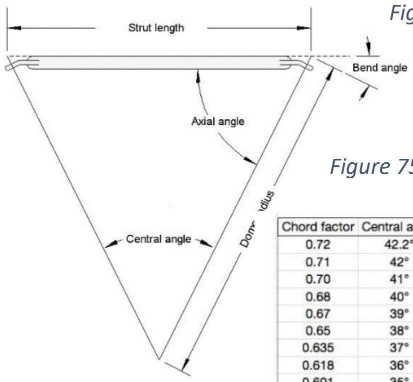


Figure 75 Bend angle

To avoid having to calculate the angles for any size dome, the strut length is divided by the dome radius and (*Geo-Dome*, 2014) made a cheat sheet using the chord factor. The chord factors in a 2v dome are 0.61803 for A and 0.54653 for B (As mentioned in Chapter 6.4) and as (*Domerama*, 2012) stated, the corresponding angles are 18 and 16.

Chord factor	Central angle	Axial angle	Bend angle
0.72	42.2°	68.9°	21.1°
0.71	42°	69°	21°
0.70	41°	69.5°	20.5°
0.68	40°	70°	20°
0.67	39°	70.5°	19.5°
0.65	38°	71°	19°
0.635	37°	71.5°	18.5°
0.618	36°	72°	18°
0.601	35°	72.5°	17.5°
0.585	34°	73°	17°
0.568	33°	73.5°	16.5°
0.551	32°	74°	16°
0.534	31°	74.5°	15.5°
0.518	30°	75°	15°
0.50	29°	75.5°	14.5°
0.483	28°	76°	14°
0.469	27°	76.5°	13.5°
0.449	26°	77°	13°
0.433	25°	77.5°	12.5°
0.416	24°	78°	12°
0.399	23°	78.5°	11.5°
0.382	22°	79°	11°
0.365	21°	79.5°	10.5°
0.347	20°	80°	10°
0.330	19°	80.5°	9.5°
0.313	18°	81°	9°
0.2956	17°	81.5°	8.5°
0.278	16°	82°	8°
0.261	15°	82.5°	7.5°
0.244	14°	83°	7°
0.226	13°	83.5°	6.5°
0.209	12°	84°	6°

Table 6 Cheat sheet bend angle

An example of prebend plate connections are the STAR connectors from (Vikingdome, 2024) However, these connectors are also designed for a strut-based geodesic dome. To not have the connector placed on the gaps between the panels, the connector should be turned 60 degrees. In this case, to calculate the bend needed for the dome structure, I should not look at the chord factor of the struts but at the median of the triangles. After drawing the triangles in SolidWorks, it was found that the chord factor of the AB point is 0.515, AA is 0.450 and BB is 0.535. Which corresponds to AB: 15°, AA: 13° and BB: 15.5°. These angles can be used in a joint that resembles the STAR connector (Vikingdome, 2024)

Figure 76 Star connector

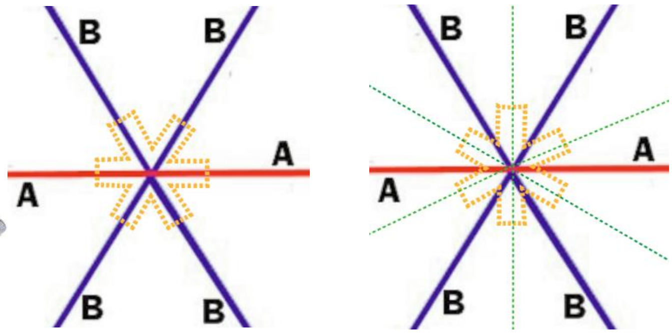


Figure 77 Joint nodal vs panel

To assemble a complete 2v geodesic dome, six 5-way connectors and ten 6-way connectors are needed. When creating a strut-based dome, ten 4-way connectors are needed for the bottom, however, when bolting the panels further in the material of the panel, there are ten 3-way connectors needed instead.

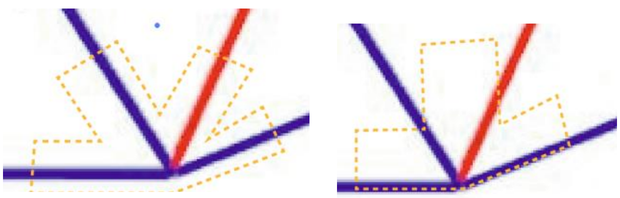


Figure 78 4 way to 3 way

Now that we know the bend angles, a 3D model can be created for an in-plane, prebend plate connection, to get a better understanding of the dimensions for a geodesic dome with the specifics imagined for the SBRD-project. Since the angle of the panel is mostly the same along the panel the size of the joint does not matter too much to fit, as long as there is enough material to bolt the joint to the panel. 20 centimetres as an outer circle was chosen for the joint, since this seems like a handleable dimension.

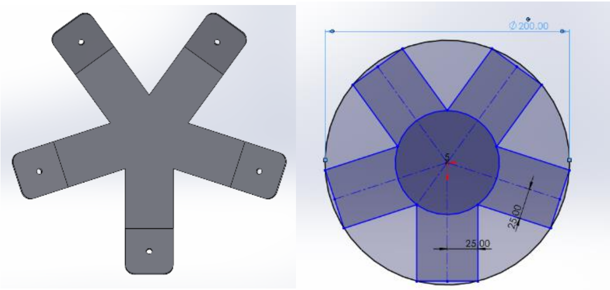


Figure 79 5-way joint design

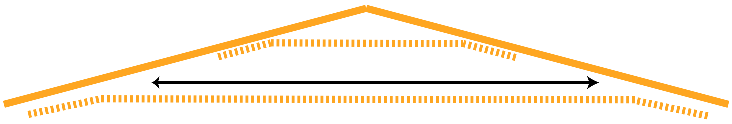


Figure 80 Dimensions joint proof

The constructed 5-way joint is added to an assembly with the AAB panels to show how the panels come together in a structure. In Figure 80, it can be seen that the panels fit closely together. In this assembly, flat panels are used, however, another problem arises when combining a plate connection with triangle panels cut out of a curved surface. The challenge is: How to bolt the connection plates perpendicular to the curved panel? The three endpoints of the triangle are exact geometry, however, the curve between the points is dependent on where in the blade the triangle is retrieved.

Figure 80 5 way joint render

The panels will have a certain curve in reference to the joint. To ensure modularity, a solution for any possible curve that might occur when cutting panels of this size out of the blade. This can be done by adding a certain amount of possibility of movement to the joint. If you are able to change the direction of the connection bolt, you are able to turn the bolt perpendicular to the curved surface.

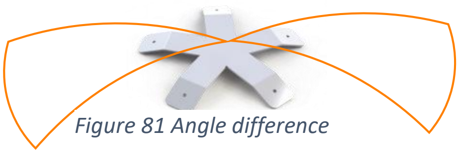


Figure 81 Angle difference

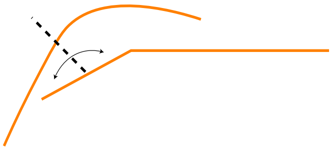


Figure 82 Ball-socket joint

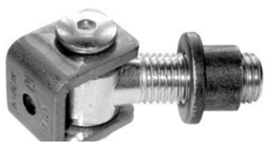


Figure 83 Gate hinge

This can be achieved through several existing parts, however, two options seem the most favourable; a “ball-and-socket-joint” or a “gate hinge”. When bolted to a plate joint the gate hinge allows for 1 degree of freedom and a ball-and-socket-joint allows for 2 degrees of freedom.

Since the axial ball-and-socket joint allows for more freedom when constructing a geodesic dome and thus allowing broader possible structural inconsistencies, this joint seems most favourable.

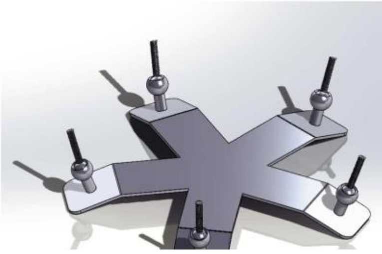
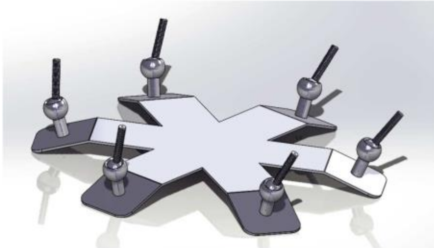
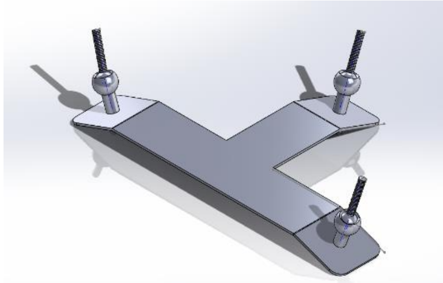
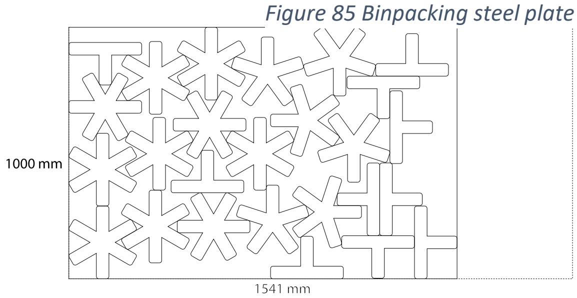



Figure 84 5, 6 and 3-wat connection



Using the dimensions of the DIN71802 M6 ball-and-socket-joint, which is widely available and cheap on websites like (Aliexpress, 2024), ball-socket joints were added to the 5-way, 6-way and 3-way plate joints in a Solidworks-assembly.

Figure 85 Binpacking steel plate



6.8 Viability (Cost Joint)

To evaluate the viability of the joint design, a calculation was made for production, material and labour costs. Firstly, the cost of the material for the plate joints is calculated. A 3mm thick plate of steel of 2000 mm x 1000 mm costs €60,96 / m^2 and a 3mm thick plate of aluminium costs 2000 mm x 1000 mm costs €154,00 / m^2 at the Practicum Modelbouw en Bewerkingen (PMB). With the Opennest algorithm in Grasshopper, a bin packing solution was searched for cutting the panel joints out of a 2000 mm x 1000 mm plate which is shown in Figure 85. Using this cutting pattern, the joints fit on a 1000 mm x 1541 mm plate. Which is roughly €97,54 for steel or €246,40 for aluminium. Since the yield strength of steel is around 228 MPa and the yield strength of aluminium is around 125 MPa (B. Liu et al., 2013), as well as, steel being worth half the cost of aluminium, steel is chosen as the material for the plate joints.

For the labour costs, I consulted (24/7Tailorsteel.com, 2024) to gather how much it will cost to laser-cut the 26 plate joints out of a 3 mm steel plate. This website can generate a quotation in less than a minute by uploading DXF files of the joints and which material you want to be laser-cut. For this project, I chose KGW DC01, since it is described as bendable, well-suited for laser-cutting and has a Yield strength of 270-410 N/mm^2. In the quotation (Appendix C), material and labour costs are not mentioned separately, however, the total cost given for the material and laser-cutting by 24/7Tailorsteel is €136,38. It can be imagined that the labour cost is somewhere around €136,38 (the total cost) minus €97,54 (the estimated material cost) = €38,84 (labour cost). However, this is such a small amount I would propose outsourcing the entire production of the plate joints to a company like 24/7Tailorsteel.

Manufacturing costs

Labour and Sheet-material	€ 136,38
Ball-socket Joint	€ 199,88
Bolts	€ 12,90
Unforeseen (10%)	€ 34,92
	€ 384,08

Table 6 Calculation manufacturing

As for the ball-socket joints, DIN71802 M6 joints are sold for €1,53 a piece (Aliexpress, 2024), to have one on every corner of each plate joint, 130 ball-socket joints are needed. (10 x 6-way, 6 x 5-way, 10 x 3-way.) Which adds up to 130 x €1,53 = €199,88. 130 x M6 x 12 mm bolts are needed to attach the ball-socket joints to the plate joints. These are sold for €4,30 per 50 bolts (123-3d.nl, 2024), which adds up to 3 x €4,30 = €12,90. Concluding, a total cost of €384,08 (including an unforeseen post of 10%) is estimated for the manufacturing of the joints. This is roughly 4% of the budgeted amount for prototyping. Since the costs of transporting and buying the blade material are budgeted separately, I think ±€400 is well within budget.

III. Budget

The total requested budget is **€ 28.600,-** (€ 26.000, - + 10% unforeseen costs).

Demonstrator development		Dissemination		Project costs	
Description	**Cost €**	**Description**	**Cost €**	**Description**	**Cost €**
Materials - blade	2.000,-	Conference & travel	5.000,-	Consortium travel	2.500,-
Transport of materials (blade)	1.500,-	Making of video	2.000,-		
Prototyping	10.000,-				
FEA study	1000,-				
Demonstrator transport	2.000,-				
Totals	**16.500.-**		**7.000.-**		**2.500.-**

Table 7 Overall budget SRBD

6.9 Feasibility (Structural Analysis)

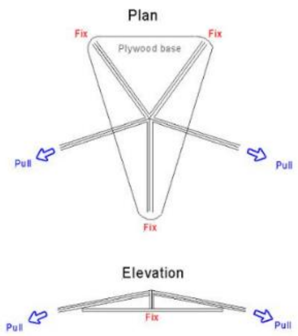


Figure 86 Structural analysis set up

To prove that the plate joint is structurally sufficient to build the geodesic dome, a structural analysis was conducted. (*Geo-Dome*, 2014) proposes a method that is based on the load distribution as explained in Chapter 6.3. This method is designed to test one single hub/joint and avoids a common mistake in analysing its strength; placing all the legs on the ground and standing on it. Instead, it fixes three of the struts and pulls on two of them, recreating the tension-compression division of the forces. Since the panels beneath the most upper joint divide the forces further, testing the joint on the top part of the dome suffices for any joint in the structure.

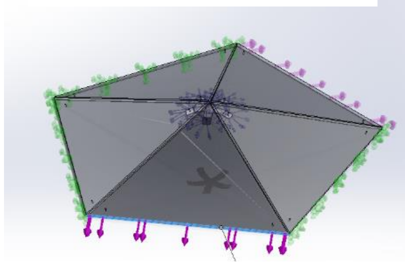


Figure 87 Structural analysis Solidworks

I recreated the testing setup as (*Geo-Dome*, 2014) proposes in SolidWorks. The website explains that the pulling forces should be 3.5 times the load the dome is imagined to withstand. In this case, I will be looking at a snow load to confirm the plate joint is structurally strong enough. To calculate this, the area of the pentagon is needed, which is 2.63m, considering snow will always fall at an angle. If, the Dutch maximum, on average, 10 cm of fresh snow is covering this area, according to (omnicalculator, 2024) this will result in 15.77 Kg of snow load covering this area. Multiplying by 3.5 as a safety factor as (*Geo-Dome*, 2014) proposes, this leads to 15,77 Kg x 9,81 Newton x 3.5 safety factor = 541 N for the pulling forces. After adding the materials of the blade material (Resor, 2013) and the steel of the joint, a FEM analysis in Solidworks is run.

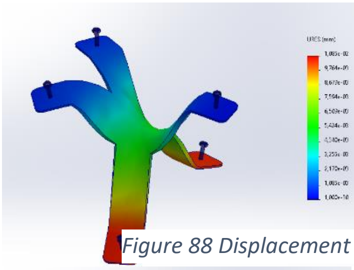


Figure 88 Displacement

Having run the simulation, I took a look at how the forces affect the joint. In Figure 88, it can be seen that the maximum displacement is around 1/100th of a millimetre. This correlates with the maximum stress around 1.6 x 10^6 N/m^2 or 1.6 MPa, which is around 1% of the yield strength of the steel plate material.

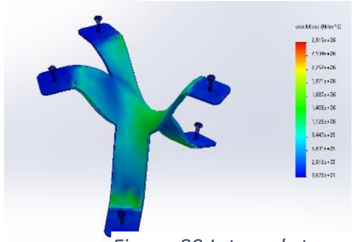


Figure 89 Internal stress

Deeming these safety factors, internal stresses and displacements sufficient to use structurally, I will be moving forward with these plate joint designs.

6.10 Desirability (Prototype)

Although I am able to cut curved triangles out of a digital blade model, as discussed in Chapter 6.7, constructing a dome digitally has been proven hard as shown in Chapter 6.3. To get a better understanding of how the dome looks, using curved triangular panels, a physical prototype is constructed.

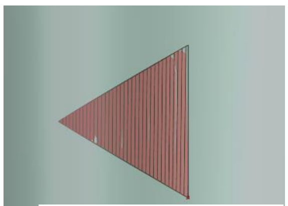


Figure 90 Baked triangle

Firstly, the Rhinoceros-file is used to create the panels needed for the scale model. 30 AAB and 10 BBB triangles are chosen rather randomly throughout the surface of the NREL 5MW blade, using the triangulation method, as described in Chapter 6.7. The arbitrariness of where the panel is cut out of the blade supports the idea that using the triangulation method will always generate geometrical accurate triangles, no matter the curvature of the blade. The 40 triangles are given some thickness, are baked and stored as a STL-file.

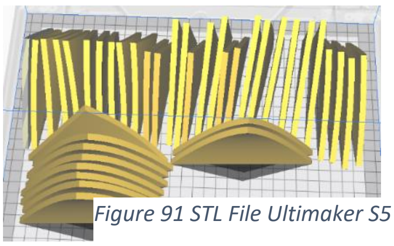


Figure 91 STL File Ultimaker S5

To create a physical scale model, the STL-files are loaded into the Ultimaker Cura-slicer, scaled to 10% and placed vertically. As a built plate adhesion, a raft was added to prevent the print from falling during printing. After uploading the g-code to the Ultimaker s5 and waiting 2 days for the print to finish, 40 scaled triangles were retrieved.

Sadly, during the first print, something went wrong. Not only were some triangles fallen over, all the triangles had weak spot on some specific layers. Since this is a sustainability project, I glued most of the weaker triangles back together instead of printing all 40 again. The triangles that could not be repaired were printed again, this time with more space between them to prevent falling again.

Figure 92 First test print

To actually construct the dome, the plate joints were printed as well. The first print attempt was done by just scaling the joints to 10%. However, this lead to very small walls, which were hard to retrieve from the print bed. To ensure a better wall thickness for the print, I gave the original Solidworks-part a thickness of 10 mm instead of the 3 mm steel plate. This accomplished a more useable scale model to build a prototype.

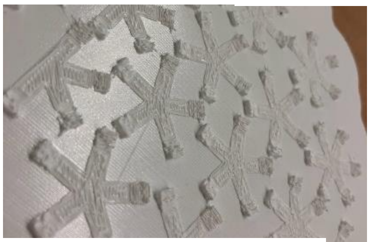


Figure 93 Insufficient layer print

Figure 94 Sufficient layer

To simulate bolt connections in the prototype, glue was used. I started with super glue from Bison, however, these tubes were mostly full of air, and since there are 120 connections in the structure, this did not seem to be an efficient option. After, I tried to use Pattex Contact glue. This glue was also quite strong, yet, it stayed liquid too long and was quite messy. Thereafter, I used Pattex repair glue and build a jig to keep the panels in the right angle while the glue dried for a longer period of time.

Figure 95 Messy glue test

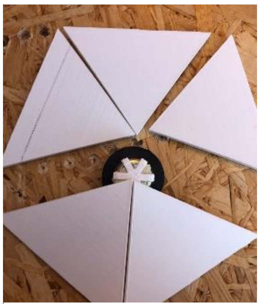


Figure 96 Glue prototype with

This method looked like it provided a strong bond, however, when I started to attach additional panels to the pentagons, the pentagons fell apart again.

Lastly, I used the Instant glue from Pattex. These tubes contain much more glue and is more liquid than the super glue from Bison, which made it easier to use.

Wistfully, the process of creating the 3D-printed prototype had too many problems to finish in time of producing the prototype in time for the deadline of this report. I will try to finish the prototype before the graduation presentation to show the end result of constructing a dome with curved panels. Subsequently, a subassembly was taped together earlier in the prototyping stage. This gives an idea of how the curved panel are fitted together within a dome structure.

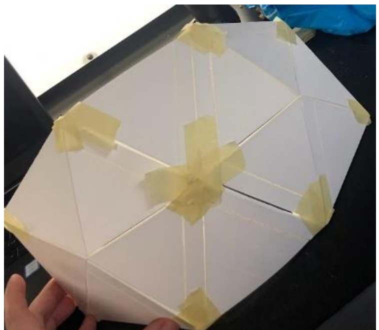


Figure 97 Sub assembly curved panels

7. Final Design

A final design approach is proposed. After creating a geodesic dome in Solidworks, using the desired dimensions provided by the SRBD team, it can be seen that these dimensions may be somewhat too small to be used as a pavilion on the Dutch Design Week. However, this is not a problem, since my design approach is completely scalable.

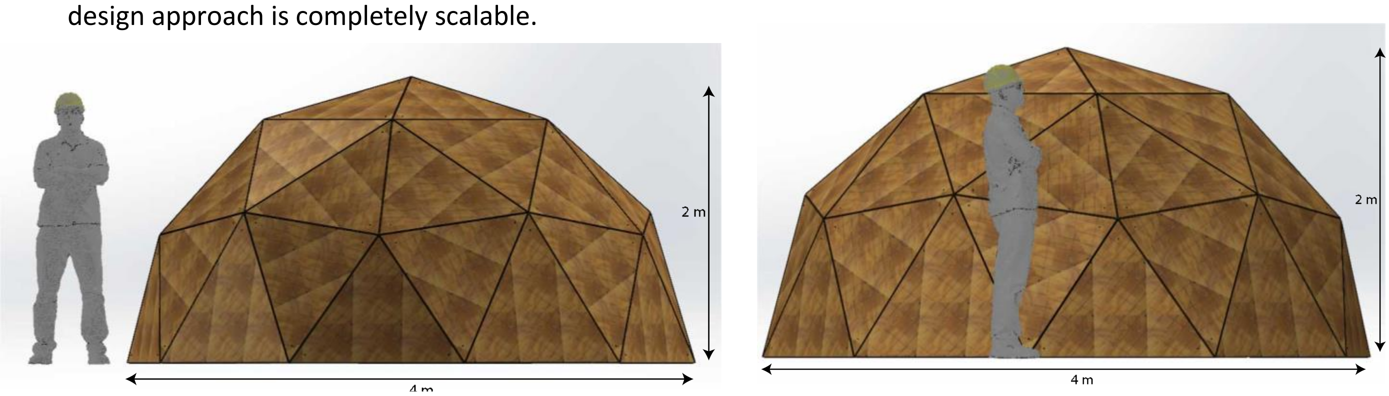
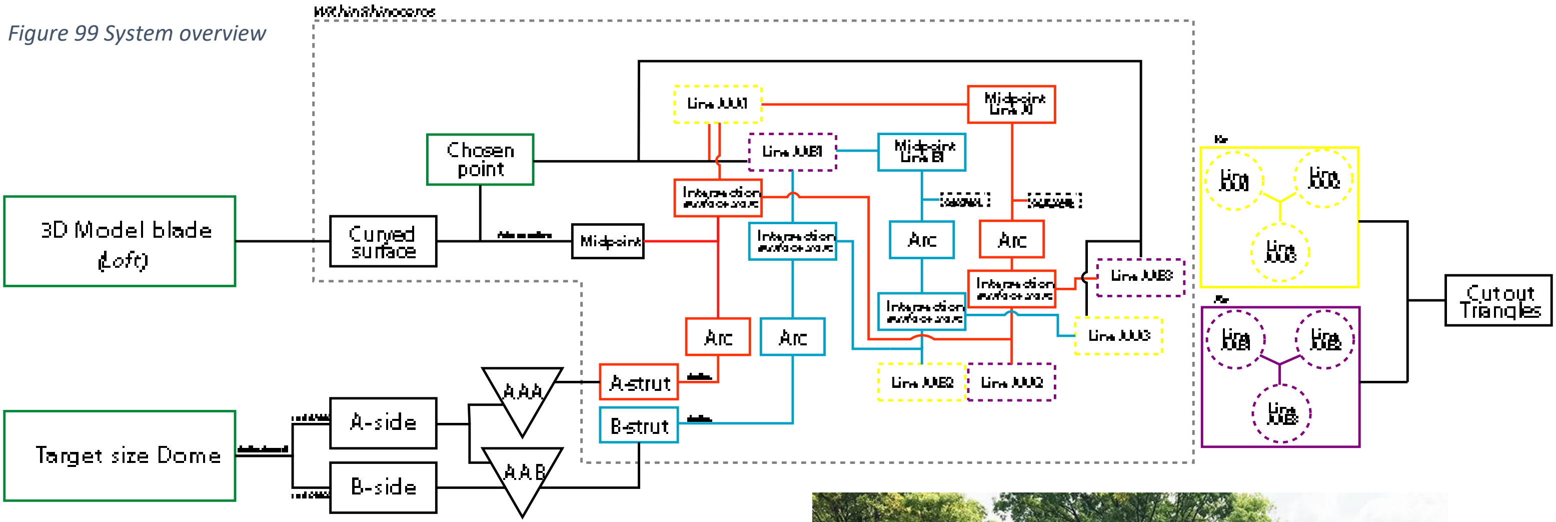


Figure 98 Solidworks Dome assembly

Using the same method as was used to create this model, the dome can be sized up to any size the source material allows. A visual Figure 97 is created to understand the process of translating from source to target. In this visual, only the three green boxes are alternating user inputs, all the other variables are dependent on these three variables. This means that if you have a 3D model of a blade, you know how large you want the dome to be and have chosen a point where you want the slicing of the panels to begin on the surface, the design of the geodesic dome can be scaled to various sizes.

Figure 99 System overview



Considering that wind turbines blades are becoming increasingly large, a number of sizes of domes can be imagined. The first concept I propose, is the one visualised in Figure 99. This might be a more suitable dimension to build at the Dutch Design Week. The space allows for an exposition and it could function as a landmark for the Design Week. In this way, more material could be repurposed as a building material. These panels would just fit a large moving truck and still fit the width of the NREL 5MW blade.


Figure 100 Concept design

The dome design is profitable for events, since the structure only exists of 2 different triangles and 3 different joints. This means that all the materials that are used to build the dome can be "thrown" into a truck, loaded out and constructed quite easily, without having to find out each part individually. It can be shipped as a Do it Yourself-package and assembled by any festival team. This opens up options for even larger scaled domes. As a future design proposal, domes as pictured in Figure 100 or even Figure 101 might be future applications of the same system of translating source material to target construction. The joint design can scaled accordingly.

Figure 101 Concept design 2

Figure 102 Concept design 3

8. Conclusion and future recommendations

By designing a pavilion and a additional assembly and connection system, I learned a lot of valuable lessons during this design project. I will try to summarise them concisely.

Main remarks:

- When designing a pavilion using wind turbine material, it is important to know which blade will be the source material for the construction. Not only will the curvature within the blade differ from blade to blade, the damage of the decommissioned blade will be a deal breaker for using some parts of the blade. Blademade has adopted this way of working already and firstly collects blade material before designing, I advise the SRBD-team do follow this method.
- Using blade material without having to analyse and calculate every single curve, imperfection or unknown variable raises a lot of trouble for structurally reusing the blade material for larger constructions. Like in this project, some of those problems can be overcome by forcing some of the geometry, however, this leads to creases, gaps or other insecurities. In my opinion the focus should lay on using smaller pieces of the blade that are as close to flat as possible. In this way, additions to the plate connections like the ball-socket joints can be avoided.
- Modularity is one of the most important parts of designing a pavilion which is easily assembled, disassembled and moved to another place. A modular design is profitable to evade complexity and make roll out widespread implementation of the dome possible.

As a main recommendation I want to add, it is very important that there is thought more about a system change **before** retrieving the decommissioned blade material. In this way, there is knowledge about which parts are damaged or transport more specific needed parts of the blade **before** designing a construction.

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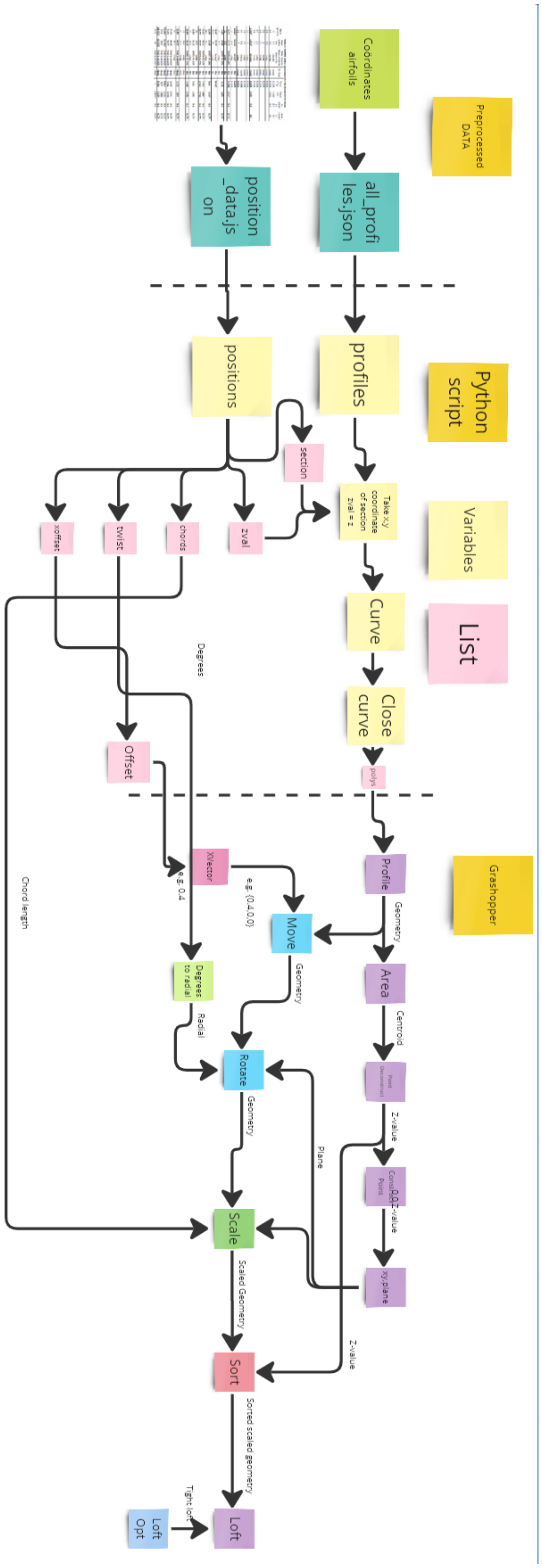
Appendix A: Grasshopper system Mariana Popescu



Bladespan	Shape	Degree	Chord
10,25	DU99-W-405	13,308	4,557
14,35	DU99-W-350	11,480	4,652
22,55	DU97-W-300	9,011	4,249
26,65	DU91-W-250	7,795	4,007
30,75	DU91-W-250	6,544	3,748
34,85	DU93-W-210	5,361	3,502
38,95	DU93-W-210	4,188	3,256

1

Triangle 1	Upper	Lower	Goal	Upper	Lower
a	1,28	1,28	1,24	0,04	0,04
b	1,27	1,27	1,24	0,03	0,03
c	1,24	1,24	1,24	0,00	0,00

Triangle 2	Upper	Lower	Goal	Upper	Lower
a	1,26	1,27	1,24	0,02	0,03
b	1,26	1,26	1,24	0,02	0,02
c	1,24	1,24	1,24	0,00	0,00

Triangle 3	Upper	Lower	Goal	Upper	Lower
a	1,27	1,25	1,24	0,03	0,01
b	1,26	1,25	1,24	0,02	0,01
c	1,24	1,23	1,24	0,00	-0,01

2

Triangle 1	Upper	Lower	Goal	Upper	Lower
a	1,28	1,27	1,24	0,04	0,03
b	1,28	1,28	1,24	0,04	0,04
c	1,24	1,24	1,24	0,00	0,00

Triangle2	Upper	Lower	Goal	Upper	Lower
a	1,26	1,27	1,24	0,02	0,03
b	1,26	1,28	1,24	0,02	0,04
c	1,24	1,24	1,24	0,00	0,00

Triangle3	Upper	Lower	Goal	Upper	Lower
a	1,26	1,24	1,24	0,02	0,00
b	1,27	1,25	1,24	0,03	0,01
c	1,24	1,24	1,24	0,00	0,00

3

Triangle 1	Upper	Lower	Goal	Upper	Lower
a	1,10	1,10	1,09	0,01	0,01

Upper	
0,04	
0,03	
0,00	
0,02	
0,02	
0,00	Lower
0,03	0,04
0,02	0,03
0,00	0
0,04	0,03
0,04	0,02
0,00	0
0,02	0,01
0,02	0,01
0,00	-0,01
0,02	0,03
0,03	0,04
0,00	0,00
0,01	0,03
0,01	0,04
0,00	0
0,00	0
0,01	0,01
0,00	0
0,01	0,01
0,01	0,01
0,00	0,00
0,00	0,04
0,01	0,04
0,00	0,00
0,01	0,04
0,01	0,04
0,00	0,00

b	1,10	1,10	1,09	0,01	0,01
c	1,24	1,24	1,24	0,00	0,00

Triangle2	Upper	Lower	Goal	Upper	Lower
a	1,09	1,13	1,09	0,00	0,04
b	1,10	1,13	1,09	0,01	0,04
c	1,24	1,24	1,24	0,00	0,00

Triangle3	Upper	Lower	Goal	Upper	Lower
a	1,10	1,13	1,09	0,01	0,04
b	1,10	1,13	1,09	0,01	0,04
c	1,24	1,24	1,24	0,00	0,00

4

Triangle 1	Upper	Lower	Goal	Upper	Lower
a	1,09	1,12	1,09	0,00	0,03
b	1,1	1,14	1,09	0,01	0,05
c	1,24	1,24	1,24	0,00	0,00

Triangle2	Upper	Lower	Goal	Upper	Lower
a	1,1	1,11	1,09	0,01	0,02
b	1,1	1,12	1,09	0,01	0,03
c	1,24	1,24	1,24	0,00	0,00

Triangle3	Upper	Lower	Goal	Upper	Lower
a	1,1	1,10	1,09	0,01	0,01
b	1,1	1,10	1,09	0,01	0,01
c	1,24	1,24	1,24	0,00	0,00

5

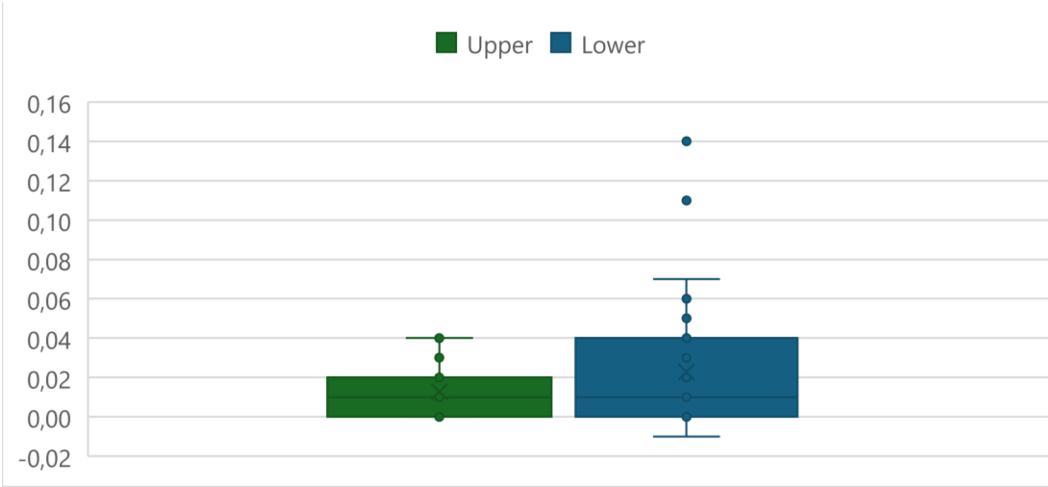
Triangle 1	Upper	Lower	Goal	Upper	Lower
a	1,12	1,11	1,09	0,03	0,02
b	1,12	1,11	1,09	0,03	0,02
c	1,24	1,24	1,24	0,00	0,00

Triangle2	Upper	Lower	Goal	Upper	Lower
a	1,1	1,15	1,09	0,01	0,06
b	1,11	1,16	1,09	0,02	0,07
c	1,24	1,24	1,24	0,00	0,00

Triangle3	Upper	Lower	Goal	Upper	Lower
a	1,11	1,2	1,09	0,02	0,11
b	1,12	1,23	1,09	0,03	0,14
c	1,24	1,24	1,24	0,00	0,00
				0,01	0,02

0,01	0,03
0,01	0,05
0,00	0,00
0,03	0,02
0,03	0,03
0,00	0,00
0,01	0,01
0,02	0,01
0,00	0,00
0,02	0,02
0,03	0,02
0,00	0,00
	0,06
	0,07
	0,00
	0,11
	0,14
	0,00

Difference goal vs reality


Upper
Lower
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
-0,02

Kik Media&Techniek

Offertedatum:
Referentie:
Omschrijving:

Geachte heer Kik,

30-3-2024
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Hartelijk dank voor uw offerte aanvraag
Overeenkomstig onze algemene leveringsvoorwaarden kunnen wij u aanbieden:

	#	Omschrijving	Aantal	4-4-2024 Prijs/St.	9-4-2024 Prijs/St.	15-4-2024 Prijs/St.	24-4-2024 Prijs/St.	3-5-2024 Prijs/St.
	1	3 way Plaat - KGW DC01 - 3 mm - Stikstof W=169,0 x H=289,0 mm	10	€ 6,14	€ 4,30	€ 4,22	€ 4,18	€ 4,12
	2	5 way Plaat - KGW DC01 - 3 mm - Stikstof W=272,9 x H=285,9 mm	6	€ 8,42	€ 5,84	€ 5,73	€ 5,66	€ 5,58
	3	6 way Plaat - KGW DC01 - 3 mm - Stikstof W=268,2 x H=289,0 mm	10	€ 9,35	€ 6,46	€ 6,34	€ 6,27	€ 6,17
			Subtotaal	€ 205,42	€ 142,64	€ 139,98	€ 138,46	€ 136,38
			Verpakkingskosten	€ 12,50	€ 12,50	€ 12,50	€ 12,50	€ 12,50
			Transportkosten	€ 16,55	€ 16,55	€ 16,55	€ 16,55	€ 16,55
			Totaalprijs	**€ 234,47**	**€ 171,69**	**€ 169,03**	**€ 167,51**	**€ 165,43**

Levering
Leveringsconditie: Af Fabriek

Transport
Transport:
Afleveradres:

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Betaling binnen 30 dagen netto

Prijzen
Prijzen: Deze aanbiedingsprijs is 48 uur geldig
Betalingsconditie:

Geldigheid
Geldigheid:

Wij vertrouwen erop u hiermee een passende aanbieding te hebben gedaan en zien uw bestelling graag tegemoet.

Aanneming van opdrachten geschiedt te allen tijde onder voorbehoud van beschikbaarheid van de bestelde materialen. In situatie van overmacht houdt zich het recht voor de levertijden aan te passen.

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