

FOILING SuMoth CHALLENGE

DREAMED-CRAFTED-EXECUTED

by



2025 Foiling SuMoth Challenge

STAGE S1 REPORT

DESIGN - BUILD METHODS - SUSTAINABILITY

sponsored by



ABSTRACT

This report provides an in-depth analysis of the conceptualization and development process that led to the creation of our latest Moth. Our objective for this year was to leverage the lessons learned from the making of our first Moth and develop an improved version across all performance parameters while maintaining, or even bettering, our strong commitment to sustainability.

By collaborating with the leading builders and suppliers within the Moth class, as well as engaging in continuous dialogue with top sailors, our team was able to find optimal solutions to the complex challenges encountered. This close interaction with experts ensured that we upheld the highest standards of performance and competitiveness.

This report delves into key aspects of the development process, including extensive research on multi-parametric optimization, hull geometry, structural design and finite element method (FEM) analysis, foil design and refinement, manufacturing processes. All this processes always take into account our main goal: sustainability. Which we pursue through precise cost analysis and the implementation of both new and old sustainable solutions such as flax, basalt and wood.

Bringing together all of these factors played a crucial role in our endeavor to create a competitive high-performance Moth.



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LIST OF ABBREVIATIONS

AOA	Angle Of Attack
AVL	Athena Vortex Lattice
BFGS	Broyden–Fletcher–Goldfarb–Shanno
BFL	Bai - Flying Lina
Cd	Drag coefficient
IFD	Internal Force Diagram
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Polymer
Cl	Lift Coefficient
DOE	Design of Experiments
EoL	End of Life
FEM	Finite Element Method
FF	Flax Fiber
FFRP	Flax Fiber Reinforced Polymer
GM	Metacentric Height
IMCA	International Moth Class Association
LC	Load Case
LCB	Longitudinal Centre of Buoyancy
LOA	Length Overall
MF	Main Foil
MFCS	Mechanical Flight Control System
MDF	Medium Density Fiberboard
MOGA-II	Multi-Objective Genetic Algorithm
MQTT	Message Queuing Telemetry Transport
NURBS	Non-Uniform Rational Base Splines
PLA	Polylactic Acid
RF	Rudder foil
RSM	Response Surface Methodology
SM\$	SuMoth Dollars
UD	Unidirectional
VARTM	Vacuum Assisted Resin Transfer Moulding
VPP	Velocity Prediction Program



INTRODUCTION

This report delves into the entire process of designing and building a sustainable moth. Our team's key aspiration for this season is to create a high-performing foiling boat that excels in terms of ease of building and sustainability. Embarking on this year's project presented a significant challenge, even with the experience we gained in the last editions. Nevertheless, our older team members provided us a solid foundation for tackling this, for many of our members, new endeavor. But even taking into consideration those factors, this year we were faced with a brand-new challenge: not to build a SuMoth winning boat, but rather a winning Sustainable Moth. This new objective pushed us to find intelligent, sustainable and elegant solutions, aimed at designing a final product which could be seen at the starting line of an IMCA regatta. For this reason, the whole team poured their heart and soul into the project, working extremely hard to stay on track and comply with rigorous self-imposed standards. To set said standard we gathered as much information as possible from the hypothetical final user: experienced Moth sailors, which we thank for their expertise and feedback.

As a university team, we receive support from our institution; however, the task of designing and constructing a sustainable foiling boat poses a significant challenge in economic terms. Our sponsors' support was crucial in ensuring the fulfillment of our goals. We hereby want to thank them for their trust and support.

Lastly, we would also like to thank the companies that opened their doors for us and shared some of their knowledge and expertise with our team, taking the time to answer some of our questions and pointing us in the right direction. We also thank our professors, who have supported us over the years and continue to support us as we embark on ever more complex and ambitious projects, and our university, who is allowing us to experiment and put theory into practice.

1. ENGINEERING & DESIGN

1.1. Concept Objectives

After the experience with our first prototype BAI-Flying Lina, which won his kick-off edition in 2023 and got an S1 and S2 Stage first place the following year, a weird feeling of unjustified satisfaction made its way through the team, when one day we asked ourselves: “why do we take part to this challenge?”

That’s when we realized that since we started, this challenge wasn’t between us participants, but rather how we all are together challenging the entire ship building industry, paving the way for a more sustainable world.

With this idea in mind, we realized that BFL was far from perfect and that there were key aspects of its design that needed to be addressed. This fueled the start of a new and exciting project that brought us to the birth of our second prototype, the one which we feel is able to take on the big guns!

1.1.1. Objectives and constraints

This said, we divided our objectives in two groups:

BFL aspects that needed to be addressed:

- *Higher freeboard:* during the take-off phase our previous prototype had the tendency to have the wingbars submerged in the water when not perfectly upright, needlessly slowing the boat down.
- *Increased LCB:* another characteristic that was very common was the tendency of nosediving during the take-off phase, thus making the handling harder and preventing the boat from reaching the take-off speed sooner.
- *General reliability:* to maximize testing time in the water, we wanted to make sure to have a building quality that enables us not to waste time constantly repairing our boat.
- *Wings weight:* to reduce the general weight of the boat we analyzed all the different parts, looking for what could be bettered. The wings were the first component to capture our attention due to their intricate construction and the excessive weight arising from manufacturing errors.

Future oriented objectives:

- *Pre take-off performance:* seeing the IMCA hull shape standard and how the sailors have gotten used to boats with virtually no form stability, we decided to design our new prototype with only performance in mind, thus eliminating the stability compromise made when designing BFL.
- *Optimized circuit system:* we planned the control system for easy access and precise adjustment.
- *Higher design cruising speed:* If take-off speed is defined by the hull shape, what makes a difference while flying on the water are the foils. New foil will be designed to provide us with higher top speeds.

- *Improved flight control:* more rigid self-built components in order to reduce slack.
- *Reduced design displacement:* We knew from the start that through better engineering and sound construction we would be able to reach a final product of around 120kg, instead of the previous 130kg.
- *Sleek finishing:* We are strong believers that the sailing experience onboard any sailboat depends not only on the raw performance but must also be a pleasure to the eye. Or, as Peter Harken suggests: “a clean boat is a fast boat”.

1.2. Global Design

Following a similar learning curve as the America’s Cup AC75 development seen in the first two editions, we designed BFL as a launch platform into the SuMoth Challenge journey and now want to build a boat that encapsulates the technological advancements we made as a team.

Faster, longer and more reliable sailing. These are the building blocks on top of which everything is being designed this year.

To ensure that our boat will be a real competitive boat, since the very start of the concept design we decided to involve our crew as much as possible in every aspect.

Once the design team goals were set out, we decided to split the team unit in different project areas figuring out the respective key focuses.

1.2.1. Hull and Deck

Starting from the lessons learnt from our experience with BFL, and taking inspiration from the IMCA standards such as the *Aerocet*, *Manta* and the *Switch One Design* class, as well as many others, we decided to design this year’s boat with the following features:

- *Faired gantry:* for better hydrodynamic performances;
- *Total top-bottom symmetry:* to reduce as much as possible the need of a second mould and obtain a greater construction height;
- *Enclosed circuit system:* for improved aerodynamics and a sleek finishing.

To ensure the best possible outcome, we decided to commit to such concept from the very first sketch of the new hull, planning every step and always thinking of future implications of every choice. This process resulted in an organic and well-engineered prototype in every detail where nothing onboard is left to chance.

1.2.2. Structures and materials

Since the birth of the SuMoth Challenge, every year so many different teams have developed innovative solutions that show how eco-friendly materials and production processes can be used to build sustainable moths. As previously stated, we take this competition not so much as a rivalry between us teams, but rather as a platform to all together challenge the traditional boatbuilding world. We

therefore believe that one should never isolate itself from the other teams but should always strive for cooperation.

For this reason, this year we decided not only to focus on Flax Fiber but rather to expand as much as possible the material choices and implement as many both basalt - new for us but previously seen in the competition - and wood, not in its traditional and “natural” form, but rather as Uni Directional fiber designed for lamination or infusion. The new boat will therefore have, apart from FF, many different components made of different materials, each carefully selected to best suit every application’s structural needs.

It will also be the year when we take a big step towards the industry's technological standards, as we intend to use prepreg flax and Carbon Fibers, as well as metal inserts to have a more precise and sounder vertical-foil junction.

1.2.3. Foils and vertical

The design objectives of the foil design process focused on several key goals:

- *High-Speed Performance*: The primary objective was to design hydrofoils capable of delivering optimal lift and minimal drag at high boat speeds, particularly in the 18-22Kn range, while maintaining efficiency across a broader speed spectrum.
- *Custom Airfoil Development*: Instead of using off-the-shelf profiles, the team aimed to create a fully customized airfoil tailored to the boat's operating conditions. This required in-depth aerodynamic optimization to balance stability, control, and efficiency.
- *Computational Efficiency*: Given the complexity of hydrodynamic simulations, a major objective was to develop an efficient computational workflow. This included the use of:
 - Genetic and robust algorithms for airfoil optimization;
 - Low-fidelity (AVL) and high-fidelity (CFD) simulations for wing refinement;
 - Response Surface Models to accelerate computational analysis;
- *Detailed Design*: for manufacturability, including high-fidelity Computational Fluid Dynamics simulations of the bulb.
- *Improved Manufacturing Process*: The final designs had to be practical for production, using CNC machining to modify the previous moulds.

1.2.4. Wings

Weight plays a crucial role when building a competitive IMCA boat. As though last year's new S-shaped wings proved great structural integrity and ergonomics, the construction phase didn't go as smoothly as we predicted, resulting in a final product that weighed 22Kg, around 4Kg more than expected. This year, to comply with smaller and faster foils, we needed to shed as much weight as possible and therefore opted for a simpler, yet lighter, construction made from custom-made

hollow tapered beams and reverted to straight wings. To ensure sufficient distance from the water, the hull has been designed with a higher free board, and the wings will go from a 23° incline to 30°.

1.2.5. Load case

Regarding the load case, all the necessary informations are provided in the first three paragraphs of section [1.3.5.](#)

1.2.6. Rig and control systems

Over the past years, due to our limited technical knowledge and the lack of proper tools, our boat's rig was made up of old components that were no longer used in competitive racing. This year, we decided to take a step forward towards even more sustainable sailing. With the support of the Trieste-based sailmaker *Olimpic Sails*, our new boat for this edition of the SuMoth Challenge will be equipped with a sail built by us.

Furthermore, we put a lot of effort into making the circuits as clean as possible, hiding them under the deck.

1.2.7. Electronics

Electronics and data acquisition play a crucial role in modern sailboat racing performance, providing sailors with real-time insights to optimize speed, strategy, and safety. Advanced sensors track variables like wind speed, boat speed, sail trim, and hull performance, while GPS and tactical software assist with navigation and race tactics. This year we embarked in the development of such technology to enhance precision, reduce guesswork, and give the sailors a competitive edge in a sport where fractions of a second can determine the outcome.

On the other hand, the hardware involved in the use onboard a small boat, as the IMCA is, can be rather invasive. For this reason one of the other goals we set has been to find smart solutions aimed at preserving the space and order onboard.

1.3. Hull Design

To obtain all the planned features, after a preliminary study we designed our first parametrized sketch; we then built a parametric model of the hull and performed an optimization process of its geometry, using *ModeFRONTIER* coupled with *Grasshopper*. Finally, we ran a CFD simulations to compare the final design with the benchmarks.

1.3.1. Preliminary study

The first stage of the hull design was selecting different moths to use as reference for different aspects.

The main reference design at the beginning of the work were:

- *Hungry Tiger*: as a performance reference;
- *Switch One Design*: as hull shape inspiration;
- *Aerocet*: for deck and wing shape;



- *BAI - Flying Lina*: as performance reference;
- *Mach2*: as performance reference;
- *Manta Moth*: as gantry inspiration;

Definition of hull type

We also looked at semi-displacement hulls, in particular the *64 series* and the *NPL series*, which we also used as a reference for geometric parameters. Given the maximum possible LOA, and pre-take-off speeds we were able to calculate the Froude Number which places the hulls in question between the displacement and semi-displacement area.

Design displacement

From there, a design displacement had to be decided. Given the information gathered in the construction of our previous boat (whose design displacement was set at 130kg), we knew that with a better optimization of the structures and lamination, summed with a new wing design, a lower design displacement was possible. But planning on possibly having electronics onboard and wanting to have a real comparison of the new and the old boat, we decided to go for the same design displacement of 130kg.

Reference analysis

After performing preliminary analysis based upon experimental data and simple resistance prediction formulas (i.e. Holtrop and Fung methods) performed at the design displacement, we choose the significant geometric quantities in relation to hydrodynamic resistance and initial stability of the hull to use as base for the parametrization of the new boat.

1.3.2. Parametric modelling of the hull shape with *Grasshopper*

The sketch hull was parameterized using *Grasshopper*, a *Rhinoceros* plug-in. The surface is generated from the network of the following curves:

- Gunwale;
- Keel;
- Two parallel middle body sections;
- Quarter and bow section;
- Fore and aft end sections;

In particular, the gunwale has been made of a middle, aft and fore curves, with the latter segments being modelled with a sinusoidal and elliptical repartition of interpolating points, which gave us a precise control over the position and amount of curvature, independently one from the other. Same goes for the keel line which had the added responsibility over the control of the bow and stern rockers.

After analyzing the *Switch One Design* class boat, along with many IMCA boats who share this features, we decided to also model a parallel middle body to investigate the direction taken by the optimizer when given the possibility of creating a constant section along the hull.

To have full range of geometric possibility, each transversal section was created with NURBS curves controlled by five control points, which were strategically parametrized with normalized values for better numeric evaluation and placed to guarantee the correct tangency at the desired sections.

Lastly, having decided to adopt a top-bottom symmetry for the entire boat, and after taking into consideration the desired construction height needed to store the vertical strut and the control systems inside a faired tunnel, a new surface was placed in between the bottom and mirrored top surface in order to be able to have another degree of freedom over the general curvature of the waterlines. The overall parametrization can be seen in Figure 6.

In the end we had over 20 input variables which we feel gave us total control over the geometry exploration and optimization.

1.3.3. Hull optimization process with *ModeFRONTIER*

After a comparison with previous CFD simulations and experimental data (*Mach2* and *Hungry Tiger*), the Holtrop method - simple and fast - proved to be the more reliable among the empirical resistance prediction methods available and, therefore, was chosen to estimate the hull drag. Hull drag was calculated at different speeds and displacements, following a typical lift curve obtained from the previous generation foils: then, the calculation of the area under the drag curve (integral of the drag function) was prepared and used as variable.

Following the parametric modelling of the hull, a single objective optimization strategy was implemented in the design process to improve the final performance characteristics of the hull with no interest in the stability aspects. This decision was taken after the benchmark hydrostatic analysis showed how most moths have close to no transversal stability ($GM \approx 0$), and in the design of BFL a performance compromise had to be made to help the unexperienced helmsman we had at the time. This year, after close consultation with the new sailor in the team who is an experienced *Waszp* and IMCA sailor, we agreed to focus only on the hydrostatic resistance aspect to reach the take-off speed as fast as possible.

The optimization process has been carried out using *ModeFRONTIER* software. The workflow presents itself with a central *Grasshopper* node in which the input variables are fed in. From there the geometry is created and analyzed with *Orca3D Rhinoceros* plug-in at the characteristic speed/displacement point, giving then as output the drag value as well as critical geometric coefficient and values. From there, the drag output goes through a calculator node for the calculation of the integral value of the drag curve resulting in a single final score for each design.

Geometric constraints have also been set. The first, overlooking the wanted freeboard of at least 100mm from the bottom of the wing structures; and the second, guaranteeing a stern width of at least 300mm to comply with the structural loads imposed on the gantry structure. The third and final constraint was to have a

LCB higher than 1800mm from the reference point, to guarantee sufficient buoyancy in the fore section.

To reach then the final design we structured the work in three distinctive phases:

1.3.3.1. Phase 1: MOGA-II design exploration

The aim here has been the exploration of the design space. For this reason, the starting input domain has been set with a wide range of existence for each variable and set as a discrete ordered with the same base value.

Then, a series of runs using *MOGA-II*, a genetic evolutionary algorithm, were executed. After each optimization run, the best designs were selected and scrutinized to adjust the input domain where it gave the best results. Also, a more precise definition was given to the variables which had the biggest impact over the objective, and parametrizing the ones that consistently showed a stable preferred value and very low influence over the objective such as the control points of the fore and aft end sections.

In the end 10 runs were completed, with a total of 10000 designs analyzed, which resulted in 45 best selected designs and a significant reduction of number of variables to 12 and their respective ranges.

1.3.3.2. Phase 2: Simplex robust optimization

At this point every best design from the previous phase has been compared to one another, to select the 13 designs needed for the second phase (where 13 is equal to $n+1$, where n is the number of variables still at play) to be used as DOE for the start of the next phase. At this point *SIMPLEX* algorithm has been selected due to its robustness and therefore capability of finding the best global design.

A total of 88 designs have been created, of which the best has been selected for the third and final phase.

1.3.3.3. Phase 3: BFGS accurate optimization

Having completed the robust analysis, the best design has been used for the final run, where *Broyden-Fletcher-Goldfarb-Shanno* algorithm has been used. BFGS uses gradient information to guide the search toward the optimal solution. Gradients (partial derivatives) point in the direction of the steepest ascent or descent, ensuring each step is informed by the local landscape of the objective function. This precision makes it ideal for a precise result, thus giving the best possible design.

The results are given in Table 1 and it can be seen how, out of the created designs, iteration number 625 has been selected as the final geometry for this year's challenge! *Watch out for our this number, as it's tradition in our team to use the final iteration id as sail number.*

1.3.4. Final geometry and validation

The final geometry was then refined in *Rhinoceros* to smooth out the curves and harmonize the overall shape. The main geometric features (as depicted in Figure 1, Figure 2, Figure 3) are summarized below:

- Sinkage of 152mm, which combined with the set construction height of 360mm results in a freeboard of 108mm with reference to the wings;
- Transom width of 302mm;
- LCB positioned at 1837mm, about 200mm more forward than BFL;
- Max beam of 380mm located at 1250mm from the stern, about 500mm more forward than BFL;
- V-shaped stern to reduce wake resistance;
- Round and voluminous stations, to reduce wetted area;



Figure 1: Half breadth plan



Figure 2: Profile plan

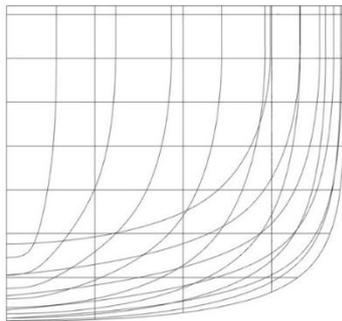


Figure 3: Body plan

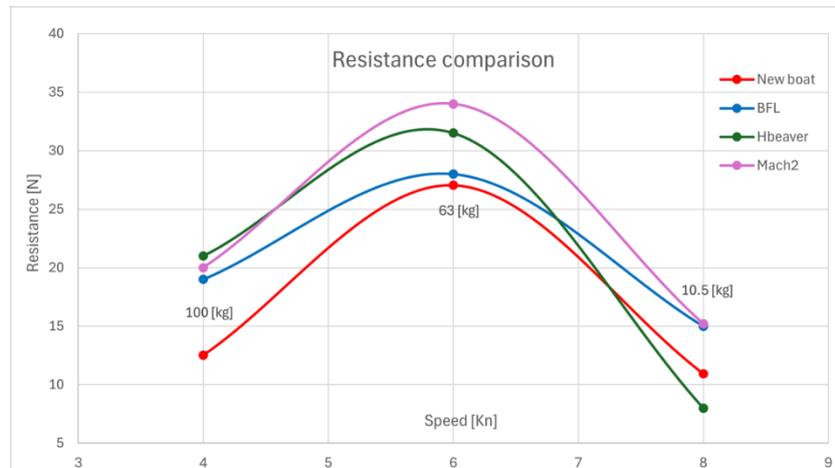


Figure 4: CFD resistance comparison with the benchmarks

A validation of the final hull shape was performed, using the CFD framework developed within the test case presented in [1.3.3.](#) The hull was tested at three different speeds and displacements, using as reference a typical foil lift curve. The results, Figure 4, significant reduction of drag compared with the other test hulls and in particular form the real performance benchmark which we set from BFL, resulting in a performance improvement of about 15% in terms of takeoff resistance.

1.3.5. Structural analysis

The structural analysis of such a boat requires a much more important preliminary phase of evaluation of the structural choices of the effective load cases. Once all the elements are finished, their analysis is used to examine the structural response of

the hull. This examination pays specific attention to the longitudinal strength in the Load Case condition of the most frequent scenarios. The purpose is to evaluate the response of the planking layers to the bending moment.

1.3.5.1. Definition of load case

Our final decision to the global longitudinal strength was to take into consideration only one LC scenario: the steady flight, whose components are specified in Table 2. This choice was made to simplify the modelling, due to the high dynamic components, the strong effect of the rig tuning and the helmsman actions.

The scheme is made of two subsystem forces whose resultant is zero.

Starting with the consideration that we are dealing with a self-balanced LC, to balance the moments we have also taken into consideration the forward pitching moment produced by the two forces: the drag of the foils and the thrust of the sail. In this case we decided to put a lever to cancel the remaining moment produced by all the other forces.

1.3.5.2. Subsystems definition and balancing

We firstly divided the forces into two subsystems:

Foils-weights

For the vertical balance of the forces it is necessary that $Lift = Weight$. By design the lift distribution is equal to 80% on the MF and to 20% on the RF, allowing the calculations of the lift values of both.

Shrouds-forestay-mast

This value was measured by using a load cell and increased by a safety coefficient of 1.5. Taking into consideration the shrouds geometries and evaluating the balance of the forces it was possible to obtain all the components.

1.3.5.3. FEM validation through analytical calculations

In order to ensure that the FEM model would respond to external loads and to make sure that the analytical theory was correct we compared it with a simplified analytical model, which consisted in a thin ideal beam that was subjected to the same self-balanced load.

By changing the crew position and the lift value for each foil, we analyzed several configuration and in each of them has been observed that between the FEM value and the analytical one there was a constant delta of about 20 Nm, as shown in Table 3. This needed to be cancelled by forcing a constant moment on the boat while comparing the value of the maximum effect of the bending moment. The previous table shows how the value is below 5%, therefore the problem introduced by the flexing analysis from a constant moment equal to 20 Nm is negligible to the aim of the FEM analysis.

1.3.5.3. Analysis of shear force and bending moment diagrams

The first preliminary analysis was to define the characterization of shear forces and bending moments on the hull by simplifying it to a thin beam. The aim was to have

a first result to evaluate what the maximum shear section and bending moment were and where transverse bulkheads and a keelson were needed.

Stating the origin of the frame of reference on the keel line facing the gantry, the lever lengths are shown in Table 2.

From the analytical calculations (Figure 7, Figure 8) we see how the stern area, leaving the transom out (discussed separately), has a tendency not to be under stress, while the one more stressed and needing of structures is the one starting from the fore wingbar.

In this limited section there is a concentration of different forces: the weight released by the foremost wingbar, the shrouds, the MF and the mast, that causes a high discontinuity in the shearing (with a subsequent change of sign) and a peak of the bending moment.

1.3.5.4. *Internal structures geometry*

We decided to continue with the great job done with BFL for the design of the internal structures. The only differences lie in:

- the beams' configuration for the wings support;
- the lightening holes of the two keelsons;
- the mast strut is now inserted in the transversal bulkhead.

The aim of this very last choice was to take full advantage of the glues, increasing the contact area between the two components, making the transmission of the shear stresses more efficient.

1.3.5.5. *Finite elements model creation*

The model was created on *Rhinoceros 3D*, imported as a *.stp* file in *ANSYS* and then we used the *ACPpre* tool for the modelling of the composite materials. First, we had to lay a groundwork on the geometrical model, creating, for each surface, sub-surfaces depending on the different ply disposition areas. Subsequently, having to deal with a rather complex sample, we split up the components and for each of them created a geometrical workflow that will lead to one only final "static-structural" form. By doing this we have a much more precise control of how the software manages the stratifications and the local frame of reference for each part of the model. Furthermore, in the static-structural form it's possible to define with great control the connection areas which are the highest cause of problems and mistakes during this type of work.

The application of rigid bodies constraints was made by following the *DNV naval register* data for the analysis of maximum bending on the middle section of the boat. By using the bottom of the hull as reference we have:

- u_z constrains: bow and stern;
- u_y constrains: centerline at midlength;
- u_x constrains: starboard and port knee beams (at midlength);

1.3.5.6. *Plies and layups design*

Compared to the previous fiber disposition of BFL, we decided to push further and use: one layer of flax twill, one layer of flax UD and, internally use *Power Ribs* increasing the bending stiffness of the single skin layer. Replacing a layer of twill with a UD one helped us to reduce the weight at about 1 kg (10% of the hull's weight after the resin infusion) without compromising the global longitudinal rigidity; we hereby provide the stress comparison of the longitudinal stress of the two outmost layers (top e bottom)(Figure 11).

To correctly understand the FEM outputs, one must analyze separately the peak values and the average ones. Regarding the peak values, they are not taken into account as they are caused by geometrical discontinuities. For the average values instead, we focused on highest average value zones, providing them with a local layer reinforcement.

We have also decided to include in the stack-up a transversal closed-loop underneath the wingbars and the bulkhead of the mast strut which presents an extra basalt layer. In those areas we don't plan using core, since it's not suitable for compression.

Longitudinal structures will be inserted under the bow, starting from the MF strut. As the glass fiber loops, there will be a basalt UD fiber reinforced layer.

Torsional forces will not be a problem, since this time we're building a structural deck with an average section having a higher inertial moment with respect to BFL.

Because the internal structures will be cut out of the old deck of our first infused skiff, we made a small test campaign finding out that we can directly utilize them as internal structures, with exception for the transom and for the mast strut's bulkhead that will need a stiffer stratification.

All the foresaid structures and layups are can be seen in [Figure 9](#) and [Figure 10](#).

1.4. Appendages Design

The evolution of the various dinghy models that were produced in the last sixty years, saw a constant decreasing of the hull volume and a ceaseless escalation of the appendage relevance. The IMCA provides an exceptional example thereof.

This chapter provides all the information and thought process necessary to elaborate and understand such a significant part of the boat.

1.4.1. Foils

1.4.1.1. *Design roadmap*

The foils design process, strengthened by the experience acquired in the previous years, had a solid foundation on which to build the new project. The main objective was to create a set of wings capable of performing well at high boat speeds. To achieve this, the team felt the need to create a new custom airfoil that would fit perfectly within the boat's operating conditions.

The design process was initially divided into three different stages:

- *2D airfoil optimization*: a 2D airfoil parametric geometry was used, coupled with an upgraded and revised version of the old *Excel Velocity Prediction Program* and with the optimizing software *ModeFRONTIER* which ran the optimization.
- *3D wing optimization*: As for the wing shape, two tools were used to combine efficiency and accuracy: a low-fidelity tool called *Athena Vortex Lattice* and a high-fidelity CFD (*StarCCM+*).
- *Detailed design*: finally, once created the parametric model, CFD analyses on the bulb shape were conducted to study the interaction in the horizontal-vertical junction.

1.4.1.2. 2D airfoil optimization

The design and optimization of the hydrofoil's airfoil shape played a crucial role in achieving efficient performance across a wide range of speeds. This section details the parametric drafting process using *Grasshopper*, the integration of airfoil geometry into a VPP, and the subsequent optimization workflow. By leveraging Bezier curves for parametrization and automating performance evaluations through *Python* and *XFOIL*, the team explored a broad design space to identify optimal airfoil configurations. The optimization process aimed to gain maximum efficiency, ensuring peak performance in the desired speed range while maintaining good characteristics across the entire operating spectrum.

Airfoil shape drafting and VPP

- *Shape drafting with Grasshopper*

The starting point was the creation of a parametric geometry of the airfoil, done as master's thesis by our team members Vittorio Muzio and Riccardo Gon, where the visco-elastic effects on 2D airfoils have been studied. The input parameters were airfoil thickness (t/c), thickness position along the chord and the coordinates of different control points.
- *VPP*

Nevertheless, the choice to design our own 2D airfoil significantly increased the size of the design space. To explore the design space, an upgraded and revised version of the *Excel VPP* created for the previous foil design was written in *Python* code. The airfoil geometry is then created in *Grasshopper* which delivers as an output a *.dat* file ready for an *XFOIL* analysis executed by the VPP.

The script initially defines key parameters, including:

- *Environmental Data*: water density and kinematic viscosity;
- *Foil and Boat Data*: chord length, area, aspect ratio, and flap excursion;
- *Speed Range*: speeds from 1 to 30 knots, with a focus on 18-22 knots (in order to obtain an airfoil designed for high cruising speed while still maintaining good performance across the whole speed range);

- *Reynolds Number Calculation*: based on chord length and velocity;
- *Flap Angles MF*: from -8° to 8° in 2° increments;
- *Angle of Attack MF*: from -1° to 4° in 1° increments;
- *Angle of Attack RF*: from -10° to 10° in 2° increments;

The script processes the input file containing airfoil coordinates, then creates an *XFOIL* run file in order to run multiple analyses in batch mode computing the Lift Coefficient (Cl) and Drag Coefficient (Cd) for each speed and flap angle (or angle of attack for the RF). The obtained results are then stored in matrices. To handle numerical issues, zero values in Cl/Cd data due to *XFOIL* not converging (i.e. in flow separation at high angles of attack) are replaced using local interpolation. Then values for intermediate speeds are linearly interpolated. Finally, the required Cl for lift equilibrium is computed, and the corresponding flap deflection (or angle of attack) is determined.

Optimization and results

The optimization consists of a workflow where the *Grasshopper* node outputs a *.dat* file of the profile to be evaluated in the VPP using *XFOIL*. This workflow allowed us to generate and test multiple feasible designs.

The main objective was to find an airfoil which would have optimal performance in the desired speed range (18-22 knots) and good performance across the rest of the range. To achieve this, having set a desired Cl for each speed, a multi-objective optimization was run, aiming to maximize the flap angle (or AOA) at 20kn, while minimizing the overall area of the drag curve.

Initial runs were executed using a genetic algorithm (MOGA-II) aiming to explore the design space; subsequently starting from the best designs a robust algorithm was used to find the best global candidate.

Finally, two optimal airfoils were chosen, one for each foil. These will be later used as fixed parameters in the 3D analyses and can be seen in Figure 12.

1.4.1.3. 3D wing optimization

Shape drafting

Once the best performing airfoils were chosen, focus shifted on 3D shape. The existing *Grasshopper* parametric geometry used in the previous year's design was revised and expanded in order to create a new wing shape, allowing the creation of a broader range of shapes that were not confined to the bi-elliptical shape. Given the larger number of possible 3D shapes, a low-fidelity optimization was initially implemented to explore all possible designs.

The input geometry parameters were the following:

- *Wingspan*;
- *Area*;
- *Delta/c0*: back or forward sweep of the foil;
- *Taper*: chord length variation along the wingspan;

- *Twist*: airfoil variation of angle of attack along the wingspan;
- *Vertical and horizontal ellipse radius*: RF dihedral;

The *Grasshopper* file was modified to return as an output an AVL geometry file (for a low-fidelity optimization) and an *.iges* file (for a high-fidelity CFD optimization); this was done with the aim of running a Multi-fidelity Response Surface Methodology optimization. Unfortunately, lack of time didn't allow it, but the created geometry was nevertheless useful even with two separate analyses.

Lo-fi optimization using AVL

The AVL geometry file (e.g. in Figure 17) is created by dividing the wing in a defined number of sections along the span and placing the desired airfoil in every section, with the angle of attack adjusted for the desired twist. A *Python* node is then used inside *ModeFRONTIER* to create an AVL *.run* file, computing the required Cl at different speeds and defining all the run cases for the analysis.

Two separate *ModeFRONTIER* workflows were defined, one for the rudder foil and one for the MF. The analyses are run from a boat speed of 6 knots up to 30 knots, with a 3kn interval, then AVL computes the efficiency (Cl/Cd) at each speed and the results at intermediate speed values are subsequently interpolated. As previously done for the 2D analyses, the aim is to maximize the overall area of the efficiency curve and the desired range area (18-22 knots).

- *RF*: the rudder foil's workflow, did not require the implementation of a flap and thus was more straightforward to set up. For each speed, a target Cl is computed based on the given chord. AVL is then run with the Cl as an input and gives in output the wing's angle of attack to satisfy the required lift, at which the Cd is extrapolated and the 3D wing efficiency is computed (Cl/Cd) and stored. Once all analyses for a given wing are computed, the total area of the efficiency curve and the area of the desired range efficiency are calculated and stored. These are then used to compare the performances of the different designs.
- *MF*: the *ModeFRONTIER* workflow shares a lot of its characteristics with the one created for the RF. The main difference is that lift is generated via a trailing edge flap and not by changing the angle of attack of the whole airfoil. Nevertheless, this variable is taken into consideration as the *ModeFRONTIER* can be fixed to the vertical strut at different AOA. The range is set between -1° and +4°.

As for the trailing edge flap, the optimization process is similar to the one utilized for the rudder foil's angle of attack: for each defined speed and Angle Of Attack, a target Cl is computed and AVL finds the correct flap deflection to achieve the desired lift. Flap deflection ranges between +8° and -8°.

Hi-Fi RSM optimization

For the last step, because CFD is slow and expensive, especially with 3D models and turbulence, we decided to implement for the first time in our team's history the Response Surface Model technique for the Hi-Fi optimization of our wings. A RSM

is a mathematical approximation that mimics the behavior of a complex simulation using data from a limited number of actual analysis, and then it builds a simple, fast model that can predict results (like lift, drag, pressure) for new design points.

Using the Uniform Latin Hypercube algorithm we created a DOE of 15 design in order to fill the domain as efficiently as possible. At this point mesh and domain independence studies were conducted (see [1.4.1.5.](#)) and the CFD simulations on those selected designs were ran.

At the time of writing this report, as the simulations are running, we are at this specific point of the design process. Thus we hereby present the planned process.

Based on our theory knowledge, we intend to use these results to build the response surface. Most of said designs will be used to train the RSM by using different models. In particular we intend to compare the Gaussian Process and Neural Network models with the cross validation process. This consists in iteratively extracting a small number of designs from the dataset and for each iteration create a new RSM, and repeating the process for a number of times equal to the dataset size. For each RSM created, error indicators are extracted and used to compute the total mean error from all iterations. This will give us an estimate of the ability to predict the correct value for every new design points.

In the end we will opt for the one that shows the least mean error and use it to find the 3 best designs, optimized for lowest drag and set lift.

Finally, these selected designs, will be validated with a CFD simulation to verify the accuracy of the design performances, and decide the final winner.

1.4.1.4. Bulb design

Another crucial aspect of the hydrofoil design stage which has been overlooked in the previous wing iterations is the bulb shape. The shape was parametrized using *Grasshopper* and high-fidelity CFD analyses were run once the final wing shape was chosen. Once again, running a direct CFD optimization would have been very time expensive; therefore, the team chose to adopt the same RSM model as the high-fidelity wing optimization to reduce computing time.

Both mesh and domain independence analyses were also conducted to minimize computing time while maintaining result accuracy. At the time of writing this report the analysis is being executed, but no results are yet available.

1.4.1.5. Mesh and domain independence study

To perform simulations while minimizing the time required to reach convergence without compromising the obtained results, a study of domain and mesh independence was conducted. These studies were carried out in preparation for all the optimizations conducted with *StarCCM+*.

The domain independence study was conducted first to ensure that the results were independent of the boundary conditions of the problem. Subsequently, the mesh independence study was performed to decouple the simulation results from the mesh density, simulating with the optimized domain derived from the previous

study. Here the main foil's CFD preparation is used as an example, but the procedure is equally repeated also for the rudder foil, bulb and wings optimization.

Domain independence

The domain study was conducted starting from a standard-sized parallelepiped block, where its standard dimensions are parameterized with respect to the characteristic length of the analyzed profile.

The profile is simulated in isolation, without hydrostatic pressure effects. The domain is a block with the profile inserted halfway, taking advantage of symmetry to reduce computational cost. A dense mesh is used to accurately represent the leading edge and trailing edge.

The main foil's characteristic length is the chord (C).

The initial block dimensions are as follows:

- From the foil's leading edge to the domain inlet, the length is $5 \cdot C$.
- From the foil's leading edge to the domain outlet, the length is $12 \cdot C$.
- The block's width is $1.5 \cdot S$ (S = wing span).
- The block's height is $10C$ ($5C$ upwards/downwards relative to the upper/lower face).

The domain dimensions are therefore parameterized according to a set of defined values, referred to as L . As the parameter L varies, the initial domain will enlarge or shrink in direct proportion to the parameter itself (as shown in Figure 13, Figure 14, Figure 15, Figure 16). It is crucial to note that although the domain size increases, the mesh remains constant across the different configurations.

The study is presented with all the values for drag and lift in Table 4 for all L parameters.

Thanks to the graphs presented in Figure 18 and Figure 19, we determined that the value $L=2$ is the best compromise among all those studied as it results in a 1% error compared to the nominal value, allowing us to confirm that the solution is independent of the domain size, while also saving on computational time.

Mesh independence

The mesh independence study is carried out in a very similar manner, maintaining the domain dimensions obtained from the previous study while varying the mesh base size parameter to make the mesh either finer or coarser.

Continuing with the previous example - the MF case - starting from a sufficiently refined mesh configuration, we varied the base size parameter both by decreasing and increasing it. As shown in Figure 20 and Figure 21 and the cell count in Table 5, the results vary significantly.

Once again, thanks to the graphs (Figure 22 and Figure 23), the optimal value was determined. Since no clear monotonic trend emerged in either case, the study was repeated several times - not shown here for brevity - and it was concluded that the

best compromise in terms of percentage error relative to the number of cells (and thus computational cost) is the mesh with a base size of 1.

1.4.1.6. Structural analysis

The structural model of the foils has been re-engineered in a way to achieve more accurate geometry during production, thus faithfully respecting the model analyzed through the CFD simulations. The FEM model has been divided into three sub-models. The layering has been managed in *ACP Pre*, with shell elements modelling that allows for precise definition of the material layers.

In this context, flax was chosen as the main material for layering in conjunction with UD and biaxial CF: two layers of UD were inserted to handle the primary stresses, while one layer of biaxial CF was applied to optimally redistribute the stresses throughout the structure. An interesting material choice we took is the use of a new treated wood-based material, discovered during the *JEC WORLDS 2025* in Paris, which demonstrated high structural performance in combination with flax and carbon.

An additional internal reinforcement was modeled to transmit the concentrated loads at the pressure center, identified through fluid dynamics analysis. This internal reinforcement was designed taking inspiration from its use in wind turbine blades and aircraft wings, where it enhances structural resistance and efficiently manages applied forces. The inner part of the foil consists of brick elements representing a foam core, providing strength and lightness to the structure.

Metal inserts

One of the aspects that needed to be addressed regarding the reliability and foil adjustments of our boats has always been the vertical-foil junction. For this reason, metal inserts have been designed (Figure 24, Figure 25 and Figure 26). As a master's thesis study from one of our teammates (Jesus Sebastian Lorenzo Piccinin), the terminal section of the vertical strut and the inner portion of the bulb have been modeled as solid to derive the forces necessary for comparing the use of a steel CNC milled insert and a 3D printed titanium powder insert, topologically optimized to improve stress distribution. The applied constraints included the maximum force, defined as 80 kg at mid-wing, based on mechanical tests required from the competition. Initially, zero displacements were imposed on the faces of the foot insert.

Even though the obtained results show promising development for the 3D printed option, we decided to build the inserts in CNC milled steel as we don't want to innovate too fast too soon, thus compromising the reliability.

1.4.2. Mechanical control system

Our control systems draw inspiration from the most advanced platforms available. To achieve a combination of high performance, low weight, and reliability, we adopted a holistic design approach in collaboration with the hull designers. This

synergy led to the creation of a fully enclosed deckhouse, seamlessly integrating all rope take-ups within a streamlined tunnel positioned behind the mast base.

This choice was driven also by aerodynamic and esthetical aspects, and for these reasons we also decided to place the transversal wing beams as low as possible into the hull, all while allowing the passage of the control lines underneath them. Three key aspects have been carefully revised:

- *Pushrod casing*: given that our flight control system is based on a pushrod configuration, the load applied on the rod would easily bend it, thus creating significant slack in the system, affecting the responsiveness of the boat. For this reason we placed an additional CF pipe, which we upcycled from a broken windsurf batten, outside the rod to prevent it from bending.
- *Gearing*: seeing the complexity and inefficiency of the previous system, which resulted in it being almost never used, this year we adopted a fixed point adjustment.
- *Wand housing*: to improve assembly and disassembly of the flight control system, we reengineered the wand-bowsprit interface. We decided to go for a fixed self-built housing relatively to the bowsprit, and sturdier construction using recycled forged chopped carbon.
- *Cylindrical slot mechanism*: this innovative design (see [2.7.5.](#)) allows for rotational movement at the foil-rod locking point, enhancing the fluidity and responsiveness of the system during flight.

1.4.3. Wings

After the experience with BFL's S-shaped wings and wingbars, we stopped and analyzed their winning and losing features. We quickly realized that, as much as they enhanced the ergonomics onboard, they proved unnecessarily complicated and unprecise to build, resulting in a product that was way heavier than planned (4kg more than the planned 18kg).

This brought us to a serious rethinking process based on what the crew, our final user, suggested us to be what the industry aims for: light, resistant and precisely built components. For those reasons we're going back to straight, instead of S-shaped, wings.

1.4.3.1. Wingbars

This new approach is necessitated by implementing a new manufacturing technique, which will enable the production of beams with specific characteristics detailed below. The primary objective is to achieve a significant reduction in the weight of the wings.

To accomplish this, the design incorporates two key features:

- *Linear tapering of the beam*: the beam thickness is maximized in the regions subjected to the highest stresses and progressively reduced as it extends away from the hull;

- *Hollow cross-section*: the new manufacturing method allows for the implementation of a hollow beam structure, further decreasing the overall weight. After evaluating various profiles, an elliptical cross-section was selected, with its major axis aligned with the primary load direction.

A preliminary study indicates that regarding the weight considerable advancements can be achieved: by still utilizing the allowed CF content and employing an experimental layup consisting of flax UD $[0]_2 / -45 / +45$, basalt UD, and CF UD, a total weight of 1.105kg per half-wingbar is expected.

Preliminary calculations and FEM validation

The initial sizing was conducted using a customized *Excel* spreadsheet, which provided a preliminary verification of bending moments, maximum stresses, and expected deformations. The maximum moment in the beam occurs at the end closest to the hull, as this is the point where the sailor's weight has the greatest lever arm. Acknowledging this, we will ensure that the tapering in this region does not compromise the beam's structural resistance. The oval cross-section is designed with its major axis aligned along the primary load direction. This configuration enhances the moment of inertia precisely where it is needed, minimizing material usage.

The resulting dimensions will be validated using a FEM model in ANSYS, allowing the team to:

- Confirm the feasibility of the chosen geometry and laminate layup;
- Assess stress distributions in each ply of the final composite component;
- Further optimize the combination and orientation of the selected materials;

Currently, the elliptical beam under study has the following specifications:

- *Inclination*: 30°
- *Length*: 0.85 m
- *Major ellipse at the hull end*: Major axis = 0.8 m, Minor axis = 0.05 m
- *Minor ellipse at the outmost end*: Major axis = 0.5 m, Minor axis = 0.03 m

Projections and rendering of the wingbars are provided at Figure 27.

To aerodynamically optimize the shape of the terrace profiles, an optimization is performed using *ModeFRONTIER*, aiming to minimize drag. The drag coefficient will be obtained through a 2D simulation in *StarCCM+*, with a two-dimensional approach chosen to isolate the drag generated by the profile itself. The simulated profiles are the result of a parametrization of an initial profile using *Grasshopper*, with 8 parameters to modify the shape of the trailing and leading edges.

1.4.3.2. Trampoline

The wings, as previously stated, will be flat instead of S-shaped, consequently being simpler to design and build. Last year a really deep work has been done to ensure the rigidity and structural reliability of the wing trampolines, which were made entirely of FF, recycled PET core and a single ply of CF on the outer layer, resulting

in a sound product which showed a maximum deflection of 18mm, respecting the 50mm self-imposed constraint.

At the time of writing this report, no numerical calculation for an improvement of the previous design has been done, but we plan to investigate this aspect.

1.4.4. Gantry

Building on last year's work, we're reusing the gantry tilting system, which provides additional rudder adjustment to enhance stability during foiling, along with a three-point attachment configuration between hull and gantry. The internal structure, composed of five carbon tubes repurposed from old windsurf masts, follows a tetrahedral geometry optimized for efficient load distribution and increased structural rigidity, as shown in Figure 28. This setup maximizes resistance to multi-axial loads, minimizing deformations and improving the system's ability to absorb operational stresses. Its effectiveness was verified through FEM analysis, assessing structural response under flight conditions up to 30 knots.

In addition to the supporting frame, an external shell was integrated - not primarily structural - aimed at improving the system's hydrodynamic and aerodynamic performance. This shell encloses the tubular structure, reducing fluid dynamic turbulence caused by tube exposure.

Although not a primary load-bearing component, studies were conducted to analyze the interaction between the external shell and the tubular frame, particularly regarding stress transmission. These analyses assessed how the shell influences load distribution, preventing stress concentrations and avoiding interference with the main structure's deformability. The goal was to ensure that the shell integration did not compromise the gantry's mechanical behavior, but rather only optimized its fluid dynamic performance.

1.5. Rig Design

To construct a high-performing Moth, a combination of engineering expertise, sailing experience and feedback is essential. Consequently, we sought advice from experienced Moth sailors, contacting ones from our area as well as top athletes in the Moth fleet.

As for the mast and boom, all the sailors we interviewed suggested buying second-hand parts and, because of the amount of work that would require - with an uncertain outcome - this year we decided to buy them.

But we were able to do something even more exciting on another aspect of the rig.

1.5.1. Sailplan

Over the past years, due to our limited technical knowledge and the lack of proper tools, our boat's rig was made up of old components that were no longer used in competitive racing. This year, we decided to take a step forward towards even more sustainable sailing. With the support of the Trieste-based sailmaker *Olimpic Sails*,

our new boat for this edition of the SuMoth Challenge will be equipped with a sail built by us.

At the end of the last edition, we had the opportunity to purchase an old *North Sails 9DSX sail*. Excited by the prospect of having a competitive sail, we decided to buy it, ignoring however some significant defects that ultimately made it unusable.

Once the initial enthusiasm faded, we realized that the material was heavily worn, with numerous holes and patches, and the stitching had been corroded by time and sun exposure. We began to question how to make the sail functional without spending more on repairs than its actual purchase value, giving a new life to otherwise unusable scrap pieces.

This is where *Olimpic Sails* came into play. Speaking with them, we discovered the possibility of using a scrapped mylar sheet that was produced for a Finn sail prototype to create a new one. Seeing this as a great opportunity, we decided to move forward with the project and, with the help of our supporting sailmakers, we started designing a hybrid sail: part Moth sail, part Finn sail.

1.5.2. Rig layout

The design of our control systems was inspired by the most successful platforms on the market. To achieve a high performance, lightweight, and reliable platform, we started with an integrated design together with the hull designers that led us to design a totally enclosed deckhouse that covers all our rope take-ups inside a faired tunnel behind the mast base.

This choice was driven also by aerodynamic and esthetical aspects, and for these reasons we also decided to place the transversal wing beams as low as possible into the hull, all while allowing the passage of the control lines underneath them. This means that a secondary housing for the placement of the deck organizer has been designed behind the fore transversal wing beam. From there, the control lines run on top of the rigid trampoline into the blocks, and finally back to the boat. The take-up for cunningham and vang controls will be stored inside the longitudinal wing structure, respectively one for each side.

1.5.3. Rigging system

Most Moths use a steel wire forestay and shrouds (for the standing rigging). We decided to go for pre-stretched Dyneema to shed weight whilst keeping reliable tensions. As for the spreaders, we're re-using the same mould and layup we designed for the previous boat (BFL's existing spreaders are presented in Figure 29).

1.6. Electronics and Data Acquisition

This year, we set the goal of developing an integrated electronic suite for our Moth, focusing on the design and implementation of a data acquisition and processing system. This system enables real-time data visualization, storage, and later analysis, providing insights into the boat's performance at sea.

The electronic suite is designed to offer support to the crew at sea and for post-training assessments, ensuring a comprehensive evaluation of performance. Moreover, it plays a crucial role in validating the boat's design considerations, helping to refine and optimize its development based on real-world data.

1.6.1. Hardware

The system was designed based on two key principles: ease of use, both for the end user and from a developer's perspective, and maximum modularity. The emphasis on modularity serves multiple purposes. First, it ensures redundancy, meaning that a malfunction in one part of the system does not compromise the entire setup. Additionally, it allows for future expandability, making it possible to integrate additional sensors or modules as needed. Finally, it simplifies development, enabling a gradual and iterative approach to working on different modules, ensuring a more flexible and efficient workflow.

Following these principles, we have decided to separate the system into a central unit, which aggregates, processes, stores, and visualizes the data, and remote units, which primarily consist of sensors responsible for data acquisition.

1.6.1.1. Remote units

The purpose of the remote units is to collect data from various sensors (which in the initial phase will include GPS, IMU, and an anemometer), perform preliminary processing, and, using protocols explained later, send it to the central unit. We decided to base the remote units on an *Arduino* platform due to the developers' familiarity with it and because it is the gold standard for prototyping.

1.6.1.2. GPS and IMU units

The first remote unit consists of an *Arduino MKR WiFi 1010* board equipped with an IMU (Inertial Measurement Unit) shield, while the second unit is made up of the same board with a GPS (Global Positioning System) shield, based on the *u-blox SAM-M8Q GNSS* module. Both units send data to the *Raspberry Pi* through serial communication.

1.6.1.3. Anemometer

Proof-of-concept testing:

We made our first test on a simple jig that enabled us to develop a first working code while still adjusting sensor distances.

First prototype:

We then modeled our first prototype in *Fusion 360*, so that we could try a real case scenario of the sensor working. Unfortunately, due to hardware and design limitations we came to a halt at this stage of development, also to give priority to a more traditional cup-and-vane anemometer design.

1.6.1.4. Central unit

The central unit is responsible for acquiring data from the remote units and aggregating them; real-time visualization of environmental parameters and vessel

dynamics; data processing and storage for subsequent analysis. After assessing RAM and computational power requirements, we selected a *Raspberry Pi 4 model B* with 2GB of RAM as the central unit.

1.6.1.5. Power management

The Power Supply Unit guarantees a stable 5V output at a maximum of 3A. It consists of a battery pack made up of eight 18650 lithium-ion cells and a step-down Switch-Mode Power Supply. The battery pack is composed of pairs of batteries connected in series, each managed by a BMS (WH-2S80A) for charging and discharging. These pairs are then connected in parallel, resulting in a nominal voltage of 7.4V.

Due to the SMPS requiring a minimum input voltage of 7V to function properly, this value is considered the fully discharged reference voltage of the battery pack, while 8.4V is taken as the fully charged reference voltage. The battery pack can be charged using a common 12V power supply (our team uses the ER24W12V model).

1.6.2. Software

The core of the software development effort has been focused on the central unit, an onboard computer responsible for collecting and analyzing data from various onboard sensors. This unit runs *DietPi*, a lightweight *Debian*-based operating system optimized for minimal resource usage.

To perform its tasks, a proprietary software project, currently named *Audace Mothics*, has been developed in-house, primarily utilizing *Python*.

1.6.2.1. System Architecture

The Mothics software is structured into three key development domains:

1. Communication with remote units for sensor data acquisition;
2. Data aggregation and processing;
3. User interface;

1.6.2.2. Communication

Mothics employs the Message Queuing Telemetry Transport protocol and serial communication to interface with the remote units. This diversification in communication protocols allows for maximum flexibility in connecting the remote units to the onboard computer.

MQTT is effective for asynchronous network communication based on a publish-subscribe model, where the central unit acts as a message broker and the remote units publish messages categorized into topics. On the other hand, serial communication ensures immediate, cable-based data exchange, which is crucial for avoiding latency.

Since MQTT is a network communication protocol, the onboard computer functions as a Wi-Fi hotspot, ensuring reliable local network availability for the distributed system.

1.6.2.3. Data Processing

Given the different nature of the various data coming from the onboard sensors, it is standardized and pre-processed within a dedicated data-handling *Python* class. More precisely, data sampled at slightly different times by the available sensors is re-sampled and aggregated into *DataPoint* objects, which are stored inside data Tracks. This process also facilitates the recording of training sessions and storing data logs for post-mortem analysis and performance evaluation.

1.6.2.4. User Interface

Mothics provides a web-based dashboard for real-time monitoring, developed using the *Flask* package for *Python*, accessible from any device connected to the local Wi-Fi network. Additionally, a custom-built command-line interface (CLI) is available via SSH connection to a *Tmux* session for direct system interaction and advanced control.

1.7. Innovative Elements

To do a simple enumeration of the innovative elements in our project would be quite complex, as every adopted design technique is either highly innovative or, when not, is grounded in sustainability. Hence, we sampled what we thought were the most interesting and innovative ideas and elements out of them all.

1.7.1. Sustainable sail

The work we did with *Olympic Sails*, as explained in [1.5.1](#), is a first of a kind. The main challenge was to design a competitive sail just by using scrap parts from other classes sails or sail's elements.

This decision does not allow us only to spare some money and precious SM\$, but is a statement to sustainability, avoiding the emission of more than 75Kg of CO₂. We did not just short term repaired a sail, we built a more efficient and durable one. As demonstrated with Lina's deck this approach gives us sailors a new point of view, where all used and outdated parts can be upcycled into brand new components that have the same performance as non-sustainable ones.

1.7.2. User friendly data acquisition, sharing and visualization

Knowing the importance of communication between team members and quick and intuitive information delivery onboard a racing boat, we decided to supply with the same possibilities a single-handed moth. Consequently, we developed an in-house built data acquisition and visualization tool, that provides both the sailor and its support boat with a real time data stream. The stream provides wind, telemetry and orientation data, plus the foiling situation based on various sensors distributed around the boat. All this data is made sailor friendly through two different methods:

- *On-board live feedback*: relevant information is provided to the sailor through intuitive tools, such as LED indicators for foiling height;



- *Off-board live and registered database:* all acquired information is stored and visualizable with a highly customizable live web page, which can provide the user with live graphs and maps.

1.7.3. Modular vertical insert

Given that last year's vertical moulds were mistakenly oversized by 4%, to avoid any excessive CNC machining operation and still enable infinite coupling between multiple foil junctions, we invented a three-pieces insert system (as presented in paragraph [1.4.1.6.](#)) where the top and bottom components are integrated during the infusion process and the middle part is custom made and held in place with a screw.

1.7.4. SRAG

Our new Gantry Angle Regulation System (Sistema Regolazione Angolo Gantry) will allow us to regulate more than the standard $\pm 1,5^\circ$ of movement, letting the crew decide between -3° and $+6^\circ$, all without needing the unpractical two wrenches, but letting us work just with one.

2. BUILD METHODS AND COST ANALYSIS

In this section we provide an overview of the intended building methods. Given the experience of our boatbuilding team, our design team had the opportunity to plan the construction always receiving feedback on the project feasibility.

Maintaining an open dialogue with the boatyard, we have structured the development process into two parallel streams: one focused on the adoption of well-established construction techniques - such as VARTM, CNC machining, compression moulding etc. - and another dedicated to the exploration of innovative building methods, materials, and technologies, as detailed in Section [2.7](#).

All the paragraphs are provided with the relative SM\$ cost expectations (in the appendages at section [6.2](#).) and, when regarding composite material, the relative resin use expectations are also provided.

2.1. Build Scope

2.1.1. People, facilities and budget

This year, Audace Sailing Team has welcomed many new members who, thanks to the experience and guidance of our team leaders, have been making an outstanding contribution in every aspect of the project. From the design and construction of the boat to social media management and marketing, everyone has played a crucial role. The possibility to participate with two different boats to this year's SuMoth Challenge was made possible not only by the financial support of our sponsors but also by the materials and technical expertise provided by the companies that believed in us. Every resource has been essential from day one, allowing us to build a competitive and sustainable boat. A significant example is our collaboration with local companies such as *Olimpic Sails* in Trieste, which supported us in sail design. Managing the project's finances has also been a complex challenge, but thanks to careful planning and strong awareness, we have successfully maintained financial stability and pursued our goal with determination.

2.1.2. Materials

- *In-house built components*: hull, wings, foils, MFCS, etc.;
- *In-house repaired components*: since the boat is a new project, no component on board will be repaired, instead all the components will be either brand new or upcycled/self-built;
- *Reused components*: windsurf mast (lateral beam of the wings and mast base), internal structures from Lina's deck, Finn sail, Moth sail, Scrap parts of maxi yacht sails;
- *Acquired components*: ropes, blocks, mast, boom;

2.2. Preliminary Build Trials

This year, a rigorous material testing campaign was started, focusing on deepening the theoretical understanding, supported by a limited number of tests. The full testing campaign is planned for next year, pending the availability of an extensometer in our university. Due to inadequate instrumentation, additional tests would have resulted in unnecessary material consumption without providing additional significant data. We started with single skin layup characterization and proceeded with sandwich characterization.

The testing started from FF UD and FF twill, since we already have the technical data from our suppliers and will be the most used by us. To operate correctly, it was important to follow the same precise procedures and regulations, which are ISO 527(-4) for tensile tests and ASTM D7264 for bending tests.

From now on we will assume a reference system relative to a unidirectional ply we set 1 as the main fiber direction, 2 as the transverse direction and 3 as the orthogonal direction following the right-hand rule. From a tensile test with longitudinal and transversal strain gauges, we can obtain:

- E_1 : tensile modulus in the longitudinal direction;
- E_2 : tensile modulus in transverse direction;
- ν_{12} : Poisson coefficient relative to 12 plane;
- ν_{21} : Poisson coefficient relative to 21 plane;
- G_{12} : shear modulus relative to 12 plane;
- G_{21} : shear modulus relative to 21 plane;

Depending on the material, various simplifying assumptions regarding the symmetry of mechanical properties can be made, reducing the number of linearly independent elements in the stiffness matrix. Starting from the 21 constants of an anisotropic material, we get:

- 9 if orthotropic ($E_1, E_2, E_3, G_{12}, G_{23}, G_{31}, \nu_{12}, \nu_{23}, \nu_{31}$);
- 5 if orthotropic and transversally isotropic ($E_1, E_2, G_{12}, G_{23}, \nu_{12}$).

By leveraging the appropriate symmetries, all the necessary constants can be derived for input into the FEM software.

Because we lack strain gauges, we didn't proceed with a complete material characterization. However, it was observed that bending tests in the small-displacement regime could be conducted to indirectly determine E_1 . In this approach, the stiffness provided by the testing machine should be considered an approximation of the longitudinal stiffness.

To verify this hypothesis we tested a small batch of 8 single skin 6 layer specimen, of which 4 were flax twill and 4 were flax UD. Following ISO 527-4, the dimensions of each specimen were 30x250mm. The results are shown in Table 6.

2.2.1. Longitudinal twill and UD tensile modulus

As shown in the tables, the experimental results display good consistency between the mean and the median. However, the standard deviation - the measure of the spread of values - indicates that for flax twill there is no issue, as the dataset exhibits a compact distribution around the mean. On the other side, we can see that regarding flax UD the output has an excessively wide distribution. This situation significantly influences the safety factor chosen for the design phase, since it's linked to the mean minus two root mean square.

Considering only the mean values, it is evident that the measured values for both materials are approximately 35% lower than those specified in the technical datasheets. This discrepancy is primarily due to the datasheets referring to twill prepreg laminated fibers (which yields a higher-quality finished product, enables the use of denser, mechanically superior resins, and reduces the void fraction in the component) compared with our produced via the VARTM process.

In the planned testing campaigns we expect consistent values with the already done testing.

2.2.2. Fiber weight fraction analysis

To make a valid comparison with the technical datasheets, it is crucial to ensure that the fiber weight fraction matches that of the supplier. In the flax twill single skin lamination this fraction is 41%, while for UD flax, it is 45%.

By measuring the dry fiber weight, the absorbed resin, and the final laminate weight, we determined the fiber weight fraction to be approximately 42.2% for twill and 45.2% for UD, leaving us satisfied with the production method.

2.2.3. Future studies

The planned testing, with strain gauges, will allow us to determine E_{11} , E_{22} , ν_{12} , ν_{21} , G_{12} , G_{21} ; allowing us to fully characterize the stiffness matrix. Then, by using symmetry hypothesis, we'll start with the following tests:

- Flax tensile tests: to compare with the already obtained results;
- Basalt tensile tests: to characterize its stiffness matrix;
- Glass and CF tensile tests: given the diverse origins of these scrap materials, to determine average tensile properties and establish a safety value by calculating the standard deviation.

2.3. Hull Build Method

2.3.1. Mould design

As we did for our first boat, we're sticking with the female strip-planking technique, with the difference that this time the mould will be separated into two different halves, port and starboard. This will allow us to have an easier de-moulding in case of any extraction problem and will also make it easier for us to sand it to a smooth final surface.

With the help of a CNC milling machine, we're cutting out forty-eight half-ribs that follow the profile of the hull, twenty-four for each side. Unable to do it ourselves, because of the CNC machining SM\$ costs, the job will be done by a local chair manufacturer that utilizes bigger machinery, being able to do the job in 50 minutes, all powered by 90KW of solar power. All the ribs will then be mounted on top of two specular wooden frames. After the alignment of the 48 components and the mounting of some wooden reinforcement, we'll proceed with the strip planking.

The strips are going to be nested into each other with a bead and cove technique (Figure 30), doing the appropriate groove with a bench cutter. The strips will then be nailed onto the rib cages and glued down with epoxy resin. We're then adding epoxy filler to level out the surfaces and, after joining the two sides with some bolts, we're completing the mould with a final layer of epoxy gelcoat to achieve a high-end finish. In the end, after a bit of sanding, the gelcoat finish will be perfect. We'll then apply a PVA-based release agent to prepare the mould for our first infusion.

2.3.2. Hull

For the construction of the various parts of the boat we chose to stick once again with our strong point: resin infusion. Resin infusion is a process used in manufacturing where a dry fabric, in our case FF, is placed in a mould and then liquid resin is injected into the mould, soaking the fabric. The process is called infusion because the resin is infused into the fabric using a vacuum bag placed over the mould. The result is a durable and lightweight composite material.

The infusion process is going to take about an hour, and after two days of catalyzation, we'll be ready to extract the hull.

Since our first flax infused skiff Lina has become obsolete, we decided to dismantle it, in order to upcycle the deck panels and use them as internal structures. Consequently, the joint with the hull will be bonded using glue and basalt fiber on the bottom half and only glue on the top half.

This time, instead of just adding a flat deck on top of the hull, we are infusing another "hull," which will become our deck. Securing everything together, with a laminated belt at the junction.

To analyze the panels that we'll make out of Lina's deck, we took samples from the deck to verify the composites' conditions. Once we assessed that the material properties met the mechanical requirements, we created the CAD files for the CNC machining, estimating around 2 hours of milling.

2.4.4. Wings

This year's wings will follow the same monobloc concept as the previous design, but with a flat shape instead of an S-shape. The wingbars will be produced using in-house built hollow moulds, which will consist of two separate halves: top and bottom. To construct these moulds, we have chosen a technique that involves laminating recycled carbon fiber over wooden mockups. Using this mould will allow us to laminate and compress from the inside the fibers.

2.4. Appendages Build Method

2.4.1. Foils

Having already got our old foil mould, we decided to modify them by adding or removing materials where needed, saving 150kg of aluminum and 20 CNC machining hours. To be able to make the modifications a viable option, we knew we would have to keep an eye on the original foils mould when designing the new ones, not diverging too much thus increasing the CNC milling hours. For this reason, we created a foil geometry which didn't come closer than 5mm to the existing alignment plug housings, maintained the original rudder anhedral shape as well as with many other small details.

For the first time in our team's history, we will use prepreg materials with CFRP and FFRP to create our vertical and foils, taking a significant step towards the commercial production standard where achieve a high-end finish and sound construction.

At the time of writing this report, no test has been done on the wood UD fiber we found during *JEC WORLD 2025* Paris. It is therefore present in the table in undefined quantity.

To make the joints between verticals and foils sturdier we're putting a 3-part metal insert inside of the composites. As further explained in section [2.7.3](#), these inserts will allow us to have modular junctions to allow for correct foil positioning and to swap foils with different junction geometries.

All these steps are making us point towards a higher quality product, also capable of doing more than what you'd expect from commercially available foils.

2.4.2. Mechanical control systems

Starting from the wand we reused the old mould of the old wand, but only a part of it. That's because our wand will be inserted inside a bowsprit fixed housing, changing our last design. The head of the wand is going to be a carbon fiber 3D printed piece, the body and the extension are going to be made of composite materials. The foresaid wand housing will be a forged carbon piece made using a 3D printed mould.

The push rod system that connects the wand to the foils will be made from broken archery carbon arrows and some brass components built with a lathe.

2.4.3. Gantry

To respect the constraint of materials, but still stand for our engagement in performance, the aerodynamic fairing of the gantry will be infused onto the same mould as the hull and the structural component will be constituted of broken masts from other boat classes. Past experience has given evidence that one of the main flaws of our previous moth was the complexity and inefficiency of the gantry angle regulation system. Pushed by the aim to perfection flight system and

minimize the complexity of the components, this year's project involves the replacement of the gantry's fastening elements, particularly the lower central attachment (instead of two laterals), which now features a left-hand thread. This allows for adjusting its attack angle using a single 10mm wrench.

2.5. Rig

As previously seen in paragraph [1.5.1](#), our sailbuilding approach rely onto upcycled parts: such as, for our sails:

- *Tacks reinforcements*: Mylard and Dacron scrap parts;
- *Sail panels*: from a failed production of Finn sail;
- *Sail eyes, battens, camber inducers, top of the mast pocket*: old North Sails 9DSX moth sail;

2.6. Electronics and Data Acquisition

In this section we will describe the physical layout of the electronic suite. The main electronic computing elements will be located in an enclosure beneath the deck. All the units of the electronic system should at present communicate over Wi-Fi.

2.6.1. Central Unit

The central unit is going to be housed in an IP67-rated enclosure located beneath the deck, aft of the foil mast. In that enclosure will be located:

- The *Raspberry Pi 4 Model B* (2GB RAM) that serves as the main computing device responsible for data processing and communication;
- Remote Unit 1, composed of an *Arduino MKR WiFi 1010* and an *MKR IMU Shield* that provides orientation, acceleration, and angular velocity data;
- Remote Unit 2, composed of another *Arduino MKR WiFi 1010* and an *MKR GPS Shield* that offers precise geolocation data for speed and trajectory tracking;
- The Battery Pack (2S Configuration), composed of 8 18650 lithium-ion cells providing a nominal voltage of 7.4V. which is described in section 1.6.1.;

2.6.2. Anemometer

The anemometer unit will be custom-built and is based on a cup-and-vane configuration. The physical elements are in-house 3D designed and printed, while the electronics components are:

- A Hall Effect Sensors to detect the rotation of the cups element and therefore measure wind speed;
- An AS5600 Position Sensor to determine the vane position and thus read the wind direction;
- An *Arduino MKR WiFi 1010* to handle data acquisition and transmit processed information to the central unit via Wi-Fi;
- A Lithium Polymer Battery to supply power to the *Arduino* board;

2.7. Innovative Elements

2.7.1. Modified foil moulds

This year, probably the most important design objective has been the new foils. For this reason, we knew from the start that new moulds were inevitable, but having made the LCA calculations and seeing the environmental impact of the brand-new moulds of the previous years we quickly realized that a solution needed to be found. Thanks to a joined effort between the LCA and design department, starting from the original moulds, geometric constraint were set to find a geometry that satisfied the performance requirements, all while allowing for the possibility to re-machine the already existing aluminum, thus saving around 20h of machining time and 33Kg of new material.

For the vertical moulds, no changes were made to the profile shape but only on the thickness distribution to better the mechanical properties, thus saving all the resin escape channels and bolt housings.

For clarity of explanation a render of the modified areas in both MF and RF verticals is provided.

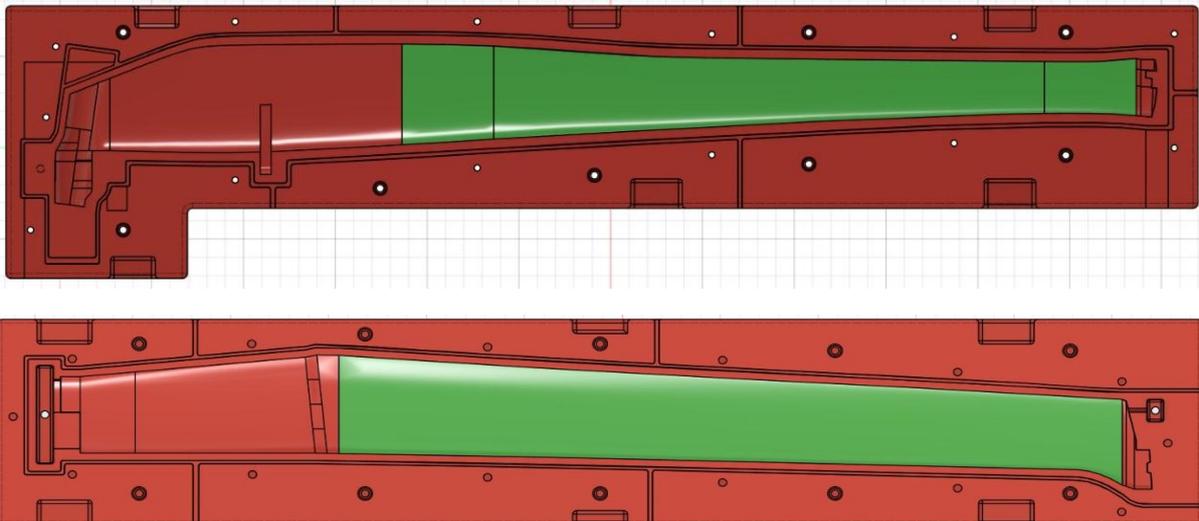


Figure 5: MF and RF verticals moulds rendering

As for the horizontal moulds, since the planned shape needed freedom to change to better fit the new required performance, geometrical constrains such as leading and trailing edge distance from several bolt housings or bulb height have been set.

This proved to be not as straight forward as we thought, but we feel the effort we put in this aspect of the design will give us the leverage to save the moulds, all while obtaining great performances. We feel that this demonstrates how when designing new components, with small but important considerations you can save a piece of equipment which would have otherwise become obsolete, giving it new life.

2.7.2. Sail materials

As previously seen in our sailplan in paragraphs [1.5.1.](#) and [2.5.](#), our sailbuilding approach relies onto upcycled parts. With the foresaid approach we're not just building a sail, we're challenging the industry to find a cheaper, more sustainable and more reliable solution.

2.7.3. Wood fiber foil reinforcement

As we go towards a more sustainable option for high performance racing, it is imperative to keep up with the latest innovations in the composite materials market. That's why we were lucky enough to visit the *JEC WORLD 2025* in Paris, an internal exposition where, among others, we were able to get in touch with [Freshape](#), a company which produces *HiWood*. Fully bio-based, completely degradable, and recyclable, *HiWood* is an eco-friendly natural reinforcement for manufacturing lightweight composites. Benefiting from a unique paper form, *HiWood* composites can reach up to 92 vol.% reinforcement providing a highly effective sustainable solution. With 45GPa tensile strength and a 1.3g/cm³ density, *HiWood* reinforced composites are not only lighter than most structural materials, such as fiberglass, aluminum and steel, but also offer outstanding performance, positioning *HiWood* as an innovative choice for the next generation of lightweight materials.

2.7.4. Completely upcycled internal structures

As previously seen in the internal structures paragraph ([2.3.](#)), all the internal structures won't be off-the shelf parts or created from scratch. On the contrary they'll be cut out from our first flax infused skiff Lina. Its deck, designed to support the aggressive steps of two 70kg crew members, was sturdy enough to be upcycled into the bulkheads and keelsons of our latest project.

2.7.5. Cylindrical slot flap mechanism

The traditional hole with a threaded screw and corresponding nut has been eliminated in favor of a cylindrical slot mechanism. This innovative design allows for rotational movement at the locking point, preventing component loss while simultaneously enhancing the fluidity and responsiveness of the system during flight. By reducing mechanical friction and minimizing structural play, this solution improves both reliability and aerodynamic efficiency, leading to a more stable and high-performance hydrofoil experience.

3. SUSTAINABILITY

In this SuMoth Challenge's edition we decided to also bring a completely new moth. In order to develop a new moth which ensures the best sailing performance and guarantees the minimum environmental footprint as well, we have been very careful in the search for new sustainable solutions. As requested by the guidelines, we will describe all the components the boat will be made of.

This year we're also introducing some electronic components such as the *GPS*, the *anemometer* and the *flight control*. These components, along with the plastic box and pipes that contain them, will not be part of the lifecycle approach as it exceeds the scope of the study; particularly, since the electronic components have been bought, we are not able to consider the full lifecycle of the materials they are made off. Also, the cited components will be used for many years to come since they are not foreseen to deteriorate quickly over time and the plastic electric containers are fully reusable in many other contexts. We will however take account of the material used to accommodate this electronic equipment such as the internal structures added to provide support.

3.1. Concept Lifecycle Approach

We will analyse now the lifecycle plans of each element of the new moth from a qualitatively point of view. Taking most of the experience from the last years, we have now the opportunity to create a brand-new boat trying to maximize the performance and to minimize the environmental impact.

When working with composites materials, the main challenge is to find a solution for the disposal of the various parts produced during the construction, in particular the infused fibers. From what we have learnt thanks to the research conducted on the same topic for BFL, we weren't able to find an affordably achievable method to separate the fibers from the resin.

Realizing that we couldn't completely solve the problem, we tried our best to find an alternative way to reduce to a minimum the waste, trying to give a second life to old parts of infused fibers left from past projects, reusing them in the new boat.

If a material is no longer suitable for its purpose, due to structural issues or for its design, we came up with the idea of cutting out the old composite parts, repurpose them as needed and reuse them as secondary or minor parts of the boat. This is because we want to keep the materials in use as long as possible and are strongly convinced that, even if their primary use cannot be accomplished, it could have a second usage or more in the future. This idea of adapting and modifying solves the issue of a specific problem that cannot be solved directly due to the lack of economic resources. Of course, this type of approach reaches a terminal point at once: the material is not up-cyclable anymore and has to be dismantled. As for the results we carried out from the simulations on *Marineshift360*, it is better to incinerate composites materials rather than put them in a landfill, so that they give back at least some amount of energy, to be more precise thermal energy.

As for the other parts of the boat, all the wooden ones, such as the hull mould, the MDF mould components, will be completely recycled for future applications thanks to the fact that wood is highly recyclable and can be reused endlessly without losing structural integrity.

Moreover, all the metallic components, such as screws and bolts used for the assemblage of the mould can be reused if not broken. In this last situation, they can be fused together to obtain some liquid metal that can be reshaped.

We will surely use some 3D printed plastic parts, consequently our idea for their lifecycle is to use PLA, a bio-based plastic that comes from either sugar cane or corn starch. Additionally, it's widely recycled through a process that involves PLA waste being shredded or ground into smaller particles to re-extrude it into new filament or to obtain pellets that can be used again for 3D printing. This process cannot be done directly by our team, but we already found local companies that can do it for us.

Lastly, as for the sails, we have decided to pursue the idea of up-cycling materials in order to reuse old dismantled sails and scrap parts to make a new performing and competitive one.

3.2. Boat elements

In this paragraph we describe qualitatively the intended build and repair methods of the several elements of the boat in terms of environmental impact. Please note that the design and construction phases are still in progress, so we will describe the materials and the techniques that are planned to be used as of this moment. If there will be any changes to the final design, these will be highlighted in the S2 report.

3.2.1. Hull

On this Moth we decided to experiment with a different material composition in the construction of the hull. Its structure does not contain a foam core, but it is purely made of infused flax twill and UD fibers. Besides, in parts that are most stressed mechanically, an additional layer of basalt fiber will be added in the laminated product to ensure the structural integrity of the hull.

The team is currently testing samples of infused [HiWood Fiber Paper](#), which is an extremely thin sheet of wood that behaves as a UD fiber and is suitable for various types of low-pressure infusion processes, including the VARTM procedure we use. This material could be used to further reinforce the hull, or in substitution of basalt fibers, given its exceptional mechanical properties. The upside of wood compared to glass, flax or other fibers is the ease in its production, and, moreover, it is 100% biodegradable and recyclable. In addition, being solely made out of wood, like flax, it has a negative carbon footprint.

3.2.1. Hull Mould

This year our design department has renovated the structure of the hull mould: it is engineered to manufacture both the hull and the deck thanks to its versatile design, producing a symmetrical boat structure. This manufacture choice is quite interesting in the boat building industry, as it diminishes significantly the amount of material needed in the process overall, sparing the construction of a second mould in its whole. The mould itself is divided into two halves, symmetrical on a vertical plane, made up of a solid wooden structure. In the technique of strip planking, the hull shape is given by the layup of several wooden planks; this allows us to modulate and discompose the whole frame with minimum waste. The only parts that cannot be recycled are the putty and the gelcoat applied on the outmost surface to obtain a smooth finish. They can still be separated from the wood assembly and differently disposed to preserve the other reusable components.

3.2.2. Wings

As for the wings, they will have a simple design, featuring a straight geometry rather than a sinusoidal profile. This choice has been made because S-shaped wings need a specific mould to be constructed and demand a lot of refinement work, resulting in a considerable amount of material disposal. The beams of the wings will be constructed with a homemade mould composed of recycled carbon, while the beams themselves will be derived from basalt and carbon with an elliptical section. Although basalt has a higher environmental impact, we have chosen it for its superior mechanical properties, which have been proven to be far more notable.

Regarding the design of the central panel, we are still choosing between a sandwich structure of core and flax twill treated with vacuum infusion, or an aluminum honeycomb with a ply of basalt. This last idea would have better mechanical characteristics but a way bigger environmental impact than the sandwich concept.

3.2.3. Internal structures

For the material composition of the internal structures the team was faced with different options. The first being the use of an aluminium honeycomb structured panel: its mechanical properties are excellent as it provides great support for the hull structure while still being very lightweight for a metal. It is also 100% recyclable for future uses, but we need to take account that this step is relatively energy consuming. The other option was to cut the internal structures profiles out of the old deck of Lina, our first skiff, made from FF based composite materials, which even at first sight seemed to be a more sustainable choice seeing that it comes from an EoL process.

After the mechanical tests were conducted by the design department to compare the two alternatives, it was evicted that both materials outperform the benchmark set to ensure structural integrity. Therefore, none of them is predicted to fail their purpose and is suitable for the aim. The other simulation run by the LCA team (conducted using *Marineshif360*), on the other hand, showed a significant

difference on their environmental impact. The manufacture of an aluminum honeycomb structure is estimated to release three times more kg of CO₂ than a natural fiber sandwich, which is definitely not negligible. Therefore the team pushed for the most ecofriendly option; it counts as “Material Reused”, it is upcycled, and can be reused in the future as well. This choice also brings additional upsides, as the economic savings both in physical money and SM\$.

3.2.4. Foils and verticals moulds

To re-shape the new foils, the team has carefully designed a new mould structure with exceptional properties: we pushed sustainability to the limit, taking an old and obsolete aluminum mould, shaped into a new performing silhouette. This action is significantly pertinent to a sustainable shift in boat building techniques for several reasons. Firstly, it prevents a whole metal component to be entirely dismissed, avoiding the waste of energy needed to bring aluminum to its melting point. In a second place we can also state that reusing an old mould, which already has a similar shape that only needs minimal processing, averts the production of several tens of kilograms of virgin aluminum from scratch. Again, there is saving of materials, costs, energy, transport fuel and restraint of various environmental impacts, ranging from CO₂ emissions to mineral resource scarcity. In addition to all these motivations, we would like to bring to the attention to the excellent recyclability of aluminum as well, which can be entirely reused at 100% and is included in our EoL programme. This property should not be overlooked, as it does not belong to most building and construction materials.

3.2.5. Foils and Verticals

The foils and verticals construction will be significantly updated for this year’s challenge. An important step is represented by the transition to FFRP and CFRP. This allows for a better performing final product, but also means that the construction process is less subject to create waste and excess materials, a key aspect which we needed to improve on, compared with the hand layup system we used in the previous editions.

3.2.3. Transport

To transport the boat from our shipyard in Trieste, Italy to the competition location at *Fraglia Vela Malcesine*, we’re using a van with a trailer. The overall weight of the two combined is estimated at a maximum of 3.5 tons. The overall distance is of 350 km. As we did last year, we set a proportionate number of kilometers traveled to balance the weight disparity on the *MarineShift360* default transport system.

3.3. Actions for a Sustainable Future

As environmental concerns grow, we continue to seek solutions to pursue our main goal: combining performance sailing with a minimized ecological footprint. We address this challenge through a shift towards circular economy principles, ensuring that research, repair and recycling are always considered in every decision we make.

It is essential for us to keep up with the latest scientific research on sustainable materials suitable for boat construction, particularly regarding their CO2 emissions. To reduce greenhouse gas emissions and decrease reliance on fossil fuels, we prioritise the use of natural fibers, for that matter, we discovered, already in the previous years, a fine compromise with the good mechanical properties of flax and its very low impact. Another important feature is the transition to bio-based composites, such as the 30% biobased resin we employ in infusion and lamination processes from a few years on.

This year we also introduced the use of basalt fiber, since, compared to glass fiber - which has almost the same mechanical properties - it is considered a more sustainable choice. In fact, during its production there is no dispersion of gases and dusts.

Beyond materials, to reduce human-created pollution and strive for a more sustainable future, it is essential to always consider more efficient manufacturing processes, that allow the minimization of waste and the reuse of excess materials. An example of such an approach is the use of the *Laminate Tools* software, which ensures that no material gets wasted, by strategically laying out patterns that optimise the cutting process and maximise the yield from each piece of available material while minimizing leftovers. This applies to the cut of the fibers in every component that requires them, for example in the hull and the foil.

One of the most innovative industrial applications showcased in this new moth is the design of the hull mould. We created a modular mould structure, divided into two symmetrical halves, so that it can be adjusted and refitted to accommodate different design requirements. By using wooden planks, it is possible to easily modify and disassembly the mould with minimal waste, enhancing the sustainability of the process. This adaptability makes the mould a sustainable solution, as it can be adjusted to meet different design needs without requiring the creation of entirely new moulds. Additionally, the mould's efficiency goes beyond just material savings, as it can be used for both the upper and lower parts of the boat. We understand this second practice we listed might not be implemented in large scale boat building industries, as the design and the look of the boat is highly impacting on product sales and is therefore not sacrificial. Also important in the process is the choice of the technical partners one works with. For example, all of the wood necessary for the hull's mould was CNC milled by a company ([Fornasariq - Tiemmeset SRL](#)), which work was entirely powered by 90KW of solar power.

Additionally, it is important to focus on optimizing the design to reduce the operating time of machinery or transportation. This is a crucial factor to consider, as it consents to lower both the energy consumption and the use of fossil fuels.

As long-distance shipping significantly increases carbon emissions. Whenever possible, we source materials from local suppliers: for instance, *Armare Ropes*, *Polarwave*, *Olimpic Sails* and *Corso Colori* are all based nearby Trieste, allowing us to reduce transportation distances.



Because the industry settings are very different from our small shipyard, we take note that some of the upcycling practices we use might not be applicable on a larger scale factory. A few examples could be re-using pieces of infused fibers or old carbon tubes coming from other companies that would be otherwise thrown away, giving them a new life as structural components in our moths. It is highly unlikely that a company producing thousands of boats could acquire a large number of secondhand components with the same dimensions, shape, and most importantly, structural integrity. Also, there is regulation on the practices allowed for a company to sell new boats, and this might not include the upcycling of secondhand materials as their first use might have altered their properties.

Similarly, another practice with great industrial potential is the upcycling of old sails. This year we decided to take a completely new approach to prove that reformed materials can still meet high-performance standards: instead of designing and producing new sails, we chose to repurpose unused and outdated ones. Thanks to this practice it is possible to give a second life to high-quality materials that would otherwise go to waste.

On the other hand, we believe that some procedures might still be applicable to large-scale production. For example, we highly recommend the transition from glass fiber to flax. This would be an innovation in the industrial sector, and it would require almost no new equipment as the manufacturing would not change at all. We recognize that it is a little more expensive than glass fiber, given that it holds position as the go-to material in boat building, but in our opinion, it represents the easiest way to reach a more sustainable approach. Audace Sailing Team will always be an ambassador of FF, which we found to be a perfect combination of mechanical performance, workability, and eco-sustainability.

4. TEAM SHOWCASE

4.1. Team members

The Audace Sailing Team was founded in 2019 by a group of naval engineering students driven by a shared ambition: to merge their passion for sailing with the technical knowledge gained during their studies. What started as a project focused on sustainable boat design and construction soon grew into something much bigger: a multidisciplinary initiative where students from various fields work together, united by their love for the sea and commitment to sustainability.

The year 2024 marked a turning point for the team. With five years of experience in designing and building skiffs and a moth, Audace took on a new challenge: constructing a second moth, using sustainable materials, applying the expertise developed from their first attempt to create something that could show the sailing industry what can be achieved respecting the earth.

The team's reputation within the university has grown significantly, attracting an increasing number of students each year. Today, Audace boasts a team of seventy active members, ensuring a continuous exchange of knowledge and ideas. Learning and sharing the knowledge between older and younger members has become a key pillar of the project, not only benefiting naval engineering students but also involving participants from other disciplines who gain valuable interdisciplinary skills.

Beyond the technical aspects, being part of Audace fosters the development of essential soft skills. Teamwork strengthens friendships and a sense of camaraderie, while participation in events and conferences provides opportunities to refine communication and networking abilities: an invaluable complement to the hands-on technical experience acquired within the team.

At the start of this year, Audace underwent a major internal restructuring. As senior members prepared to graduate, a new wave of students brought fresh energy to the team. While this turnover was a sign of growth, it also required careful reorganization to ensure smooth operations.

In line with our objectives for the year the first few months were dedicated to intensive training sessions. These covered a wide range of topics, from sailing techniques and moth dynamics to software applications for design modifications and the mechanical properties of different materials. Following this, the team shifted its focus to researching innovative materials and optimization strategies, aiming to achieve the best balance between sustainability, durability, and performance.

To enhance efficiency, the team adopted a more structured organizational model, dividing responsibilities among specialized groups. The core departments include design, construction, LCA and materials, crew, marketing & communication. Among these, the design department is the most complex, structured into six

subgroups: architecture, foil dynamics, velocity prediction (VPP), CAD modeling, structural analysis, sensors and production. Meanwhile, the marketing and communication team works in close synergy to maintain strong relationships with stakeholders and sponsors. Effective coordination between all departments is crucial, reinforced by weekly meetings to align schedules, track progress, and meet deadlines efficiently.

4.2. Sponsors

Since its inception, sponsorship has been a fundamental pillar of Audace. Support from sponsors has enabled every aspect of our work, from boat construction to participation in international competitions. Over the years, our collaboration with the university has strengthened, providing crucial financial backing and access to essential infrastructure.

To secure additional funding and long-term sustainability, we have also sought private investment, structuring sponsorships into different tiers. Our partners were selected not only based on financial support but also on their alignment with our core values of sustainability and high performance. Today, our sponsor network includes five levels:

- **Main sponsor** – *BAI* (Broker Assicurativo Italiano)
- **Golden sponsors** – *Esteco, Intesa Sanpaolo*
- **Silver sponsor**
- **Sponsors**
- **Supporters**

A key factor in choosing our sponsors was the desire to work with local companies that could help us pursue an eco-friendlier approach. For instance, instead of purchasing a new sail, we partnered with *Olympic Sails*, a company based in Trieste, which helped us repurpose an older sail, giving it a second life. When it came to fittings such as pulleys, we turned to *Polar Wave*, a Slovenian company specializing in metal components like foil end fittings. Similarly, for the paint and resin used in our moth's construction, we collaborated with *Corso Colori*, another Trieste-based company, alongside *Triaschem*, which provided us with the necessary materials while staying true to our sustainability goals. One of the only exceptions to our local sourcing approach is *XM Tech*, based in Vicenza, which supplies us with the foil moulds. Despite the distance, their expertise in the field made them the best possible choice, ensuring top-quality results for our project.

4.3. Acknowledgments

Throughout this year, the contribution of every team member has been essential. Thanks to the guidance and coordination of our leaders, each person has been able to provide valuable support, contributing to the project's success. A special thank goes to some students who have stood out for their dedication and sense of duty, despite not holding key positions within the team:

- Riccardo Cantore: a member of the design department, for his consistent contributions;



- Zeno Tarlao: crew chief, provided not only technical help but guided the design department in the right direction;
- Nicholas Zupancich and Arianna Guacci: members of the marketing team, for their essential work into the production of the deliverables for the SuMoth;
- Luca Palazzi and Fabrizio Curci, who, despite not being in charge of the shipyard, efficiently managed the boat's work and provided valuable guidance to new team members;
- Lorenza Miani: the newest member of the LCA department, who, beyond her assigned role, has always very collaborative and despite the absence of previous experience has always been eager to learn.

Their dedication has been crucial to the growth and success of the project.

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6. APPENDICES

6.1. Figures

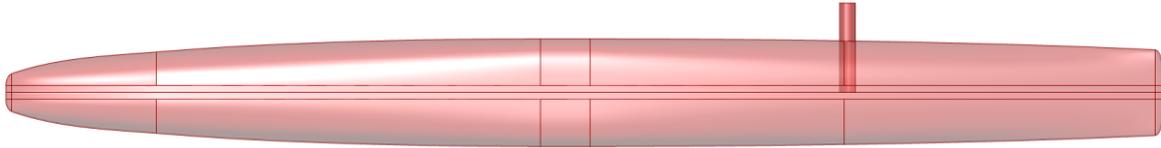


Figure 6: Grasshopper hull model

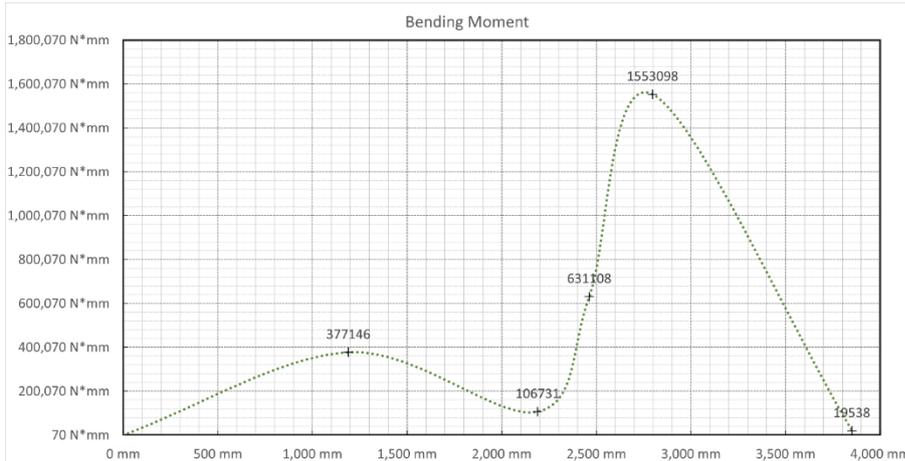


Figure 7: Bending moment graph

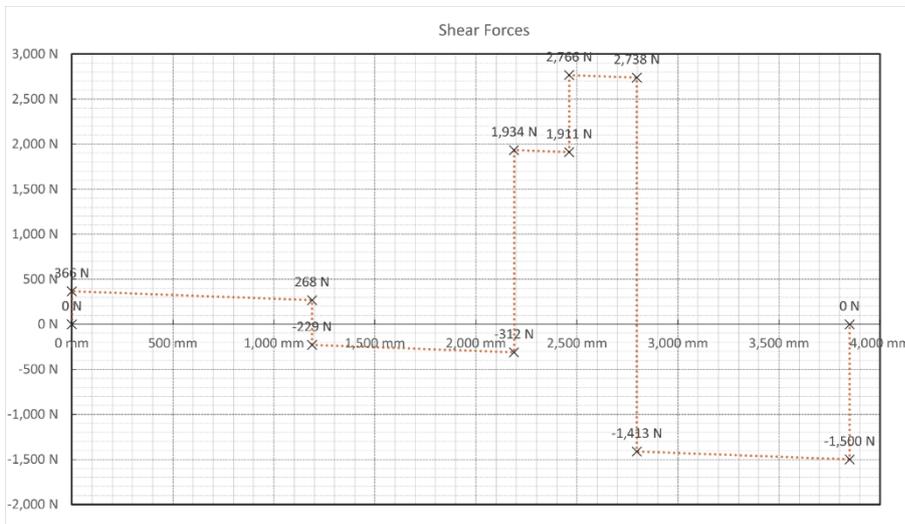


Figure 8: Shear forces graph

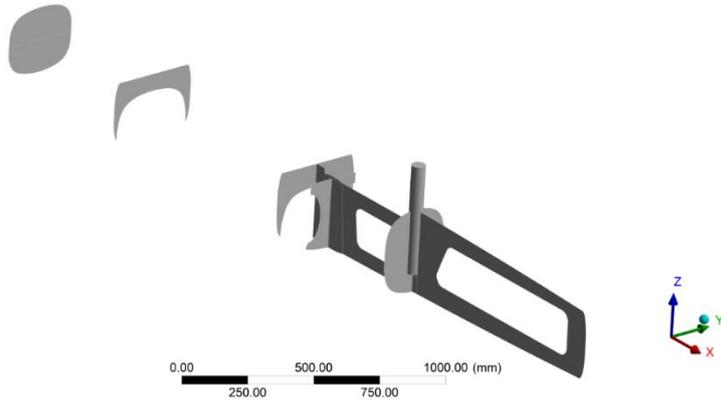


Figure 9: Internal structures rendering

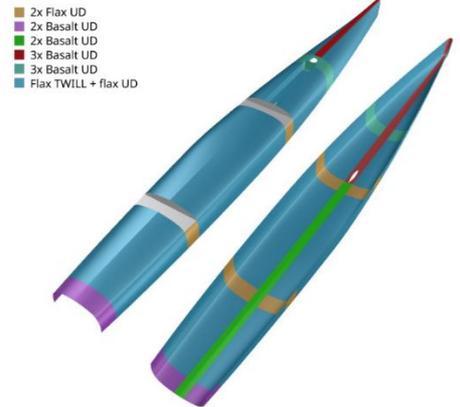


Figure 10: Fiber's layout

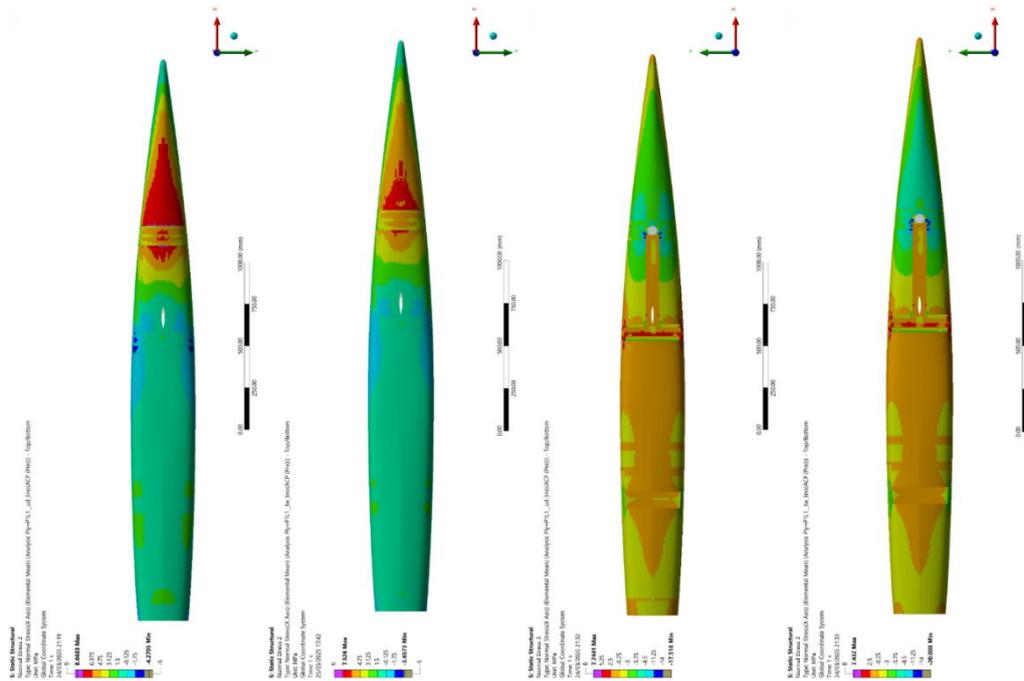


Figure 11: σ_x flax UD bottom ply; σ_x flax twill bottom ply; σ_x flax UD deck ply; σ_x flax twill deck ply

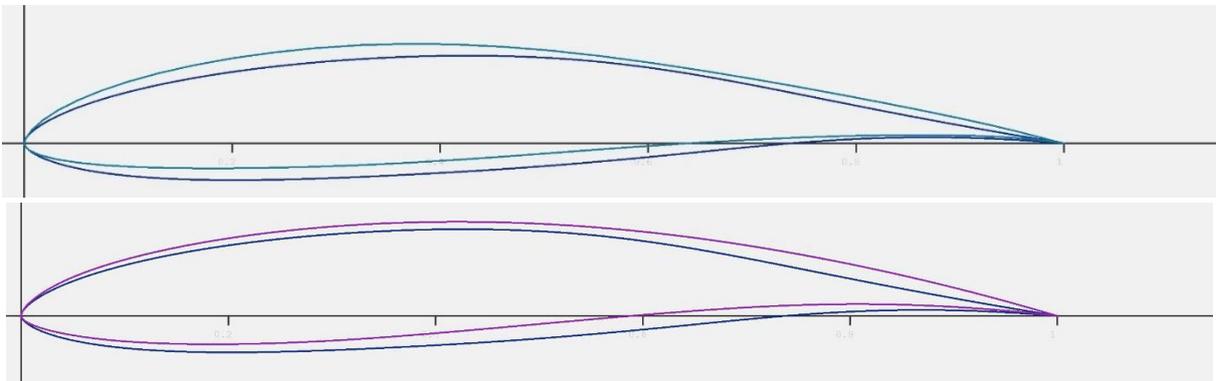


Figure 12: MF and RF airfoil shape compared to Eppler393 (previous airfoil)

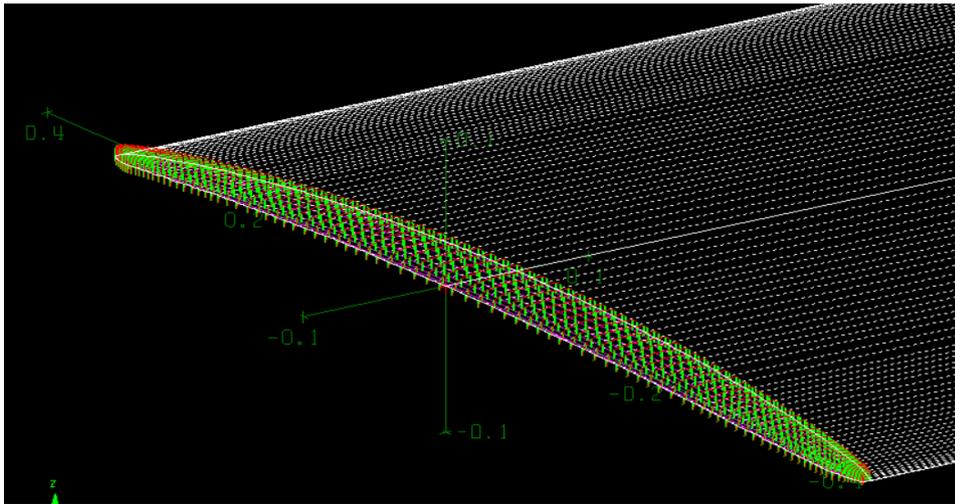


Figure 17: AVL geometry environment



Figure 13: Domain with $L=0,75$

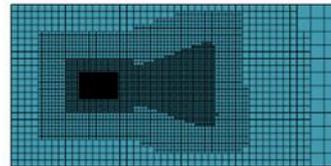


Figure 14: Domain with $L=1,5$

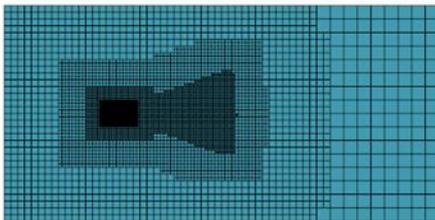


Figure 15: Domain with $L=2$ (our final choice)

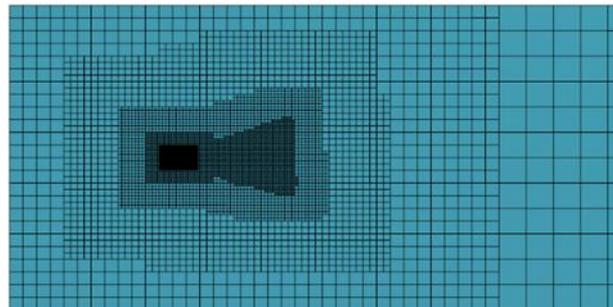


Figure 16: Domain with $L=3$

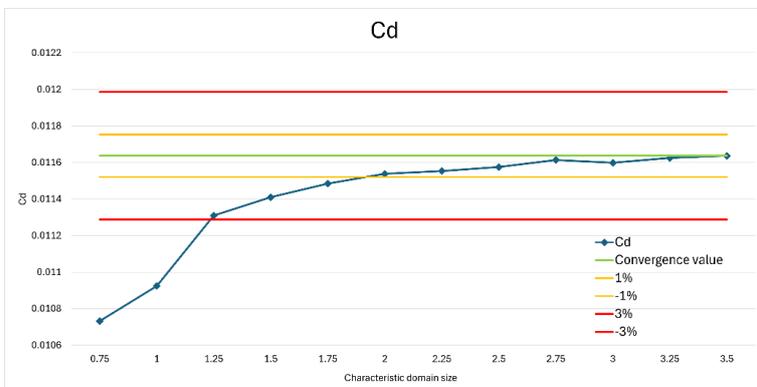


Figure 18: Cd domain independence results

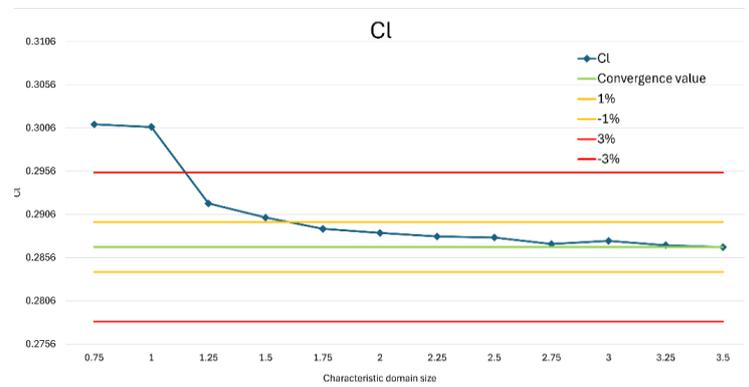


Figure 19: Cl domain independence results

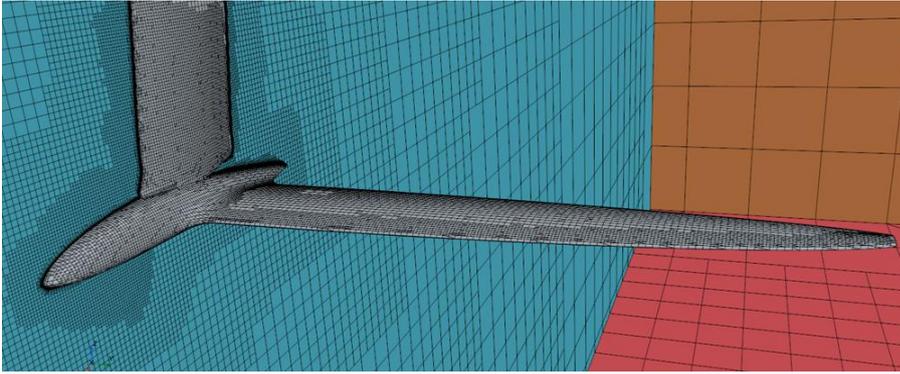


Figure 20: Mesh independence with L=7

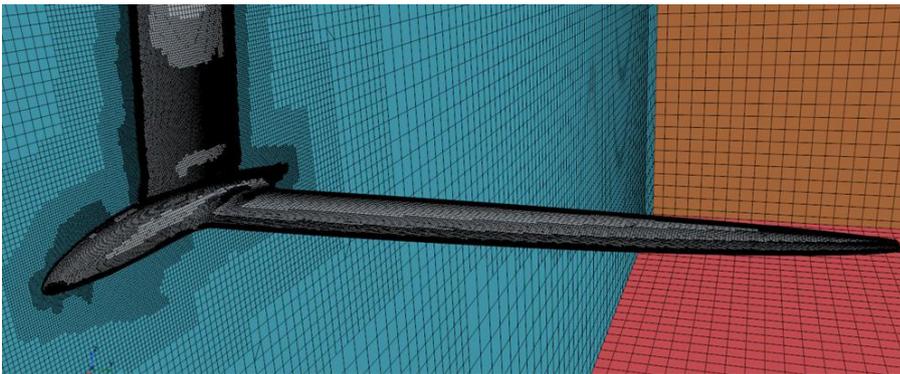


Figure 21: Mesh independence with L=1

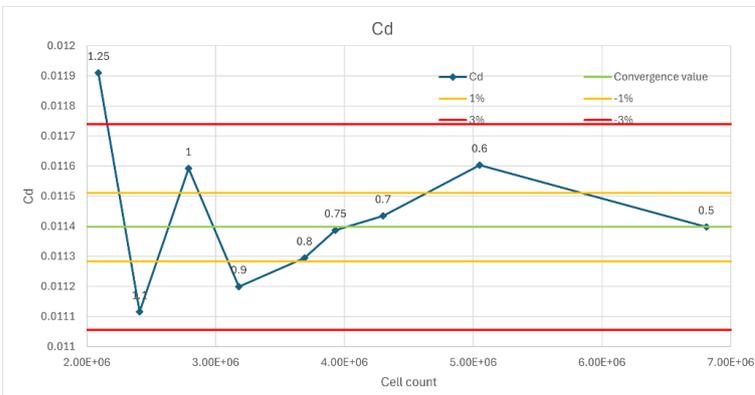


Figure 22: Cd mesh independence results

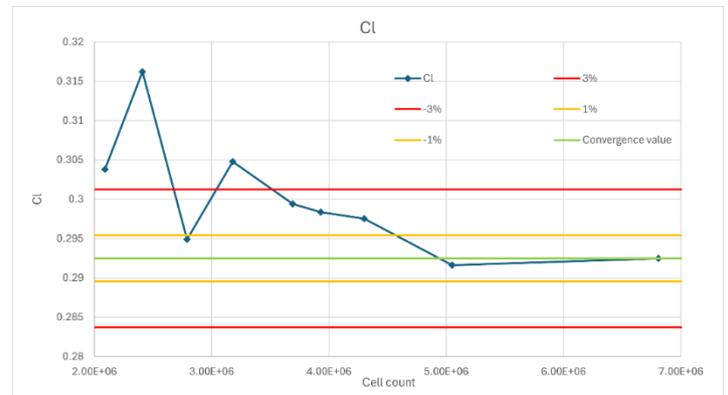


Figure 23: Cl mesh independence results

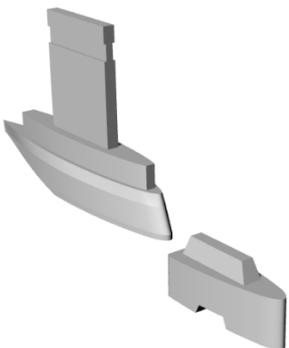


Figure 24: Vertical insert and joint

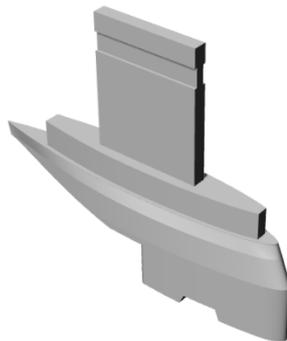


Figure 25: Vertical insert and joint coupling

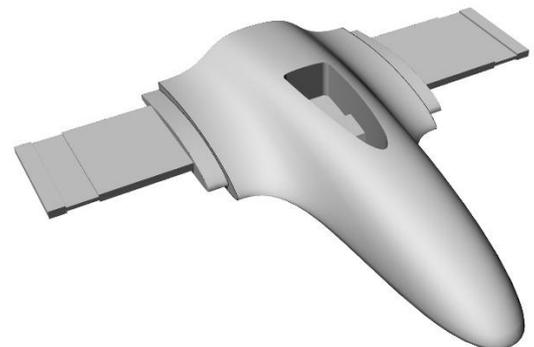


Figure 26: Foil insert coupling

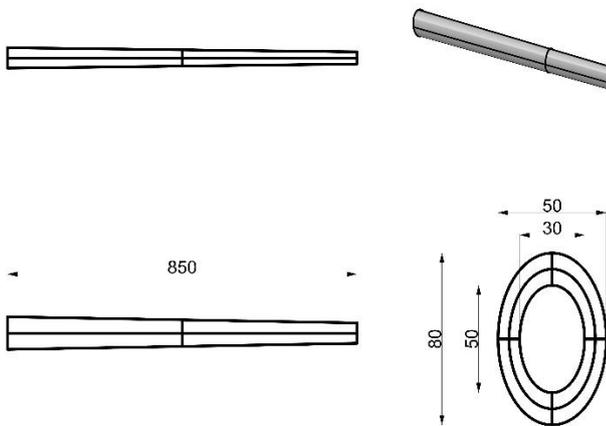


Figure 27: Wingbars projections and rendering

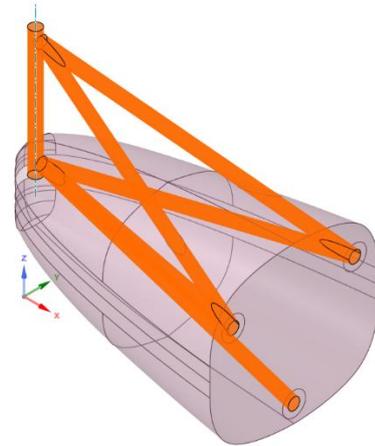


Figure 28: Gantry design rendering



Figure 29: BFL's Spreaders

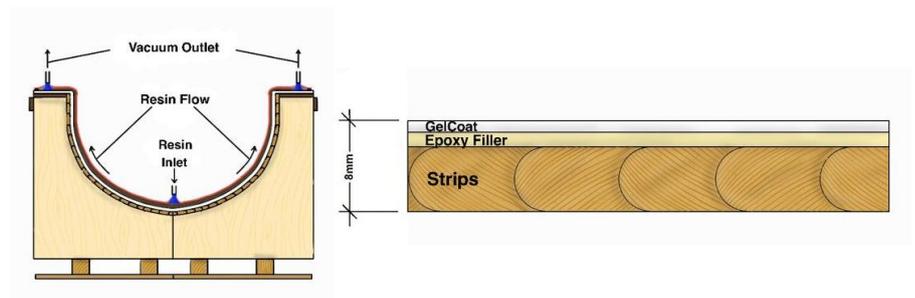


Figure 30: strip planking bead and cove mould and infusion technique sketches

6.2. Tables

	ID	RESISTANCE	STERN [mm]	LCB [mm]
MOGA-II	526	120,79	300,94	1824
	410	119,041	314,199	1699
	365	118,517	302,548	1832
	417	118,237	299,579	1849
	512	118,376	302,55	1843
	668	118,504	305,499	1840
	738	118,399	302,548	1839
	771	120,116	300,086	1892
	386	118,286	308,845	1762
	381	117,273	296,628	1831
	755	118,231	298,683	1820
	757	118,903	306,58	1795
	764	118,459	295,125	1809
SIMPLEX	45	117,916	302,227	1863
BFGS	625	116,673	302,638	1837

Table 1: Hull optimization best results

FORCE	[N]	lever [mm]
Hull weight	-278.282	0
Wing's weight	-196.132	1107.04
Crew weight	-784.528	1750.6
Main foil	1009.318	2108.05
Rudder foil	171.171	2108.05
Shrouds	2533.300	2225.83
Forestay	-4151.000	2715.83
Mast	1500	3768.83
Torque sail-foil resistance	115	1625.54

Table 2: Load case forces

		Analytic result [N*mm]	Ansys result [N*mm]	Δ [%]	Δ [N*mm]
crew coefficient	0,6	1,62E+05	1,83E+05	12,61	20467,38
lift coefficient	0,74				
crew coefficient	0,6	1,36E+05	1,57E+05	15,02	20443,06
lift coefficient	0,75				
crew coefficient	0,6	1,10E+05	1,30E+05	18,6	20418,74
lift coefficient	0,76				
crew coefficient	0,6	8,35E+04	1,04E+05	24,43	20404,42
lift coefficient	0,77				
crew coefficient	0,6	5,72E+04	7,76E+04	35,61	20385,11
lift coefficient	0,78				
crew coefficient	0,6	3,10E+04	5,13E+04	65,75	20365,79
lift coefficient	0,79				
crew coefficient	0,6	4,70E+03	2,50E+04	433,02	20345,47
lift coefficient	0,8				
crew coefficient	0,6	-2,16E+04	-1,25E+03	-94,2	20326,45
lift coefficient	0,81				
crew coefficient	0,6	-4,79E+04	-2,75E+04	-42,44	20306,83
lift coefficient	0,82				
crew coefficient	0,6	-7,41E+04	-5,38E+04	-27,37	20287,51
lift coefficient	0,83				
crew coefficient	0,6	-1,00E+05	-8,01E+04	-20,19	20268,19
lift coefficient	0,84				
crew coefficient	0,6	-1,27E+05	-1,06E+05	-15,99	20249,87
lift coefficient	0,85				
crew coefficient	0,6	-2,58E+05	-2,38E+05	-7,81	20148,27
lift coefficient	0,9				
crew coefficient	0,55	-1,66E+05	-1,46E+05	-12,23	20295,89
lift coefficient	0,85				

Table 3: Numerical FEM model with analytical calculations

Design Study												
L	0,75	1	1,25	1,5	1,75	2	2,25	2,5	2,75	3	3,25	3,5
Drag	58,5687	59,6174	61,7223	62,2717	62,6738	62,9697	63,0531	63,169	63,3803	63,2962	63,4423	63,5051
Cd	0,0107321	0,010924	0,01131	0,011411	0,011484	0,011539	0,011554	0,011575	0,011614	0,011598	0,011625	0,011637
Cd fin	0,0116366	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637
-3%	0,0112875	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288	0,011288
3%	0,0119857	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986	0,011986
-1%	0,0115202	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152	0,01152
1%	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753	0,011753
Design Study												
Lift	1642,75	1641,07	1592,79	1583,86	1576,72	1574,18	1571,97	1571,27	1567,15	1569,13	1566,36	1565,24
Cl	0,3010158	0,300708	0,291861	0,290225	0,288917	0,288451	0,288046	0,287918	0,287163	0,287526	0,287018	0,286813
Cl fin	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813	0,286813
-3%	0,2782086	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209	0,278209
3%	0,2954174	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417	0,295417
-1%	0,2839449	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945	0,283945
1%	0,2896811	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681	0,289681

Table 4: Domain independence results

Design Study										
Base Size	[-]	0.5	0.6	0.7	0.75	0.8	0.9	1	1.1	1.25
Cell count	[-]	6810000	5050000	4300000	3930000	3690000	3180000	2790000	2410000	2090000
Tempo totale	hr	9.85	5.46	4.59	5.36	3.88	3.28	3.8	2.56	2.85
Drag	N	62.1988	63.3235	62.4004	62.1415	61.638	61.1184	63.2612	60.6595	64.9959
Cd	[-]	0.01139725	0.011603334	0.011434	0.01138675	0.011294	0.011199	0.01159192	0.011115	0.01191
Lift	N	1596.15	1591.48	1623.71	1628.26	1633.91	1663.33	1609.35	1725.62	1657.93
Cl	[-]	0.29247691	0.291621186	0.297527	0.29836072	0.299396	0.304787	0.29489567	0.316201	0.303797

Table 5: Mesh independence results

	E_1 [GPa]		E_1 [GPa]
	stress range [1-1.5MPa]		stress range [1-1.5MPa]
UD1_150	6,12534	TW1_150	8,36206
UD1_150	7,58471	TW1_150	8,41508
UD2_150	7,29419	TW2_150	8,4378
UD2_150	7,35518	TW2_150	8,58791
UD3_100	8,32147	TW3_100	8,27671
UD3_100	8,86702	TW3_100	8,1933
UD2_100	6,25347	TW4_100	8,42686
UD2_100	6,47829	TW4_100	8,24127
mean	7,28495875	mean	8,36762375
median	7,324685	median	8,38857
rot mean square	0,980636789	rot mean square	0,12753827
mean - 2sigma	5,323685172	mean - 2sigma	8,11254721

Table 6: Test campaign results

PART NAME:		MATERIAL SAMPLES										
Substacks	REINFORCEMENT	Density	Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT	Mass (g)	TOTAL	TOTAL	
	MATRIX											SQM
A	FLAX	1.3 g/cm ³	0.25	6	300	INFUSION	45%	48.0%	450	32%	67%	
	EPOXY	1.15 g/cm ³						52.0%	487	35%		
B	FLAX	1.3 g/cm ³	0.25	6	150	INFUSION	45%	48.0%	225	16%	33%	
	EPOXY	1.15 g/cm ³						52.0%	243	17%		
C	FLAX	1.3 g/cm ³	0	0	200	HAND LAY...	35%	37.8%	0	0%	0%	
	EPOXY	1.15 g/cm ³						62.2%	0	0%		
D	BASALT	2.9 g/cm ³	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
	THERMOPLASTIC	1.05 g/cm ³						40.2%	0	0%		
E	CARBON FIBER IM	1.77 g/cm ³	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
	EPOXY	1.15 g/cm ³						34.7%	0	0%		
									Total Composite (g)	1,405	g	
									Total Fibers (g)	675	g	
									Total Fibers (%)	48.05%		
									Total Resin (g)	730	g	
									Total Resin (%)	51.95%		

Table 7: material samples resin calculation sheets

MOULD		SM\$ expected cost	
		110,7	
Material	Cost per unit	Quantity	Cost
Std. Epoxy Lamination Resin	25	2,5	62,5
Wood Others	0	72	0
Steel All	10	1,5	15
Machining (CNC)	40	0,83	33,2

Table 8: Hull mould SM\$ cost expectation

HULL		SM\$ expected cost	
		205,3	
Material	Cost per unit	Quantity	Cost
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	150	0,14	21
Dry fabric glass fibers E Glass	25	0,1	2,5
Dry fabric Flax All	0	7,5	0
Bio-Based Epoxy Lamination	15	2,6	39
Wood Others	0	0,2	0
PET Standard	20	1,5	30
PET Recycled	0	1	0
PLA All	10	1	10
Machining (CNC)	40	2,07	82,8
3D printing	20	1	20

Table 9: Hull SM\$ cost expectation

PART NAME:		HULL										
Substacks	REINFORCEMENT	Density	Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT	Mass (g)	TOTAL	TOTAL	
	MATRIX											SQM
A	FLAX	1.3 g/cm3	3.5	2	300	INFUSION	45%	48.0%	2,100	42%	88%	
	EPOXY	1.15 g/cm3						52.0%	2,271	46%		
B	CARBON FIBER IM	1.77 g/cm3	0.5	1	340	INFUSION	45%	55.7%	170	3%	6%	
	EPOXY	1.15 g/cm3						44.3%	135	3%		
C	GLASS FIBER	2.6 g/cm3	0.75	1	200	HAND LAYUP	30%	49.2%	150	3%	6%	
	EPOXY	1.15 g/cm3						50.8%	155	3%		
D	BASALT	2.9 g/cm3	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
	THERMOPLASTIC	1.05 g/cm3						40.2%	0	0%		
E	CARBON FIBER IM	1.77 g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
	EPOXY	1.15 g/cm3						34.7%	0	0%		
									Total Composite (g)	4,980	g	
									Total Fibers (g)	2,420	g	
									Total Fibers (%)	48.59%		
									Total Resin (g)	2,560	g	
									Total Resin (%)	51.41%		

Table 10: Hull resin calculation sheet

WINGS		SM\$ expected cost	
		220,5	
Material	Cost per unit	Quantity	Cost
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	150	1,1	165
Dry fabric Flax All	0	1,388	0
Dry fabric Basalt Fibers All	0	0,5	0
Bio-Based Epoxy Lamination	15	3,5	52,5
Aluminum All	10	0,3	3

Table 11: Wings SM\$ cost expectation

PART NAME:		WINGBARS										
Substacks	REINFORCEMENT	Density	Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT	Mass (g)	TOTAL	TOTAL	
	MATRIX											SQM
A	CARBON FIBER IM	1.77 g/cm3	1.25	1	340	INFUSION	45%	55.7%	425	37%	66%	
	EPOXY	1.15 g/cm3						44.3%	337	29%		
B	FLAX	1.3 g/cm3	1.25	1	150	INFUSION	45%	48.0%	188	16%	34%	
	EPOXY	1.15 g/cm3						52.0%	203	18%		
C	BASALT	2.9 g/cm3	1.25	0	300	INFUSION	45%	67.4%	0	0%	0%	
	EPOXY	1.15 g/cm3						32.6%	0	0%		
D	BASALT	2.9 g/cm3	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
	THERMOPLASTIC	1.05 g/cm3						40.2%	0	0%		
E	CARBON FIBER IM	1.77 g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
	EPOXY	1.15 g/cm3						34.7%	0	0%		
									Total Composite (g)	1,153	g	
									Total Fibers (g)	613	g	
									Total Fibers (%)	53.14%		
									Total Resin (g)	540	g	
									Total Resin (%)	46.86%		

Table 12: Wingbars resin calculation sheet

PART NAME:		WING TRAMPOLINES											
Substacks	REINFORCEMENT	Density		Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT	Mass (g)	TOTAL	TOTAL	
	MATRIX	g/cm3	g/cm3	SQM	plies	g/sqm		Vol. Fract	FRACTION		PER ELEMENT	%	
A	CARBON FIBER IM EPOXY	1.77	g/cm3	2	1	340	INFUSION	45%	55.7%	680	15%	28%	
		1.15	g/cm3						44.3%	540	12%		
B	FLAX EPOXY	1.3	g/cm3	2	2	300	HAND LAY...	35%	37.8%	1,200	27%	72%	
		1.15	g/cm3						62.2%	1,971	45%		
C	FLAX EPOXY	1.3	g/cm3	0	0	200	HAND LAY...	35%	37.8%	0	0%	0%	
		1.15	g/cm3						62.2%	0	0%		
D	BASALT THERMOPLASTIC	2.9	g/cm3	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
		1.05	g/cm3						40.2%	0	0%		
E	CARBON FIBER IM EPOXY	1.77	g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
		1.15	g/cm3						34.7%	0	0%		
										Total Composite (g)	4,391	g	
										Total Fibers (g)	1,880	g	
										Total Fibers (%)	42.81%		
										Total Resin (g)	2,511	g	
										Total Resin (%)	57.19%		

Table 13: Wing trampolines resin calculation sheet

FOILS' MOULD		SM\$ expected cost		FOILS		SM\$ expected cost	
		810				475	
Material	Cost per unit	Quantity	Cost	Material	Cost per unit	Quantity	Cost
Aluminium	10	1	10	Dry fabric carbon fibers High Modulus CF (i.e. M40)	250	1,6	400
Machining (CNC)	40	20	800	Dry fabric Flax All	0	1,8	0
				Bio-Based Epoxy Lamination	15	5	75
				Wood UD fiber (HIWOOD)	undefined	undefined	

Table 14: Foils and foils' mould SM\$ cost expectation

PART NAME:		FOILS											
Substacks	REINFORCEMENT	Density		Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT	Mass (g)	TOTAL	TOTAL	
	MATRIX	g/cm3	g/cm3	SQM	plies	g/sqm		Vol. Fract	FRACTION		PER ELEMENT	%	
A	FLAX EPOXY	1.3	g/cm3	1	10	300	INFUSION	45%	48.0%	3,000	30%	63%	
		1.15	g/cm3						52.0%	3,244	33%		
B	CARBON FIBER IM EPOXY	1.77	g/cm3	1	6	340	INFUSION	45%	55.7%	2,040	21%	37%	
		1.15	g/cm3						44.3%	1,620	16%		
C	FLAX EPOXY	1.3	g/cm3	0	0	200	HAND LAY...	35%	37.8%	0	0%	0%	
		1.15	g/cm3						62.2%	0	0%		
D	BASALT THERMOPLASTIC	2.9	g/cm3	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
		1.05	g/cm3						40.2%	0	0%		
E	CARBON FIBER IM EPOXY	1.77	g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
		1.15	g/cm3						34.7%	0	0%		
										Total Composite (g)	9,904	g	
										Total Fibers (g)	5,040	g	
										Total Fibers (%)	50.89%		
										Total Resin (g)	4,864	g	
										Total Resin (%)	49.11%		

Table 15: Foil resin calculation sheet

MFCS		SM\$ expected cost	
		34,725	
Material	Cost per unit	Quantity	Cost
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	150	0,06	9
Dry fabric glass fibers E Glass	25	0,1	2,5
Bio-Based Epoxy Lamination	15	0,175	2,625
PLA All	10	0,06	0,6
3D printing	20	1	20

Table 16: MFCS SM\$ cost expectation

PART NAME:		MFCS										
Substacks	REINFORCEMENT	Density	Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT		TOTAL	TOTAL	
	MATRIX							Vol. Fract	FRACTION			Mass (g)
A	FLAX	1.3 g/cm3	0.25	1	340	HAND LAYUP	30%	32.8%	85	33%	100%	
	EPOXY	1.15 g/cm3						67.4%	175	67%		
B	FLAX	1.3 g/cm3	0	0	200	HAND LAY...	35%	37.8%	0	0%	0%	
	EPOXY	1.15 g/cm3						62.2%	0	0%		
C	FLAX	1.3 g/cm3	0	0	200	HAND LAY...	35%	37.8%	0	0%	0%	
	EPOXY	1.15 g/cm3						62.2%	0	0%		
D	BASALT	2.9 g/cm3	0	0	200	HAND LAY...	35%	59.8%	0	0%	0%	
	THERMOPLASTIC	1.05 g/cm3						40.2%	0	0%		
E	CARBON FIBER IM	1.77 g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
	EPOXY	1.15 g/cm3						34.7%	0	0%		
									Total Composite (g)	260	g	
									Total Fibers (g)	85	g	
									Total Fibers (%)	32.64%		
									Total Resin (g)	175	g	
									Total Resin (%)	67.36%		

Table 17: MFCS resin calculation sheet

GANTRY		SM\$ expected cost	
		26,93	
Material	Cost per unit	Quantity	Cost
Dry fabric Basalt Fibers All	0	0,3	0
Dry fabric Flax All	0	0,45	0
Bio-Based Epoxy Lamination	15	0,162	2,43
Tacky tape	8	0,5	4
Vacuum bag	2	3	6
PE vacuum hose	1	2	2
Peel ply	5	2,5	12,5

Table 18: Gantry SM\$ cost expectations

PART NAME:		GANTRY										
Substacks	REINFORCEMENT	Density	Ply area	Num. of	Area Weight	PROCESS	FIBER	WEIGHT		TOTAL	TOTAL	
	MATRIX							Vol. Fract	FRACTION			Mass (g)
A	FLAX	1.3 g/cm3	0.25	2	300	INFUSION	45%	48.0%	150	12%	26%	
	EPOXY	1.15 g/cm3						52.0%	162	13%		
B	BASALT	2.9 g/cm3	0.25	4	300	INFUSION	45%	67.4%	300	25%	37%	
	EPOXY	1.15 g/cm3						32.6%	145	12%		
C	FLAX	1.3 g/cm3	0.25	2	340	INFUSION	45%	48.0%	170	14%	29%	
	EPOXY	1.15 g/cm3						52.0%	184	15%		
D	GLASS FIBER	2.6 g/cm3	0.25	1	200	HAND LAY...	35%	54.9%	50	4%	8%	
	EPOXY	1.15 g/cm3						45.1%	41	3%		
E	CARBON FIBER IM	1.77 g/cm3	0	0	260	AUTOCLAVE	55%	65.3%	0	0%	0%	
	EPOXY	1.15 g/cm3						34.7%	0	0%		
									Total Composite (g)	1,202	g	
									Total Fibers (g)	670	g	
									Total Fibers (%)	55.72%		
									Total Resin (g)	532	g	
									Total Resin (%)	44.28%		

Table 19: Gantry resin calculation sheet