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# SuMoth Challenge 2022

*Stage S1 - Design Report*

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# Abstract

Designed to tackle the challenges within the current foiling arena, which is considered reasonably unsustainable, expensive and elite, the sustainable Moth aims to improve sustainability and accessibility whilst remaining competitive. The design brief is inspired by the requirement for more sustainable and efficient sailboat designs with coherent manufacturing techniques. With under nine months to design, build, test and conduct optimisation for the SuMoth, the design process involved establishing the requirements laid out by the International Moth Class Association (IMCA) and *SuMoth* which led to the group choosing to focus on the hull, wingbars, and Flight Control System (FCS) to ensure project success. The group structure was based on proficiency and interest of each group member, where the group roles were then allocated. The Southampton SuMoth Team consisted of 6 multidisciplinary master students from Aeronautics Engineering, Mechanical Engineering and Ship Science. The three Ship Science students focused on the research and development of the hull and wingbars, as well as the validation of Finite Element Analysis, while the Mechanical Engineering team member developed the Flight Control System, and the Aeronautic team member was responsible for the sustainability analysis. Materials and on-land structural testing validated manufacturing choices and computational modelling respectively. To improve the environmental impact, natural flax fibres, recycled PET core, cork core, and bio resins were used; and the SuMoth's Life Cycle Analysis (LCA) was quantitively assessed. Both an ultrasonic FCS and wooden wingbars were designed to improve accessibility. The proposed design achieves significant environmental benefit in terms of global warming potential, but increased water consumption compared to a typical carbon Moth. The fully rigged SuMoth has a total mass of 61.7 kg, corresponding to a 63% increase compared to a Maguire Exocet carbon Moth and a 5,377.43 $SM standardised total cost, which therefore complies with the *SuMoth* Rules. This is 46% less than the allowable standardised budget.

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# Nomenclature

| | |
|---|---|
| CAD | Computer-Aided Design |
| CFRP | Carbon Fibre Reinforced Polymer |
| COG | Centre of Gravity |
| FCS | Flight Control System |
| FEA | Finite Element Analysis |
| Foiling | Hydrofoiling |
| GDP | Group Design Project |
| IMCA | International Moth Class Association |
| LCA | Life Cycle Assessment |
| LCG | Longitudinal Centre of Gravity |
| LSTL | Large Structure Testing Laboratory |
| LVDT | Linear Vertical Displacement Transducer |
| NAP | Neutral Axis Position |
| PET | Polyethylene Terephthalate Core |
| QFD | Quality Function Deployment |
| SG | Strain Gauge |
| SuMoth | Sustainable Moth |
| TSRL | Testing and Structures Research Laboratory |

# 1. ENGINEERING AND DESIGN

## 1.1. Hull Design

### 1.1.1. Introduction

The hull design is a challenging process which constitutes the main structure of the SuMoth. The IMCA box rules allows for great freedom in terms of design and structure choices. However, many constraints regarding the structure and the weight need to be considered beforehand, as the structure needs to withstand several internal and external loads that are described in the next section. It was crucial to have a durable and stiff hull as the SuMoth needs to react correctly to many loads acting simultaneously when sailing as well as withstanding fatigue over time.

A foiling dinghy usually tends to be governed by the stiffness of its structure needing to be reactive and sensitive. The carbon-epoxy is known to have a high stiffness to weight ratio: it is therefore a challenge to adapt the same criteria to natural fibres on a SuMoth. Regarding the weight of the hull, initial calculations showed that this was one of the main challenges as natural fibres tend to require more material to match the stiffness criteria. Although weight drives sailing and foiling performances, our hull specific objective was to be within 60% of the typical carbon Moth. Indeed, this allows more freedom for the team and also allows to spread the ‘additional’ weight wisely (e.g. in the wing bars to create increased righting moment, or reinforcements around critical areas such as the mast and centreboard case).

Another important preliminary design option from a manufacturing point of view was the mould. The mould of a hull is a complex structure to build – often in composite – as it requires time, budget, and a certain know-how. Indeed, building a mould would have required time to spend designing and optimising the hull form before starting its production. Female moulds are usually built with transverse wooden section that are CNC-machined, longitudinal strip planking glued between the section and several layers of fibres applied on top to have a smooth surface. Due to time and financial constraints, the team decided to reuse a female mould that *Shock Sailing* lent us for the duration of this project. Reusing a pre-existing mould allows the project to reduce the carbon footprint and energy consumption by a large amount. Building a one-off mould for this project would have been counterproductive as it would not have had any commercial or production purposes.

Therefore, although we did not have any freedom in hull form due to the mould, the freedom in materials choices in both the *SuMoth* and the IMCA rules was a great opportunity for the group to carry out research on alternative materials to find the best layup that matches the stiffness and weight criteria. It was important to carry out theoretical, experimental and sustainability analyses before starting the manufacture. Once the main body of the hull was completed, the group was able to structurally test it on land by performing a longitudinal bending test to validate and measure the 3D model, in order to investigate further optimisation options.

### 1.1.2. The hull: “hub” of interacting forces

A free-body diagram was required to better understand the structural challenges of the hull. Several simultaneous forces are interacting through the hull which links all the other sub-components such as the rig, the appendages and the wingbars. Figure 1 shows an isometric view of the boat heeling at 25° windward and moving forward through the water. The hull acts as a “hub” where all the forces interact. The aerodynamic and hydrodynamic forces are shown and simplified by keeping only the final components, as well as rig internal forces such as mast compression and shrouds tension.

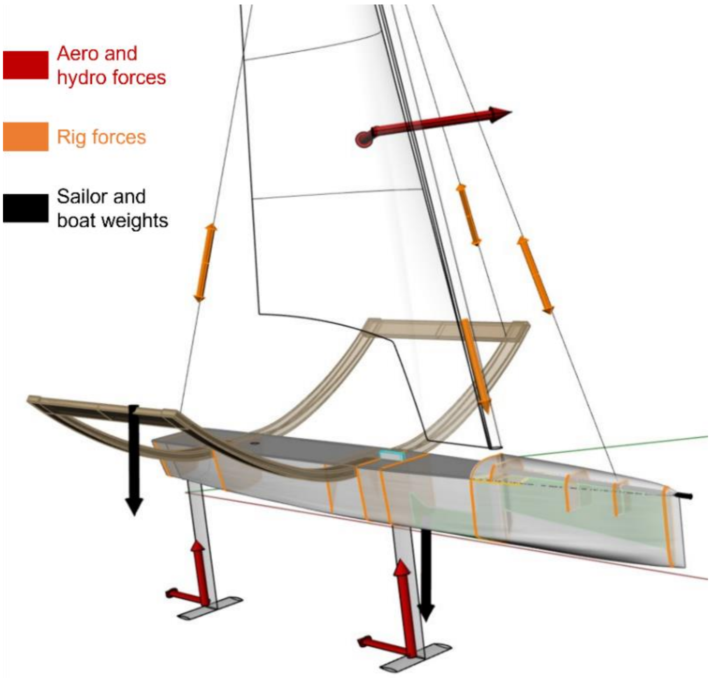



*Figure 1: Isometric view of a simplified Free Body Diagram*

Figure 1 helped investigate the critical areas where internal loads are concentrated and more likely to lead to material failure. The following areas were highlighted during the concept design phase:

- Wingbar mounts, due to high bending moments at the fixed supports created by the sailor's weight and the shrouds.
- Centreboard case, due to the vertical and longitudinal forces components acting on the main foil.
- Mast foot area, due to the high compression load created by the aerodynamic forces, shrouds tension and vang's tension.

### 1.1.3. Estimations of forces

Before going into detailed hull design, the approximate estimation of the forces acting on the hull was made. These were mostly calculated as separate systems by finding the relationship between forces and moments. Therefore, most of the estimations were done by using the crew weight and the total weight of the boat. The forces were calculated in XZ and YZ plane equilibrium where the X, Y and Z coordinates are representing longitudinal, transverse, and vertical directions, respectively. To determine the forces, the following assumptions were made:

- The vessel is sailing at 20 knots and the most severe force in X and Y directions are at downwind and upwind, respectively.
- There is no yaw motion.
- The vessel is at the upright equilibrium.
- The centre of effort in the foils is at the half-length of depth from the waterline and half the mast height from the waterline.
- The water is still and there is no force related to the free surface.

- The weight of the vessel is distributed between the main foil strut and rudder foil strut by the distance from midships, which is assumed to be the centre of gravity (COG). This may have a large effect as the longitudinal centre of gravity (LCG) is usually shifted aft.
- The main and rudder horizontal foils have a NACA 63-412 profile and vertical struts have NACA 0012 and 0010 profiles, respectively.
- Sail force remains the same upwind and downwind.

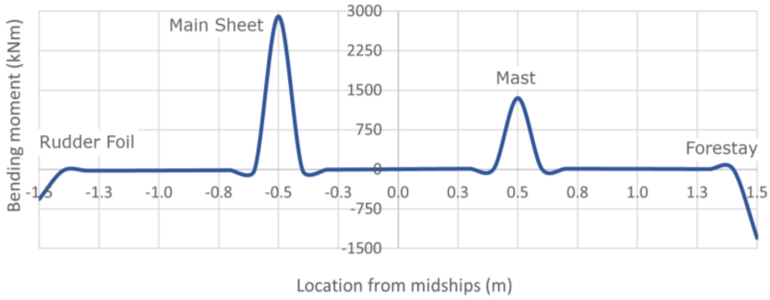



*Figure 2: Initial estimation of longitudinal bending moments*

By distributing the weights and finding the required lift, the angle of attack and the drag force were obtained using the angle of attack against the lift coefficient and drag coefficient plots are obtained from the *X-Foil* program (Drela, 1989). The results for the bending moment over the hull were found to be as presented on Figure 2.

## 1.1.4. Research

### a) Natural fibres

Naturally sourced composite materials have gained popularity recently in the sailing industry thanks to intensive research from manufacturers and their will to reduce their environmental impact to tackle the global warming challenge. It is important to understand the mechanical properties and the behaviour of each available materials, as well as its sustainability impact regarding the environmental footprint ($CO_2$ footprint, water and energy consumption) in order to make the best compromise. Figure 3 shows the potential of naturally sourced composite materials in terms of specific strength vs. specific stiffness compared to synthetic materials such as Carbon fibres and E-glass.

Effectively, the specific stiffness of natural fibres is of great interest for alternative materials in a structure such as a SuMoth as it is mainly a stiffness-driven design. The group investigated a wide range of alternative fibres, which are highlighted in Figure 5. After researching and comparing with current projects in the sailing industry, four types of fibres were considered to replace synthetic fibres in the SuMoth, based on their mechanical properties. These were: cotton, jute, flax and hemp. Their mechanical properties can be found in Table 1 (P. Wambua et al., 2003).

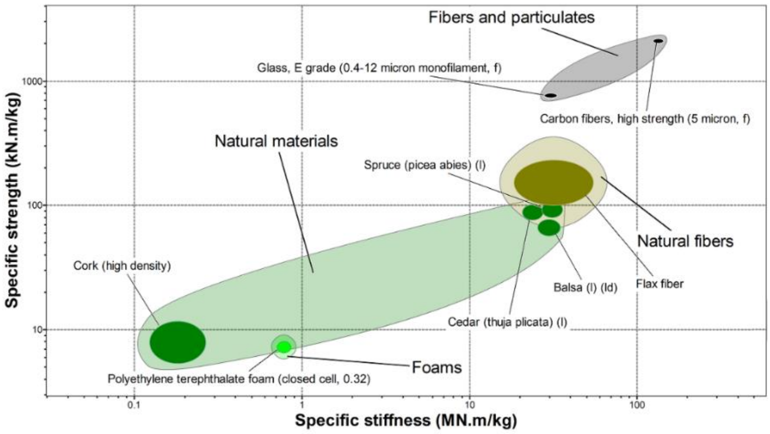



*Figure 3: Specific stiffness vs specific strength for a range of composite materials from Granta Edupack*

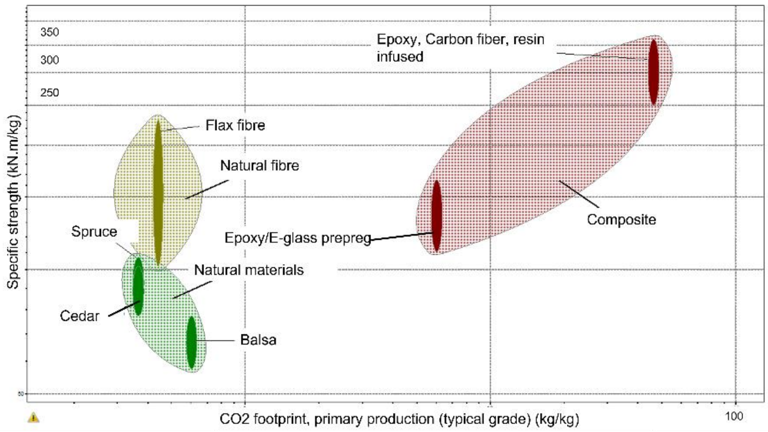



*Figure 4: CO2 footprint vs. specific strengths for a range of materials*

*Table 1: Mechanical properties for a range of natural fibres*

| Fibre | Density ($g/cm^3$) | Elongation strength (%) | Tensile strength (MPa) | Young's Modulus (GPa) |
|---|---|---|---|---|
| **Cotton** | 1.5-1.6 | 3.0-10.0 | 287 - 597 | 5.5 - 12.6 |
| **Jute** | 1.3-1.46 | 1.5-1.8 | 393 - 800 | 10.0 - 30.0 |
| **Flax** | 1.4-1.5 | 1.2-3.2 | 345 - 1500 | 27.6 - 80 |
| **Hemp** | 1.48 | 1.6 | 550 - 900 | 70 |

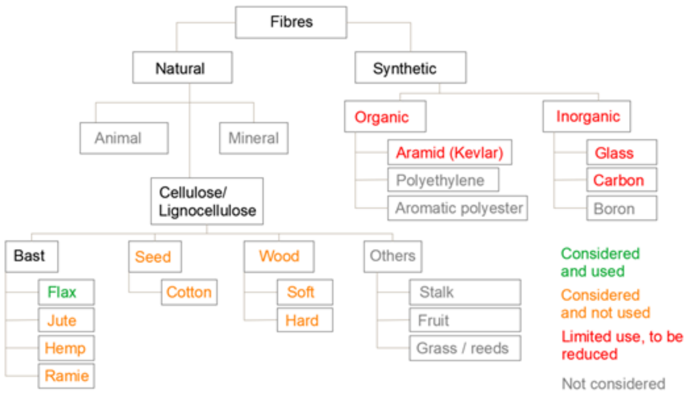



*Figure 5: Flow chart diagram of the fibre types, based on (M. Asim et al., 2018)*

Based on its mechanical properties, previous published research, and its significant growth in the UK, it was concluded that flax fibre was the best compromise for this project. The only downside that the group needed to consider carefully was the water usage for its production compared to conventional composite materials used in the industry.

### b) Natural and recycled cores

Since the design requirements for the SuMoth were high stiffness and low weight, it was necessary to implement a core in the sandwich composite structure to gain moments of inertia and improve the mechanical performances. The marine industry tends to use polymethacrylimide (PMI), polyvinyl chloride (PVC) and polyethylene (PET) foam cores, which are known for their strength to weight ratio. High-performance industries usually use honeycomb cores, which are either 'Nomex' (made from aramid – Kevlar) or thin aluminium.
A more limited range of natural and recycled cores was noticed on the market compared to the wide range of natural fibres used in composite applications. The most popular ones were found to be wood (Sitka Spruce, balsa, bamboo, plywood), recycled PET foam and cork core. Wood tends to have high densities, which was one of the reasons the group used it as the main material for the wingbars. This extends the weight from the centreline and therefore increase the righting moment. After some literature review and discussions with *Matrix Composites* – composite materials supplier in the UK and project sponsor – it was decided to deepen our research in both 100% recycled PET and cork cores, supplied and distributed by *Matrix Composites.* The PET core is obtained from recycling PET plastic as shown in the opposite infographic, which allows to recycle waste and reduce both the environmental footprint and the cost (ArmaPET, n.d). Its main structural advantages given by the manufacturer were the high compression and shear strengths, as well as the excellent impact absorption due to its thermoplastic properties. Foam cores are also usually versatile regarding the manufacturing methods.

On the other hand, cork core is obtained from controlled density cork granules and specific binder which allows to infuse complex shapes such as the forward bottom part of the hull. Additionally, cork core offers favourable properties on impact and slamming. Cork core is also cost effective as shown in Table 2.

*Table 2: Unit cost comparison per SQM for a 3mm core sheet (EasyComposites, n.d)*

| Core type | Unit cost per SQM |
|---|---|
| **PVC foam** | £18.26 |
| **PMI foam** | £60.41 |
| **kevlar Honeycomb** | £53.15 |
| **Recycled PET foam** | £15.30 |
| **Cork Core** | £11.09 |

### c) Bio-based resins

The resin system in a composite structure binds the reinforcement fibres and the core together and transfers mechanical loads through the rest of the structure. Resin systems usually need another system to cure called a hardener. This project's challenge was therefore to combine natural reinforcement fibres, natural and recycled cores, as well as bio-based resin all together. A bio-based resin is a system that derives some or all of its constituent from biological sources (J. Sloan, 2011). These constituents are usually plant-based. It was therefore crucial for the group to find a bio-based resin system derived from renewable resources that offers the same mechanical performances of standard petrol-based resins. Although extensive research has been completed recently on a wide range of bio-based resins, only a few were available for this specific project and matched the mechanical criteria. Two bio-based resins were therefore considered: Infugreen810, offering a very low viscosity properties for infusion of thick laminates, as well as GreenPoxy33, offering high theoretical mechanical properties. Both resin systems offer a 38% of bio-based carbon content. A partnership with Matrix Composites was therefore made for the core materials and bio-resins, in exchange of our materials testing results.

### 1.1.5. Materials testing

A typical carbon Moth is made of a sandwich of ultra-high modulus (UHM) carbon fibre and thin foam core, which is extremely light, stiff, and strong. However, carbon fibre has a negative sustainability impact. Based on the previous research section, other options were investigated. Six different sheets were laid up and cut into specimens for testing. 200gm$^{-2}$ flax fibres, 300gm$^{-2}$ E-glass fibres, 5mm PET core, 2mm cork core, and GreenPoxy33 and Infugreen810 resins were used, as shown in the Table 3 below.

*Table 3: Sheet layup with their associated resin and hardener*

| No. | Layup | Resin | Hardener |
|---|---|---|---|
| 1 | Flax200: 0/90, 0/90 | 197g GreenPoxy33 | 46g fast |
| 2 | EG300: 0/90, 0/90 | 164g GreenPoxy33 | 36g slow |
| 3 | EG300: 0/90, 0/90 | 159g Infugreen810 | 40g slow |
| 4 | Flax200: 0/90, ±45, 5mm PET core, ±45, 0/90 | 429g GreenPoxy33 | 94g slow |
| 5 | EG300: 0/90, 0/90, 5mm PET core, 0/90, 0/90 | 416g Infugreen810 | 104g slow |
| 6 | Flax200: 0/90, ±45, 2mm cork core, ±45, 0/90 | 281g GreenPoxy33 | 62g slow |

These specimens were tested using the electro-mechanical test machines in the TSRL. Three-point flexure tests (BS EN ISO 14125, 2011) and tensile tests (BS EN ISO 527-4, 1997) were carried out on the specimens. A minimum of three specimens were run for each test for an average to be calculated. Water absorption was also investigated by soaking the specimens in a water tank for five days before testing. The specific strength and specific stiffness were determined to compare their strength to weight ratio and their stiffness to weight ratio respectively. Results are shown in Figure 6.

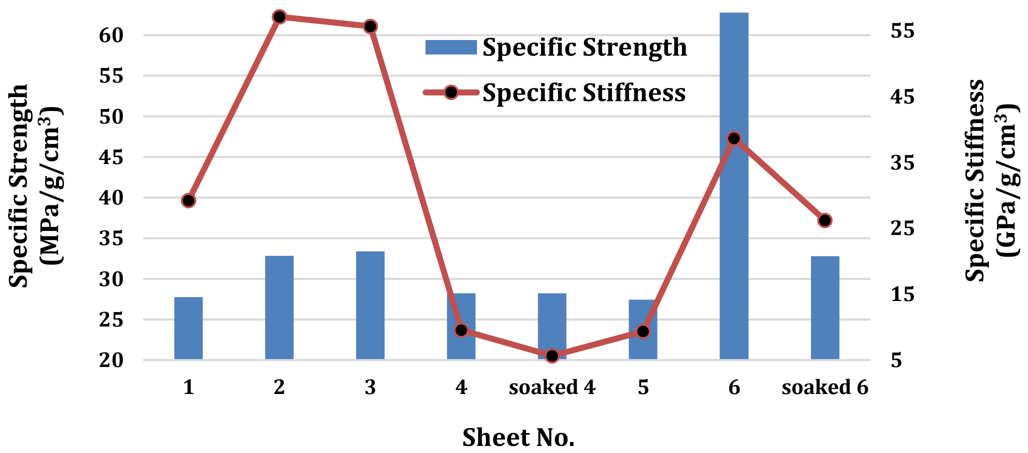



*Figure 6: Specific Strength and Specific Stiffness for all six sheets including results for soaked sheets 4 and 6*

From Figure 6, looking at the sheets with no core, it is clear that E-Glass (no. 2, 3) is significantly stiffer than flax (no.1) and noticeably stronger. There is very little difference between the two choices of resin when comparing sheets 2 and 3. When GreenPoxy33 resin is used the specimen is stiffer but has lower strength compared to using Infugreen810 resin. With the uncertainty in the layup process and the testing, these differences can be considered negligible and therefore both resins can be used for manufacture.

Sheets 4 and 5 compare the difference between E-glass and flax when laid up with two layers on each side of a 5mm PET core. Both these sheets have similar values for specific strength and specific stiffness with sheet 4 being marginally greater for both values. It is worth noting that a different resin has been used for these infusions, but more importantly the flax fibres have been laid up perpendicular to each other as seen in Table 3. It is also worth noting that sheet 5 had air bubbles in the infusion and this may weaken the specimens tested. These are some of the reasons for the sheet made with flax being able to match the sheet made with glass. Comparing both of these sheets to sheet 6, shows a 129% increase in specific strength and a 304% increase in specific stiffness when using cork core. Considering the fact that the cork core is 2mm, the PET is 5mm and the cork absorbs less resin, then the specimen has a 13.3% decrease in mass and a 31.9% decrease in volume compared to specimens from sheets 4 and 5. On top of this the cork core can easily curve into a mould and be used for complex shapes, whereas the PET core is brittle making it only really applicable for flat sides. Overall, cork core has been shown to be the favoured core type.

Investigating the effects of soaking, the specific stiffness reduces considerably for both sheets, however more significantly for sheet 6. Moreover, the specific strength increases slightly for sheet 4 but decreases massively for sheet 6. This is a great advantage of using a PET core, especially when the product's purpose is water-based. If the specimen soaking time was greater than 5 days, there may have been a point where soaked sheet 6 had a lower stiffness and strength than soaked sheet 4. However, waterproof protection in the form of paint is used on the hull, meaning that this is not as critical as it may initially seem. Additionally, a 5-day soaked sheet 6 is still notably stronger and stiffer than a 5 day soaked and non-soaked sheet 4.

When comparing the specimens with core to the ones without, it appears that the PET core lowers the specific stiffness. This is because the PET fails before the flax or glass fibres. Thus, in the samples with PET core, the fibres will still be intact while the core has a fracture in it.

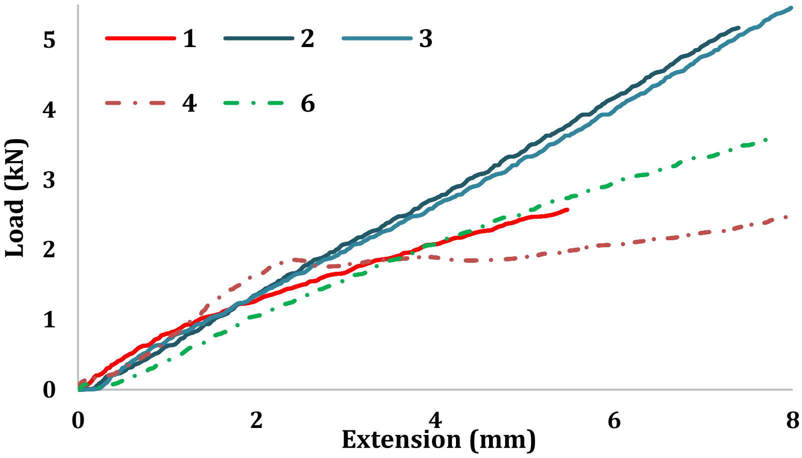



*Figure 7: Load vs extension for 5 different specimens where the dashed lines represent the cored specimens*

From the tensile testing, the extension from a given load was investigated. In sheet 4 the slope of the line becomes less steep around 2 kN which is where the PET core cracks. However, the specimens with PET core were hard to clamp properly and therefore this extension for the given load may be exaggerated due to slippage of the specimen through the clamps. The stiffer a material is, the less it will extend for a given load. Therefore, it is clear from Figure 7, that the two glass specimens are stiffer than the other specimens. This agrees with what is found from the flexure testing as Figure 6 shows that the specific stiffness of the glass is much greater than the other specimens. Figure 7 also agrees with the flexural testing as it shows that using a cork core results in a stiffer specimen than one with a PET core.

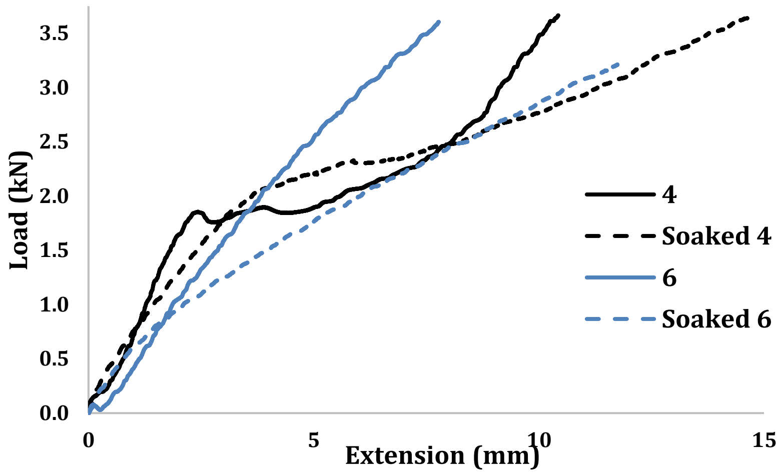



*Figure 8: Load vs extension for the PET core and cork core specimens unsoaked and soaked*

Figure 8 shows the influence of soaking on the tensile properties. This agrees with the results from the flexural testing as seen in Figure 6. The difference between sheet 4 soaked and unsoaked is relatively small whereas the difference between soaked and unsoaked sheet 6 is substantially greater. It is worth noting that both the soaked and unsoaked cork cored specimens stay intact throughout the loading whereas the unsoaked specimens from sheet 4 has a clear crack shown in Figure 8 at approximately 1.8kN. Unsoaked 4 specimens' fracture at around 2kN where an initial crack is seen. This indicates that soaking PET cored specimens reduces the crack propagation. At approximately 2.45kN, three of the specimens all intersect where they have an extension close to 8mm. At this point, these specimens diverge with the soaked ones following a similar trend whereas the unsoaked specimens from sheet 4 require much more force to extend it. The key conclusions from this hull material testing are:

- Negligible difference between using Infugreen810 and GreenPoxy33 bio-resins.
- Flax fibre is a suitable skin to use.
- Varying the orientation of the fibres benefits the material properties.
- The choice of skin is less important when PET core is used.
- Cork core is far superior to PET core in terms of both specific strength and stiffness.
- Soaking affects the specific strength and stiffness for PET core less than with cork core.

From material testing, the main conclusion is that a cork core is favoured over the PET core. However, over 90% of the hull was manufactured from PET core meaning there is great opportunity for future improvement. The cork core is lighter, thinner, absorbs less resin, stiffer and stronger than the PET core. The only area where PET is superior is when the specimen is soaked. However, this is irrelevant as the soaked cork specimen still has greater mechanical properties than the soaked PET specimen. Additionally, the cork core is much easier to lay up than the PET as it can be used for complex shapes rather than flat surfaces. These material results show that flax fibres are capable of being used and is a suitable choice for alternative fibres. If this analysis could have been completed before the manufacturing, the recommended hull layup would be: 0/90, $\pm$45, 3mm cork core, ±45, 0/90 with Infugreen810 resin and using an extra slow hardener. It would be suggested to make all the bulkheads out of flax 200g laid up as: ±45, 3mm cork core, ±45 with Infugreen810 resin. Through using the cork core, a 13.3% weight saving can be made. This can be combined with taking a layer of flax off the hull and if the infusion worked with an extra slow hardener, then this hull would be approximately 5kg lighter than the SuMoth manufactured for this project which would be a mass decrease of around 19%.

# 1.2. Wingbars

## 1.2.1. Introduction

The wingbars are the part of the Moth the sailor sits on, posing significant loads which leads to an engineering design problem. Due to the high speeds of the Moth, the shape can have large effects on the drag of the boat.

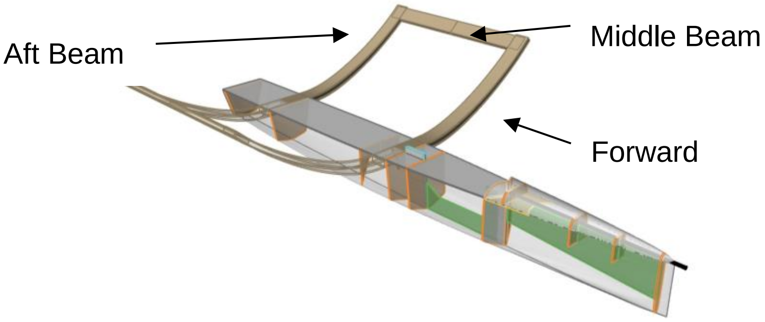



*Figure 9: Wingbar beam definitions*

The aim was to successfully research, design, build and test the wingbars to compare the deflections and bending stresses to the theoretical and computational results, hence validating these.

The wingbar specific objectives include:

- Improve the accessibility of the current International Moth through design.
- Complete theoretical engineering beam theory analysis to predict the wingbar initial dimensions.
- Manufacture the wingbars to comply with the IMCA and SuMoth rules.
- Verify initial dimensions and deflections using mid-manufacture testing, to conclude final design.
- Compare the structural performance of a WASZP foiling dinghy with the SuMoth wingbar design.

The wingbar analysis took place in four stages:

1. Theoretical calculations to obtain initial dimensions, the materials selection for manufacture, and the loads to use within the experimental testing.
2. Wingbar manufacture and mid-manufacture testing.
3. Experimental transverse testing of the manufactured wingbars to validate the FEA.
4. Computational modelling comparison for further optimisation

Theoretical, experimental, and computational wingbar deflections were compared. The FEA predicts the bending and shear stress which were compared to the theoretical values.

### 1.2.2. Research

The design specification of the SuMoth was driven by the IMCA 'box-rule' and the *SuMoth* regulations. The key regulations for the wingbars include the overall beam not exceeding 2.250m. The two driving design questions are compared in Tables 4 and 5.

*Table 4: Comparison between fixed and removable wingbars*

| Fixed | Removable |
|---|---|
| Potential transport issues associated with the width on trailers | Structure not as stiff as a fixed wing system |
| Not as accessible | Easier to transport than fixed |

*Table 5: Comparison between solid and soft trampolines*

| Hard Wings | Soft Sail Material Trampolines |
|---|---|
| Potential transport issues | Easier to transport as they can just roll up and be tied |
| Much heavier | Lighter |
| Longer to manufacture | Cheaper |
| Structural integrity and deflection add another level of engineering analysis | Easier to repair and maintain |

Quality Function Deployment (QFD) analysis was used where ease of transport, material accessibility, sustainability, structural integrity, ease of manufacture, and cost were all taken into consideration in Figure 10.

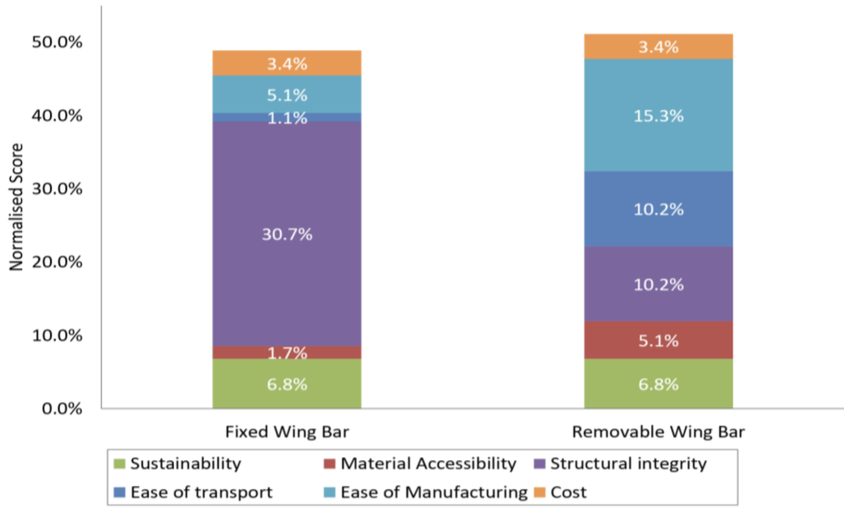



*Figure 10: QFD analysis on fixed versus removable wingbars*

A removable wingbar system with soft sail material trampolines was decided on based on the QFD. Material research was conducted keeping in mind the sustainability and accessibility of the final product. Previous *SuMoth Challenges* have used bamboo for the wingbars however, this has high shipping costs and $CO_2$ offsets. Upcycled broken windsurfer masts was another option but finding identical broken windsurfing masts for both port and starboard sides with the correct dimensions proved challenging. Another issue was identifying how far to cut from the break and how to confirm there was no fracture or damage. An assessment using infrared cameras could have been used however this was not possible at the time.

Wood is a common material used in the marine industry as its cradle to grave sustainability is superior despite being heavier and varnish being required to prevent water absorption and rot. Additionally, the *SuMoth* Rules states that wood equates to 0SM$, making it desirable to use. From industry research, lighter sailors are putting weights in their wingbars to provide more righting moment. Therefore, using wood and opting for a heavier more sustainable wingbar may improve the accessibility as it would mean competitive International Moth sailing is not only for heavier, mainly male sailors. This is achieved through increasing the horizontal moment due to additional weight in the wingbars. As a result of the 25° windward heel, even the leeward wingbar is to windward of the centre of lift on the foil horizontal as the struts are commonly over 1.2m in height. After extensive research, three material concepts were considered:

1. Using recycled PET, Western Red Cedar and Sitka Spruce wood
2. Western Red Cedar and Sitka Spruce wood (core and capping)
3. Sitka Spruce wood

Initial calculations decided which would be best. Wood material properties typically vary based on the region and moisture content therefore material testing was conducted and compared to the data sheets.

### 1.2.3. Materials testing

Materials testing was carried out in the TSRL. Sitka Spruce wood has a Flexural Young's Modulus data sheet value of 11.20 GPa. However, as wood is a natural material the value varies based on the tree and region. Offcuts of wood from the manufacture of the wingbars were tested and compared to 11.20 GPa. The wood was cut into specimen sizes and tensile testing was carried out on three specimens following British Standards specifications (BS ISO 13061-4, 2013). From testing, the Flexural Young's Modulus was found to be 11.14 GPa. This is 0.54% lower than the value found from data sheets. Similarly to previous project tensile testing, the specimens slipped in the clamps which may have caused some error. The theoretical calculations used a Flexural Young's Modulus from the data sheet (11.20 GPa) due to testing being completed after manufacture. All other calculations for the deflections and bending stresses use the materials testing value (11.14 GPa).

### 1.2.4. Theoretical wingbar calculations

The first phase of analysis used beam theory to calculate the maximum bending moment and maximum shear force. To simplify calculations, the wingbar is split into a front, middle, and aft beams as shown in Appendix B. The sailor's mass is positioned on the end of each wingbar when assessing the beams individually, meaning the bending moment and shear force results are worst-case, with no load sharing. When sailing a Moth, the upwind body position of the sailor is forwards whereas downwind the position is aft, meaning results for the bending moments and shear forces would be relatively accurate.

The maximum bending moments and shear force values for each of the three beams is shown in Appendix B. The forward beam is taken as a cantilever with a 723N vertical point load to account for the shroud and a 981N downwards load for the sailor mass positioned at the end of the beam as shown in Appendix B. The shroud load was estimated based on first principals of sailing hydrodynamics and aerodynamics, where a righting moment calculation found an estimate for the shroud tension being 723N with an 100kg sailor. This used the principal that the righting moment equals the heeling moment where measurements for the hull beam, wingbar angle, wingbar dimensions, foil dimensions, and lever arms were based on the *Shock Sailing* International Moth which has been built from the same mould.

The middle beam is calculated both for pinned and fixed supports due to the actual wingbar being a combination of the two which are later compared. The middle beam has a 981N downward load for the sailor positioned in the middle of the beam for the worst-case result. The aft beam is modelled as a cantilever with the 981N sailor load positioned at the end of the beam.

Appendix B is based on an acceleration of 9.81 $ms^{-2}$ (1g) however, future calculations for the initial dimensions of the wingbar are based on an acceleration of 14.72 $ms^{-2}$ (1.5g) due to the higher accelerations experienced in manoeuvres. This has been selected from industry experience from discussions with *Shock Sailing* and *Jeremy Rogers Limited* and although this exact number is not necessarily known, it could be tested as a future project. An investigation into how the acceleration affects the bending stress has been completed later in the report.

The aft beam had the highest bending moment due to no upwards force from the shroud and being modelled as a cantilever beam. The bending moment is almost double the forward beam which has similar forces other than the shroud which acts in the upwards direction. Therefore, there can be a mass saving on the forward beam as dimensions could be reduced.

**Theoretical calculation assumptions used for initial dimensions:**

- SuMoth wingbar angle of 25°.
- An acceleration of 9.81 $ms^{-2}$ (1g) has been used however initial dimension calculations use 14.72 $ms^{-2}$ (1.5g) to evaluate the 'worst case'.
- A sailor mass of 100 kg to allow a range of sailors to sail the SuMoth, hence improving the accessibility. This ensures project objective 3 is met.
- The SuMoth is perfectly symmetrical and has a centre of gravity about the centreline of the hull.
- The estimate of the centre of effort is 2m above the mast bearing.
- The shroud tension assumes the shroud is perpendicular to the wingbar.
- The centre of gravity of the sailor is assumed to be on the edge of the wingbar. This is likely to be fractionally further outboard and this could be a future investigation to gain a more accurate position of the sailor whilst hiking.
- The wingbar sections are straight and uniform with no taper for the theoretical calculations where the aft and forward beam dimensions are taken from the root.
- Beams are assumed to be horizontal to the water, so the vertical component of the sailors' mass is taken. This is the 'worst-case' scenario and effectively simulates the upwind condition.

### 1.2.5. Initial wingbar dimensions

Based on previous Bernoulli-Euler beam theory completed, a maximum bending moment and shear force for each of the three beams has been found at an acceleration of 14.72 $ms^{-2}$ (1.5g). From this, the required second moment of area was found using beam deflection equations taking the Flexural Young's Modulus as 11.20 GPa assuming a deflection of 25mm based on the wingbar length from the hull edge with 100kg (2.5% deflection) (Green et al., n.d., *Mechanicalc*, 2022).

The width and thickness dimensions of the beam for the required second moment of area were found through using the equation for the second moment of area of a rectangular cross section. The width was limited to 100mm to limit aerodynamic losses and minimise weight. This was also based on industry research, experience and advice from leading manufacturers, *Maguire Boats* and *Shock Sailing*. Additionally, this width was selected based on the control line clam cleats widths for the downhaul, vang, ride height and wand length, if a traditional FCS was chosen, as these are mounted on the wingbars in the fitout stage.

These dimensions were checked to ensure the wingbar did not exceed the allowable Flexural Yield Strength (2.07 x $10^7$ Pa) and allowable interlaminar shear strength (6.70 x $10^6$ Pa) for Sitka Spruce through using Engineer's bending theory (Green et al., n.d., MatWeb, n.d.).

Three manufacturing laminations were considered: only Sitka Spruce, only Western Red Cedar, and a combination of Western Red Cedar with Sitka Spruce capping on the bottom and top. Using only Sitka Spruce with no capping was found to be the lightest solution being 8% lighter than when cappings were used, whilst remaining above the allowable bending stress and interlaminar shear strength values for Sitka Spruce.

*Table 6: Sitka Spruce Initial Wingbar Dimensions*

| Beam | Width (m) | Thickness (m) |
|---|---|---|
| Front | 0.100 | 0.065 |
| Middle | 0.100 | 0.061 |
| Aft | 0.100 | 0.083 |

The predicted overall mass based on Table 6 dimensions was 17.4kg, using a Sitka Spruce density of 450 $kgm^{-3}$, excluding the glue and no radii on the edges and corners (Trada, 2022). Additionally, Infugreen810 and GreenPoxy33 bio resins from *Matrix Composites* were compared. This concluded that GreenPoxy33 was the preferred bio resin for manufacture as it is more viscous leading to easier manufacture. It is also very fractionally less dense than Infugreen810.

# 1.3. Computational Modelling

## 1.3.1. Classical Laminate Plate Theory (CLPT) numerical tool

A numerical code based on the CLPT was written on Python to estimate the theoretical strain results in the uppermost and lowermost laminates with the same conditions as in the experiment. Given the manufacturer's data concerning the fibres and the resin used, the CLPT calculates the equivalent properties of a laminate comprised of a given number of plies (lamina) and therefore estimate its behaviour (such as longitudinal strain $\varepsilon_x$) under a certain load. As the CLPT assumes a thin laminated plate, only the uppermost laminate for the deck [+/-45; 0/90]° and the lowermost laminate for the bottom [0/90; +/-45; +/-45]° were considered as the strain gauges were bonded to these. The effect of the core, acting as a support for the laminate was thus not considered in the CLPT.

Based on simple beam theory and the bending moments induced from the load cases (boat weight and loads), an equivalent tensile or compressive stress can be obtained at any distance from the neutral axis, at any cross-section. An equivalent tensile or compressive load is calculated by multiplying the equivalent stress with the area of the concerned laminate. To match the experimental results, the active width of a 120-Ohm uniaxial strain gauge and the ply thickness measured from the material's testing experiment were considered, that is 2.54mm and 0.325mm respectively. The deck has a different stacking sequence than the hull bottom and side meaning the area considered for the uppermost and lowermost laminates are therefore different. Although

the hull's COG was located above the forward support, at the centreboard case, the weight of the boat was accounted for when calculating the bending moment at each cross section.
The following manufacturer's data were used as inputs for the CLPT initial calculations:

*Table 7: Initial CLPT data, based on manufacturer's datasheet*

| | **Flax Fibre** | **Infugreen810** |
|---|---|---|
| Density, ρ (g/cm$^3$) | 1.14 | 1.16 |
| Flexural modulus, E (GPa) | 9.40 | 2.80 |
| Poisson's ratio, v | 0.22 | 0.30 |
| Weight fraction, W | 0.50 | 0.50 |

## 1.3.2. Hull FEA methods

The model of the hull was created in *Rhinoceros V5* and imported into *Ansys DesignModeller*. The bulkheads were modelled in *Ansys* in order for their locations and sizes to be adjustable. This feature was later found to be prone to error as *Ansys* is not an optimal platform to handle surface models. Since the manufactured hull is made from composite materials, the model had to be optimal for simulating the composite material behaviour under load. Therefore, the *Ansys Advanced Composite Prep/Post (ACP)* was decided to be loaded to *Ansys Mechanical*. This program creates detailed composite laminates that allows analysis for Classical Laminate Plate Theory (CLPT) at each node level. Therefore, failures such as first ply failure can also be detected after completing the simulation. To use this module, the model had to be created using surfaces only. This is due to the thickness being defined after defining layups on the *ACP*. All the material properties that were used on the hull were added from their datasheet provided by the manufacturer. The loading conditions were defined for comparing with experimental values. This allows direct comparison between theory, experimental and FEA results.
The convergence analysis of the hull model was also conducted, and results were confirmed to be converging with increasing mesh node count.

## 1.3.3. Wingbar FEA Methods

The model for the wingbar was originally created on *Rhinoceros V5*. However, to create the model that can be parametrically driven by *Ansys* and is modelled as 3D solid body rather than combination of surfaces, the model was remodelled in *Solidworks*. This model contained 4 parameters which were able to be changed from *Ansys* and rebuilt in *Solidworks* before importing to the mesh. These parameters were the thicknesses at the root by the hull and at the outboard end of both fore and aft wingbar sections. The wingbars were manufactured from Sitka Spruce wood, therefore, the corresponding material properties were inserted to the *Ansys* engineering data. As the wood has orthotropic elasticity, this required the Flexural Young's Modulus, Poisson's ratio, and Shear Modulus for all directions. The material testing of the Sitka Spruce specimens were conducted only in 1-direction. Therefore, all the other data was inserted from Ross (2010). This also shows the difficulty in experimental measurements of some properties. Wood shows different elastic behaviour in each direction. Therefore, the coordinates in the *Ansys* had to be changed between fore, aft and middle sections of wingbar to model the grain direction correctly. The manufactured fore and aft sections of the wingbar were made of multiple thin plies of Sitka Spruce wood which were shaped and bonded using GreenPoxy33 and wood chip filler. Although the ideal model would have the grain direction following the curve of the wingbar shape, this was difficult to achieve on *Ansys*. Therefore, the coordinate systems were decided to have the X direction, parallel to the line connecting top and bottom ends of the bar. Additionally, the effect of the GreenPoxy33 and woodchip acting as the glue was neglected. The convergence analysis was done in 6 different mesh densities. From the convergence analysis, the model's solution was found to be close to the result at $2.27 \times 10^5$ nodes. Therefore, for the later results the same mesh settings were used for the analysis. The model was analysed at the same loading conditions as for the theoretical calculation conditions and the bottom sections of the wingbars nearest to the hull were kept fixed. The sailor and shroud loading were modelled as remote forces with sphere of influence to make it more similar to the real-life loading condition. The results were compared against the SuMoth wingbar's experimental and theoretical results, and the experimental results of the WASZP wingbar. Additionally, some severe cases were analysed.

# 1.4. Flight Control System (FCS)

## 1.4.1. Current solution

The current flight control system (FCS) is a purely mechanical solution to control the ride height of a Moth. The ride height is controlled by a flap on the trailing edge of the main foil. This is contrary to the method that controls the ride height by changing the rake angle of the foil. (New, 2021).

**Key terms:**

**Wand** - The rotating strut at the bow that pivots to keep one end on the water surface. The end in contact with the water typically has a spoon shape.

**Push rod** - The strut that moves laterally, that conveys the movement of the wand to the crank on the top of the foil. N.B. there is also typically another push rod that is internal to the main foil vertical. This is not going to be a significant part of this report and will be referred to as the foil vertical pushrod.

Being a mechanical system there is no distinct actuator, whereas the movement is provided by a lever that acts as a force multiplier further up the wand. The mechanical advantage of the wand is approximately 72:

$$\left(\frac{wand\ length}{distance\ from\ pivot\ to\ pushrod}\right) = \frac{1800}{25} = 72$$

The current system is highly customisable and tuneable with the sailor being able to adjust the gearing of the system, the pushrod length and the wand length. These all directly affect the performance of the main foil, with various other adjustments available both in the dock tune and dynamically on the water that directly or indirectly affect performance of the vessel. This demands expertise to use effectively.
There are some issues with the current system. The main one being that the calibration and setup is a very long winded and complicated, with it taking up to a year to set up correctly. This severely limits the accessibility of the International Moth Class. Another issue is that the class is chasing ever smaller gains in drag reduction. The wand provides a drag that if removed would result in a small performance gain that a competitive sailor would be keen to benefit from.

## 1.4.2. Options for replacement

Two alternative solutions were investigated to replace the mechanical wand system. The first being a passive control system and the second being an electronic control system. While an electronic

system is relatively simple to envision- and there are a number of different solutions that fit this title, the concept of a passive foil is in this case referring to one specific solution.
The passive foil control system is based on balancing the weight of the flap to the lift of the flap. As the speed of the boat increases, the pressure difference between top and bottom parts of the foil raises. Thus, the flap lifts and the drag become smaller while the same lift force is kept.
The concept has been tested and confirmed to be working in normal water flow without free surface effects (Newman, 1977). Also, this concept could be a large simplification in whole system's complexity as the only thing needed was the spring to control counter force acting on the flap.
These two methods and the traditional wand were compared using the quality function deployment method. The assessed qualities in the QFD analysis were ease of sailing, accessibility, robustness, sustainability, wave performance, ease of manufacture and cost.
However, as the behaviour in waves was not tested and the set-up process could have been more complex, it was decided to progress with the electronic system with a slight advantage in QFD.

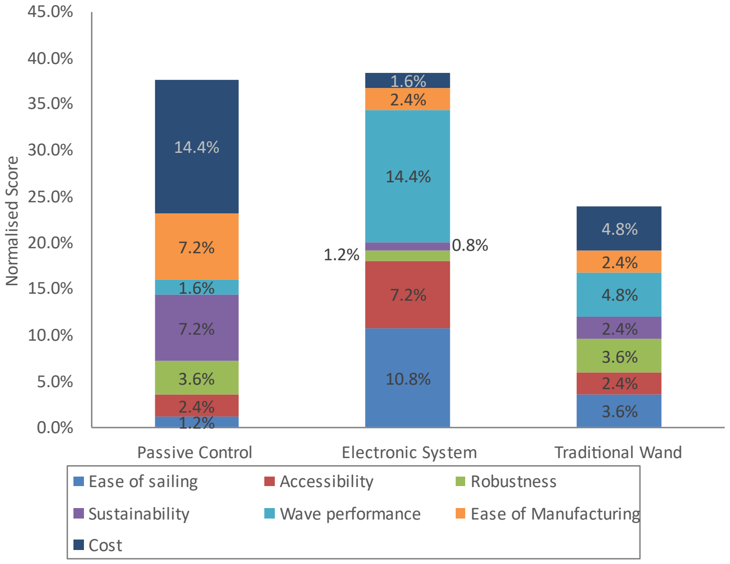



*Figure 11: QFD analysis of flight control systems*

The results, shown in Figure 11, show that for these categories both novel solutions perform superiorly to the traditional wand system, with the electronic system being marginally better than the passive system, thanks to its capabilities in waves and the ease of sailing and despite its higher price tag.

## 1.4.3. FCS Design – Hardware

The main functions of the traditional wand system are to measure the flight height of the boat over the water and to drive the foil flap via a pushrod system. There is also an element of measuring the speed of the vessel, however this process is less integral than the other two. As such the two major aspects to replicate are the height sensing capabilities and the actuation of the foil flap.

### Height sensing

A number of options exist to measure the distance of the surface of the water electronically, such as RADAR/LIDAR, ultrasonic or contact sensors on the foil mast. The solution that was chosen was to use an ultrasonic range sensor for several reasons. A point to note here is that all electronics must be waterproof to a submersible level, meaning an ingress protection (IP) rating of IPx7 or higher is required. This puts a significant limitation on the range of equipment that is suitable for the purpose, eliminating some of the more affordable solutions, a significant factor in a project with a limited budget.

- **RADAR/LIDAR:** Radar is the first and most traditional range sensing method. It operates by emitting radio waves and measuring the delay in the time between the emission and reflection. LIDAR works on a similar principle but instead uses light to measure distance. These systems tend to have a wide range of measurable distances which would not be fully utilized in this application, and there are few viable modules and what few there are, are expensive.
- **Ultrasonic:** As opposed to the previous examples, ultrasonic sensors don't use parts of the electromagnetic spectrum and, as the name suggests, uses ultrasonic waves reflecting off a surface to sense the distance. Ultrasonic is defined as sound waves greater than about 20 kHz (Krautkrämer and Krautkrämer, 2013) and typically sensors use the frequency range between 40 and 250 kHz. Acting to the detriment of ultrasonic sensors is the reliance on environmental aspects for an accurate distance measurement, as they are affected by both temperature and density. This is less critical in this application as relative height changes are more relevant. A key benefit of ultrasonic sensors is that they are popular among the hobbyist community, and as such there exists a wealth of options for suitable modules. Ultimately this solution was therefore chosen.
- **Contact sensors:** Another option is to use contact sensors attached to the foil. These could either take the form or discrete electrical contacts that get bridged by the water to obtain a digital value for height, or two long contacts that use the varying resistance to assess height. This was disregarded as the group was not planning on making foils and it would add too many complications to adapt existing foils.

### Actuation method

The method of moving the foil flap faces similar restrictions to the sensor module as it must be waterproof to the same level and is also constricted on price. There were several solutions that were examined as outlined below:

- **Linear actuator:** Initial impressions suggest that the linear actuator would be the ideal solution for this application, as the existing solution is to use a pushrod that acts in a linear fashion on the top of the foil. There are some limitations such as the actuation speed and power requirements. They are also expensive especially when considering the level of water resistance that is required (also IPX7 or higher as, while more protected, the actuator will still be vulnerable in the event of a capsize or similar). These features can be commonly found in hydraulic systems however on the scale of the SuMoth, a full hydraulic system is completely unfeasible due to weight restrictions and volume restrictions, this has the implication that on a larger vessel that requires flight control, a hydraulic system might be appropriate and effective especially if other hydraulics are in use. As such alternative methods of actuation were sought that would better fit the criteria of the application.
- **Servo motor:** Another method of actuation that was investigated was to use a servo motor with a connecting rod to generate linear motion. This is a minor disadvantage of the addition of the connecting rod however the added complexity is outweighed by the increased availability of the module. This increased availability is because there is also a significant use for servomotors among hobbyists and as such there is a wide variety of specification to choose from. Another potential limitation comes from the high loads in the pushrod however high torque models of servos should be able to provide sufficient force especially as the server arm can be very short due to the minimal movement in the pushrod. The popularity with hobbyists has also driven the price down allowing it to become a more accessible solution in this system. This combination of factors let us to decide to use servo motors in the final project.

## Control Unit

The final major component of the FCS is the control unit. There is a multitude of small form factor microcontrollers that would potentially be suitable, the most applied ones being the *Arduino nano* and the *Raspberry Pi Pico*. As these are well documented and easily used, the search was constrained to these options for ease of programming and to make the best use of time. Both controllers should perform similarly however there are some differences between them such as the *Pico's* 3.3 Volt pin out as opposed to the *Arduino's* 5 Volts. This could have formed an issue when interfacing with the servo. When combined with increased experience using *Arduino* in previous projects, the decision to use the *Arduino nano* was made.

## Other Hardware

In this case the system is also designed to use an MPU9250 Inertial Measurement Unit (IMU). This is to mitigate potential limitations of the use of a hobbyist ultrasonic sensor at this stage, however it may be further utilised in future iterations of the software as algorithms get more complex.

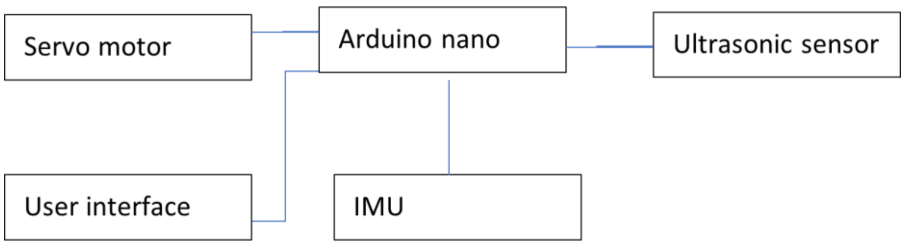



*Figure 12: Overall system layout*

## Software

In this project the aim for the software side of the FCS is to simply achieve stable flight such that it performs at least as well as the traditional wand system. While the introduction of an electronic control system allows for more complex control systems, the simple aims suggests simple control. The challenge of stable flight is effectively a balancing problem, and there have been many examples of effective balancing systems. A common control solution for this is the PID controller or Proportional, Integral, Differential controller. The major difficulty when implementing this kind of control system is to tune the relevant gains for each element of control. This is particularly difficult to accurately achieve the optimal gains for the application when attempting to do so ahead of the main manufacture, and often takes some amount of trial and error. In order to minimise the level of tuning that is required once the boat is sailing, a simulation environment was created inside of *Simulink* to best recreate the forces that would act on the boat and thus how a specific controller is likely to react.

The simulation is based on estimates for the properties of the SuMoth and thus will require some tuning to allow it to perform at its best. The simulation models the following:

- **Height above the water surface**: Calculated using the mass of the SuMoth and the lift of the foils, as controlled by the PID controller.
- **Angle of the boat**: Calculated by the differing levels of lift from the main and rudder foils and a theoretical centre of mass

The measurement of the height is modelled to be off a bowsprit such that the angle of attack of the SuMoth will affect the height measured. The lift of the rudder can be varied by changing its angle of attack relative to the hull, as it would on the real SuMoth. This level of customisability was added to ensure that the control system would provide a robust response to inaccurate estimates for

values. There is an imposed limit on the flap angle of 10º of deflection as it is assumed that from 0º to 10º the relationship between lift and flap angle is linear, as it is for an airfoil (Traub and Coffman, 2019).
In order to tune the gains of the controller, the *Simulink* inbuilt PID tuner was used, which uses a transfer function-based method to obtain appropriate values. This calculates a transfer function based on the overall structure of the model and allows the response time and transient behaviour to be varied. The tuning of the response must be done carefully, as if the response is too aggressive, then the response tends to overshoot, this is a poor quality as this runs the risk of the boat flying too high. Additionally, if the response is too slow then the boat would become slow to take off or to respond to the sailor's input, it may make for a robust flight but would be difficult to sail well. If the response is made to be too fast or too robust then the control system would be driven too hard and it is likely to run into hardware limitations, it is also likely if the response is too fast then the boat would feel sensitive and would also be difficult to sail.
**Error! Reference source not found.**13 shows the anticipated response for the system using the gains of: proportional 58, integral 30 and differential 26. The conditions shown in the modelled system are a flat sea state, a request from the sailor to increase the ride height to 1 m at 10 s and a change of the rudder foil angle of attack at 20 s, in this case the system provides an adequately timely response with minimal overshoot. The large change in ride height is analogous to a take-off condition and is representative of the largest change in height that is expected to be seen when sailing. This shows that this control system will be able to handle take off. The fine tune of the vessel's attitude is left to the sailor and is simulated by the change in angle of attack of the rudder. In this case it is clear that the system can handle this case also, and the system can adjust flap angle to maintain level flight.

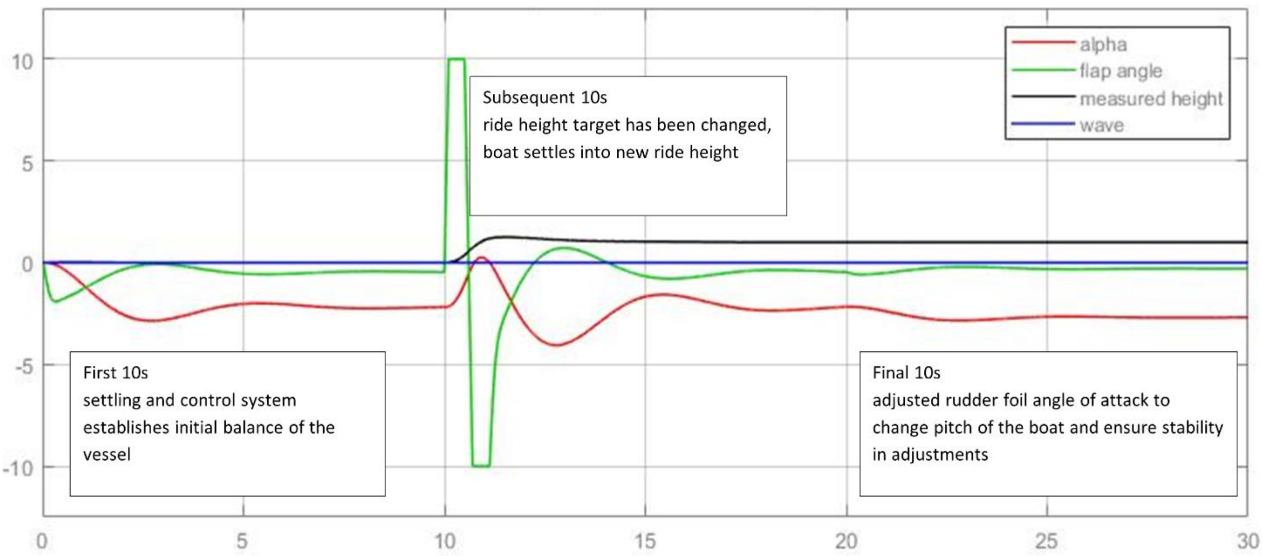



*Figure 13: Predicted behaviour of vessel under control in flat sea state, 10 s is an increase of height from 0 to 1 m and at 20 s a change of rudder angle of attack. Wave is the simulated sea state, measured height is the height calculated as if at the bowsprit, flap angle is the angle of the foil flap and alpha is the angle of attack of the boat.*

# 1.5. Foils

Due to time constraints, it was decided at the beginning of the year to not design the foils and work in partnership with professional industries to manufacture them in order to comply with the *SuMoth* Rules. *Maguire Boats* therefore loaned us the complete rudder foil and main foil horizontal. Since the *SuMoth* rule states that the foils and verticals allow a maximum of 80% per mass CFRP, *Maguire Boats* have manufactured a new main foil vertical. This enables the team to comply with this rule as 1186g of glass fibre has been added into the typical manufacture of the main foil vertical. The glass was added in the core of the main foil vertical on the neutral axis which reduces pitching of the SuMoth. This approach minimises radius of gyration. The total main and rudder foils and verticals package has a total CFRP content of 79.4%.

# 2. MANUFACTURING AND COST ANALYSIS

## 2.1. General description

As mentioned previously, the Southampton SuMoth Team decided to focus on the hull manufacture, including hull shell, deck, foredeck, and internal structure, as well as the wingbars and the flight control system. Any other parts were obtained from sponsors, second handed, except the main foil vertical which was manufactured by *Maguire Boats* in order to comply with the SuMoth Rules. The team's manufacturing Gantt chart shown in the Appendix B breaks down the tasks and the associated number of hours.

## 2.2. Hull

Composite materials are used for this project as it allows for a unique layup to be chosen. A composite is defined as a material made up from two, or more, constituent parts. The combination of these parts creates a new material which will have different properties compared to the constituent parts. Advantages of using composites are that specific material choices can be used which in this case is essential to ensure a sustainable product. Composites allows the group to tailor the material to suit structural requirements and produce complex shapes. Composites are also very durable with great fatigue and environmental tolerance as well as having good specific strength and specific stiffness.

The process of making a composite material is to lay down skins (fibres) on each side of a core, then this needs to be infused with a resin and hardener mixture. A heated environment improves infusion quality and can be done as a wet lay-up where each layer of fibre and core is brushed in resin, laid on top of the next layer and then left to cure. Vacuum infusion is preferred for its reduced void content. The laid-up materials are placed under a vacuum bag, where a sealed tube is connected to a vacuum pump. An additional sealed tube at the other end is used to input the resin. The vacuum sucks the resin through the material and ensures there are limited to no air bubbles in the end product. It is worth noting that many layers of skins or core can be used where orientating them in different ways results in improved material properties.

For the SuMoth hull manufacture, sub-components include bulkheads, centreboard case, foredeck and deck. The mould was placed on top of two trestles and was prepared by removing tape and repairing any damaged parts. The mould was waxed five times to ensure for easy hull release. Twill flax fibres were cut from the roll and laid up inside the mould. The PET core was cut to size and perforated at roughly an inch apart. This allowed the resin to be distributed properly during the hull infusion.

The hull was laid up as seen in Figure 14. At the front of the mould where the bow is narrow, it is hard to fit the PET core. Therefore, cork core was used as it can be shaped into complex forms.

On the bottom of the hull where the centreboard case goes, an extra strip of +/-45 flax was used on either side of the core as this is a critical point where additional strength is required.

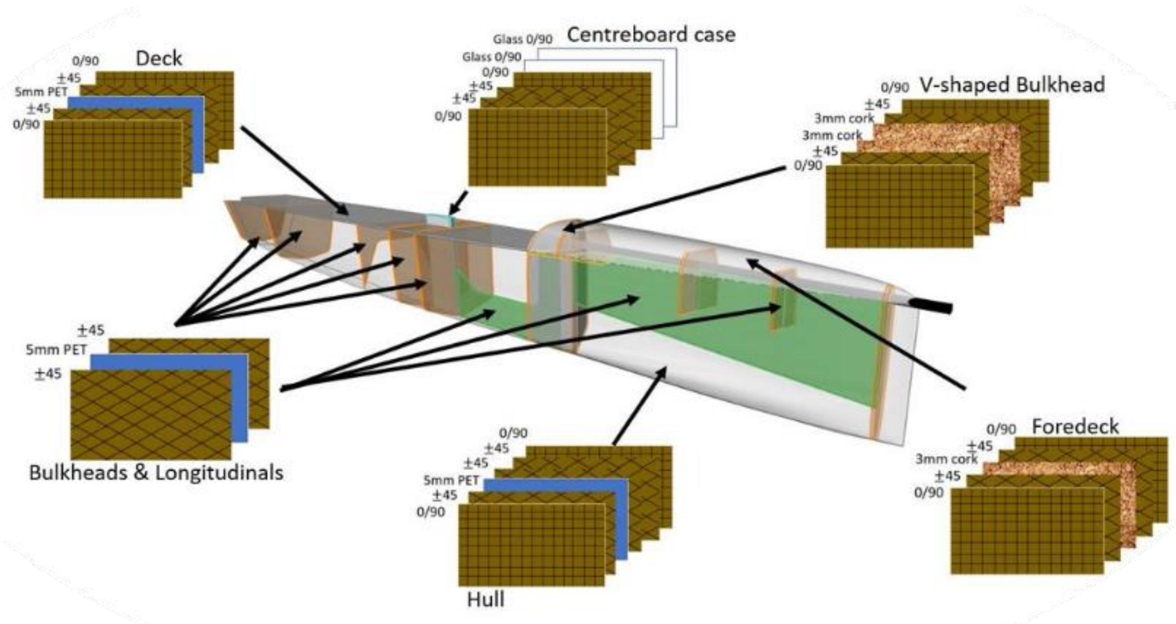



*Figure 14: Materials used in the layups of all the hull and the other components that are fitted into the hull. The back skin represents the outer layer of each component.*

The hull infusion preparation began with laying down consumables that were sealed with tacky tape. 9.26 kg of Infugreen810 bio-resin and hardener was mixed, and the vacuum pump was switched on.  Once the hull was infused, the vacuum bag was removed along with the infusion consumables. Adding a layer of distribution mesh and peel ply offers an even distribution of the resin and leaves a clean finish.

*Figure 15: a) Infusion of the hull in the mould with the vacuum bag. b) release of the hull c) bonding of internal structure d) a wingbar mount being laid up. e) wand tube and kingpost stuck in the hull along with bulkheads.*

The hull was then released from the mould which took a lot of effort, making the group realise that the five layers of wax was not sufficient, and that next time Teflon should be used to ensure an easier release from the mould. Furthermore, the hull also exothermed at the bow where bridging of material occurred, and resin built up (Figure 15).

The hull needed to be fitted with bulkheads, longitudinals, centreboard case, carbon tubes, wingbar mounts and the deck. The deck was laid up the same as the hull minus the duplicate layer of +/-45 flax. Teflon was stuck down on the mould and was waxed before laying up. The same steps as for the hull were followed with a vacuum infusion using Infugreen810 bio-resin. The deck released from the mould with much more ease confirming that sticking Teflon on the mould is a viable method to allow for the product to be released properly.

The centreboard case was made by wrapping the mould in the materials shown in Figure 14. The silica is used to waterproof the case and an extra layer of flax and glass was wrapped around the top, where the pins which connect the main foil to the hull are located. This was infused with GreenPoxy33 resin. Four holes were drilled in the bottom of the hull and then using a jigsaw, a rectangle was cut out and then sanded. The centreboard case was then bonded into the hull using a mix of GreenPoxy33 resin, hardener, silica, and wood chip filler. The bulkheads were made by laying up a single sheet of flax +/-45, 5mm PET, +/-45, infused with Infugreen810 resin and then cut. Flax offcuts from the hull layup were used to layup the bulkhead sheet, which meant that the flax had to overlap. The width of the overlap was around 50mm to ensure that this method of using flax offcuts did not hinder the material properties of the bulkheads. The influence of overlap width is later investigated in the report.

The V-shaped bulkhead supports the kingpost which holds the mast and therefore must withstand large loads. As seen in Figure 14, this bulkhead was consequently made stronger and was infused with Infugreen810 resin. The wingbar mounts were made by using the wingbars as a mould where a layup of 0/90, +/-45, 3mm cork core, +/-45, 0/90 (Figure 15) was used. The wingbar mounts were manufactured using wet layup with Infugreen810 resin.

All the bulkheads were bonded in and the upcycled carbon fibre wand tube and kingpost were bonded in Figure 15. Areas that required extra strength such as around the kingpost, centre board case, and bulkheads were secondary bonded with strips of glass fibre and Infugreen810 resin. A block of PET was bonded and shaped onto the front of the hull to make the bow. The deck was cut and bonded onto the hull between the V-shaped bulkhead and the wingbar mounts.

## SuMoth Cost Analysis

*Table 8: Quantity and cost in SuMoth Dollars for Hull items*

| Hull items | Qty. | Units | Cost in $SM |
|---|---|---|---|
| Infugreen | 14.00 | kg | 210.00 |
| Flax | 6.60 | kg | 0.00 |
| PET Core | 4.97 | kg | 0.00 |
| Cork Core | 0.99 | kg | 0.00 |
| Glass fibre | 0.50 | kg | 12.50 |
| Carbon | 1.46 | kg | 358.75 |
| Primer Paint | 2.00 | kg | 50.00 |
| Undercoat | 2.00 | kg | 50.00 |
| Topcoat | 1.00 | kg | 25.00 |
| Infusion mesh | 5.00 | $m^2$ | 15.00 |
| Spiral tubing | 3.00 | m | 3.00 |
| Peel ply | 6.00 | $m^2$ | 30.00 |
| Knitted infusion mesh | 0.27 | $m^2$ | 0.80 |
| Paint brushes | 10.00 | item | 20.00 |
| Spray glue | 0.40 | kg | 6.00 |
| Masking tape | 10.00 | 15m roll | 80.00 |
| Tacky tape | 4.00 | 15m roll | 16.00 |
| Oven post cure | 8.00 | hours | 160.00 |
| **TOTAL** | | | **1037.05** |

## Commercial Cost Analysis

*Table 9: Breakdown of the hull cost in pounds*

| Hull Cost Breakdown | | | | |
|---|---|---|---|---|
| *Items* | *£/unit* | *Quantity* | *Unit* | *Total* |
| Infugreen810 + hardener | £22.65 | 15.9 | kg | £360.10 |
| PET Core | £15.28 | 4.38 | m² | £66.93 |
| Cork Core | £11.09 | 1.28 | m² | £14.16 |
| Flax fibres | £7.95 | 27.24 | m² | £216.53 |
| Glass fibres | £3.95 | 0.5 | m² | £1.98 |
| Carbon tubes | - | - | - | £360.00 |
| **TOTAL (excl. VAT)** | | | | **£1,019.69** |

# 2.3. Wingbars, Trampolines and Toe Straps

The technique of ply lamination has been taken from the manufacturing process of the Contessa tiller which has been used for over 50 years. All wingbar beams were manufactured with the fibres in the direction of the load being on axis. This is the strongest direction for the wood fibre being largely unidirectional rather than orthotropic for most metals.

A homemade mould was built using old wooden blocks drilled into a recycled piece of woodchip board. This was used to produce a single forward beam and aft beam with an angle of 25°. Lofting onto the woodchip board took place, where a wingbar beam of 2.25m and angle of 25° was drawn to correctly position the wooden blocks which were glued and screwed in place. Sitka Spruce wood planks were cut into 7mm plies which ensured easy bending around the mould. The plies were glued together using a GreenPoxy33 bio-resin and wood chip mix. This filled mix made the resin more viscous and easier to handle for bonding the plies together. Once laminated, the plies were bent round the mould former and clamped onto the blocks. Once the resin mix had set, the clamps were removed, leaving the wingbar at an angle of 25° port and starboard. Additionally, two straight middle beam sections were also manufactured. Assembly of the forward, aft and middle beams used tenon joints and the same GreenPoxy33 resin and woodchip mix for gluing the joints.

*Figure 16: Aft wingbars were bent and clamped around the homemade mould*

The tapering of the wingbars was manufactured as shown in Figure 16. Straight plies were laid on top of each other and tapered through cutting wedges off. A final ply was added on top to avoid the edges of plies being exposed.

A mid-manufacture test was completed on the forward and aft beams at dimensions less than the initial theoretical predictions in Table 6, allowing a decision to be made regarding adding plies. This shows how adaptable the wingbar manufacture is. 20kg, 40kg, and 60kg masses were hung using rope on both sides of the wingbar. A large mass was positioned in the centre of the wingbars which simulated the fixed boundary condition. A stick, masking tape and pen were used to mark the top of the wingbar with each mass loaded. Despite the inaccuracy of the experiment, this gave an idea of how the wingbar performed with the decreased dimensions.

A linear response was found for the mid-manufacture testing. The results were identical on both port and starboard sides of the wingbar due to their symmetrical geometry. The final manufactured dimensions are shown in Table 10 and testing is shown in Figure 17. Based on other International Moth designs and industry experience, deflections were small compared to initial estimations indicating no additional plies were required.

*Table 10: Sitka Spruce Manufactured Wingbar Dimensions*

| Beam | Width (m) | Thickness (m) |
|---|---|---|
| Front | 0.098 | 0.054 |
| Middle | 0.098 | 0.036 |
| Aft | 0.098 | 0.060 |

*Figure 17: Mid-manufacturing testing*

The wingbar supports moulded directly from the underside of the wingbar and fitted into the hull. These were made by sticking Teflon release tape around the centre section of the wingbars and wet laminating flax around them. The supports were glued and secondary bonded into the hull and then the Teflon was removed giving a small clearance for paint and varnish. Carbon plates made from second hand material from *Jeremy Rogers Limited* was used to form top plates to retain the wingbars. These carbon plates are located above the wingbars and bolted into big heads which are glued into the hull, fixing the wingbars securely into the hull. The shroud fittings and control line cam cleats are situated on the front beam of the wingbar.

The trampolines were upcycled from old sail material from previous projects at *Sanders Sails* in Lymington. In recent years *Sanders Sails* have been known for their sustainability and upcycling and the team worked with them to find the best solution. A laced system allowed the trampolines to be tensioned fore and aft. Velcro was used over the middle beam outer edge of the wingbar which kept the retrieval lines for the control line systems hidden and clear of the sailor for safety purposes.

The toe straps were manufactured by *Ingen Sailing* and used Sam Whaley’s knowledge to develop the best system for the SuMoth. The toe straps used inspiration from his previous designs on the WASZP foiling dinghy.

### SuMoth Cost Analysis

*Table 11: Cost breakdown of wingbars in SuMoth Dollars*

| Wingbars | Qty | Cost in $SM |
|---|---|---|
| GreenPoxy | 0.2 kg | 3.00 |
| Sitka Spruce | 15.6 kg | 0.00 |
| Carbon strips | 0.15 kg | 37.50 |
| Lacquer | 0.2 kg | 5.00 |
| Brass insert | 0.1 kg | 1.00 |
| Toe strap | $80 | 80.00 |
| Upcycled trampoline | - | 0.00 |
| **TOTAL** | | **126.50** |

### Commercial Cost Analysis

*Table 12: Cost breakdown of wingbars in pounds*

| Wingbars Cost Breakdown | | | | |
|---|---|---|---|---|
| *Items* | *£/unit* | *Quantity* | *Unit* | *Total* |
| Sitka Spruce Wood planks | - | - | - | £355.30 |
| GreenPoxy33 Resin + hardener* | £27.04 | 0.2 | kg | £5.40 |
| **TOTAL (excl. VAT)** | | | | **£360.70** |
| **TOTAL HULL + WINGBARS (excl. VAT)** | | | | **£1,380.39** |

## 2.4. Appendages

The foils were manufactured by *Maguire Boats* to comply with the *SuMoth* Rules. However, a lot of manufacturing information is missing and two prices were therefore calculated to avoid any vagueness:

### SuMoth Cost Analysis – Materials wise

*Table 13: Cost of appendages in SuMoth Dollars*

| Item | Material | Qty | Cost in $SM |
|---|---|---|---|
| Rudder package | CF HM | 2.266 | 551.25 |
| Main foil horizontal | CF HM | 0.918 | 229.50 |
| Main mast | E Glass | 1.186 | 29.65 |
| Main mast | CF HM | 1.447 | 361.75 |
| **TOTAL** | | | **1172.15** |

### SuMoth Cost Analysis – Based on commercial price

The foils were bought to *Maguire Boats* at a commercial cost of £400 (i.e. 505$). Therefore, an equivalent $SM cost can also be calculated:

*Table 14: Cost of Rudder in SuMoth Dollars*

| Item | Commercial price | Qty | Cost in $SM |
|---|---|---|---|
| Rudder + main package | 500$ | 1 | 505.00 |
| **TOTAL** | | | **505.00** |

The higher of the two cost, which is $SM1172.15 is considered as the final calculation for the total SuMoth dollars.

## 2.5. Rig

*Table 15: Cost of Sail, rigging and blocks in SuMoth Dollars*

| Sail, rigging, blocks | Qty | Cost in $SM |
|---|---|---|
| Sail (shrouds, mast, podder) | $500 | 500.00 |
| Blocks (industrial excess) | $2000 | 2000.00 |
| Ropes | $500 | 500.00 |
| Boom dry CF HM | 0.74 kg | 185.63 |
| Boom Bio-based Epoxy | 0.91 kg | 13.61 |
| **TOTAL** | | **2699.24** |

## 2.6. Control system

*Table 16: Cost of flight control system in SuMoth Dollars*

| Flight Control System | Qty | Cost in $SM |
|---|---|---|
| Tiller | 0.30 kg | 75.00 |
| Tiller extension | 0.27 | 67.50 |
| Wand | 200$ | 200.00 |
| **TOTAL** | | **342.50** |

## 2.7. Fittings

*Table 17: Cost of fittings in pounds*

| Description | Qty | Cost in £ |
|---|---|---|
| BLK – 40mm FLY UNCARDED | 1 | 202.24 |
| BLK-29MM CARBO T2 | 5 | 134.70 |
| BLK-16MM AIR CHK (416A) | 4 | 73.72 |
| BLK-18MM FLY DBL UNPACKAGED WITH LINE | 2 | 85.18 |
| BLK-MICRO (224A) | 3 | 39.96 |
| Angled Micro Cam Riser | 4 | 34.16 |
| WEDGE KIT-MICRO CAM | 4 | 19.68 |
| BLK-40MM CARBO RATCHET | 1 | 69.50 |
| 29mm Fly Block | 2 | 322.16 |
| BLK-18MM FLY NARROW HEAD | 1 | 24.52 |
| 1.00 Wire Sheave | 2 | 56.62 |
| BLK-16MM ANTI-CAPSIZE (442A.ASSY) | 2 | 48.26 |
| BLK-16MM AIR PVT CHK (432A) | 8 | 159.44 |
| SHV-16MM | 3 | 34.50 |

| | | |
|---|---|---|
| 65mm Asym. C/Hook No Eye (B/L ~450kg) | 2 | 14.36 |
| CAM CLEAT-MICRO AL II (468A) | 3 | 103.20 |
| 14mm Lead Ring UN-CARDED | 1 | 26.04 |
| Racing Sail Line (Starboard) Hard Anodised | 1 | 8.41 |
| Racing Sail Line (Port) Hard Anodised - Loose | 1 | 8.00 |
| FAIRLEAD-MICRO CAM XTREME II | 2 | 36.20 |
| Stainless Eye Strap UN-CARDED | 4 | 9.84 |
| 4mm Shallow Bow Shackle (loose) | 1 | 5.38 |
| BLK-MICRO TRPL (228A) | 1 | 49.25 |
| BLK-MICRO DBL W/BKT (227A) | 1 | 37.07 |
| Bullet Cheek Block for Wire | 1 | 28.88 |
| BLK-1in WIRE THRU-DECK | 1 | 54.84 |
| BLK-MICRO THRU-DECK | 1 | 32.74 |
| BLK - 40mm FLY UNCARDED | 1 | 202.24 |
| BLK-MICRO (224A) | 1 | 13.32 |
| BLK-MICRO THRU-DECK | 1 | 32.74 |
| Stainless Eye Strap UN-CARDED | 5 | 12.30 |
| Triple Micro Block w/Becket | 1 | 50.94 |
| BLK-40MM CARBO T2 | 1 | 40.76 |
| 29mm Carbo Pivot Lead W/Carbo Cam UNCARDED | 1 | 68.52 |
| **Total (£)** | | **2139.67** |
| **Total (-25% for industrial excess) (£)** | | **1604.75** |

## 2.8. Total

| Part | Cost in $SM |
|---|---|
| Hull | 1037.05 |
| Wing | 126.50 |
| Appendages | 1172.15 |
| Rig | 2699.24 |
| Control system | 342.50 |
| **Total** | **5377.43** |

# 3. SUSTAINABILITY ANALYSIS

## 3.1. General description

Due to time constraints, only the hull and wingbars were manufactured from scratch by the team. The hull geometry is based on the second-hand mould sourced by the team from *Shock Sailing*, and it was made of flax fibre with PET and cork core, infused with Infugreen810 bio-resin. The wingbar was made with Sitka Spruce Wood and shaped with a homemade mould.

The *Jeremy Rogers Limited* yard shed has LED lights and 16 solar panels which equate to a maximum rating of 4kW. This meant that our entire manufacture process throughout the winter of 2021/22 was neutral in terms of energy usage.

## 3.2. Boat and elements lifecycle

The boat is intended to be used for further projects at the University of Southampton and through regular maintenance and good upkeep of the boat it will have a long lifetime. However, the end life of the boat has also been considered. Composites are difficult to recycle compared to other materials. Usually, the resin can be separated from the composite part through using pyrolysis or solvolysis (Coughlin, 2021). For our SuMoth there are concerns with using pyrolysis and the flammability of flax fibres during the process. However, the PET core would decompose at the high temperatures during pyrolysis meaning that it can be separated from the flax. Therefore, to recycle the hull the paint will be stripped off and then the parts of the hull with cork core will be separated from the parts with PET core. The sections with cork core are the foredeck, V-shaped bulkhead, bow of the hull and a small section around the centreboard case.

Pyrolysis will be used to recycle all the secondary carbon parts, foils and mast. This will separate the resin from the carbon allowing for this to be recycled. The sail could be upcycled in the future through turning it into accessories including bags and wallets. The wingbars which are built out of wood and bonded with bio-resin are coated in varnish making them challenging to recycle or upcycle. Burning the wood releases harmful chemicals from the varnish making this an unsuitable choice. The varnish can be removed by sanding off the outer layer around the wingbars and then they can be grinded and compressed for future projects where the material properties are less important such as for furniture.

## 3.3. Hull

The hull was made from flax composite sandwich with PET and cork core. Reinforcements are made to the area that require high strength, such as the joints with wingbars, with additional layers of glass fibres. High modulus CFRP were used for the kingpost and tubing to hold the foredeck. Table 18 shows the material breakdown of the hull.

*Table 18: Materials used in the hull and their associated masses including the percentage of CFRP*

| Item | Mass (kg) |
|---|---|
| Bio-Based Epoxy | 14.00 |
| Dry fabric Flax | 6.60 |
| PET core | 4.97 |
| Cork core | 0.99 |
| Dry fabric glass fibers | 0.50 |
| Dry fabric carbon fibers HM | 1.44 |
| Brass accessories | 0.10 |
| **Total mass** | **28.60** |
| **Percentage of CFRP** | **5.0%** |

Assumption in the life cycle assessment includes:

- Global average is used for flax fibre
- 100% recycled PET core
- Cork core is modelled with Balsa core as a proxy material
- The bio-based epoxy is modelled as global average

The hull was cured with other products made in *Jeremy Rogers Limited*, which further reduces the environmental footprint of the curing process.

## 3.4. Foils

The foils sourced from Maguire boat, which are made of the combination of CFRP and GFRP. The mass breakdown of the foils is shown in Table 19:

*Table 19: Materials used in the foils and their associated masses including the percentage of CFRP*

| Item | Mass (kg) |
|---|---|
| CFRP (High Modulus) | 4.57 |
| GFRP (E-glass) | 1.19 |
| **Total mass** | **5.76** |
| **Percentage of CFRP** | **79.40%** |

As the foils are made of high strength materials, it is expected that they will have a long service life and could be reused for multiple purposes. Both CFRP and GFRP could be recycled but at the cost of high energy consumption.

## 3.5. Wings

Wingbars are made from plies of Sitka Spruce wood and bonded with Infugreen810 bio-resin. It was shaped with homemade mould made from recycled woodchip board and wooden blocks. Table 20 shows the material breakdown of the wingbar.

*Table 20: Materials used in the wingbars and their associated masses including the percentage of CFRP*

| **Item** | **Mass (kg)** |
|---|---|
| Bio-Based Epoxy | 0.20 |
| Sitka Spruce wood (Wingbar) | 15.60 |
| CFRP (Wingbar strips) | 0.15 |
| Polyester (Trampoline) | 2.00 |
| **Total mass** | 17.95 |
| **Percentage of CFRP** | **0.94%** |

## 3.6. Rig and Sail

Table 21 shows the material breakdown of the rig. The mast and prodder are upcycled from a Mach 2 and the sail is also upcycled from *Doyle Sails*. The front half of the boom is upcycled from a *Maguire Boats* broken boom and the aft half is built from CFRP and infused with Infugreen810 resin.

*Table 21: Materials used in the rig and their associated masses including the percentage of CFRP*

| **Item** | **Mass (kg)** |
|---|---|
| CFRP (Mast and prodder) | 2.40 |
| Polyester (Sail) | 3.50 |
| CFRP (Boom) | 2.50 |
| **Total mass** | 8.40 |
| **Percentage of CFRP** | **58.33** |

## 3.7. Control system

Table 21 shows the material breakdown of the control system.

*Table 22: Materials used in the flight control system and their associated masses including the percentage of CFRP*

| **Item** | **Mass (kg)** |
|---|---|
| Bio-based polyester (Ropes) | 1.00 |
| CFRP (Tiller) | 0.30 |
| CFRP (Tiller extension) | 0.27 |
| Blocks | 1.32 |
| CFRP (Wand) | 0.75 |
| Total Mass | 3.64 |
| **Percentage of CFRP** | **36.26** |

## 3.8. Summary

The overall mass breakdown of the SuMoth is shown in the

| Item | Mass (kg) |
|---|---|
| Hull | 28.60 |
| Wing | 17.95 |
| Foils | 5.76 |
| Rig | 8.40 |
| Control system | 3.64 |
| **Total mass** | **64.35** |
| **Percentage of CFRP** | **19.24%** |

## 3.9. Actions for a sustainable future

Bio-based materials are one of the easiest ways to reduce the environmental footprint from the traditional composites. However, the increase in demand for bio-based materials could leads to other environmental and social issues. Although it could absorb significant amount of $CO_2$ during their lifetime, increase logging activities could lead to mass deforestation and loss of habitat for wild animals. The effort of regrowing trees would take many years to happen. Farming other bio-based materials could results in increase fertilisers used, increasing the impact of eutrophication. It could also lead to the increase in land used and potentially compete with the farming of food crops.

Reducing the use of materials is the best way to reduce the environmental footprint, by replacing a product before its service lifetime creates unnecessary need for material usage and disposal. Prioritising the use of recycling waste materials would promote circular economy and reducing the environmental burden for end-of-life treatments and the dependency on natural resources. When it is not possible to use recycled materials, choosing bio-based materials over non-bio-based materials whenever possible. Collaboration between industry leaders is important to ensure the environmental and economical sustainability of the industry.

# 4. MARINESHIFT 360 LCA

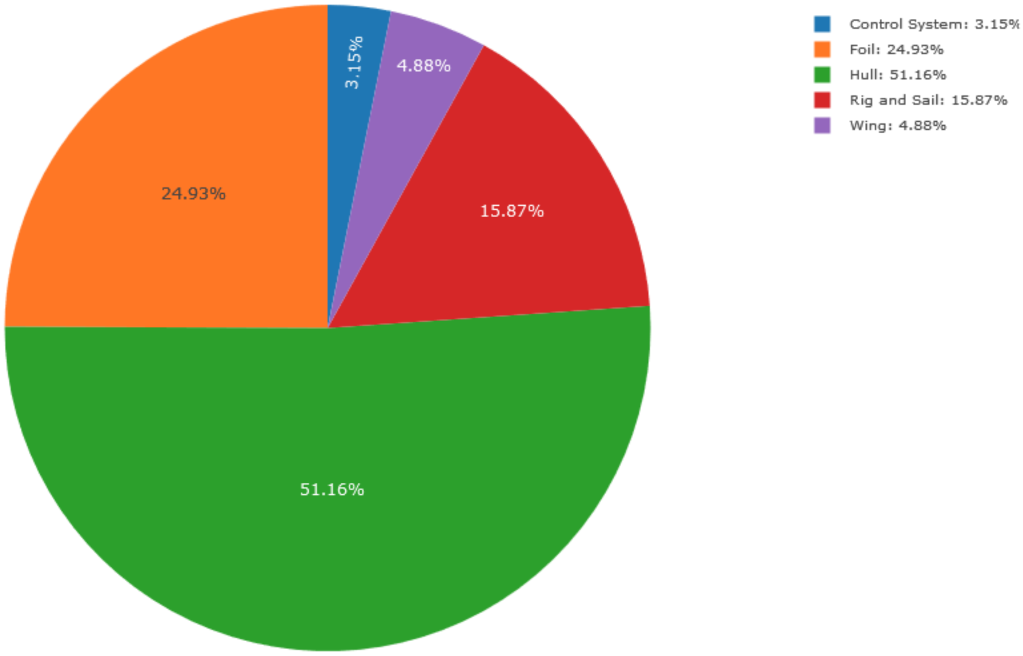



*Figure 18: Global Warming- Fossil*

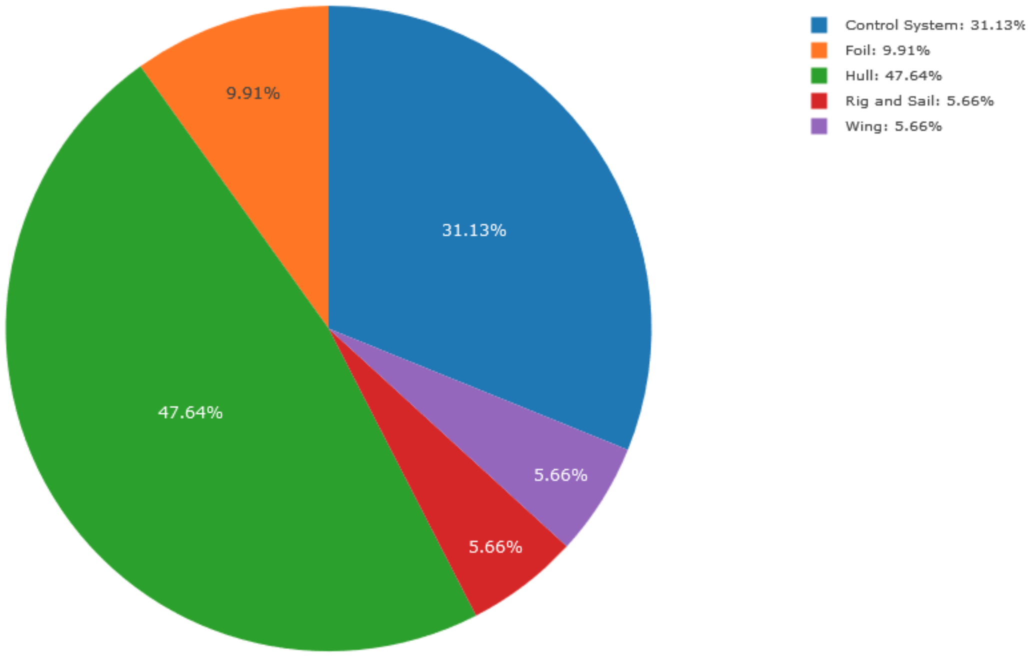



*Figure 19: Mineral Resource Scarcity*

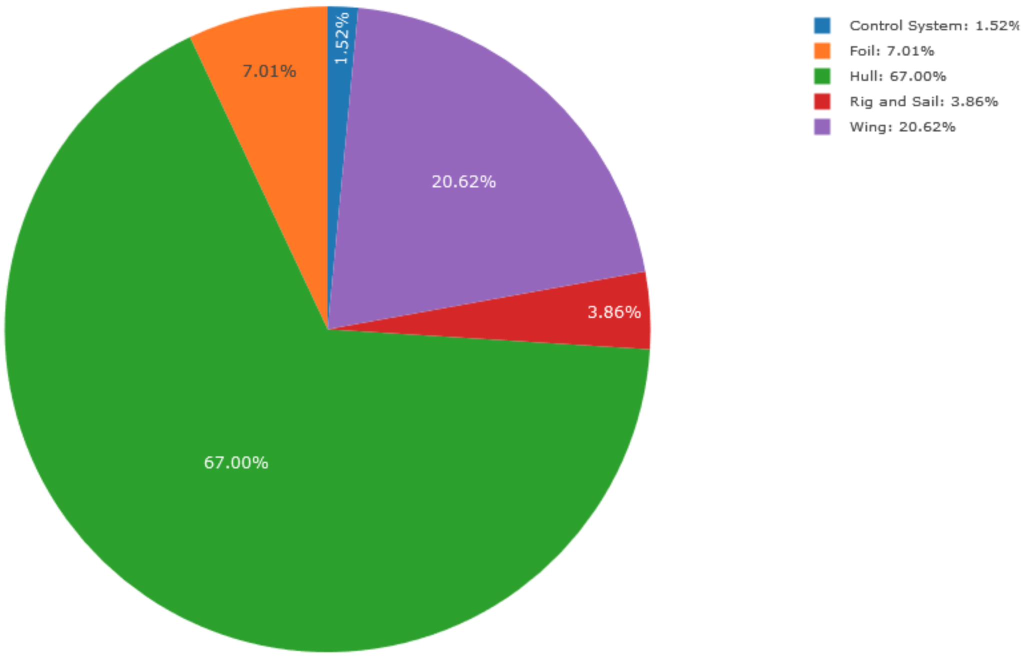



*Figure 20: Energy Consumption- Renewable*

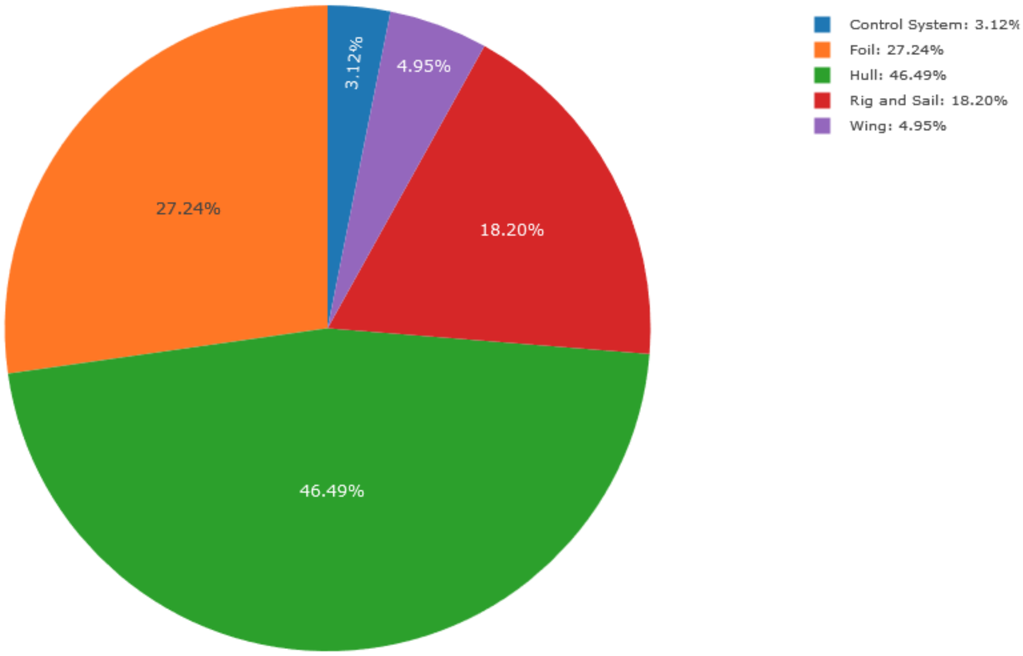



*Figure 21: Energy Consumption- Non-Renewable*

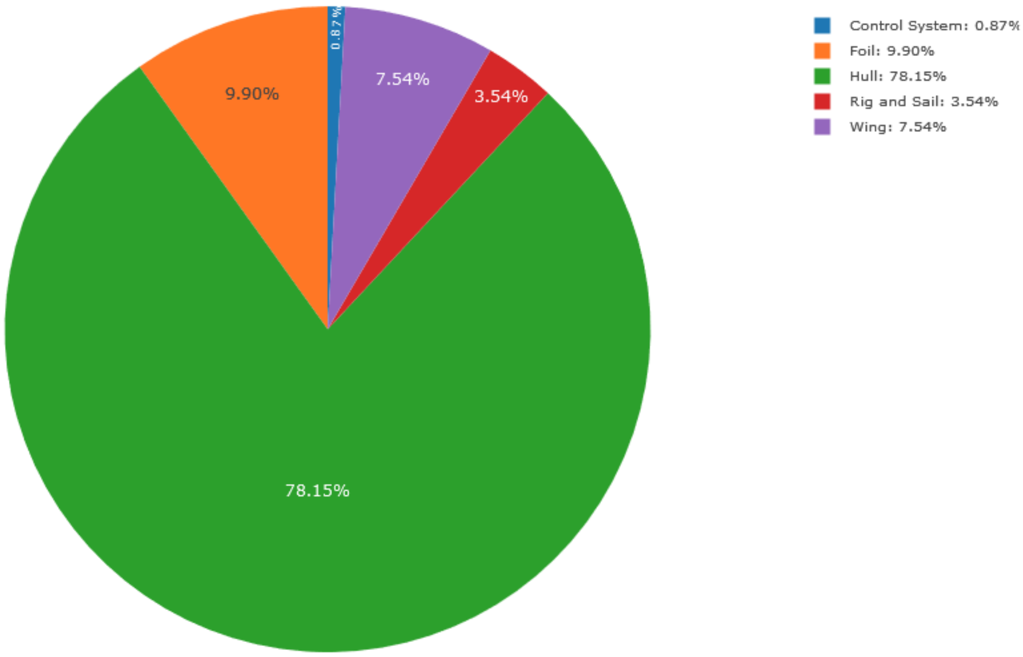



*Figure 22: Water Consumption*

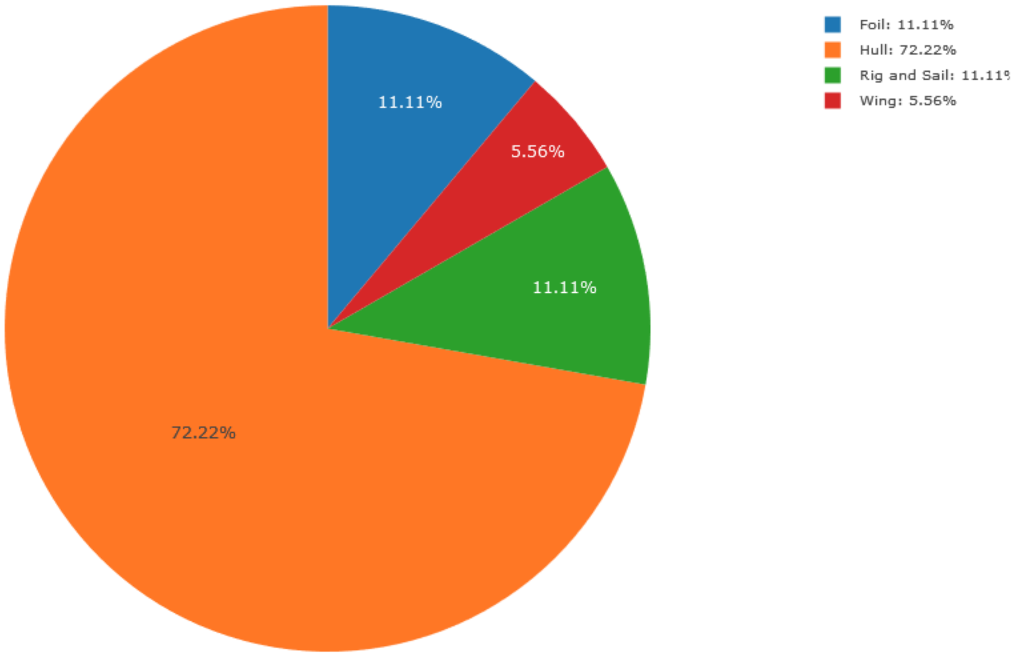
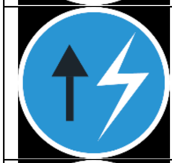
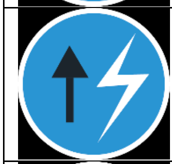



*Figure 23: Marine Eutrophication*

## 4.1. General results

| | | |
|---|---|---|
|  | Global warming – fossil (kg $CO_2e$) | 742.78 |
|  | Global warming – non-fossil (kg $CO_2e$) | -69.75 |
|  | Mineral resource scarcity (kg Cue) | 2.10 |
|  | Energy consumption – renewable (MJ) | 2380 |
|  | Energy consumption – non-renewable (MJ) | 15220 |
|  | Water consumption ($m^3$) | 1951 |
|  | Marine eutrophication (kg Ne) | 0.19 |
|  | Waste factor (%) | 43.31 |

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# A. APPENDIX A - MS360 LCA

## A.1. Boat lifecycle assessment discussion

MS360 LCA tool provides an extensive list of the commonly used materials in the marine industry, including a wide range of bio-based materials. This allowing the process of lifecycle assessment to be more accessible to manufacturers different level of expertise. The results are easy to interpret with the visualisations provided in the results dashboard.

Though the bio-based materials are provided in the list of LCA, the percentage of bio-composition is difficult to define in the tool. We expect that the different composition of bio-based polymers and resin would make a difference to the environmental footprint. The assessments for the purchased parts are thought to be difficult, as the information on the production process from the manufacturer is difficult to obtain.

## A.2. Boat lifecycle assessment scheme

In this section present in a scheme the elements evaluated on the full assembly.

| Assessment | Element | Global warming - fossil (kg CO2e) | Global warming - non-fossil (kg CO2e) | Mineral resource scarcity (kg Cue) | Energy consumption - renewable (Mj) | Energy consumption - non-renewable (Mj) | Water consumption (m3) | Marine eutrophication (kg Ne) |
|---|---|---|---|---|---|---|---|---|
| Blocks | Manufacturing Metal Parts | 10.99 | 0.46 | 1.25 | 36.74 | 133.12 | 0.10 | 0.00 |
| Blocks | Manufacturing Metal Parts (transport) | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Boom | Manufacturing Composites | 104.85 | 1.14 | 0.11 | 84.00 | 2471.87 | 0.62 | 0.01 |
| Boom | Manufacturing Composites (transport) | 0.01 | 0.00 | 0.00 | 0.00 | 0.14 | 0.00 | 0.00 |
| Brass accessories | Manufacturing Metal Parts | 1.68 | 0.02 | 0.40 | 6.54 | 28.67 | 0.05 | 0.00 |
| Bulkhead | Manufacturing Composites | 19.14 | -5.97 | 0.05 | 128.46 | 419.57 | 1.88 | 0.02 |
| Bulkhead | Manufacturing Composites (transport) | 0.04 | 0.00 | 0.00 | 0.01 | 0.57 | 0.00 | 0.00 |
| Centre board case | Manufacturing Composites | 25.22 | -4.32 | 0.06 | 94.34 | 501.84 | 0.99 | 0.01 |
| Centre board case | Manufacturing Composites (transport) | 0.07 | 0.00 | 0.00 | 0.01 | 1.05 | 0.00 | 0.00 |
| Deck | Manufacturing Composites | 103.46 | -22.71 | 0.19 | 452.27 | 2108.26 | 4.28 | 0.04 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Deck | Manufacturing Composites (transport) | 0.14 | 0.00 | 0.00 | 0.03 | 2.28 | 0.00 | 0.00 |
| Foil | Manufacturing Composites | 370.40 | 2.01 | 0.42 | 333.54 | 8293.15 | 3.86 | 0.05 |
| Foil | Manufacturing Composites (transport) | 0.01 | 0.00 | 0.00 | 0.00 | 0.15 | 0.00 | 0.00 |
| Foredeck | Manufacturing Composites | 20.42 | -4.69 | 0.04 | 99.13 | 434.31 | 1.33 | 0.01 |
| Foredeck | Manufacturing Composites (transport) | 0.02 | 0.00 | 0.00 | 0.00 | 0.36 | 0.00 | 0.00 |
| Gantry Tube | Rubber Tube | 0.39 | 0.04 | 0.00 | 1.51 | 13.49 | 0.00 | 0.00 |
| Gantry Tube | Rubber Tube (transport) | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 |
| Hull | Manufacturing Composites | 401.77 | -121.91 | 0.73 | 2173.48 | 8206.17 | 19.90 | 0.17 |
| Hull | Manufacturing Composites (transport) | 0.58 | 0.00 | 0.00 | 0.12 | 9.33 | 0.00 | 0.00 |
| Kingpost | Manufacturing Composites | 35.01 | 0.38 | 0.04 | 26.89 | 824.96 | 0.20 | 0.00 |
| Kingpost | Manufacturing Composites (transport) | 0.04 | 0.00 | 0.00 | 0.00 | 0.55 | 0.00 | 0.00 |
| Mast and prodder | Manufacturing Composites | 129.12 | 1.42 | 0.14 | 99.28 | 3044.19 | 0.75 | 0.02 |
| Mast and prodder | Manufacturing Composites (transport) | 0.01 | 0.00 | 0.00 | 0.00 | 0.20 | 0.00 | 0.00 |
| Paint | Painting | 47.07 | 0.42 | 0.45 | 68.30 | 1036.45 | 0.68 | 0.00 |
| Paint | Painting (transport) | 0.03 | 0.00 | 0.00 | 0.01 | 0.54 | 0.00 | 0.00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ropes | Running Rigging | 5.12 | 0.66 | 0.01 | 11.81 | 94.04 | 0.07 | 0.00 |
| Ropes | Running Rigging (transport) | 0.03 | 0.00 | 0.00 | 0.01 | 0.46 | 0.00 | 0.00 |
| Sail | Manufacturing Sails (simplified) (transport) | 0.86 | 0.00 | 0.00 | 0.07 | 11.78 | 0.00 | 0.00 |
| Sail | Manufacturing Sails (simplified) | 0.86 | 0.00 | 0.00 | 0.07 | 11.78 | 0.00 | 0.00 |
| Tillers | Manufacturing Composites | 30.66 | 0.34 | 0.03 | 23.58 | 722.96 | 0.18 | 0.00 |
| Tillers | Manufacturing Composites (transport) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Trampoline | Manufacturing Sails (simplified) | 47.28 | 0.36 | 0.18 | 76.30 | 975.88 | 0.63 | 0.00 |
| V-shape bulkhead | Manufacturing Composites | 24.71 | -7.96 | 0.04 | 133.94 | 504.88 | 1.06 | 0.01 |
| V-shape bulkhead | Manufacturing Composites (transport) | 0.03 | 0.00 | 0.00 | 0.01 | 0.55 | 0.00 | 0.00 |
| Wand | Manufacturing Composites (transport) | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 |
| Wand | Manufacturing Composites | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 |
| Wingbar | Manufacturing Timber | 22.05 | -72.66 | 0.05 | 904.21 | 526.91 | 2.32 | 0.02 |
| Wingbar | Manufacturing Timber (transport) | 0.01 | 0.00 | 0.00 | 0.00 | 0.19 | 0.00 | 0.00 |

# Overall results & CO2 equivalent impact

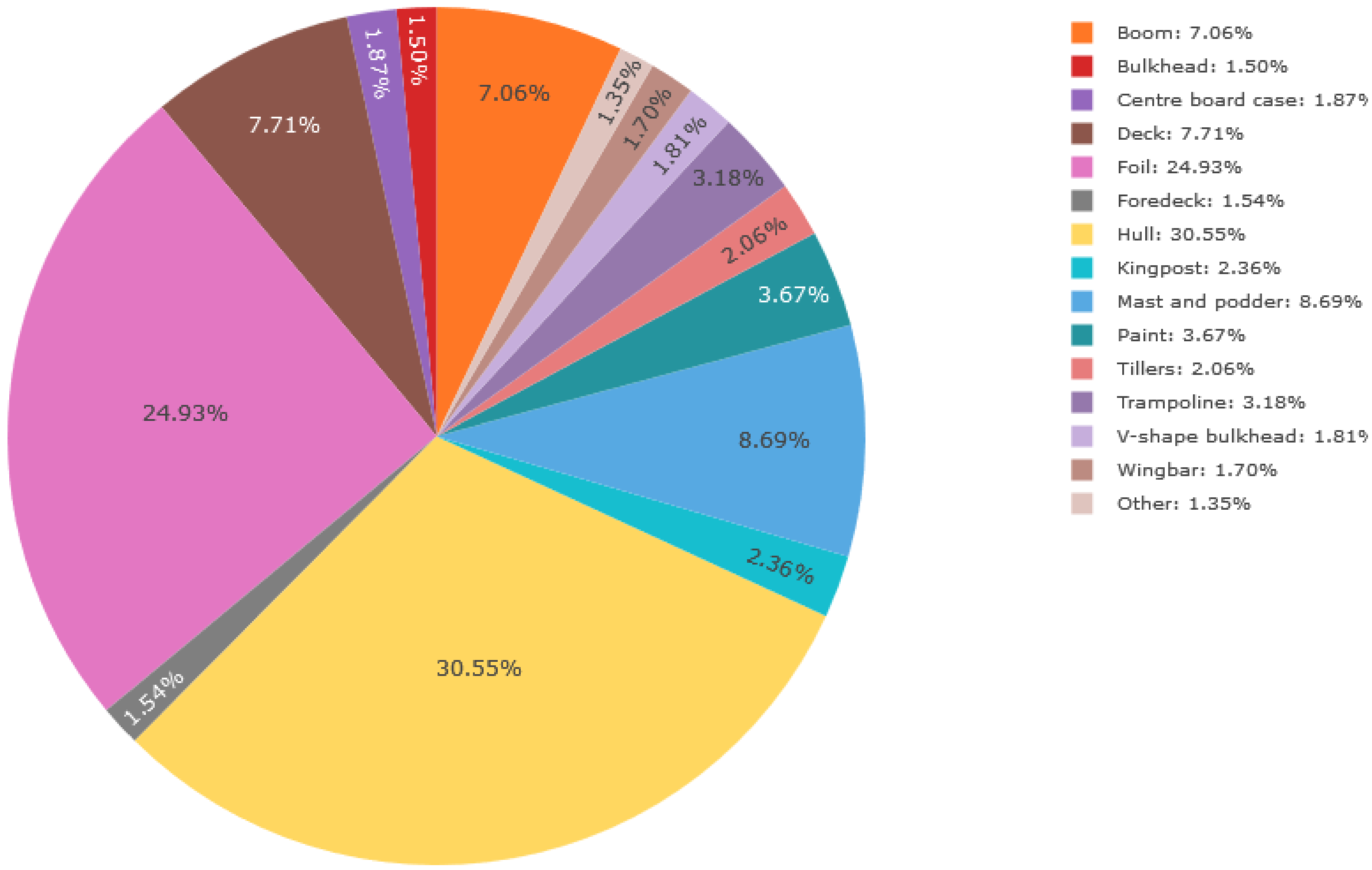


*Figure 24: Global Warming- Fossil*

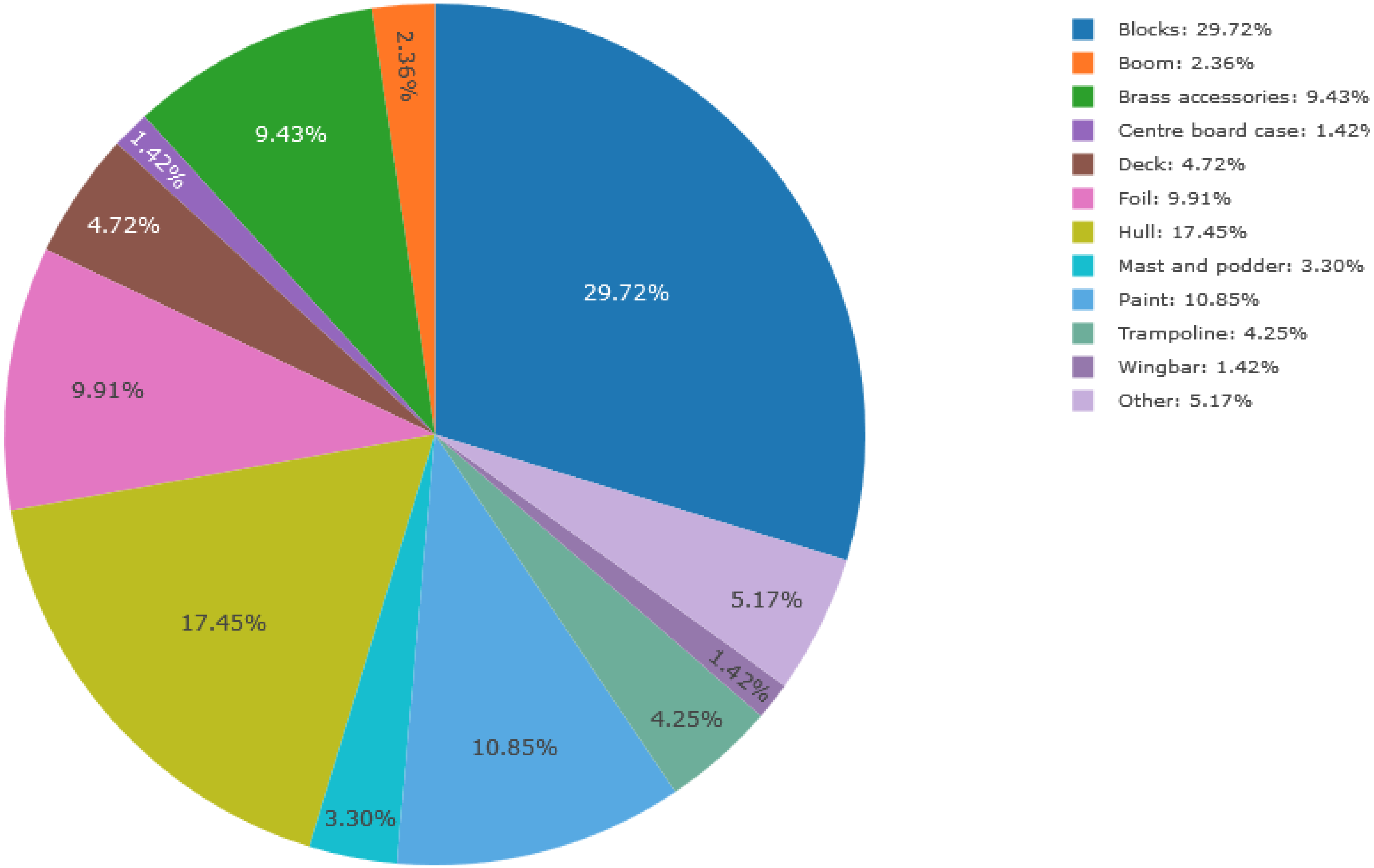


*Figure 25: Mineral Resource Scarcity*

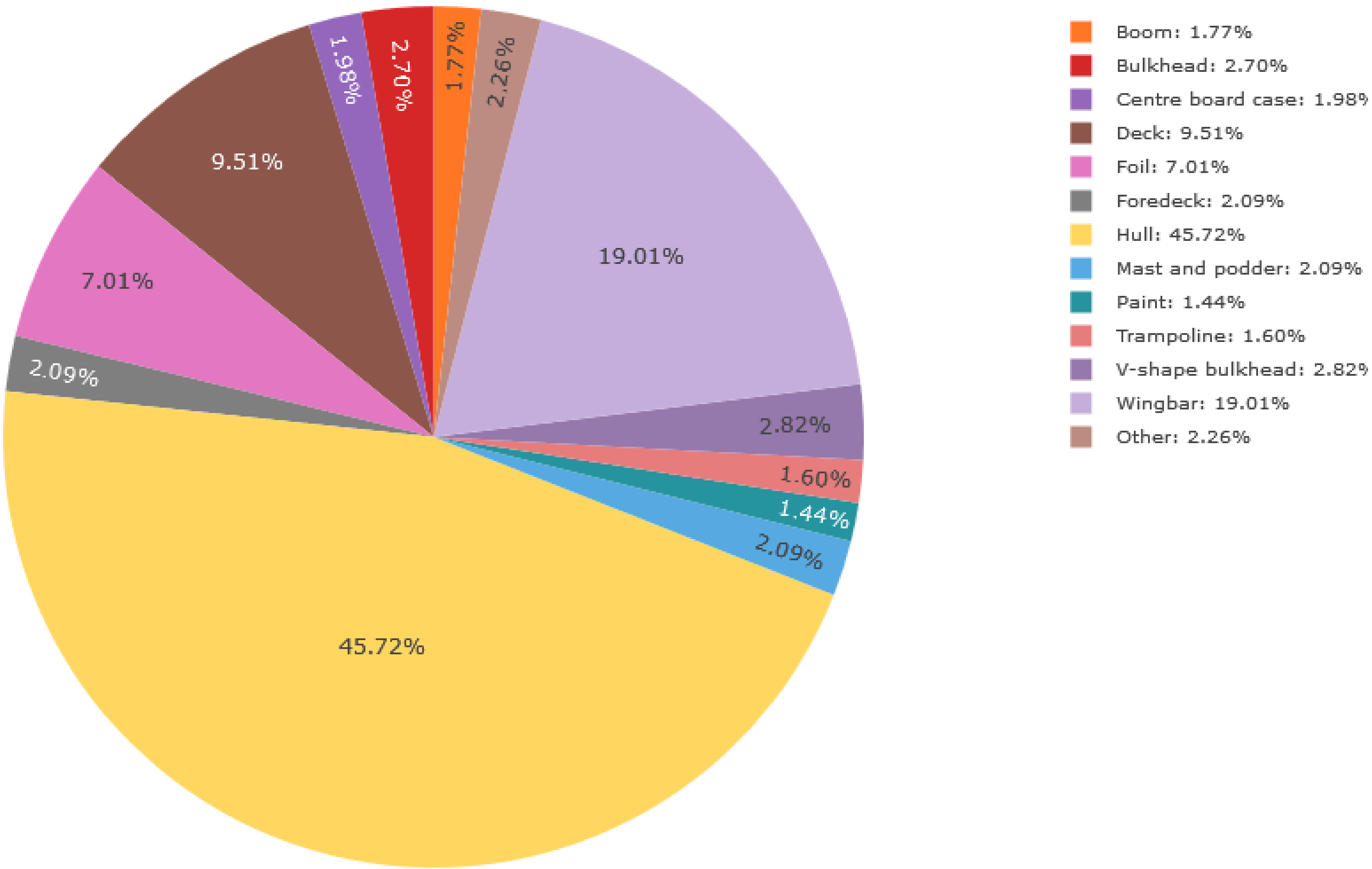


*Figure 26: Energy Consumption- Renewable*

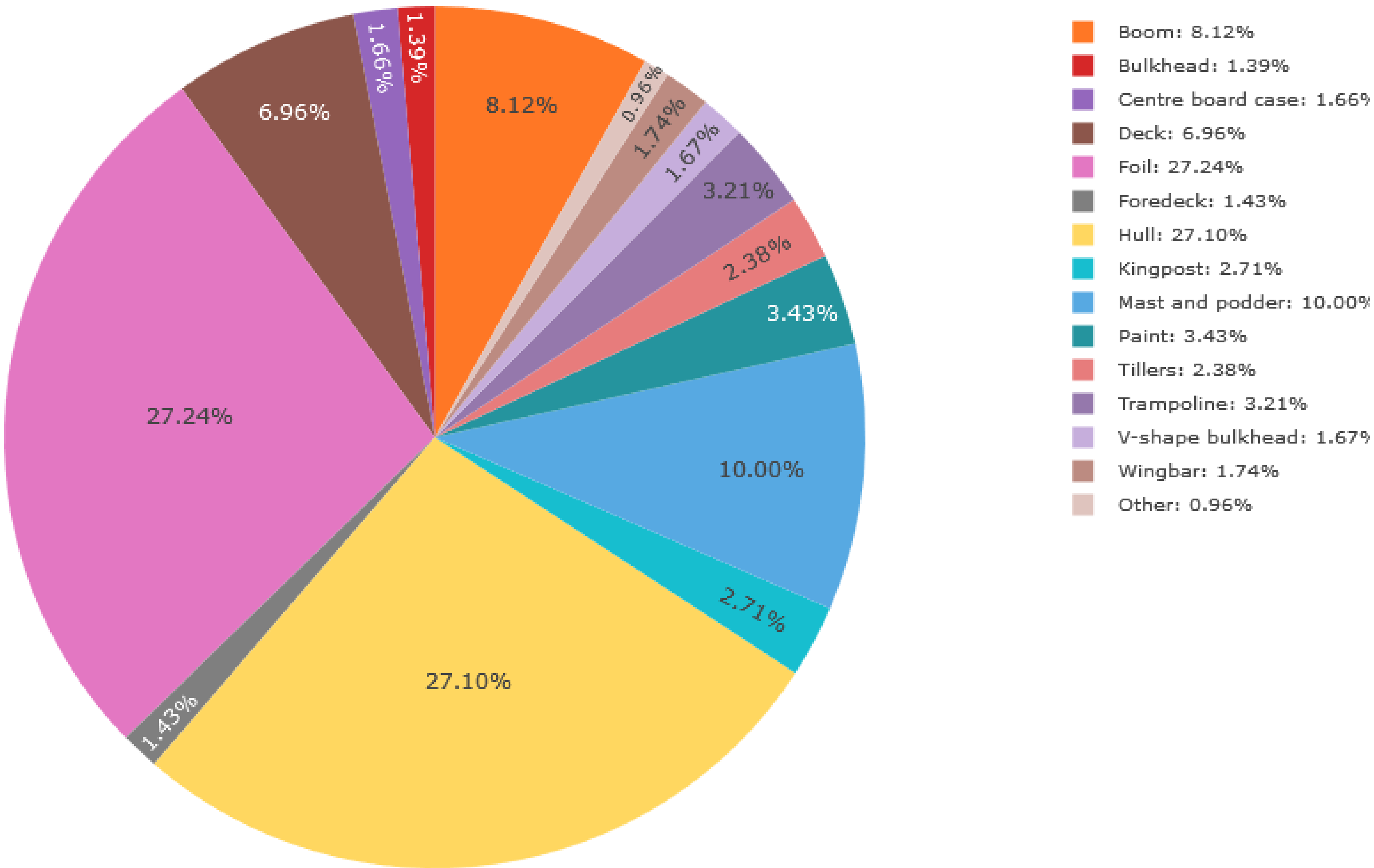


*Figure 27: Energy Consumption- Non-Renewable*

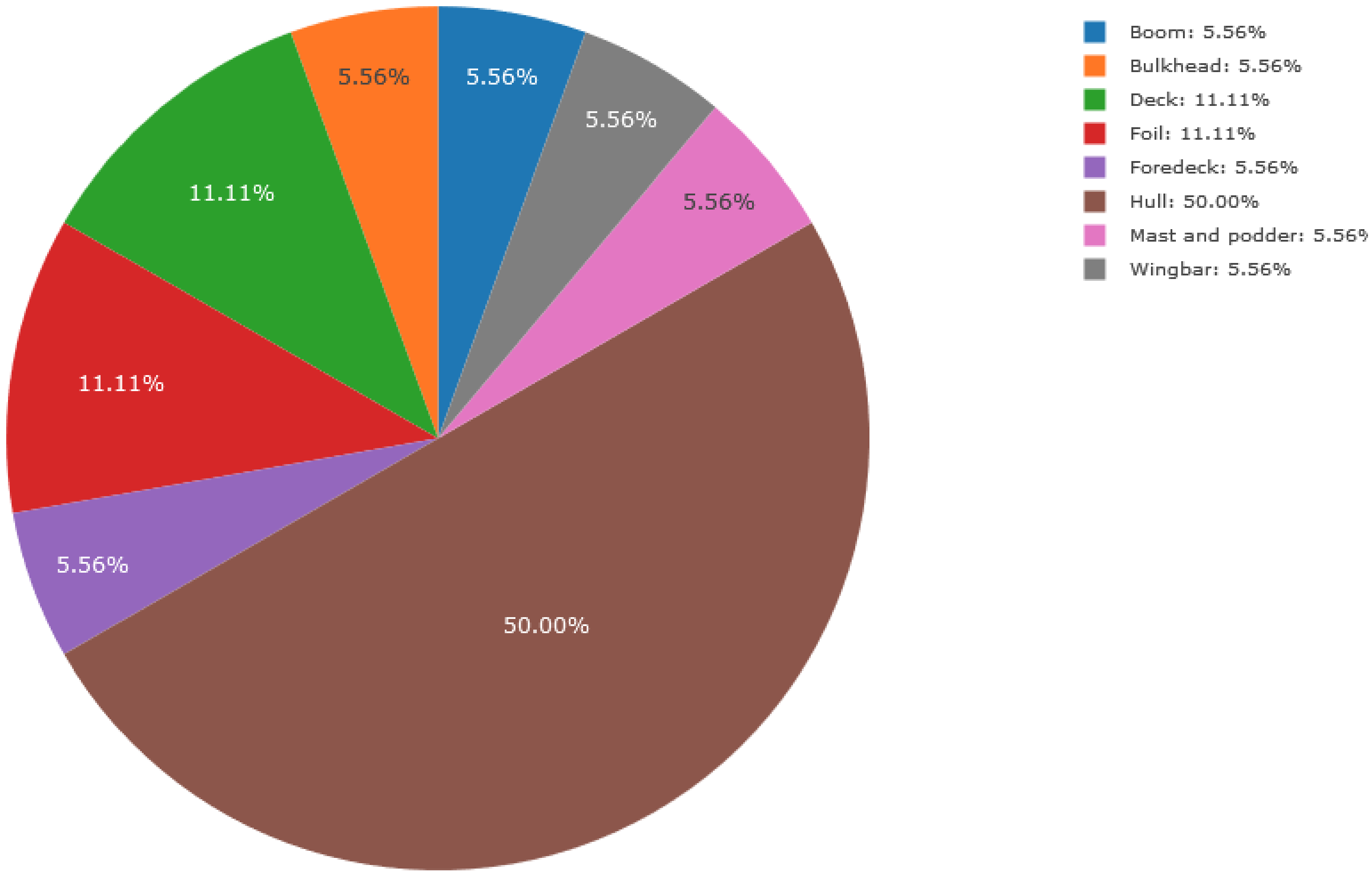


*Figure 28: Water Consumption*

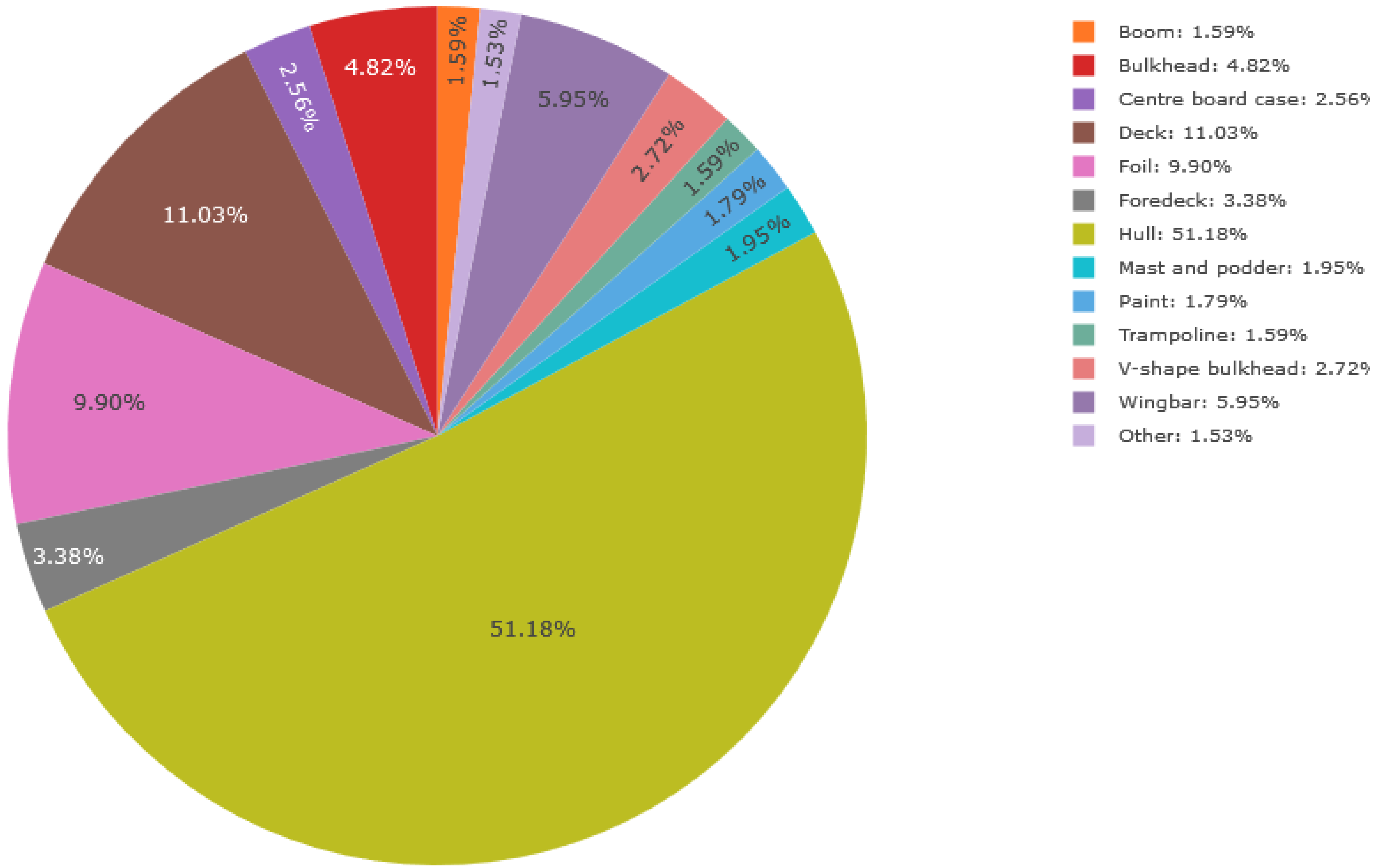


*Figure 29: Marine Eutrophication*

# Appendix B

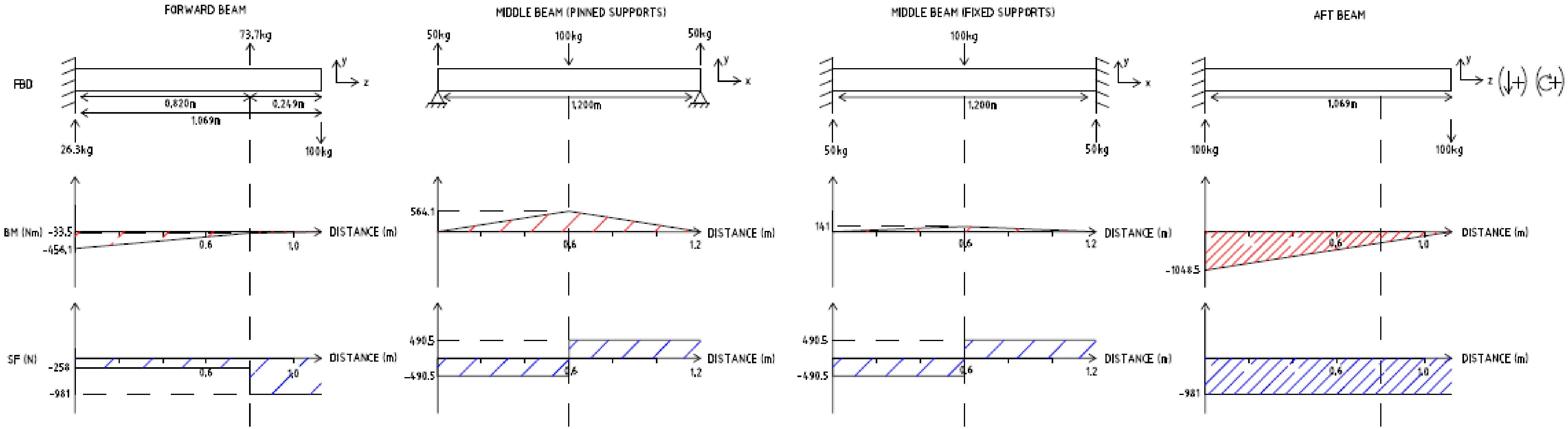


*Figure 30: Free body diagram, bending moment diagram (Nm) and shear force diagram (N) for the forward, middle and aft beams at an acceleration of 9.81 ms-$^2$ (1g)*

| TASK ID | TASK TITLE | START DATE | DURATION IN HOURS |
|---|---|---|---|
| 1 | **Wing Bars** | | **69** |
| 1.1 | Cut wood using circular saw and thicknesser | 20th Dec | 9 |
| 1.2 | Make the former | 21st Dec | 6 |
| 1.3 | Primary lamination beam 1 | 23rd Dec | 6 |
| 1.4 | Primary lamination beam 2 | 24th Dec | 6 |
| 1.5 | Shaping the taper beam 1 & 2 | 27th Dec | 4 |
| 1.6 | Secondary lamination beam 1 & 2 | 28th Dec | 4 |
| 1.7 | Shaping beam 1 & 2 | 29th Dec | 8 |
| 1.8 | Mark & cut joints | 30th Dec | 6 |
| 1.9 | Primary lamination middle beams 3 and 4 | 2nd Jan | 6 |
| 1.10 | Shaping middle beams 3 and 4 | 3rd Jan | 4 |
| 1.11 | Assembly | 4th Jan | 4 |
| 1.12 | Finishing: Sanding and varnishing | 5th Jan | 6 |
| 2 | **Hull** | | **68** |
| 2.1 | Set up 2 elevated tables and tressels | 4th Jan | 2 |
| 2.2 | Prep the mould (removing tape & repairs) | 6th Jan | 4 |
| 2.3 | Wax the mould (5 applications of Mirror Glaze) | 8th Jan | 6 |
| 2.4 | Cut dry fibres & cores, layup with spray glue | 9th Jan | 8 |
| 2.5 | Prep for hull infusion | 14th Jan | 4 |
| 2.6 | Hull infusion | 15th Jan | 4 |
| 2.7 | Release hull from mould | 16th Jan | 4 |
| 2.8 | Shape & fit foam block on the bow | 11th Feb | 4 |
| 2.9 | Finishing & repairs | 12th Feb | 16 |
| 2.10 | Paint hull in primer | 14th Feb | 16 |
| 3 | **Deck** | | **25** |
| 3.1 | Prep the mould (removing tape & repairs) | 19th Jan | 2 |
| 3.2 | Wax the mould (5 applications of Mirror Glaze) | 19th Jan | 2 |
| 3.3 | Cut dry fibres & cores, layup with spray glue | 20th Jan | 4 |
| 3.4 | Prep for deck infusion | 21st Jan | 2 |
| 3.5 | Deck infusion | 21st Jan | 2 |
| 3.6 | Finishing & repairs | 22nd Jan | 2 |
| 3.7 | Cut deck | 31st Jan | 1 |
| 3.8 | Glue deck to hull | 31st Jan | 4 |
| 3.9 | Secondary bonding deck to hull | 1st Feb | 6 |
| 4 | **Bulkheads & Centreboard (CB) Case** | | **47** |
| 4.1 | Cut dry fibres & cores | 22nd Jan | 4 |
| 4.2 | Prep V shape bulkhead and CB case moulds (removing tape & M | 22nd Jan | 2 |
| 4.3 | Layup 1.5 x 1.0 m panel, V shaped bulkhead & CB case using spr | 23rd Jan | 4 |
| 4.3 | Prep for infusion & infuse 1.5 x 1.0 m panel, V shaped bulkhead & | 23rd Jan | 3 |
| 4.4 | Cut & fillet radius into the hull | 24th Jan | 24 |
| 4.5 | Secondary bond into the hull | 28th Jan | 10 |
| 5 | **Foredeck** | | **14** |
| 5.1 | Cut dry fibres & cores | 5th Feb | 3 |
| 5.1 | Prep the mould (removing tape & repairs) | 5th Feb | 1 |
| 5.1 | Layup foredeck | 5th Feb | 3 |
| 5.1 | Prep for infusion & infuse | 6th Feb | 2 |
| 5.1 | Cut & fillet radius into the hull | 8th Feb | 3 |
| 5.1 | Secondary bond into the hull | 8th Feb | 2 |
| 6 | **Assembly & miscellaneous** | | **8** |
| 6.1 | Fit carbon tubes for bolt ropes in tramps | 27th Jan | 3 |
| 6.2 | Fit carbon tubes for flight control system | 27th Jan | 5 |
| | **Total duration of tasks (hours)** | | **231** |
| | **Commercial cost (£45 per hour) (£)** | | **10395** |

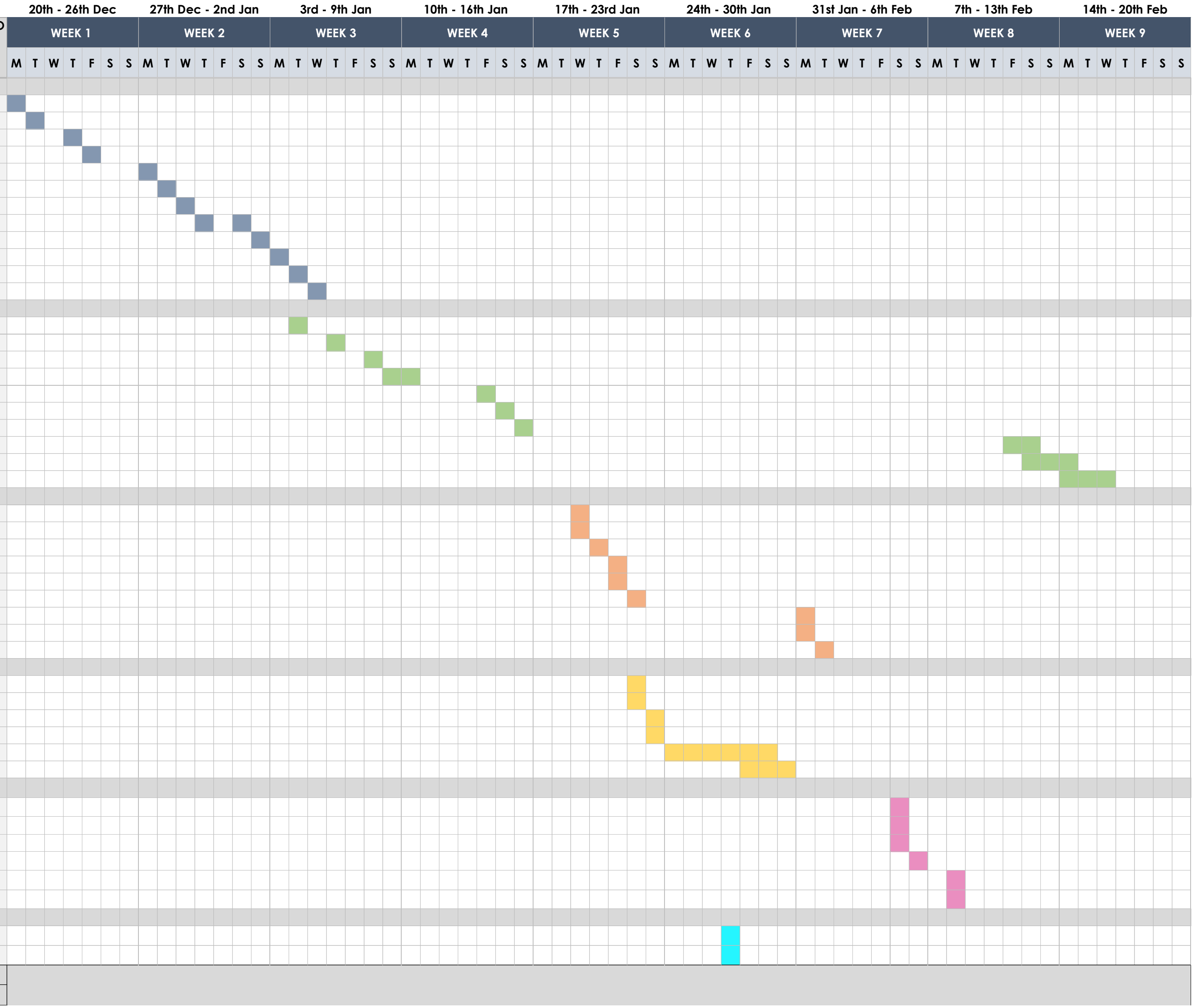


*Figure 31: Manufacturing Gantt Chart*