



University of Wales Trinity Saint David
School of Engineering

‘Design for X Project – DfAM Task One’

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1. Introduction.

This technical report aims to investigate the potential benefits of transitioning the fabrication process of a component produced by traditional subtraction fabrication methods to adopting additive manufacturing processes. The report will analyse the various aspects involved in this transition, including design optimisation, manufacturing considerations, material selection, and cost evaluation. For this case study, the component selected for optimisation and design for an AM process was a bespoke pipe shoe used to elevate and support piping from a structural base (Figure 1).

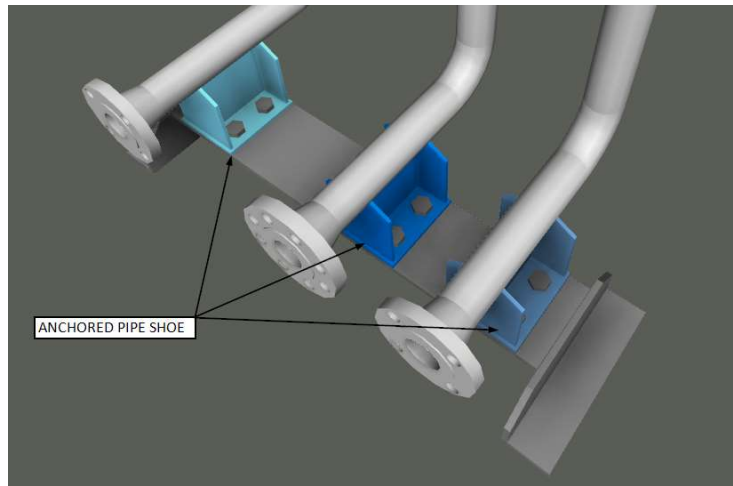


Figure 1 – Pipe Shoes 3D Model (Totec Design Ltd, 2021)

The pipe shoe is a frequently used part in industrial plants that facilitate the transportation of fluids or gases through piping to different destinations. Different types of pipe shoes are available, and various commercial off-the-shelf options are available for purchase (Figure 2).



Figure 2 - Clamped and Non-Clamped Pipe Shoes (QPS, 2017)

For this report, an academic investigation was conducted on the technical aspects of design for AM, including design optimisation techniques, material selection criteria and manufacturing process considerations, forming a comprehensive evaluation.

2 Pipe Shoe.

2.1 Pipe Shoe Function.

A pipe shoe has two functions; it is used to elevate piping from its supporting structure and fix or guide the piping depending on the piping configuration; by elevating the piping from the supporting structure, the piping is protected from wear and corrosion, prolonging the life of the piping system. Fixing the shoe or allowing it to slide can help piping systems that grow or contract with changing temperatures (Figure 3); a fixed shoe is commonly known as an anchor in pipe stress analysis. Another common reason to use a pipe shoe is for insulated piping; the shoe allows for efficient insulation application while elevating the insulation away from any sources of moisture. In various piping systems, the height of the shoe is governed by space, and the dimension of the shoe can be dictated by supporting steel locations, resulting in bespoke shoe designs.

“Bare pipes that rest on surrounding objects are subject to grinding, friction, and wear” (Appmfg, 2023).



Figure 3 - Anchor Directing Thermal Growth (Pipingtech, 2023)

2.2 Traditional Fabrication Process.

The traditional fabrication method for pipe shoes has commonly used laser-cut profiled plates for shape requirements, bonded by welding, and welded to the piping (Figure 4). This process would include the cost of the profile plates, the ability to interpret a technical drawing and labour for fitting, welding, and inspection.

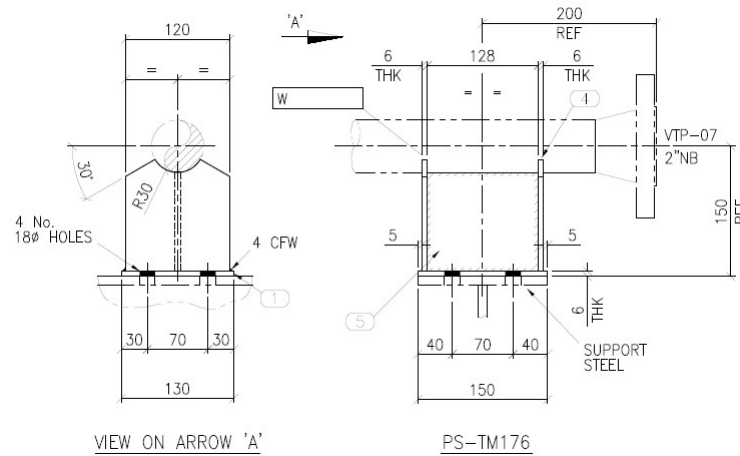


Figure 4 – 2D Fabrication Detail of Typical Pipe Shoe (Totec Design Ltd, 2021)

3 Design for Additive Manufacturing.

3.1 Additive Manufacturing.

Initially utilised as a rapid prototyping tool, AM has quickly become a viable option for manufacturing functional components; many industries have adopted the process, including aerospace, automotive, consumer products and medical, where a cost-saving or design improvement was evident. (Vaneker, et al., 2020)

Design for Additive Manufacturing requires a new perspective; traditional manufacturing principles do not transfer to this process. Replicating conventional part geometry using additive manufacturing may lead to costlier components that still need post-processing to achieve the desired design characteristics. AM can be considered an additional tool alongside traditional approaches, increasing the options for creating previously impossible components with traditional methods or, if cost-effective, replacing these methods where all design principles could be met. (Godec, et al., 2022)

AM processes have removed the restrictions on component design compared to other manufacturing processes like injection moulding and CNC machining (All3dp, 2023). Additively manufactured parts display unique attributes, including strengthening internal structure shapes, part consolidation, complex geometric shapes, mass customisation and multi-material design.

3.2 DfAM Principles.

(Altair, 2022) state the following fundamental principles that can be followed before attempting to design for additive manufacturing:

Designing for the correct process:

Understanding which AM process best suits the chosen component is the first step to creating a component; knowledge of each process is essential to understand the design constraints imposed on each process.

Design for minimal material use:

When designing for AM, the minimal amount of material required to produce the part successfully is a key requirement. Achieving this can be affected by part orientation, self-supporting structures, and the use of 45° chamfers.

Design for improved functionality:

AM offers opportunities to produce complex internal structures, textures, and geometries, removing the restrictions of traditional processes and creating more freedom for designers.

Design for part consolidation:

Another aim is to reduce part numbers by consolidating multiple parts into fewer final parts. Consideration for maintenance and future repair needs to be taken.

4 Methodology.

4.1 Material Selection.

Pipe shoe material will always match the parent pipe material where the shoe must be welded to the pipe due to stiffness requirements in the pipe stress analysis; in this case, the piping material requirement was **Stainless Steel 316L**, and the shoe material would be the same grade.

4.2 Manufacturing Process.

Utilising research into the AM field, the following processes were identified as potential options for producing the shoe, and an evaluation was conducted to select the process; such considerations for the shoe were the requirement for welding to the pipe after production, the structural properties to withstand operation forces and cost comparison. The AM process was selected at the design stage to consider the restrictions applied by the processes identified. Utilising the AM process would remove the need for the assembly of the shoe's separate parts and consolidate them into one part.

4.2.1 Powder Bed Fusion.

Powder Bed Fusion, also known as PBF, as shown in Figure 5, involves powdered metals evenly distributed on a machine bed and the use of a laser or electron beam to selectively fuse the desired shapes layer by layer; this operation is conducted in a vacuum of inert gas to protect the powder from oxidation. (Twi-global, 2023)

Types of powder bed fusion for metals: Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective laser sintering (SLS) and Selective heat sintering (SHS)

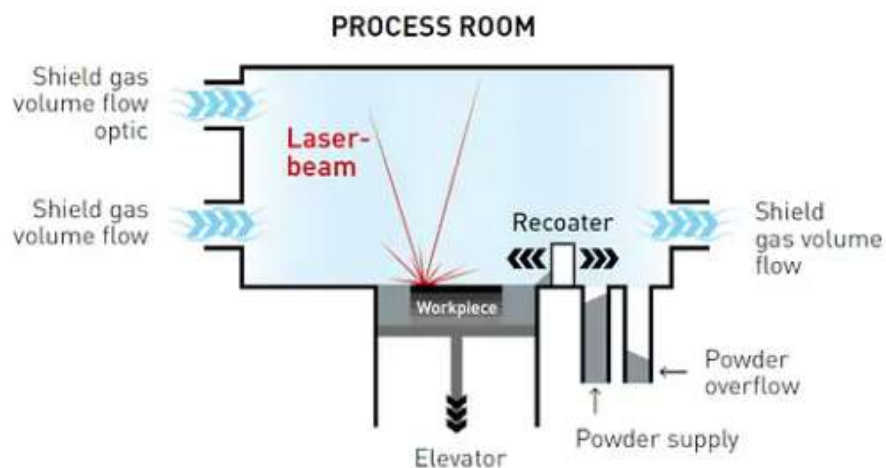


Figure 5 – Laser Powder Bed Fusion (Dmgmori, 2023)

The benefits of this process are low costs, a wide range of materials supported, fewer supporting requirements due to the powder acting as a support, and the ability to recycle some unused powder. (Engineeringproductdesign, 2023)

There are some disadvantages in that the print time can be slow, post-processing may be required, structural properties can be weak, and issues with residual stresses caused by fast heating and cooling of the new layer of powder turned molten, fusing to the cooling solid layer of previously melted powder below it (Figure 6) creating shear forces between the layers (Renishaw, 2023)

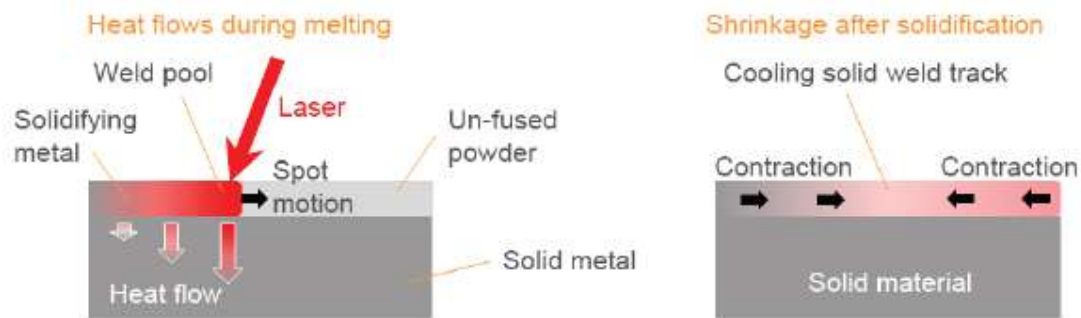


Figure 6 - Laser melting of a new weld track (Renishaw, 2023)

Residual Stress can also lead to distortion of the component, resulting in cracking and curling between layers; this is primarily found in parts with large cross-sections (Figure 7). Due to this phenomenon occurring during the process, post-stress relief heat treatments are of no use (Kardys, 2017).



Figure 7 - Cracking and Distortion (Renishaw, 2023)

Several solutions to the residual stress issues faced by PBF have been introduced: the use of electron beam over laser beam, heating of the chamber, heating of the build plate, avoiding areas of uneven thickness and significant cross-sectional changes in the design.

According to (Selmi, et al., 2023) stainless steel 316L parts produced by PBF contain comparable strength levels, in strength and fatigue, as traditionally welded laser cut plate, and the weld performance can be achieved between two 3D printed parts or with parts produced by traditional methods.

4.2.2 Direct Energy Deposition.

Direct Energy Deposition, also known as DED, deposits material from a nozzle in the form of a powder or wire onto a base and is heated with an electron beam or a laser (Figure 8) both electron beam and laser require full vacuums or gas shielding for operation (Carlota, 2019).

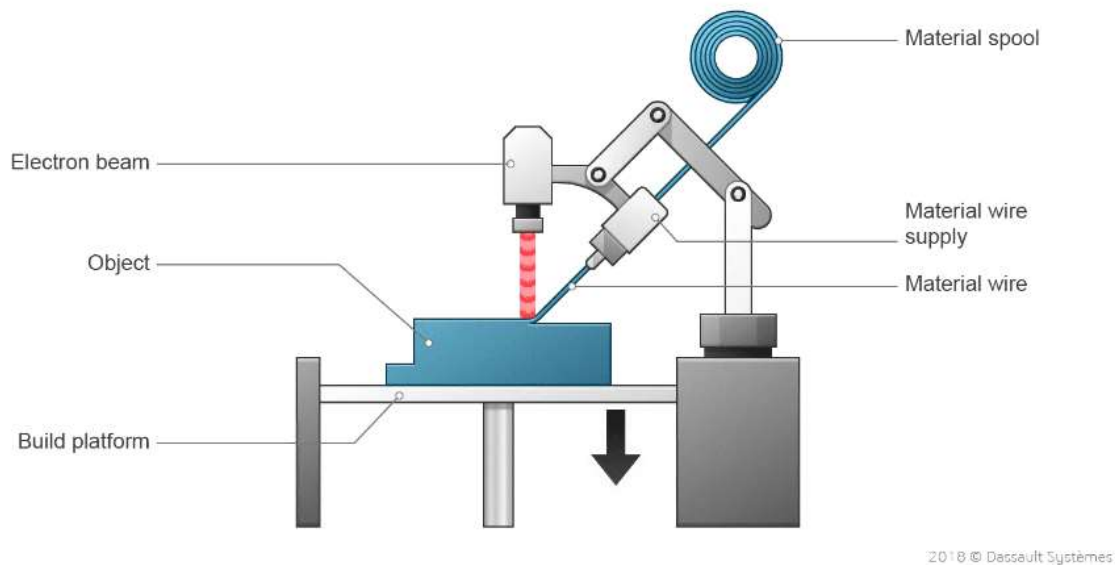


Figure 8 - DED Electron Beam Diagram (Dassault-Systemes, 2023)

Using a nozzle mounted on a multi-axis robotic arm and a similar concept for the build platform, results in material application in multiple directions; the material is deposited layer on layer between 0.25mm and 0.5mm thick. Some advantages are the ability to influence the grain structure, creating desirable properties, larger part sizes, and producing composite material parts. (Twi-global, 2023)

All3dp (2023) state that one benefit of the process is that it does not require support structures due to the multi-directional movement of the nozzle or head, but this is contradicted by (Engineeringproductdesign, 2023) who state, that due to the build process and the inability to utilise support structures, some designs cannot be constructed.

There are some disadvantages to this process, including substantial initial investment in equipment, post-processing can be intensive when high surface finish is required and the complexity of the design stage when using this process to its potential (All3dp, 2023).

4.3 Design and Development.

To utilise the benefits of AM, the original design was analysed using FEA, topology, and generative design; this was completed using Autodesk Fusion 360. (Autodesk, 2023)

Using AutoCAD software (Autodesk, 2023) the pipe shoe and wrapper plate were modelled as one uniform solid (Figure 9) to utilise in an FEA and topology study.

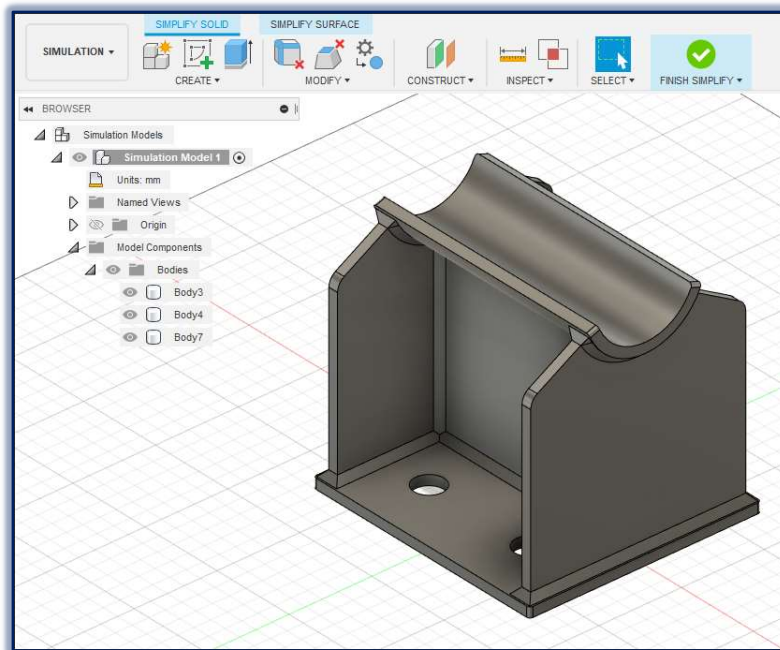


Figure 9 – Pipe Shoe

For generative design requirements, the pipe body, fixings and supporting base structure were added (Figure 10). All studies and generative designs were applied using Fusion 360 (Autodesk, 2023).

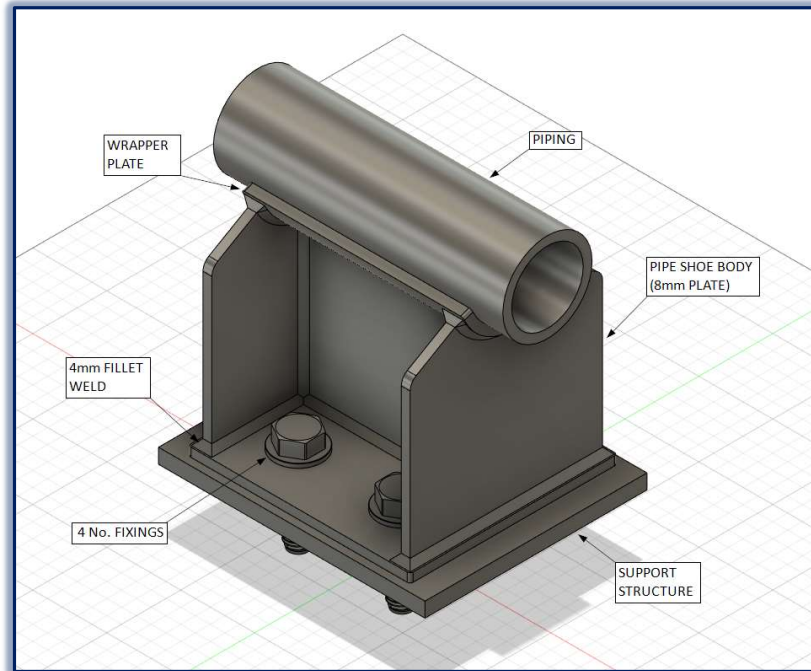


Figure 10 – Generative Design 3D Model.

4.3.1 Finite Element Analysis.

The Shoe was analysed using the static stress tool (FEA) in Fusion 360 (Figure 11)

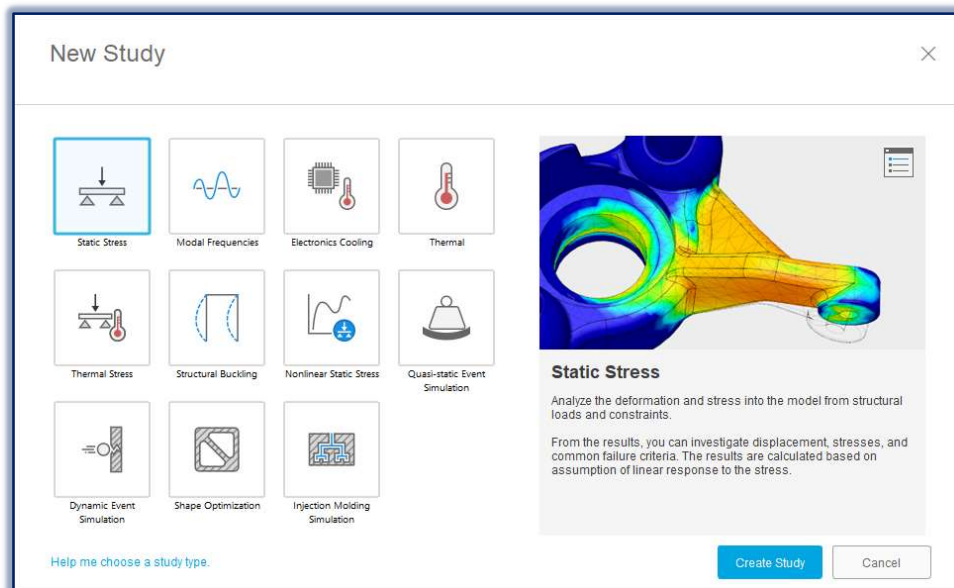


Figure 11 – FEA Selection

Simulated loads were applied in all directions.

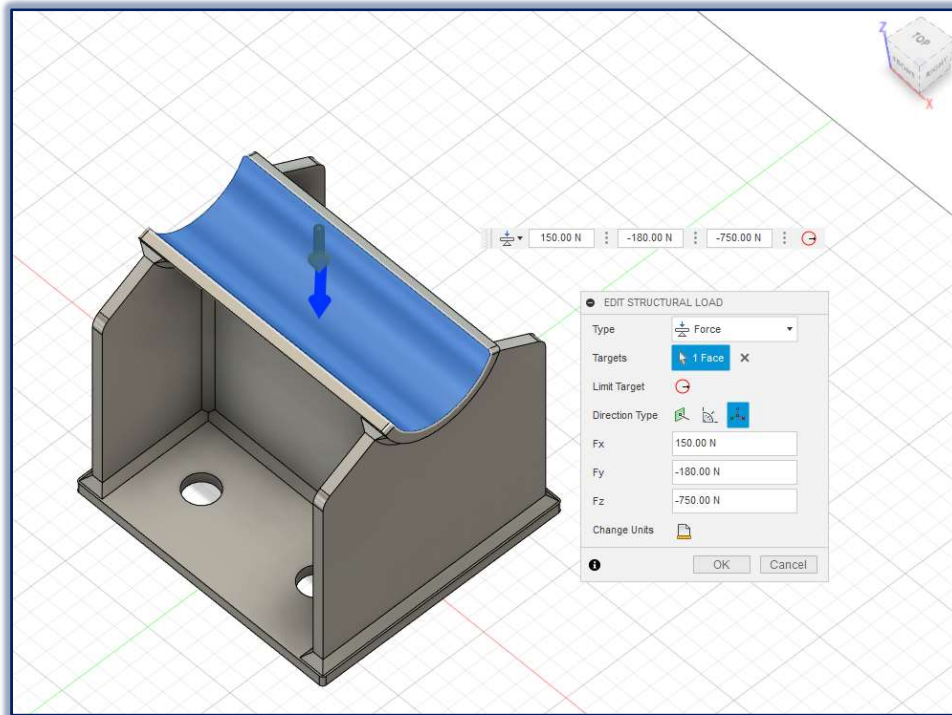


Figure 12 – Load Case

To achieve a higher level of accuracy in the FEA results, a finer mesh was applied (Simutechgroup, 2023)

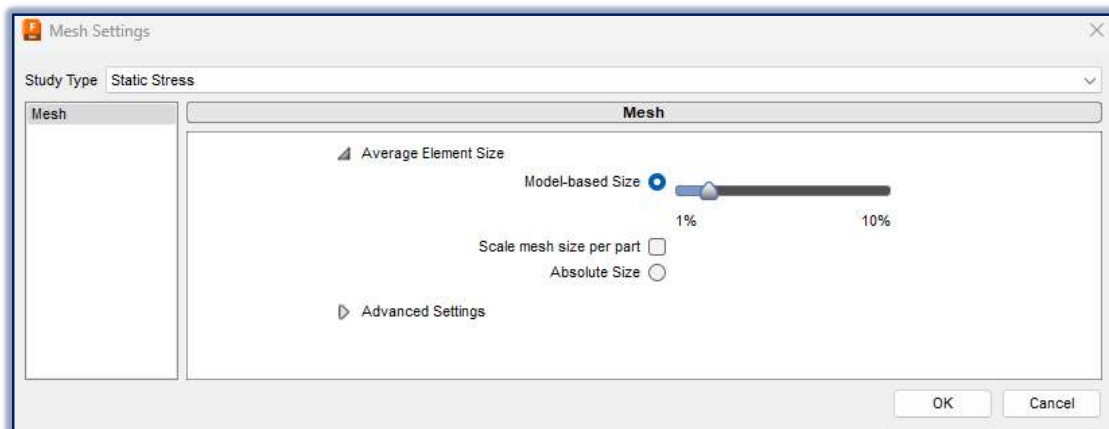


Figure 13 – Mesh Settings

4.3.1.1 Results.

The following results were achieved from the static stress study:

Minimum safety factor: 6.85 (Figure 14)

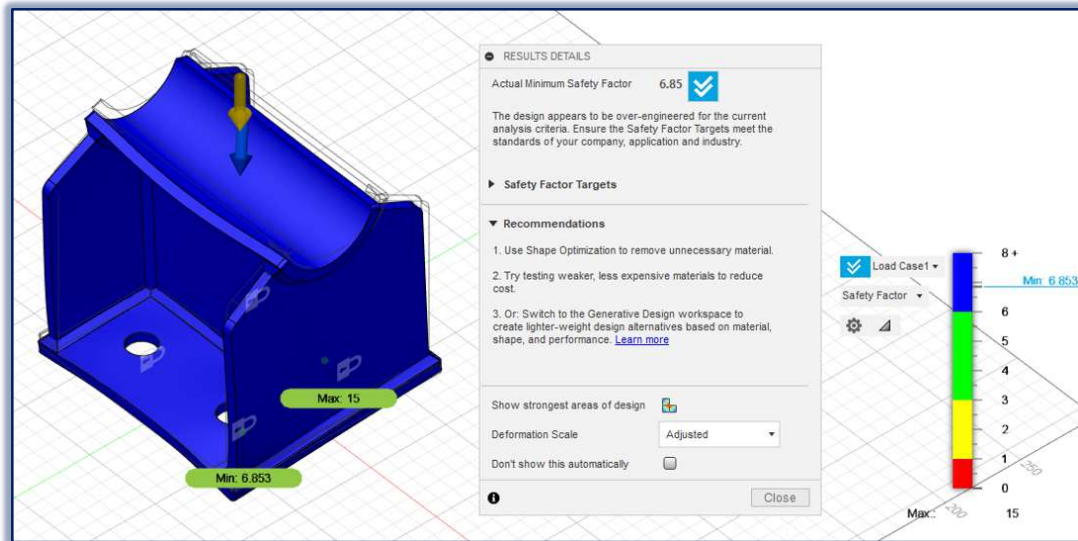


Figure 14 – Factor Of Safety

Stress: Min = 0.002493 MPa, Max = 24.81 MPa (Figure15).

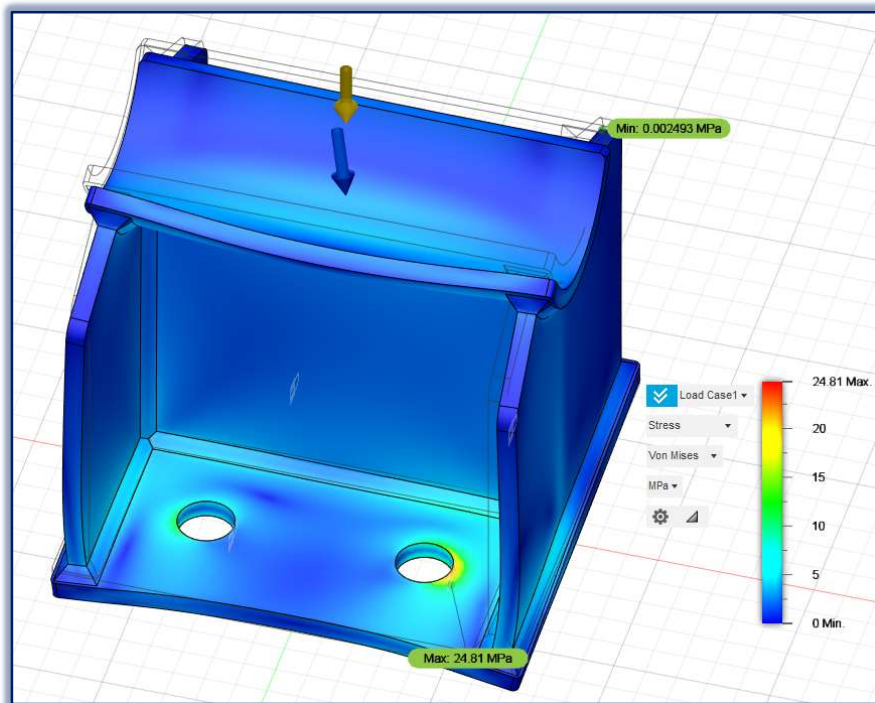


Figure 15 – Stress

Strain: input (Figure 16).

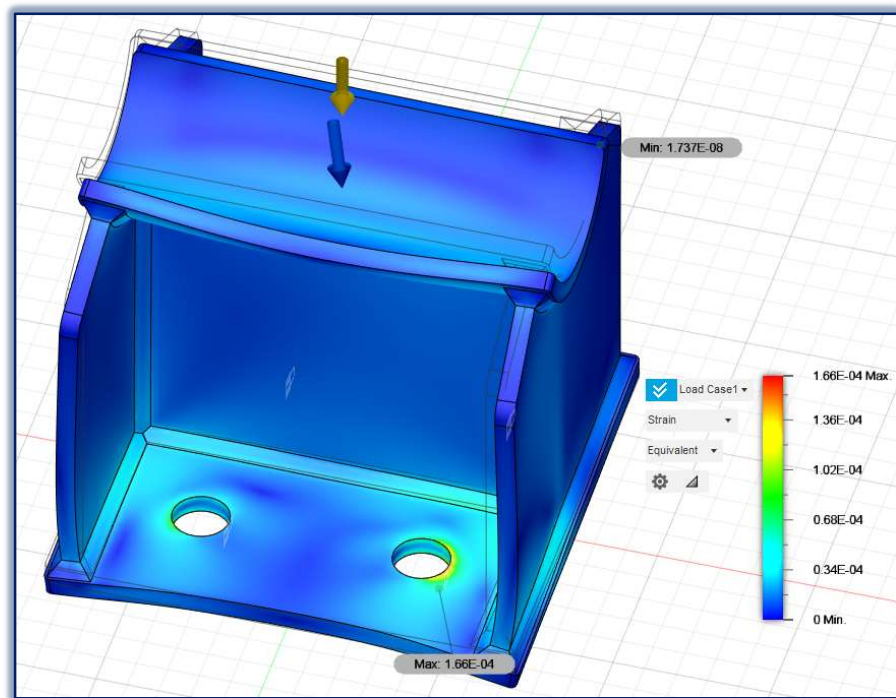


Figure 16 – Strain

Displacement: Min = 0mm, Max 0.01141 (Figure 17).

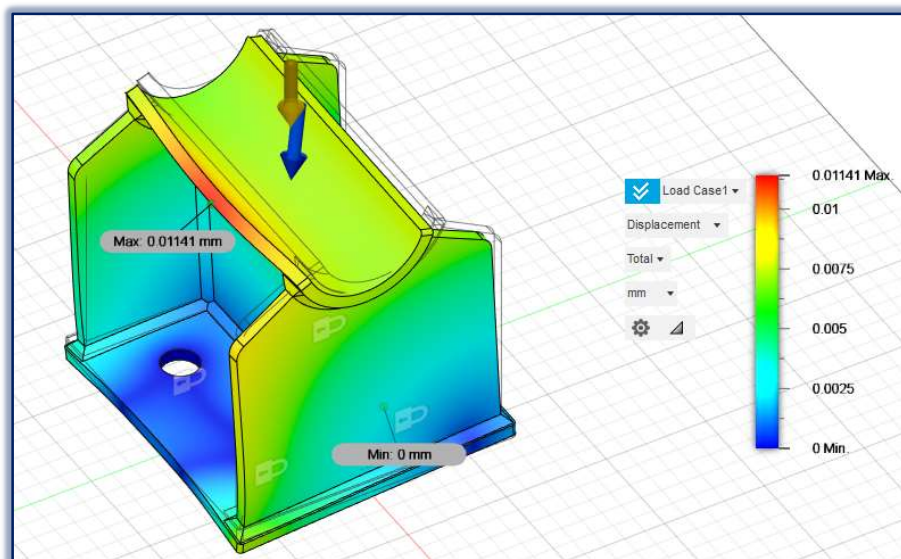


Figure 17 – Displacement

Based on the evaluation of the results, it was found that the safety factor was 6.85. Normally, pipe support components are designed to a factor of 2.5. (Pipingtech, 2023). The choice of material for this component was stainless steel 316L, which displays a yield strength of 170MPa. After analysing the maximum stress acting on the component, which was calculated to be 24.81MPa, it can be concluded that this part is suitable for optimisation.

4.3.2 Topology Optimisation.

To apply topology to the shoe, areas of preservation for functionality requirements were determined, in this case, the wrapper plate thickness required for welding the shoe to the pipe and the areas where the shoe is bolted to a support structure; these areas are indicated in green (Figure 18).

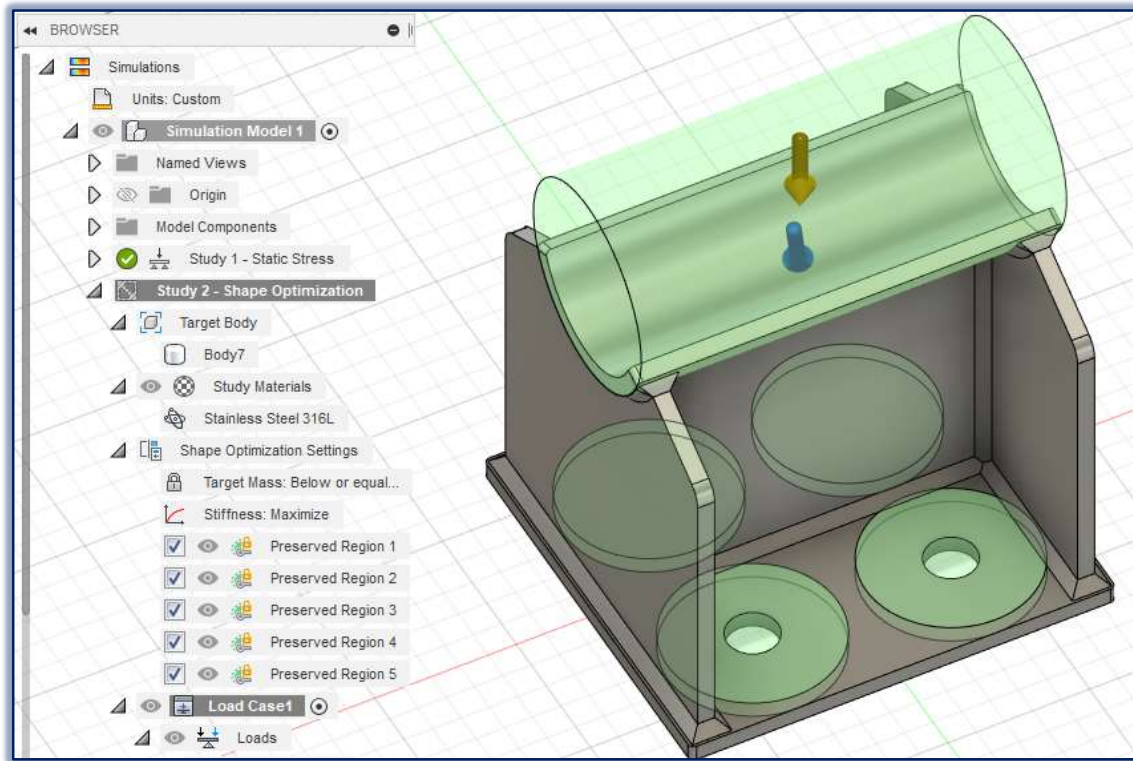


Figure 18 – Preserved Areas

Simulated loads were applied to the shoe using four load cases to achieve forces in all planar directions simulating the pipe's potential movement (Figure 19).

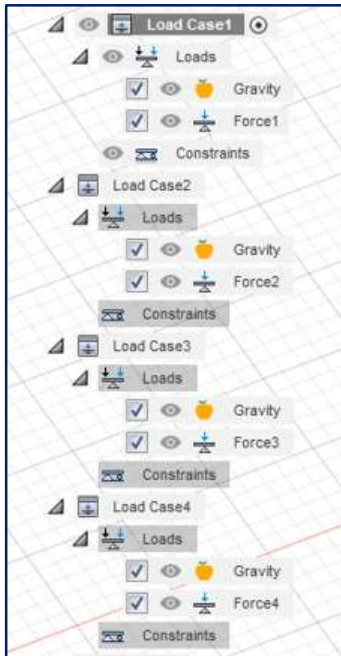


Figure 19 – Load Cases

Structural constraints were applied on the shoe where the fixing bolt holes were located; these are indicated in blue in the model (Figure 20).

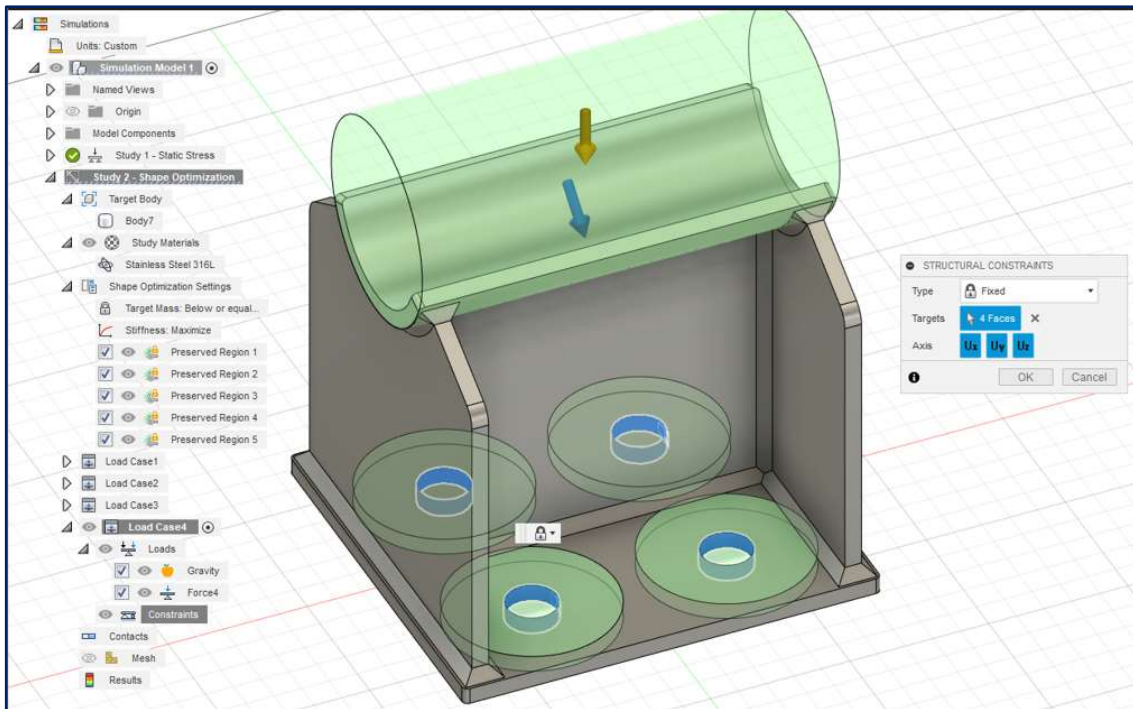


Figure 20 – Structural Constraints

4.3.2.1 Results.

The following optimisation was produced by Fusion 360:

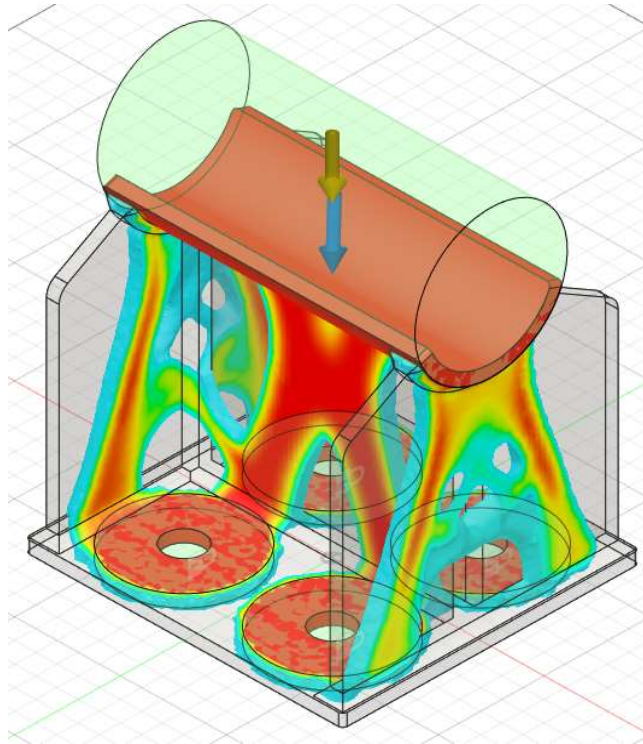


Figure 21 –Topology Isometric View

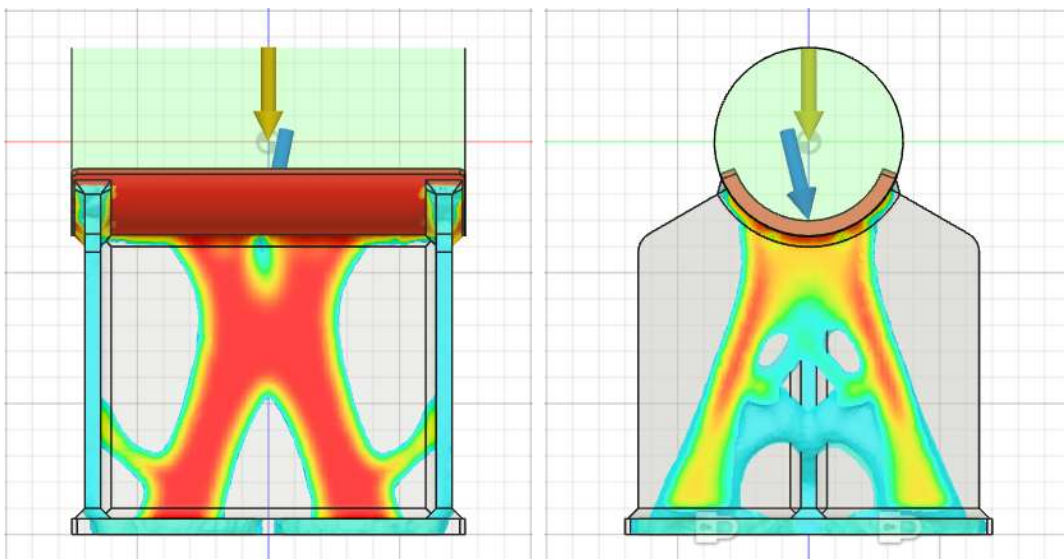


Figure 22 – Topology Side and End Views

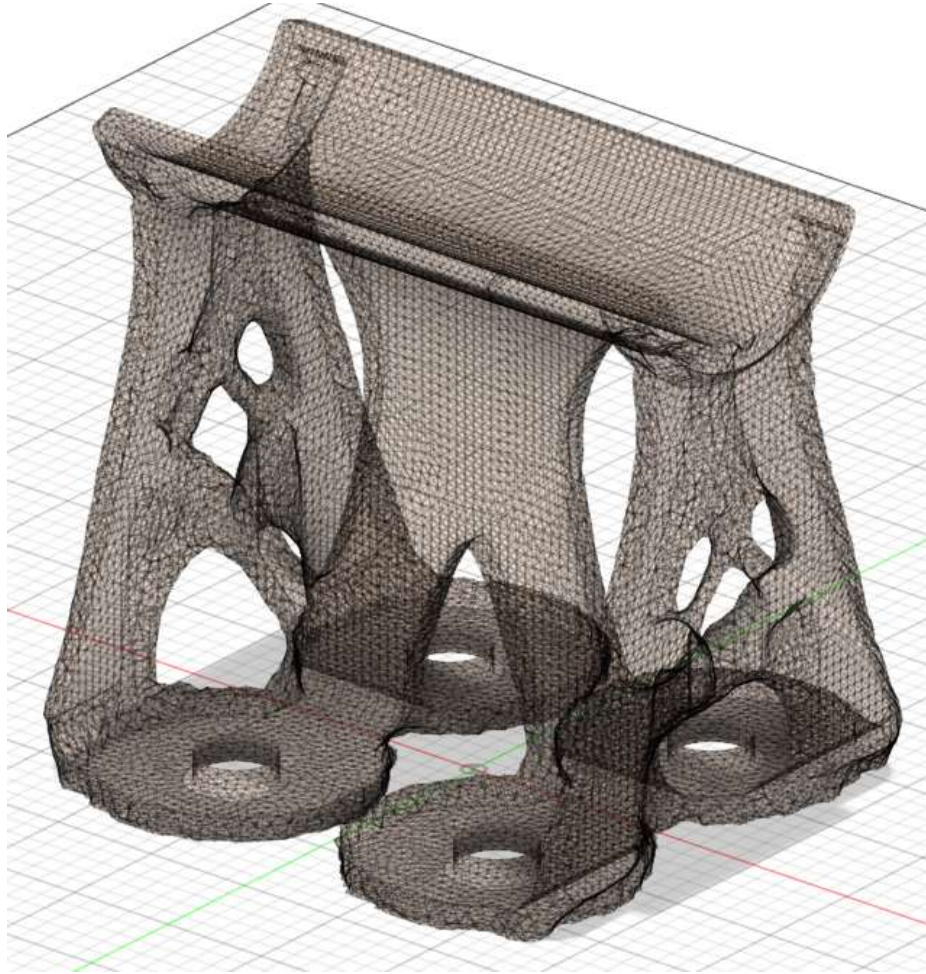


Figure 23 – Topology Mesh Isometric View

Compared to the original design, the topology output has reduced weight by 42%, leaving only the necessary structural material. Traditionally, topology has been applied to conventional manufacturing processes and does not consider factors critical to additive manufacturing processes. To achieve a design more aligned with the AM process, the generative design tool was applied, and the topology output was used to compare the structural integrity of the generative design.

4.3.3 Generative Design.

Generative design is a design exploration process. Designers or engineers input design goals into the generative design software, along with parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints. The software explores all the possible permutations of a solution, quickly generating design alternatives. It tests and learns from each iteration what works and what doesn't. (Autodesk, 2023)

To achieve a functional component from the generative design feature, the following parameters were input, preserved geometry, obstacle geometry and starting shape (Figure 24).

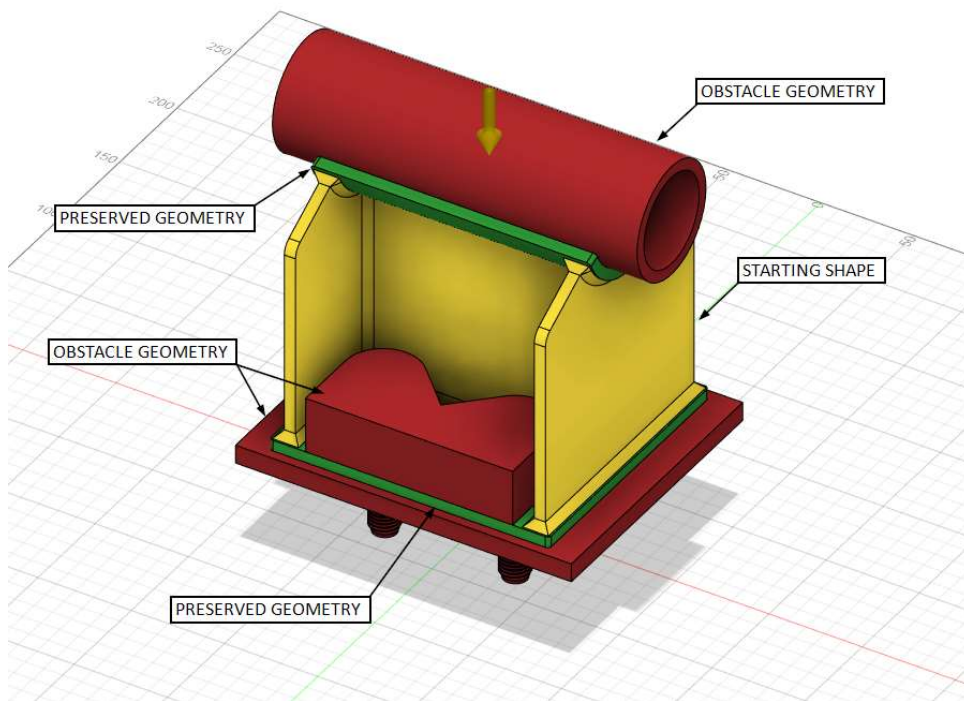


Figure 24 – Generative Design.

The next step was to input the objectives for the component and goals for manufacturing (Figure 25)

OBJECTIVES AND LIMITS

▼ Objectives

Minimize Mass ☒

Maximize Stiffness ☐

▼ Limits

Safety Factor 2.50

Displacement ☐

OK Cancel

▼ ☒ Additive

Orientation X+ Y+ Z+ X- Y- Z-

Include all directions ☒

Overhang Angle 45.0 deg

Minimum Thickness 3.00 mm

Figure 25 – AM Settings

All orientation directions will be considered, and the 45° overhang option has been input to minimise any overhangs less than 45° to aid the AM process. Four load cases were also applied to the study to simulate the loads experienced in operation.

4.3.3.1 Results.

The following designs were processed:

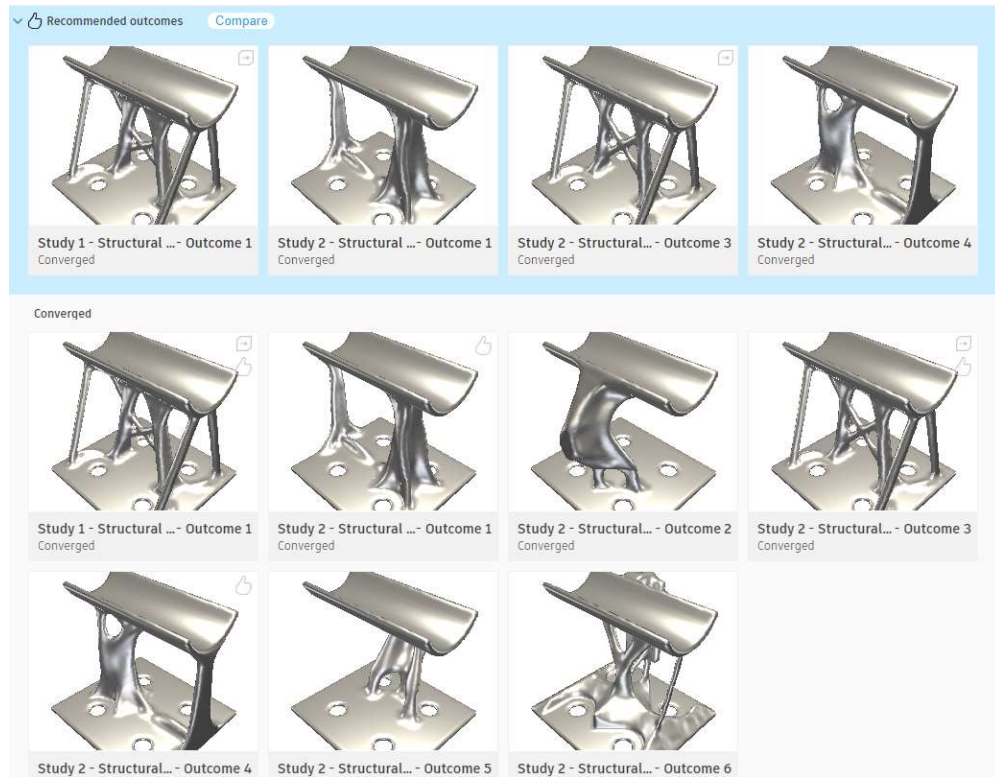


Figure 26 – Generative Design Options

To select a suitable design for optimum structural integrity, the topology output and generative designs were compared (Figure 27) and the generative design was selected for the AM design

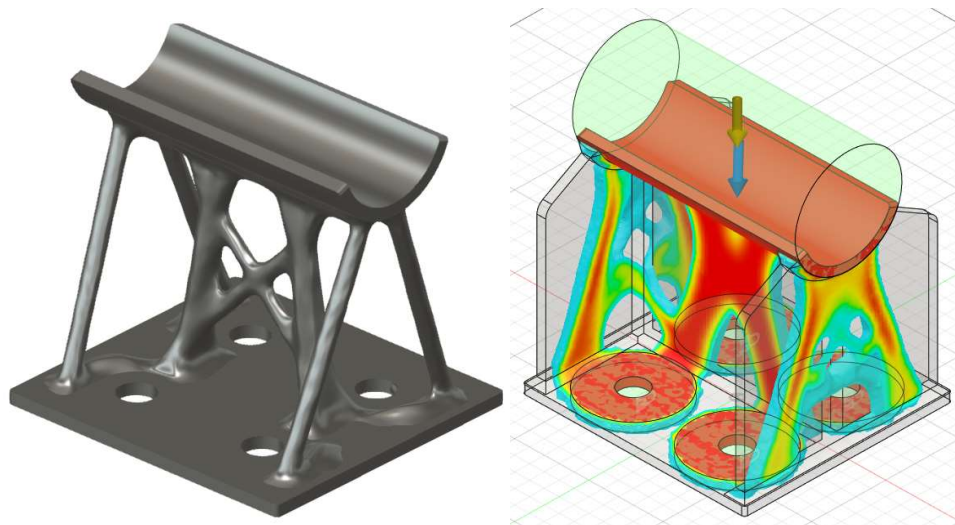


Figure 27 - Generative Design and Topology Comparison

4.3.4 Additive Manufacturing Process Selection.

Although DED had some advantages, such as faster printing, a larger print area, and better mechanical properties of the final product (Engineeringproductdesign, 2023), the AM process of choice for this part was DMLS, and a significant factor in this decision was the uncertainty of producing the part with DED without support structures, as well as the potential complexity of the design process.

Structural integrity was a primary concern for the DMLS process due to anisotropy factors of the layering process. Still, research suggests that this process, in 99% of cases, can produce homogenous masses of material (Protolabs, 2023), a study by (Kim, 2021) on 316L material, in particular, argues that AM- created parts contained higher mechanical properties than conventionally manufactured parts.

The pipe shoe will be manufactured in accordance with specification: [ISO/ASTM52911-1-19 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals](#) (ASTM, 2019)

4.3.5 Orientation Selection.

To optimise the design for AM, the orientation of the part for printing can influence such factors as support structure volumes, the coating blade direction of build and minimising large cross-sectional areas that would experience heat build-up (Figure 29).

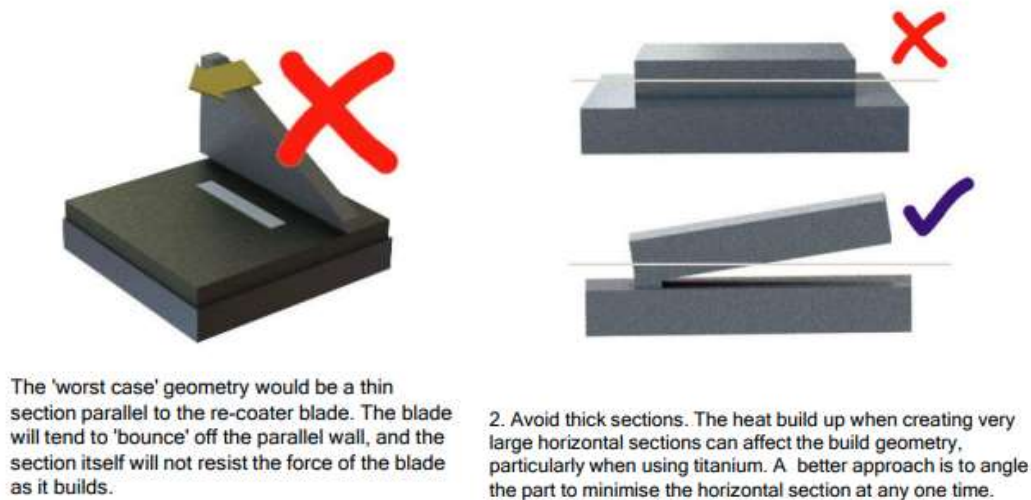


Figure 28 - Orientation Considerations (Crucible design, 2015)

Utilising the additive build extension in Fusion 360 (Figure 30), it was possible to explore different orientation options to achieve efficient support volumes; as seen in Figures 31 to 34, the orientation can impact the support volume and area.



Figure 29 - Additive Build Extension

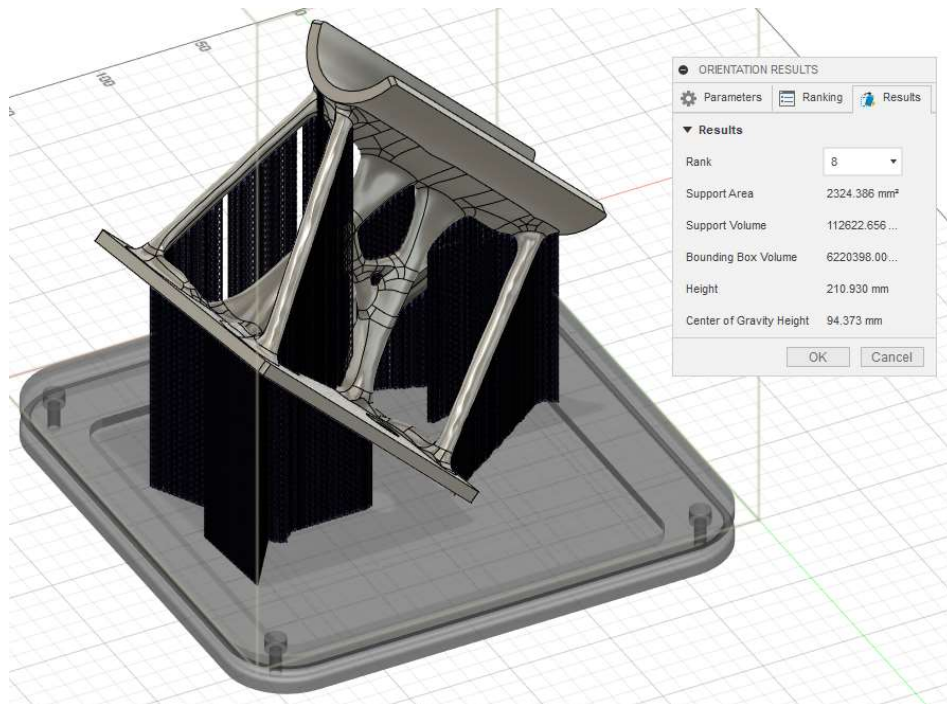


Figure 30 - Lowest Support Volume Orientation

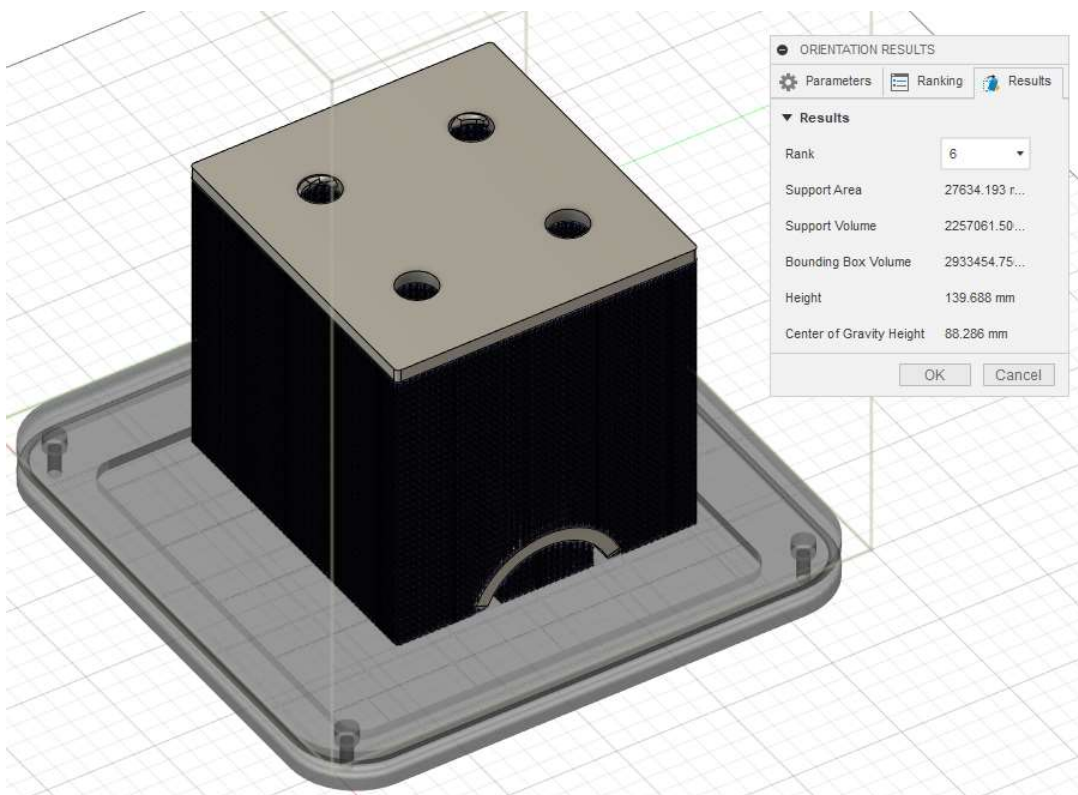


Figure 31 - Highest Support Volume Orientation

Final print orientation was decided based on the lowest support volume requirements (s 31 and 33).

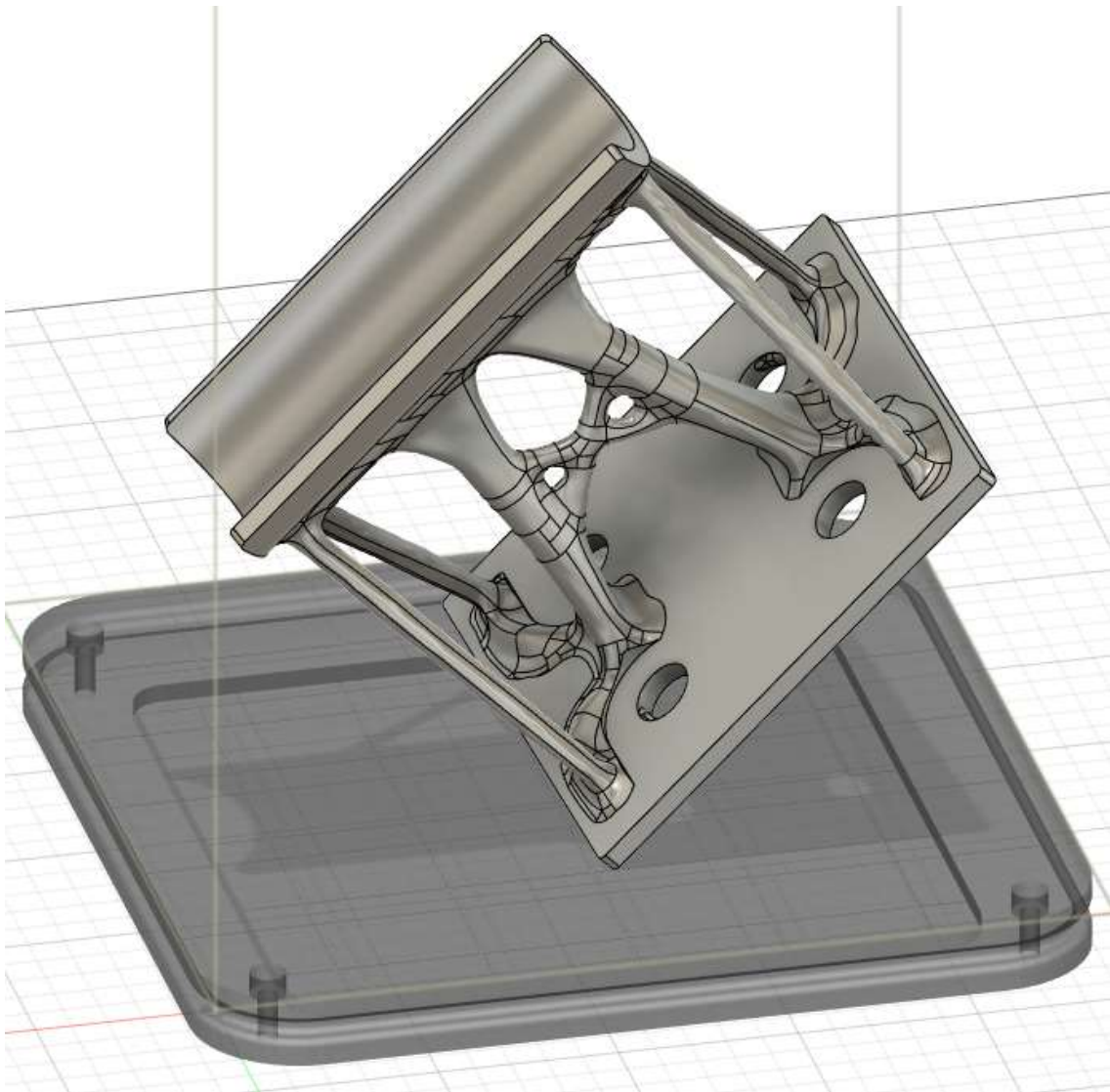


Figure 32 – Print Orientation

4.3.6 Internal Structure.

Due to the welding requirements of the wrapper plate to the pipe and fixing the baseplate to a support structure with bolts, this application would not be suited to any support structure optimisation. Welding of a modified structure could lead to warping of the plate, and any compression of fixing bolts on this type of structure requires further investigation for compression strength.

4.3.7 Cost Comparison.

Using the (Hubs, 2023) general cost guide for DMLS parts, the following cost was estimated for the shoe:

Pipe Shoe Costing Estimate For DMLS Process	
Material, 3.6kg at £280/kg	£1,008.00
DMLS	£2,400.00
Stress Relief	£450.00
Part/Support Removal	£120.00
Heat Treatment	£800.00
CNC Machining	£800.00
Total	£5,578.00

Figure 33 – DMLS Costing

The following costs were estimated for traditional manufacturing process:

Pipe Shoe Costing Estimate For Traditional Manufacturing	
Material, Laser-Cut Profile Plates (Cut to Exact Size)	£160.00
Assembly/Welding	£125.00
Pickle and Passivate (Required for Stainless Steel Finish)	£80.00
Weld Inspection	£100.00
Total	£465.00

Figure 34 – Traditional Manufacturing Cost

2. Final Design.

The final design was produced in a detail drawing for visual representation and checking purposes, and a step file was created for printing the part.

See Drawing PSGD-001 (Appendix A).

5 Conclusion.

5.1 Cost.

When exploring alternative methods to produce this component, it's important to consider cost as a key factor. The cost analysis shows that traditional manufacturing methods are currently the best option for this part.

5.2 Design.

AM processes have some advantages in the application of a shoe in the piping industry as every support can experience unique forces and moments, and the ability to design a unique shoe for every application would achieve weight reduction and reduced material wastage compared to traditional methods. There are some structural reservations over the generative designs in this instance, and the chosen design looks visually vulnerable to any accidental impact that could occur in operation in an industrial plant setting. Also, it would be prudent to carry out further design analysis, for example, a structural buckling analysis.

5.3 Life Cycle.

Pipe shoes are generally designed to match the life span of the piping it is connected to; due to potentially hazardous substances being transported by the piping, the traditional design is robust and suits this purpose. In this case, the generative design could be easily damaged, and the life cycle may not match the original design, leading to safety concerns in some instances. The shoe would be welded to the piping and be expected to last the life of the piping system itself.

6 Appendices.

Appendix A: Detail drawing PSGD-001

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1 Introduction.

For this task, a concept design was received for a portable wind turbine (Figure 1) initially designed for 3D printing; the concept required transitioning to a conventional manufacturing process where a high volume of unit production per week was required. Consideration was taken for the manufacturing process and material selection to suit further design requirements.



Figure 1 - Concept Design

2 Concept Design Appraisal.

To transition from a 3D printed prototype to a high-volume production process, a design evaluation was conducted to refine the design. The Quality Function Deployment (QFD) method was utilised to identify and prioritise customer needs and expectations. Alongside the QFD (Appendix A), a design specification was developed to outline the necessary product requirements.

2.1 Quality Function Deployment.

QFD is a methodology that translates customer needs into design requirements, ensuring that a product or process meets those needs. It was developed in Japan in the late 1960s to incorporate customer feedback into the design process and has since found a place in service industries too. It reduces start-up costs, reduces development times, and improves product quality (Erdil & Arani, 2018).

The QFD identified such requirements as portability, durability, lightweight, affordability and power conversion for the final design (appendix A).

				Column #	1	2	3	4	5	6	7	8	9	10	11	12
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	X	▼	▼	X	X	▼	▲	▲	▲	X	X	▲
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Blade dimensions	Blade Material	Main Chassis/Body Material	Main Chassis/Body Dimensions	Tail Dimensions	Tail Material	Interchangable parts/repair	Quick Setup	Blade Folding Operation	Tripod or stand attachment	Interchangable power storage	Produce Power
1	9	12.7	8.0	Lightweight	⊖	⊖	⊖	⊖	⊖	⊖	▲		▲			
2	9	12.7	8.0	Convert wind to power efficiently	⊖	⊖			⊖	⊖				▲		
3	9	11.1	7.0	Durability	▲	⊖	⊖	⊖	⊖	⊖	▲	▲	▲	▲		
4	9	9.5	6.0	Power storage				▲			⊖	▲			⊖	⊖
5	1	7.9	5.0	latest power outlets											▲	
6	9	11.1	7.0	affordability	⊖	⊖	⊖	⊖	⊖	⊖	▲			▲	⊖	▲
7	9	11.1	7.0	Repairability					▲	▲	⊖				⊖	
8	9	9.5	6.0	Ease of assembly								⊖	▲	⊖	▲	
9	9	14.3	9.0	portable	⊖	⊖	⊖	⊖	⊖	⊖			⊖	⊖		
10																

Figure 2 - Partial QFD.

2.2 Design Specification.

A design specification was developed to ensure that the product is produced in a way that meets all objectives and customer requirements. This document outlines the product's requirements, features, and limitations as a helpful guide throughout development.

The design specification for the turbine highlighted some of the following requirements shown in Figure 3.

Portable Wind Turbine - Design Specification	
Aspect	Specification for component
Purpose	Produce and store power off-grid with the use of wind for the charging of device.
Function	Rotating turbine blades efficient at catching wind, with folding or removable parts for ease of transportation.
Quantity	1000 - 2000 unit requirement per week, High Volume Production.
Aesthetics	Uniform colour with smooth visuals.
Ergonomics	Final shape after parts folded away to be easily packable and held in one hand
User Need	Portable and light weight for carrying or packing, waterproof design
Materials	High strength-to-weight ratio material.
Weight And Size	Suitable for carrying in a backpack with other items and ability to carry in one hand.
Cost	Cost to be kept to a minimum without detriment to quality or durability.
Safety	All relevant codes of practice to be identified and adhered to.
Sustainability	Component life span to be maximised and material which is widely recycled.

Figure 3 - Design Specification.

3 Manufacturing Process Proposal.

A suitable material was required that would effectively meet the specific criteria outlined in the design specifications related to material choice to be able to determine the appropriate manufacturing process for the wind turbine.

It was decided that plastic would be a more suitable material choice over metal and alloy due to the cheaper cost of the raw materials, durability, weight, recyclability, and manufacturing and design flexibility (Partwell, 2020).

After research on plastic materials and manufacturing techniques, it was determined that injection moulding using polycarbonate/acrylonitrile butadiene styrene (PC-ABS) would be the most appropriate choice for high-volume turbine production.

3.1 Material Selection.

PC-ABS is a versatile engineering thermoplastic that offers several advantages as a material choice for the turbine:

Strength and Durability: PC-ABS is a durable material that combines polycarbonate toughness with ABS strength and rigidity (Figure 4). It can withstand impact and mechanical stress without breaking or deforming (Xometry, 2022).

Mechanical Property	Test Method	Value (English/Metric)
Tensile Strength	ASTM D638	5,900 psi/ 41 MPa
Tensile Modulus	ASTM D638	278 ksi/19 GPa
Tensile Elongation	ASTM D638	6%
Flexural Strength	ASTM D790	9,800 psi/68 MPa
Flexural Modulus	ASTM D790	280 ksi/ 19 GPa
IZOD Impact notched	ASTM D256	3.7 ft-lb per in / 196 J per m
IZOD Impact un-notched	ASTM D256	9 ft-lb per in/ 481 J per m

Figure 4 - Mechanical Properties (Xometry, 2022)

Lightweight: Despite its strength and durability, PC-ABS is relatively light compared to other engineering materials. This feature is beneficial in applications where weight reduction is a priority (Xometry, 2022).

Dimensional Stability: A notable feature of PC-ABS is its dimensional stability, enabling it to retain its form and size despite fluctuations in temperature or environmental conditions (Fastradius, 2021).

Ease of Processing: PC-ABS is easy to process for creating complex shapes and components, resulting in cost-effective manufacturing and reduced production expenses (Fastradius, 2021).

Surface Finish: PC-ABS has a smooth and glossy surface finish, which adds to its aesthetic appeal. This quality often eliminates additional surface treatments or coatings, reducing application time and cost (Xometry, 2022).

Electrical Insulation Properties: PC-ABS displays excellent electrical insulation properties, making it suitable for applications in the electrical and electronics industry. It offers good resistance to electrical current flow, preventing short circuits and electrical damage (Europlas, 2023).

3.2 Manufacturing Process.

Injection moulding and CNC machining were considered when choosing a production process and Injection moulding was selected as the ideal process for this product. The following table (Figure 5) outlines some of the benefits that were considered, would have an impact on the production process:

Table 1. Comparison Between CNC Machining and Plastic Injection Molding		
Attribute	CNC Machining	Plastic Injection Molding
Typical tolerances	0.001"	0.005"
Fast per part cycle times	No	Yes
Fast Lead Times for Tooling	Yes	No
Easily make design modifications	Yes	No
Wide range of available materials	Yes	No
High-volume production (>1000 pcs)	No	Yes
Large upfront investment	No	Yes

Figure 5 - Process Comparison (Xometry, 2022)

Cost-effective: CNC machining was also considered in this case but ultimately did not appear cost-effective for the required volume. Injection moulding was chosen for its efficiency in large-scale production and cost-effectiveness once initial setup costs were covered (Americanmicroinc, 2021).

Design flexibility: The injection moulding process enables the creation of intricate and complex part designs with varied shapes, sizes, and features like thin walls, undercuts, and internal threads. This flexibility makes it possible to manufacture various products across various industries. Alternative methods like CNC have greater flexibility when it comes to design alterations. (Americanmicroinc, 2021) The design was anticipated not to require any modifications due to a concept design already produced and reviewed.

High production speed: Injection moulding is a rapid manufacturing process. Once the mould is set up, the cycle time to produce each part is typically short, allowing for high production volumes within a short timeframe (Hatch, 2022).

Material Versatility: Injection moulding and CNC machining support a wide range of materials. In this instance, where plastic was the desired choice of material, injection moulding was selected for the process.

Minimal material wastage: Injection moulding minimises material wastage as the process only uses the necessary amount of plastic required to fill the mould cavity. Any excess material can be recycled and reused, reducing costs and environmental impact. This was a significant decision where sustainability was a requirement. The final product and the production material must be easily recycled (Amtekplastics, 2023).

Consistent part quality: Injection moulding creates precise and consistent parts with tight tolerances and minimal variation. This aspect was essential due to several push-fit connections designed into the final product (Melito, 2022).

4 Design for X

4.1 Design for Assembly.

Product designers widely employ the Design for Assembly (DFA) approach to optimise the assembly process and enhance manufacturing efficiency. DFA can significantly reduce costs, assembly time, and potential errors by focusing on designing products that simplify and streamline assembly. The approach considers critical factors such as component integration, reducing part count, ensuring ease of access, and ergonomic considerations to achieve these objectives. This methodology allows product designers to deliver high-quality products that meet customer demands while maximising production efficiency.

To optimise the wind turbine design for assembly, the first step was categorising its components based on their function into "A" and "B" parts using the considerations shown in Figure 6. The former is considered essential as they perform a primary function, while the latter are non-essential components like fasteners and locators.

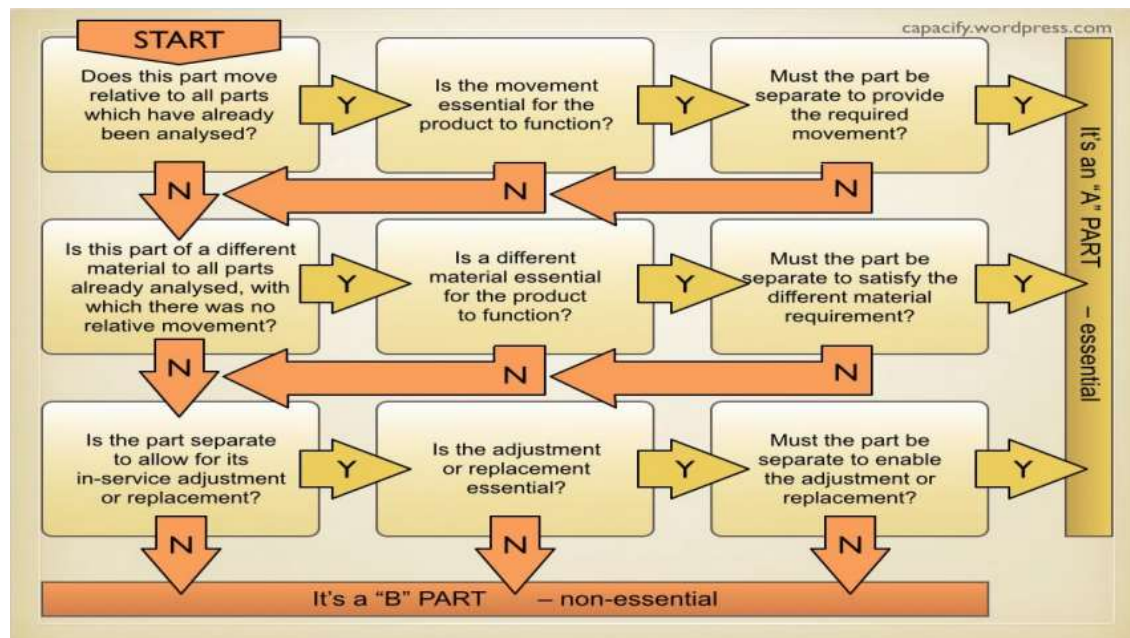


Figure 6 - Component Appraisal

4.1.1 Design Efficiency.

The results from the functional analysis are used to calculate the design efficiency using the formula - **number of essential parts** divided by the **total number of parts**, expressed as a percentage (Ebrary., 2023).

Part Description	Essential Part	
	Y	N
Total number of parts = 43		
Wind Blade Lock (Yellow)	0	1
Wind Blade Mount (Red)	1	0
Blade Inserts 4 No. (Blue)	0	4
Blade Mount Bolting 4 No.	0	4
Wind Blades 4 No. (Green)	1	4
Generator (Grey)	1	0
Generator Mounting (Blue)	1	0
Generator Bolting 4 No.	0	4
Battery Mounting (Blue)	1	0
Battery Pack	1	0
Battery Fixing Plate	0	1
Battery plate screws X4	0	4
Battery back retaining clip assembly	0	1
Bearing Mount (white)	1	0
Bearing (white)	1	0
Large Circlip	0	1
Small Circlip	1	0
Bearing washer	1	0
Tail Pipe	0	1
Flange Screw X4	0	4
Flange	0	1
Threaded tail lug	0	1
Tail locking nut	0	1
Wind Tail (Yellow)	1	0
Design Totals	11	32
Design efficiency		25.58%

Figure 7 - Design Efficiency

In this instance, the turbine consisted of 11 essential parts and 43 parts in total, resulting in a design efficiency of 25.58% (Figure 6); Lucas/Hull suggest a target value of 60% for optimal results (Ezpeleetaa, et al., 2019). To meet this target, it will be necessary to design out a high quantity of parts in the current design.

4.1.2 Handling Index.

Using the Lucas method to score the individual components by size and weight, handling difficulties, orientation, and rotational orientation, a handling index and ratio can be obtained as quantitative data for comparing new designs or evaluating existing designs against target scores (Figure 8).

Part Description	Manual Handling				
Total number of parts = 42	Size & Weight of Part	Handling Difficulties	Orientation of Part	Rotational Orientation of Part	
	A	B	C	D	Total
Wind Blade Lock (Yellow)	1	0.2	0	0	1.2
Wind Blade Mount (Red)	1	0	0.1	0	1.1
Blade Inserts 4 No. (Blue)	1	0	0.1	0.2	1.3
Blade Mount Bolting 4 No.	1.5	0.2	0.1	0.2	2
Wind Blades 4 No. (Green)	1	0.4	0.1	0.2	1.7
Generator (Grey)	1	0.4	0.1	0.2	1.7
Generator Mounting (Blue)	1	0.4	0.1	0.2	1.7
Generator Bolting 4 No.	1.5	1.1	0.1	0.2	2.9
Battery Mounting (Blue)	1.5	0	0.1	0.2	1.8
Battery Pack	1	0	0.1	0.4	1.5
Battery Fixing Plate	1	0	0.1	0.2	1.3
Battery plate screws X4	1.5	1.1	0.1	0.2	2.9
Battery back retaining clip assembly	1.5	1.1	0.1	0.2	2.9
Bearing Mount (white)	1.5	0.6	0.1	0	2.2
Bearing (white)	1.5	0.6	0	0	2.1
Large Circlip	1.5	1.4	0	0	2.9
Small Circlip	1.5	1.4	0	0	2.9
Bearing washer	1	0	0	0.2	1.2
Tail Pipe	1	0	0	0	1
Flange Screw X4	1.5	0.2	0.1	0.2	2
Flange	1	0	0.1	0.2	1.3
Threaded tail lug	1	0	0.1	0.2	1.3
Tail locking nut	1	0	0.1	0.2	1.3
Wind Tail (Yellow)	1	0	0.1	0.2	1.3
Design Totals	29	9.1	1.8	3.6	
	Handling Index				43.5
	Handling Ratio				3.95

Figure 8 - Handling Index

A handling ratio can be obtained by dividing the **handling index** by the **number of essential parts**.

The turbine components produced a handling ratio of 3.95, and the target ratio, as suggested by Lucas/Hull, is 2.5 (Ulloa, et al., 2018), suggesting the components do not pass the evaluation.

4.1.3 Fitting Index.

A fitting index and ratio were obtained by attributing scores to part placing & fastening, process direction, insertion, access & vision, alignment, and insertion force.

Part Description	Manual Fitting						
	Part Placing & Fastening	Process Direction	Insertion	Access & Vision	Alignment	Insertion Force	Total
	A	B	C	D	E	F	
Total number of parts = 42							
Wind Blade Lock (Yellow)	6	0	0	0	0	0	6
Wind Blade Mount (Red)	1.3	0	0	0	0	0.6	1.9
Blade Inserts 4 No. (Blue)	6	0.1	0.7	0	0	0	6.8
Blade Mount Bolting 4 No.	6	0.1	0.7	0	0	0	6.8
Wind Blades 4 No. (Green)	6	0.1	0	0	0	0.6	6.7
Generator (Grey)	6	0	0.7	0	0	0	6.7
Generator Mounting (Blue)	6	0	0.7	0	0	0	6.7
Generator Bolting 4 No.	6	0	1.2	0	0.3	0.3	7.8
Battery Mounting (Blue)	6	0	1.2	0	0	0	7.2
Battery Pack	3.3	0.1	0	0	0	0.6	4
Battery Fixing Plate	6	0	0	0	0	0	6
Battery plate screws X4	6	0	1.2	0	0	0	7.2
Battery back retaining clip assembly	6	0.1	0	0	0	0	6.1
Bearing Mount (white)	3.3	0	0	0	0	0.6	3.9
Bearing (white)	3.3	0	0	0	0	0.6	3.9
Large Circlip	6	0.1	0	0	0	0.6	6.7
Small Circlip	6	0.1	0	0	0	0.6	6.7
Bearing washer	3.3	0	0	0	0	0	3.3
Tail Pipe	6	0	0	0	0	0	6
Flange Screw X4	6	0.1	0.7	0	0	0	6.8
Flange	6	0	0	0	0	0	6
Threaded tail lug	6	0	0	0	0	0	6
Tail locking nut	6	0	0	0	0	0	6
Wind Tail (Yellow)	6	0.1	0	0	0.7	0	6.8
Design Totals	128.5	0.9	7.1	0	1	4.5	
	Fitting Index						142
	Fitting Ratio						12.91

Figure 9 – Fitting Index

The fitting ratio was obtained by dividing the **fitting index** by the **number of essential parts**.

The turbine components produced a fitting ratio of 12.91, and the target ratio, as suggested by Lucas/Hull, is 2.5 (Ulloa, et al., 2018), suggesting the components do not pass the evaluation by a considerable amount.

4.2 Design For Quality.

The quality of a product has a direct impact on sales and how the customer perceives the product (Velling, 2021). Quality can involve factors such as performance, serviceability, durability, reliability, and aesthetics.

4.2.1 Performance.

The effectiveness of the wind turbine's blades in converting wind into energy to rotate the generator is a crucial factor in determining the product's overall performance. According to Velling (2021) and Adeyeye, et al., (2021), wind turbine design typically incorporates three blades over four blades due to the reduced drag experienced by fewer blades, resulting in higher power conversion efficiency. Lowering the blade count below three can introduce instability to the turbine. This design modification reduced the number of parts, reducing costs and assembly time.

4.2.2 Durability.

The prototype design did not display the level of durability required for its purpose and its portable nature. There were high levels of snagging areas on the product that could lead to breakage when removed or replaced into a carrying device. A sleeker design with fewer sharp edges and corners was factored into the product re-design.

The weather resistance capabilities of the prototype design were also an essential factor for durability. Exposed electrical components (Figures 10 and 11) were likely to fail in specific weather conditions where the product would be operated and were considered for re-design with weather resistance an essential factor.

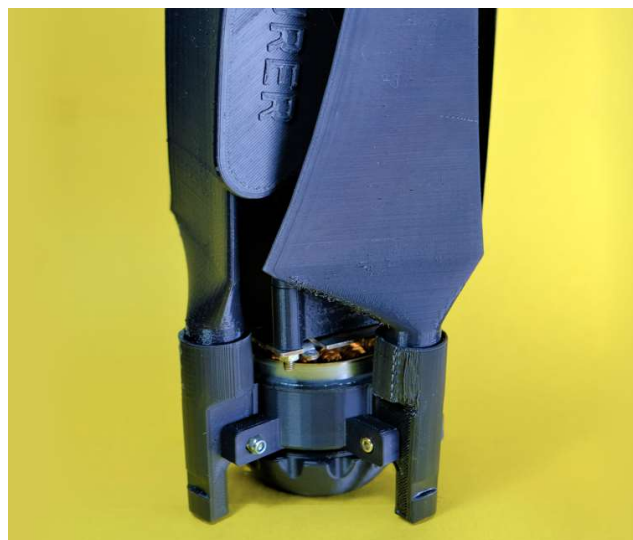


Figure 10 - Exposed Generator

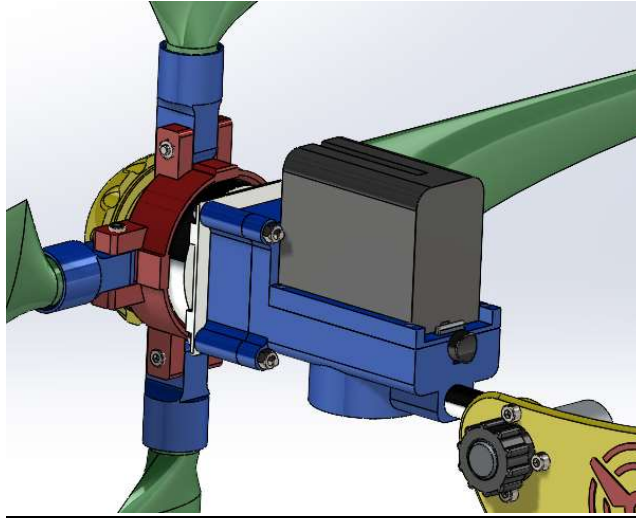


Figure 11 - Exposed Battery Pack

4.2.3 Aesthetics.

The prototype design displayed non-aesthetic aspects such as exposed parts, visible fasteners, sharp edges, and corners. These features were another highlighted aspect for removal or improvement in the redesign process. A uniform colour and a smoother, sleeker design encompassing major parts, enhancing the assembly's weather resistance, was another highlighted aesthetic aspect for a redesign.

4.2.4 Serviceability.

To increase the product's serviceability, reducing the number of parts and fasteners was recommended, and fast connections using clips were utilised for ease of maintenance.

4.3 Design for Sustainability.

Considering sustainability during the design stage is crucial, as it can affect how the public perceives a product. To promote sustainability, the redesigning of the product will incorporate easily recyclable materials wherever possible and a mechanical parts recovery scheme to recycle any precious metals for reuse. This also extends to the product's packaging, where 100% recyclable and biodegradable materials shall be used.

To increase the product life cycle, design considerations for interchangeable parts were adapted into the design; for example, the wind generator must be removable from the main body and the turbine blade mount for ease of replacement.

4.4 Design for Reliability.

To assess the reliability of the prototype, a failure mode and effects analysis was conducted (Appendix B), and the following issues were highlighted as potential failure modes.

Exposed rotary blades – due to regular transportation of the product, it was anticipated that exposed parts were likely to snag and potentially snap due to the nature of the basic design.

Exposed electrical components – The prototype is expected to be operated in undesirable weather conditions and potentially fail due to water ingress.

Failure of electrical and mechanical parts – General failure of these components is to be expected in very low quantities.

A solution for these issues was then addressed in the re-design of the product where possible, and warranties and spares would cover part failure issues for out-of-warranty parts.

FAILURE MODE AND EFFECTS ANALYSIS															
Item: <u>Portable Wind Turbine</u>		Responsibility: <u>Design & Development</u>		FMEA number: <u>PWT-001</u>											
Model: <u>Turbine</u>		Prepared by: <u>N/A</u>		Page : <u>1</u>											
Core Team: <u>PWA</u>		FMEA Date (Orig) <u>27/06/2023</u> Rev: <u>A</u>													
Process Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	C I a s s	Potential Cause(s)/ Mechanism(s) of Failure	O c c u r	Current Process Controls	D e t e c	R P N	Recommended Action(s)	Responsibility and Target Completion Date	Action Results			
												Actions Taken	S e v	O c c	D e t
Rotary Blades	Foreign object trapped in product	Product will not function	7		Exposed areas on product where objects can be trapped	2	None	7	98	Re-design	03/07/2023	Re-design of blade mount	1	1	2
	Blade snaps during transportation /Storage	Reduction in efficiency	5		Blades exposed during storage due to design	4	None	2	40	Re-design	03/07/2023	Re-design product body for contours to include blades	1	2	3
Generator	Malfunction	Non-production of power	7		Generator exposed to water ingress	8	None	7	392	Re-design	03/07/2023	Re-design product body for weather resistance.	1	2	3
Generator	Malfunction	Non-production of power	7		Defective Generator	1	None	10	70	Warranty of parts and availability of spares for out of warranty parts	03/07/2023	1 year warranty on mechanical parts. Spares available on website	2	3	4

Figure 12 - Partial FMEA Document

5 Re-design

A complete re-design using solid works was carried out to address any issues identified in the design and development stages and any expected customer requirements identified at the design specification stage. (The complete re-designed assembly is shown in Figure 13).

All materials (excluding mechanical and electrical components) will be manufactured using injection moulding techniques from PC/ABS material.

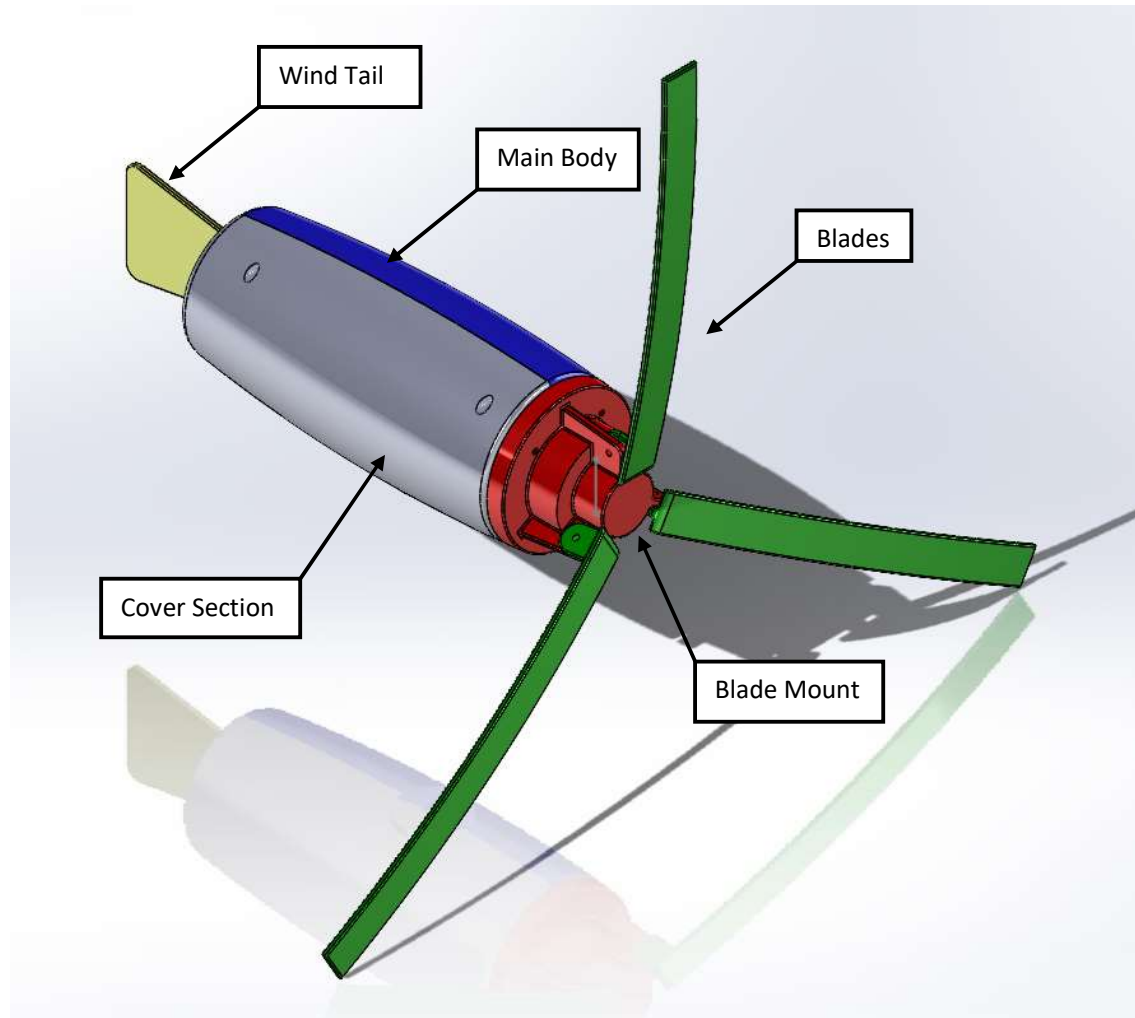


Figure 13 - Assembly

5.1 Turbine blades

It was noted during research that a three-blade design was more efficient than the original prototype design, and this was rectified with a three-blade, equ-spaced design for stability and efficiency.

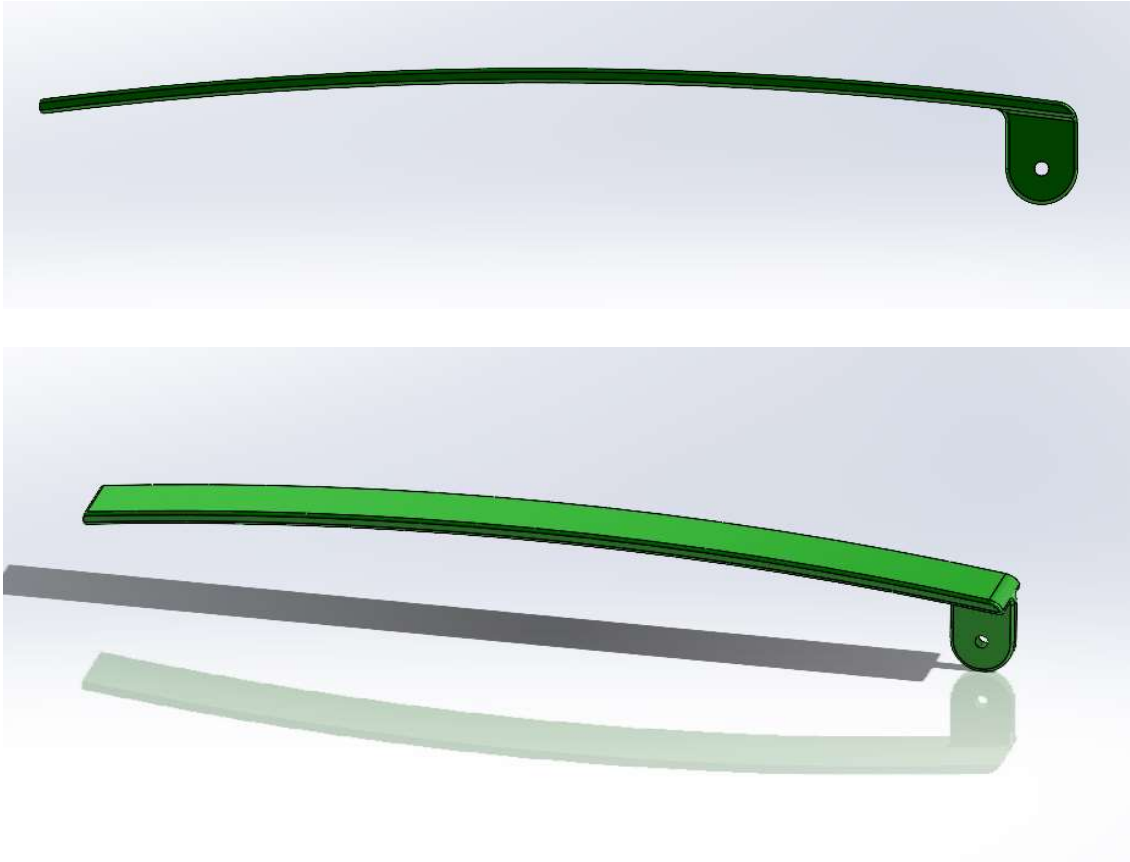


Figure 14 - Turbine Blade

5.2 Blade Mount.

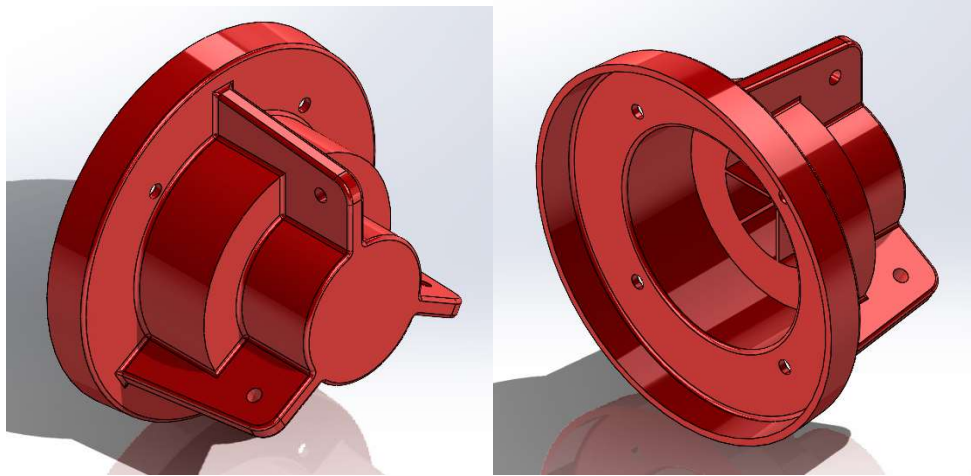


Figure 15 - Blade Mount

The mount for the blades underwent a redesign to accommodate the new 3-blade design and achieve a more aesthetic look.

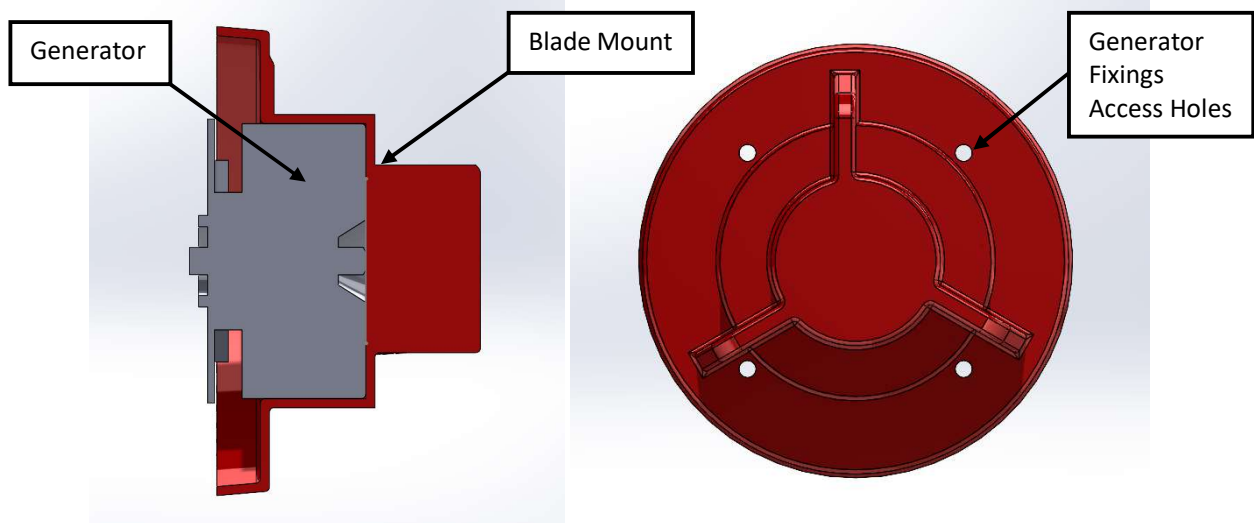


Figure 16 - Blade Mount and Generator Section View

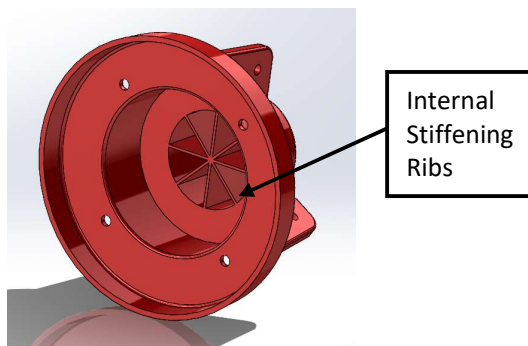


Figure 17 - Rear View

5.3 Main Body

To achieve a smooth and sleek design and conceal exposed parts, the main body of the product underwent a significant redesign. A tubular shape was created to enclose the battery and bearing assembly (Figure 15) and the wind tail section when not in use (Figure 16). The generator mounting end also included a water ingress channel to protect the generator.

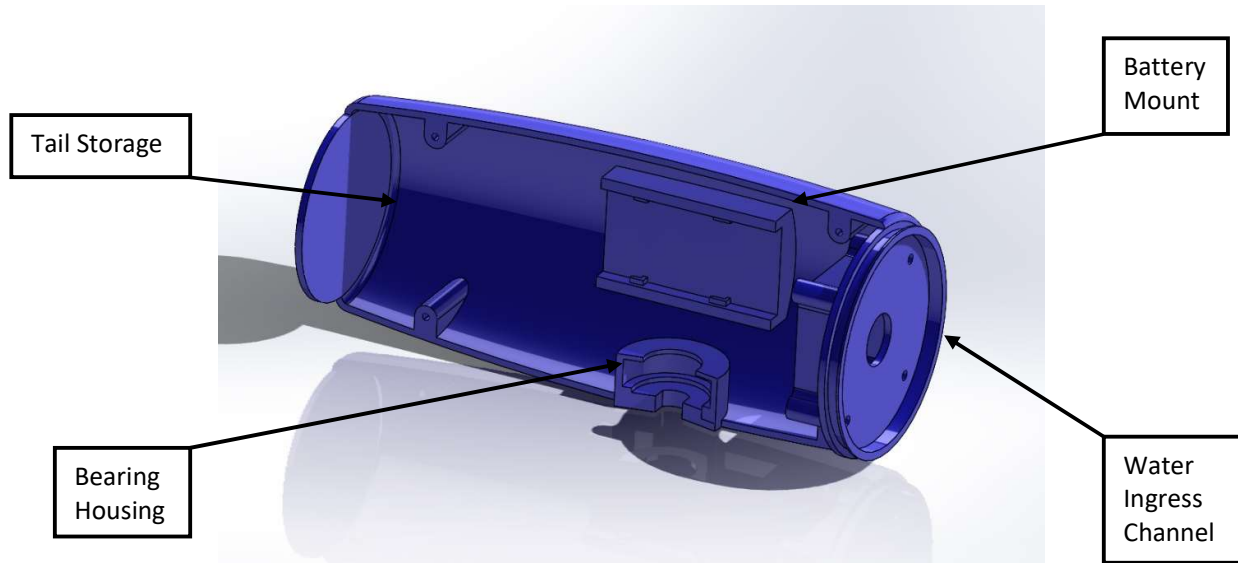


Figure 18 - Main Body Design

One notable feature of the main body is the overlapping recess that, when connected with the main body, creates a channel for water to flow around the generator. This effectively diverts any water from causing damage to the generator (Figure 16).

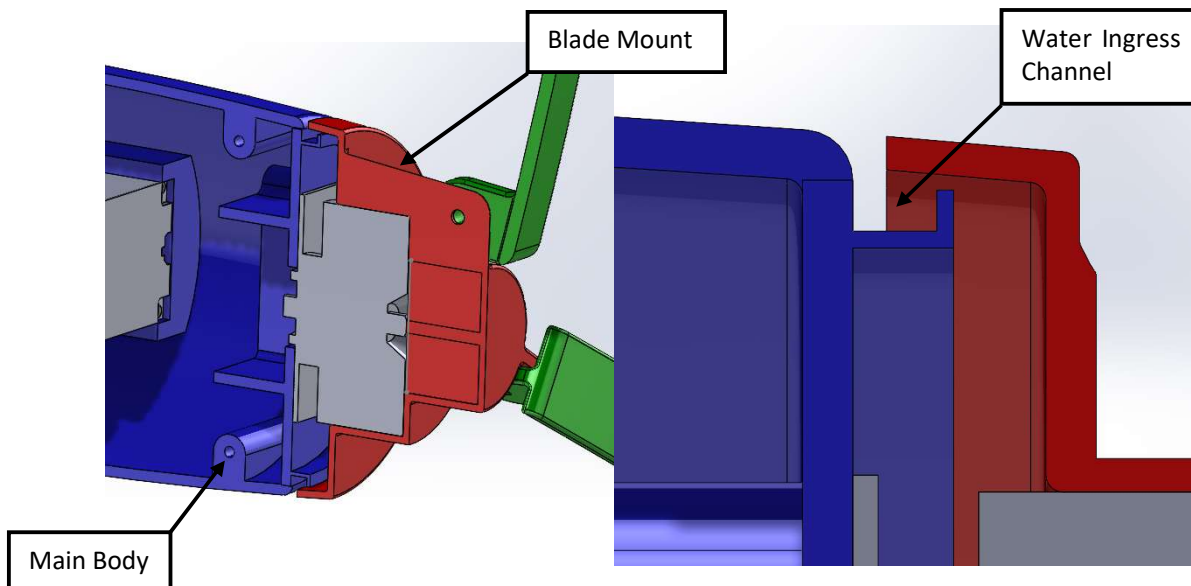


Figure 19 - Blade Mount Section Views

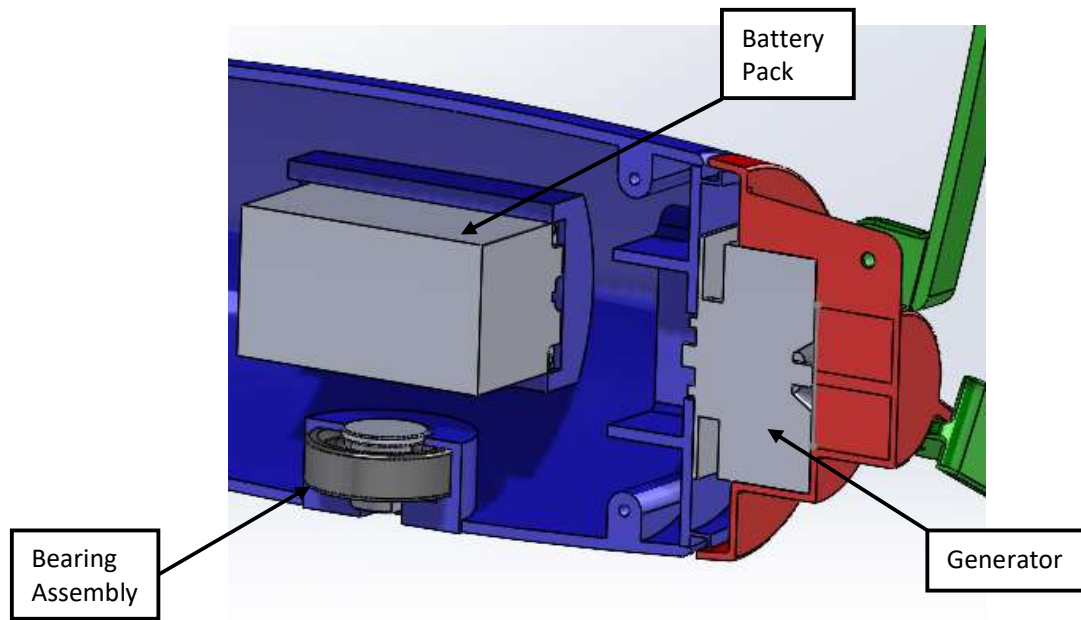


Figure 20 – Main Body Features

The bearing housing, is a push fit retainer for the bearing, allowing the removing the requirement of the large circlip from the original prototype.

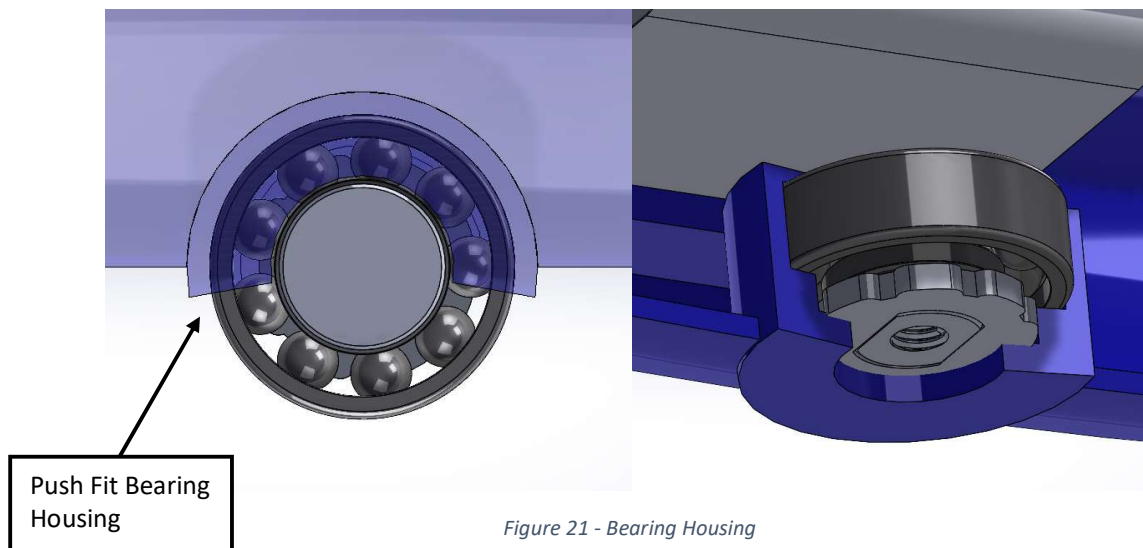


Figure 21 - Bearing Housing

5.4 Wind Tail

The wind tail re-design considerably reduced the number of parts in the original prototype design by implementing a simple slot feature. The wind tail is stored in the main body when not in operation.

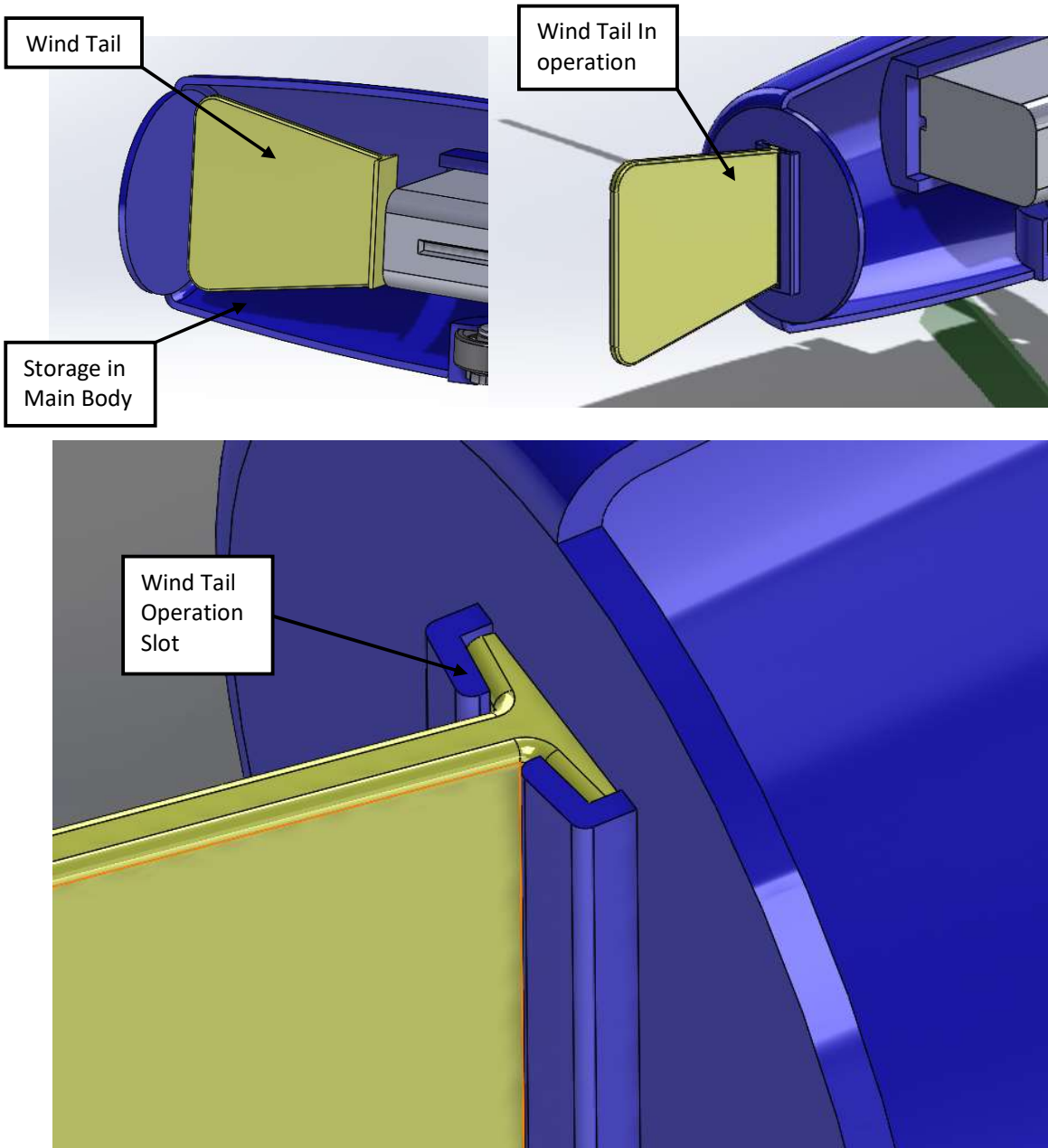


Figure 22 - Wind Tail Fixing

5.5 Body Enclosure

The body enclosure is purely an extension of the main body and bearing housing which encloses the internal components and seals the unit, this completes the form of the main body's elliptical tube shape.

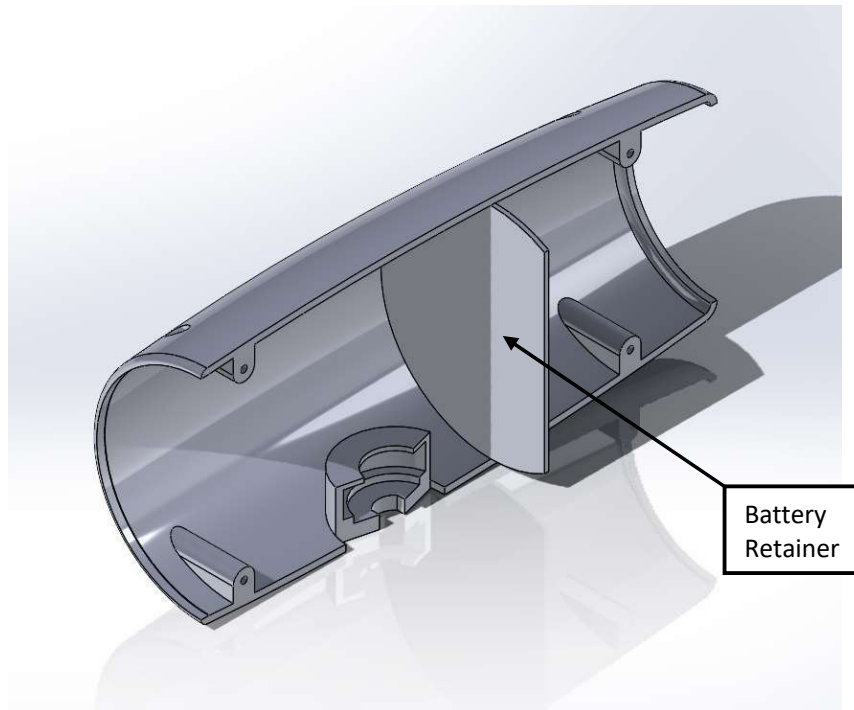


Figure 23 - Body Enclosure

The body enclosure also now acts as the battery locking mechanism, holding the battery in place while in operation, the enclosure is fixed to the main body using four screws.

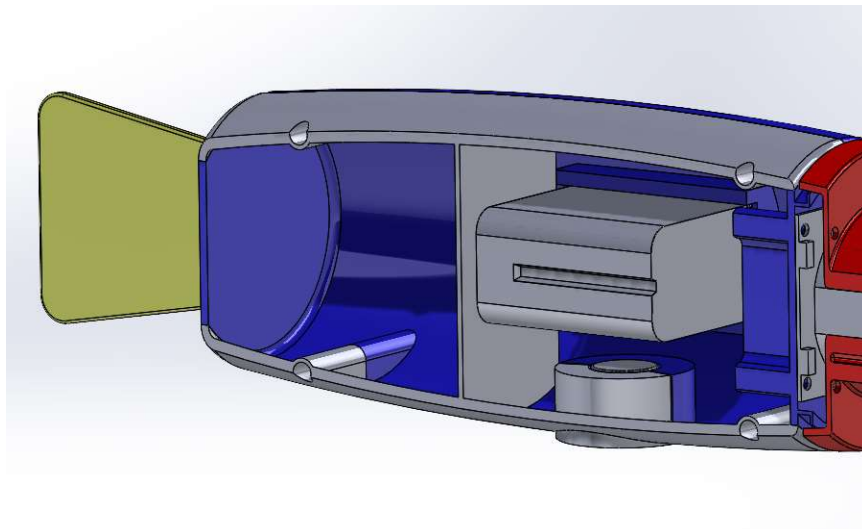


Figure 24 - Battery Retainer

6 Conclusion

It was important to implement the many design tools available to transition the 3D printed prototype to a high volume conventionally manufactured product. Various analysis tools found that the original prototype was unsuitable for its purpose in many ways, and a complete redesign was required.

One of the main factors considered was the weather resistance of the prototype; by using the failure mode and effect analysis, exposed mechanical and electrical parts were identified as likely to fail because of this, this feature was also identified in the initial design spec. By creating a weather-resistant design, the product life cycle would be greatly improved and increase customer satisfaction achieving a positive view of the product.

Efficiency of the product was also noted during the Design for X stage; utilising the Lucas method enabled a complete review of all parts. For example, attention was brought to the number of blades after using the analysis tool, through research, it was found that by removing the fourth blade, the product would be more efficient in capturing wind to convert to energy. This improved the product performance and reduced the number of parts, reducing cost and assembly time.

Another aspect highlighted in the Design for X stage was the aesthetics of the prototype. It was noted that there were too many edges and corners and exposed fasteners. The design failed to demonstrate a visually appealing and durable product suitable for its intended use. The design rectified this with an enclosed elliptical tube encasing mechanical and electrical parts, creating a more desirable look.

Using various techniques such as QFD, design specification, and design for X methods (which includes the Lucas method and failure modes and effects analysis) enabled the identification of the shortcomings of the prototype and making necessary improvements in its redesign. This emphasises the significance of analysis tools during the design phase.

A final analysis of the design efficiency (Figure 25), handling index (Figure 26) and fitting index (Figure 27) were completed on the new design.

Part Description	Essential Part	
Total number of parts = 21	Y	N
Wind Blade Mount (Red)	1	0
Blade Mount Bolting 3 No.	0	3
Wind Blades 3 No. (Green)	1	0
Generator (Grey)	1	0
Generator Bolting 4 No.	0	4
Main Body	1	0
Main Body Enclosure	1	0
Main Body Bolting 4 No.	0	4
Battery Pack	1	0
Bearing Mount (white)	1	0
Bearing (white)	1	0
Small Circlip	1	0
Wind Tail (Yellow)	1	0
Design Totals	10	11
	Design efficiency	47.62%

Figure 25 - Re-design Design Efficiency

Part Description	Manual Handling				
Total number of parts = 21	Size & Weight of Part	Handling Difficulties	Orientation of Part	Rotational Orientation of Part	
	A	B	C	D	Total
Wind Blade Mount (Red)	1	0	0.1	0	1.1
Blade Mount Bolting 3 No.	1.5	0.2	0.1	0.2	2
Wind Blades 3 No. (Green)	1	0.4	0.1	0.2	1.7
Generator (Grey)	1	0.4	0.1	0.2	1.7
Generator Bolting 4 No.	1.5	1.1	0.1	0.2	2.9
Main Body	1.5	0	0.1	0.2	1.8
Main Body Enclosure	1.5	0	0.1	0.2	1.8
Main Body Bolting 4 No.	1.5	0.2	0.1	0.2	2
Battery Pack	1	0	0.1	0.4	1.5
Bearing Mount (white)	1.5	0.6	0.1	0	2.2
Bearing (white)	1.5	0.6	0	0	2.1
Small Circlip	1.5	1.4	0	0	2.9
Wind Tail (Yellow)	1	0	0.1	0.2	1.3
Design Totals	17	4.9	1.1	2	
	Handling Index				25
	Handling Ratio				2.50

Figure 26 - Re-design Handling Index

Part Description	Manual Fitting						
Total number of parts = 21	Part Placing & Fastening	Process Direction	Insertion	Access & Vision	Alignment	Insertion Force	
	A	B	C	D	E	F	Total
Wind Blade Mount (Red)	1.3	0	0	0	0	0.6	1.9
Blade Mount Bolting 3 No.	6	0.1	0.7	0	0	0	6.8
Wind Blades 3 No. (Green)	6	0.1	0	0	0	0.6	6.7
Generator (Grey)	6	0	0.7	0	0	0	6.7
Generator Bolting 4 No.	6	0	1.2	0	0.3	0.3	7.8
Main Body	6	0	1.2	0	0	0	7.2
Main Body Enclosure	6	0	1.2	0	0	0	7.2
Main Body Bolting 4 No.	6	0.1	0.7	0	0	0	6.8
Battery Pack	3.3	0.1	0	0	0	0.6	4
Bearing Mount (white)	3.3	0	0	0	0	0.6	3.9
Bearing (white)	3.3	0	0	0	0	0.6	3.9
Small Circlip	6	0.1	0	0	0	0.6	6.7
Wind Tail (Yellow)	6	0.1	0	0	0.7	0	6.8
Design Totals	65.2	0.6	5.7	0	1	3.9	
	Fitting Index						76.4
	Fitting Ratio						7.64

Figure 27 - Re-design Fitting Index

	Prototype	Re-design
Design efficiency	25.58%	47.62%
Handling Index	43.50	2.50
Handling Ratio	3.95	2.50
Fitting Index	142.00	76.40
Fitting Ratio	12.91	7.64

Figure 28 - Design Comparisons

It is evident from the analysis that the redesign has improved the design considerably, the total number of parts has reduced from 43 to 21 and the design efficiency has almost doubled, the design efficiency is still not at the desired target of 60%, this may be the result of opting for screws for fixing the main body to the enclosure, the decision for this was to ensure the weather resistance of the product and considered a required trade-off. The handling ratio is now in line with the Lucas/Hull preferred ratio of 2.5, and the fitting ratio has been reduced.

7 Appendices

Appendix A: Quality Function Deployment (Task_2_QFD.xlsx)

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