FOILING SuMoth CHALLENGE

AUDACE SAILING TEAM

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Foiling SuMoth Challenge Stage 1 - 2024

DESIGN, MANUFACTURING & SUSTAINABILITY

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Abstract

The combination of high dynamic loads, which are cyclically applied over time, high speeds, and the instability resulting from interaction with various types of fluids make Moth class boats extremely complex engineering objects. This complexity is further stressed when considering the need to respect sustainability parameters. This report brings together the analyses and solutions found to fix common structural problems in these sailing boats without affecting their performance. The Audace Sailing Team has looked at the issues with their latest boat, BAI - Flying Lina, to stop them happening again by making big changes. The results of this work can be summarized with a common underlying process: the use of a variety of engineered materials, supported by theoretical studies, and 1:1 scale simulations. This allows a significant improvement in performance under specific load conditions. This report therefore explores various design and construction aspects related to key elements of BAI-Flying Lina Moth, including wings, gantry, foils, and more. It is also presented the theoretical foundation for more sophisticated and comprehensive analyses through the development of codes, VPP (Velocity Prediction Program) analysis methods and fluidodynamic interactions on objects of various geometry shapes , such as foils. From this work emerges the BAI - Flying Lina 2.0.
Eco-sustainability is a key focus in our work, given its importance in the SuMoth Challenge, where we're evaluated for it. Ongoing material studies are conducted and Life Cycle Assessments to ensure minimal environmental impact from both materials and production processes.

Keywords

Audace Sailing Team ● SuMoth Challenge ● Sailing ● University
Foil ● Sustainability ● Flax fiber ● Moth ● Engineering ● Innovation

Contents

INTRODUCTION 1

1 ENGINEERING AND DESIGN 2
1.1 State of art . . . 2
1.2 Concept and goals . . . 3
1.3 Foils . . . 3
1.3.1 Introduction . . . 3
1.3.2 Foils . . . 4
1.3.3 Verticals . . . 8
1.4 Wings and rig . . . 8
1.4.1 Shape design . . . 9
1.4.2 The Hydrodynamic Study . . . 10
1.4.3 Structural Analysis . . . 11
1.4.4 FEM Analysis . . . 12
1.5 Gantry . . . 12
1.5.1 Tilting System . . . 13
1.5.2 Structures . . . 13
1.5.3 Fluid Dynamics Analysis . . . 14
1.6 Electronics . . . 16
1.6.1 Sailing data collection and analysis . . . 16
1.6.2 Flying control system . . . 16
1.7 VPP . . . 17
1.7.1 Goals . . . 17
1.7.2 Simplifying assumptions . . . 17
1.7.3 FS-Equilibrium . . . 19

2 MANUFACTURING AND COST ANALYSIS 20
2.1 General description . . . 20
2.2 Foils . . . 20
2.3 Wings . . . 20
2.4 Gantry . . . 21
2.5 New materials & mechanical test . . . 22
2.6 Cost analysis . . . 22

3 SUSTAINABILITY ANALYSIS 23
3.1 General description . . . 23
3.1.1 Functional unit . . . 23
3.1.2 Material inventory . . . 24
3.1.3 Design phase . . . 24
3.2 Boat and Elements Lifecycle . . . 25
3.3 Wings molds . . . 25
3.4 Wings . . . 26
3.5 Foils . . . 26
3.6 Foils molds . . . 26

3.7 Verticals molds 27
3.8 Main and rudder verticals 27
3.9 Gantry 27
3.10 Transport 27
3.11 Conclusions 27
3.12 Actions for a sustainable future 28

4 TEAM **29**
4.1 An overview 29
4.2 Our internal structure 30
4.3 Board of directors 30
4.4 Sponsors and marketing 30
4.4.1 Main sponsor 31
4.4.2 Golden sponsor 31
4.4.3 Silver sponsor 31
4.4.4 Sponsor 31
4.4.5 Supporter 32

References **33**

A MARINESHIFT360 LCA Study **A-1**
A.1 Introduction A-1
A.2 Goal of the study A-1
A.3 Scope of the study A-1
A.3.1 Functional Unit A-1
A.3.2 Assumptions and Limitations regarding the simulations A-1
A.4 BAI Flying Lina 2.0 - Life Cycle Assessment A-2
A.5 Global impact: the lifecycle of the refit project considering the boat components kept from last year A-3
A.6 Further comparisons and design choices A-5
A.6.1 Wings moulds A-5
A.6.2 Wings frame: comparison between reused material and PVC A-8
A.6.3 Foil A-8
A.6.4 Main and rudder verticals A-8
A.6.5 Rudder control A-9
A.6.6 Gantry A-9
A.7 Considerations on End of Life A-10

List of Figures

1.1 Workflow 2
1.2 First and last iterations 2
1.3 Hull layup and internal structures 3
1.4 Foils design process 8
1.5 Pre-take off performance with the old wings configuration 9
1.6 Comparison between the Mackay (Left) and Manta (Right) Moths 9
1.7 Profile of the New Wings 10
1.8 20° Heeling with old (left) and new (right) wings 10
1.9 Lift Generated by the wings with different longitudinal sections 10
1.10 Comparison of the trailing edge of the rectangular section profile (right) and the symmetrical profile (left) 11
1.11 Transversal beam cross section and internal panel 12
1.12 FEM simulation of the internal panel and external frame 12
1.13 cambia 13
1.14 Tubular structure 13
1.15 Preview of the closed surface around the gantry's structure 14
1.16 Comparison of the wake generated without (left) and with (right) the closed surface 14
1.17 Trimmed mesh for the free surface with special attention to the Kelvin Cone 14
1.18 Total Drag in the different configurations(left) and total Drag with Variable Displacement (right) 15
1.19 Wake generated in air without the gantry's closed surface (left) and with the gantry's closed surface (right) 15
1.20 Focus on the waves generated from the Stern without (left) and with the closed surface (right) of the gantry 15
1.21 Polar diagram generated by our code 18
2.1 Filler plies and shell lamination 20
2.2 Core placement and first fittings on the boat 21
2.3 Tubular structure with the lower part and closed gantry 21
4.1 Group picture 29
A.1 Global warming – fossil and Energy consumption – non-renewable A-3
A.2 Global Warming – fossil and Energy consumption - non-renewable A-4
A.3 Mineral resource scarcity and Energy consumption – renewable A-4
A.4 Water consumption and Global warming: non-fossil emissions of the whole refitting process of BAI Flying Lina 2.0 . . . . . A-4
A.5 Global warming – fossil and Energy consumption - non-renewable A-5
A.6 Mineral resource scarcity and Energy consumption – renewable A-6
A.7 Water consumption and Waste factor A-6
A.8 Marine eutrophication A-6
A.9 Global warming – fossil (wings moulds comparison) and Global warming - non-fossil (wings moulds comparison) A-7
A.10 Energy consumption – non-renewable (wings moulds comparison) and Energy consumption - renewable (wings moulds comparison) A-7
A.11 Marine eutrophication (wings moulds comparison) and Water consumption (wings mould comparison) A-7

A.12 Energy consumption – non-renewable (wings frame comparison) A-8
A.13 Global warming – fossil (wings frame comparison) and Marine eutrophication (wings frame comparison) A-9

List of Tables

1 Wings cost 22
2 Foils cost 22
3 Gantry cost 23
4 Rig cost 23

List of Abbreviations

IMCA	International Moth Class Association
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
GRP	Glass Reinforced Plastic
MDF	Medium Density Fibreboard
HDF	High Density Fibreboard
UD	Unidirectional
PET	Polyethylene Terephthalate
PVA	Polyvinyl Acetate
PVC	Polyvinyl Chloride
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CNC	Computerized numerical control
FEM	Finite Element Model
NURBS	Non-Uniform Rational Base Splines
NACA	National Advisory Committee for Aeronautics
VPP	Velocity Prediction Program
LCA	Life Cycle Assessment
GWP	Global Warming Potential
ISO	International Organisation for Standardisation
EoL	End of Life
MS360	Marine Shift 360
SM$	SuMoth dollars
VARTM	Vacuum Assisted Resin Transfer Moulding
KISS	Keep It Simple Stupid
FSM	Foiling SuMoth
FSMC	Foiling SuMoth Challenge
FW	Foiling Week
3R	Reduce Reuse Recycle
11HR	11th Hour Racing

INTRODUCTION

The field of engineering and design continuously pushes the boundaries of innovation: within the sailing world, IMCA is a perfect platform for progress advancements, being a competitive development class and this report is a testament to this. In the following document, all the work, studies and research that have led to a significant refitting of BAI – Flying Lina (our latest boat, a Moth participating in the SuMoth Challenge 2023) will be summarized, providing solid theoretical foundations for future projects as well. BAI – Flying Lina is a project initiated at the end of 2022 with the aim of entering the Audace Sailing Team into the SuMoth Challenge 2023. The Team's experience and knowledge of what concerns foil sailing were limited initially, which prompted the inception of a three-year project to eventually possess all the necessary skills to create a Moth as competitive as possible. This journey begun in 2023 when the Team startedto construct a well-optimized hull according to design parameters that ensured good maneuverability in water without limiting performance, while also maintaining a philosophy of modularity for all components, particularly the junctions. This allowed for the structuring of work to improve structural performance and the concept of certain elements of the vessel without the need to build a new hull. The starting point of the subsequent work was thus the analysis of the criticalities present in the 2023 design of BAI – Flying Lina (citation), both from a design and practical standpoint. Another significant advantage of this working methodology is the ability to work on feedback from the various crew members who sailed on the first version of the Moth. This aspect of the design approach enabled the team to experiment new concepts for certain elements of the boat, especially the wings, with a greater awareness of the consequences in water. Moreover, it's necessary to consider the arrival within the team of individuals with several years of experience in the foil sailing world, who already know how to sail on this type of boat. Another significant step was observing the different movements and reactions of these new skippers aboard the Moth, especially to understand and predict possible critical points. An accurate description follows of how it was possible to transition from theoretical concept to the actual realization of the vessel, with careful consideration and descriptions of the materials used. The content of the report aims not only to strengthen the structural integrity of the vessel but also to provide the basis for achieving more performance-oriented flight profiles while keeping the induced environmental footprint as limited as possible. "Eco-sustainability is a fundamental aspect of our work, as evidenced by our dedicated department focused on researching materials with minimal environmental impact: LCA (Life Cycle Assessment). This department significantly influences our material and production method choices. Moreover, it evaluates the entire lifecycle of our products, from production to disposal. Detailed analyses are conducted on each component to accurately calculate our environmental footprint. As Audace sailing Team participate to the SuMoth Challenge, eco-sustainability analysis calculations ought to be very accurate in order for the Moth to be evaluated with a better score for the competition. The study on VPP and foil design models, in conclusion, also aims to provide reliable foundations that may have partial or complete validation as early as 2024 for multi-year studies.

1 ENGINEERING AND DESIGN

1.1 State of art

The decision not to build a new boat this year was also based on the need to consolidate and develop optimal design methods to achieve the best results in line with our knowledge. From this perspective, last year saw extensive research into optimizing hull shapes, leading to the development of a highly articulated workflow, while this year, it was necessary to improve many critical points in the remaining parts. The work on hull design started with modeling the Mac2 hull forms in Rhino, allowing for parameterization of the entire geometry with Grasshopper, which has been a complex process as the available material for these applications is limited, leading to the independent development of many ideas. Subsequently, the focus shifted to selecting parameters that would guide optimization, considering possible implications in the production phase, more specifically emerged the concept to incorporate a symmetrical top to bottom hull to reduce the number of molds required while preserving a certain design flexibility. Regarding performance, greater stability was preferred, hence opting for a wider beam than average, while minimizing resistance in the displacement phase to facilitate crew maneuvers and takeoff. Within modeFrontier, the necessary workflow was configured, launched in four iterations to narrow down the search for the best forms. Finally, appropriate fluid dynamics analysis were conducted to validate the results.

Fig. 1.1: Workflow

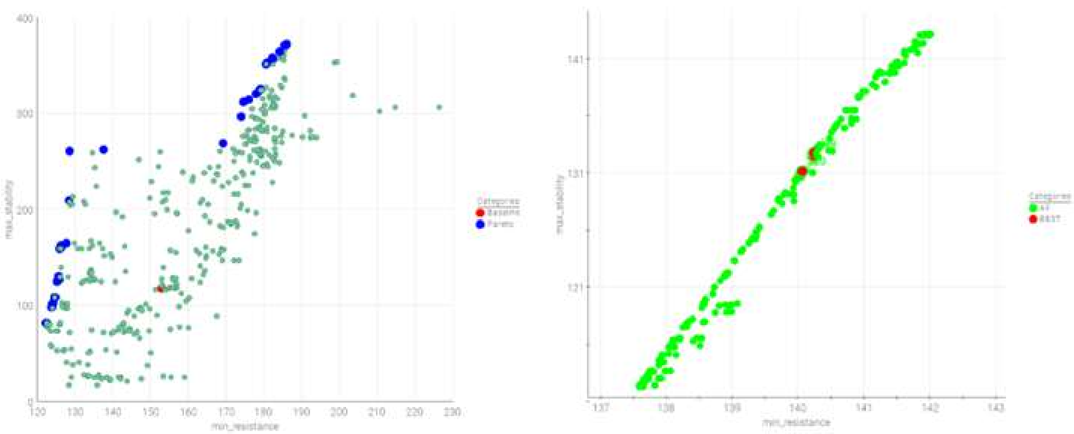

Fig. 1.2: First and last iterations

In the structural domain, the priority was to reduce overall weight, leading to a thorough analysis of the stresses and deformations generated on the hull. Particularly, between wings supports, we were able to use a single material skin reinforced with power ribs. However, the main innovation was the addition of a longitudinally reinforced core keel with flax UD and transverse core rings extending to the deck, also reinforced with flax UD.

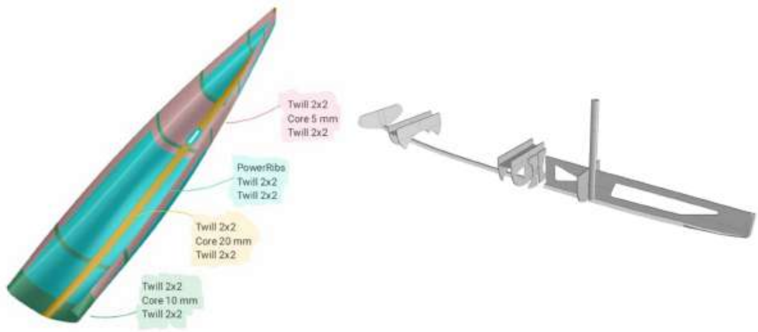

Fig. 1.3: Hull layup and internal structures

The most stressed area of the hull is found around the mast step and centerboard case, resulting in a higher concentration of both transverse and longitudinal structures. In this area, the hull was constructed as a sandwich for increased resistance to potential stresses 1.3.
The stern section is also constructed as a 1 cm thick flax sandwich to withstand the forces generated by the gantry during navigation. Supporting beams were also designed for the wings recesses.
The internal structures were initially planned in flax sandwich, but subsequently, carbon scraps were recovered and utilized for their construction, prioritizing greater overall safety from a solidity point of view. This decision was made due to the lack of precise load data for each individual component, with only estimations available.

1.2 Concept and goals

This year's work had two main aspects: firstly, transmitting knowledge to new team members who joined this year to prepare them for next year's construction of a new moth. Secondly, the development of the previous exposed ideas and introducing innovations, such as studying a Velocity Prediction Program (VPP) tailored to our needs and implementing sensors to collect various types of data for refining design analyses.
The general objectives were:

1. Sustainability Focus: the challenge was to balance the use of flax fibers instead of carbon fibers (with lower stiffness and strength) through appropriate structural design.
2. Reliability of Appendage Structures: producing solid laminates and supports, maximizing the use of carbon fiber after a careful initial analysis.
3. Construction easiness (and Cost Reduction): in-house parts should be made using proven techniques and knowledge from past experiences, and where possible, utilizing leftover materials or remnants from previous projects to reduce costs and outsourcing.

1.3 Foils

1.3.1 Introduction

Regarding the foils, we started from the experience gained last year. The final product achieved was more than satisfactory. In fact, we succeeded in our aim: the development of a set suitable

for beginners, hence stable and optimized for take-off in light wind conditions and therefore not high boat speeds. These choices proved to be winning, a low-speed take-off allowed us continuous flight during regattas and, although it was not our primary goal, we also managed to achieve a top speed of over 20 knots. With more experience in the field of foils both in design and use in the water, we decided to set ourselves the goal of designing a more performant set of foils, sacrificing the take-off phase in favor of higher top speeds. To achieve this, we made an initial step forward compared to last year by designing a wing profile optimized for our usage conditions. Subsequently, the workflow did not deviate from the principles previously used, in fact, the use of simple and reliable tools followed by verification with more accurate methods was again implemented, improving the tools already in possession.
The design process was divided into three stages:

- Airfoil design: Using the experience in researching the wing profile from last year and understanding the characteristics to pay attention to, we decided to structure a workflow for optimizing a custom wing profile.
- Wing design: The second stage was the optimization of the wing geometry. We decided to make the VPP tool in Excel more convenient by rewriting it using a similar reasoning and the same analytical formulas. ModeFrontier was extensively used to explore the design space generated by the new objectives in a short time. Identifying the range of motion of the variables, a workflow with the usual CFD tool, Star-CCM+, was used again to choose the design with adequate precision.
- Detailed design: Finally, the drawings were defined with greater precision, including the bulb, and the drawings for the creation of molds to be made with the CNC were obtained.

1.3.2 Foils

The optimization of the wing profile was divided into three steps:

- Parameterization of the wing profile through Grasshopper
- 2D optimization using modeFrontier coupled with XFOIL
- 3D validation on XFRL5 with the Vortex Lattice Method

The parameterization of the airfoil was based on the master's thesis work of two former members of Audace who were among the team's founders. The chosen method was that of Bezier curves, which are particular parametric curves. Specifically, the thesis work focused on the parameterization of a self-adaptive foil; in our case, only the first part was relevant, namely the creation of the profile's camber and thickness. This parametric method allows for direct modification of the profile and limits the number of variables in the design space.
The optimization consists of a main workflow where the GH node outputs a .dat file of the profile to be evaluated in an inner loop with XFOIL. Thanks to XFOIL, an analytical tool that allows quick analysis of the profile, we could analysed a large number of designs in a short time. Each design was analysed at various angles of attack and flap settings, and at different Reynolds numbers chosen based on the performance of the profile used last year. This modeFrontier cycle aimed to maximize efficiency at the target Reynolds' numbers without neglecting efficiency at take-off speeds. After several runs, we decided to reduce the boundaries of the variables to values similar to those of the Eppler profile, as it still proved to be the best.

After evaluating the results, the best designs were further analysed using the 3D module of the XFLR5 software. This allowed us to further narrow down the best designs by choosing the best one based on a broader range of results.
The resulting airfoil profile is similar to the Eppler profile, with a thinner thickness and performance over a wider range of angles. Last year's foil design was governed by a VPP (Velocity Prediction Program) built in Excel. This method proved to be very effective for performing quick analyses with a wide range of parameter variations, with an acceptable degree of approximation. Drawing inspiration from the first and fourth SuMoth Masterclasses (KISS - Preliminary Design with Julien Chaussée and Practical Design Considerations with Kevin Ellway), we developed a simple prediction program based on simple yet reliable aerodynamic equations, integrated with 2D section data (CL and CD) from XFOIL and correction coefficients from the literature (B. Beaver and J. Zseleczky, 2009). Using the same formulas for prediction, we decided to rewrite this VPP using MATLAB. Besides rewriting the performance prediction code, a script was created to make the organization of the CL and CD database of the chosen airfoil profile faster and more flexible. The code receives the following input parameters:

- Span of both the main foil and the rudder.
- Root chords and elliptical ratios. The area is calculated subsequently with a simple function based on the foil's planform construction.
- Lift ratio (
- Maximum angles of attack for the main and rudder.
- Maximum flap angle.

The program allows the calculation of the following outputs for the speed range between 0 and 30 knots:

- Total lift generated by the wings
- Total drag
- Angles of attack of the main and rudder
- Flap angle

At each iteration, based on the lift generated by the design, the drag generated by the hull at the corresponding displacement is calculated. This was done to account for the hull drag curve in the overall efficiency of the system and the corresponding takeoff speed. We used the following equations valid under the assumption of elliptical lift distribution. The parametric model used for the first set of foils was reused, modifying only one of the input variables; the root chord is directly inserted without calculating it from the root. The operation of the two Grasshopper scripts, one for the main wing and one for the rudder wing, is as follows. The wing surface was created from two guiding curves, the trailing edge, and the leading edge, and 21 sections uniformly positioned along the wingspan (Sweep2 command). Just as it did for the hull, the software works only on one half of the part, and at the end of the workflow, it performs a symmetry operation. The geometric parameters defining the main wing are:

- Wingspan (from 80 to 115 cm)

- Chord (from 9 to 11 cm)
- Flap position (% of the chord at the root, from 25 to 45%)
- Delta, a shape parameter that defines the position of the major axis of the ellipse and thus the curves of the leading edge and trailing edge (distance of the axis from the trailing edge in % of the chord at the root, from 25 to 75%)

For the main wing, the flap is modelled as a separate surface. However, the effect of the small gap between the rigid wing and the flap on the CFD results, which does not exist in reality, was neglected. The geometric parameters defining the rudder wing are:

- Wingspan (from 40 to 80 cm)
- Root chord (from 6 to 8 cm)
- Delta, a shape parameter that works exactly as for the main wing (distance of the axis from the trailing edge in % of the chord at the root, from 25 to 75%)

Unlike last year's foils, the curvature of the wing in the yz plane (dihedral angle) was not included as it did not show a significant improvement in performance.
To obtain the CFD simulation to be implemented in the foil optimization cycle, we used as a starting point a simulation used to verify experimental data from the Hungry Beaver Moth foil tank tests. This simulation is included in the thesis work of a member of the design team. The experimental data are documented in the paper "Full Scale Measurements on a Hydrofoil International Moth" by B. Beaver and J. Zseleczky.
The first simulation was based on the experimental conditions of the tank tests. It included a stationary model with a free surface, a K-epsilon solver with prismatic layer settings aimed at achieving a Y+ > 30 (about 60), and finally curvature, surface, and volume controls on the foil and vertical. However, our goal was to obtain a comparison of just the foil with a low computational load while maintaining good result reliability: therefore, we chose to adopt a single-phase model (fully immersed body without free surface).
To reduce the number of cells, we conducted a sensitivity study on the mesh: we varied the base size and cell size on local controls to decrease the number of cells without losing accuracy. Another step to further reduce the number of cells was a domain independence study. The initial volume, created for a simulation with a free surface and an extra object (the vertical), was set to an excessively large size for our purposes. Through these modifications, we managed to halve the number of cells from 1.6 million to about 0.8 million (depending on the size of the analysed geometry). Finally, we decided to use a k-omega model, which better resolves near the boundary layer, and adjusted the prismatic layer to achieve a $Y+ < 1$.
The data focused on by the simulation are the integral values of lift and drag. For added confidence in choosing the right foil, we also set up a check to detect cavitation and exclude it if the phenomenon occurred. We achieved this by monitoring the pressure, indicating the onset of cavitation if it dropped below the fluid's vapor pressure, which is unlikely at the speeds and angles analysed. The time to run a simulation varied between approximately 25-30 minutes; for each proposed design, a series of two simulations were performed to verify the wing's performance at two speeds (take-off speed, approximately 8.3 knots, and reference downwind speed, 18 knots) and consequently with different pitch and flap angles. These angles were modified within modeFRONTIER through a macro recorded in Star. The macro set the new parameters

and performed the operations of importing the next design, meshing, running, and finally exporting the obtained results.
Before performing the complex and time-consuming CFD analysis, we decided to use our MATLAB VPP code, coupled with the modeFRONTIER optimization process, to drastically narrow down our design space. After some preliminary iterations to configure the workflow and better define the parameter ranges, we ran an optimization process using the MOGA-II evolutionary algorithm. We adopted a multi-objective approach for the optimization, aiming to maximize efficiency at cruising speed (22 knots) and minimize take-off speed while maintaining total lift fixed at 130 kg. modeFRONTIER compared a few thousand different combinations in a few hours. Consequently, we fixed some parameters and reduced the range of others to set the design space for high-fidelity simulation. Note that the last three geometric variables (Delta shape parameters and flap size) have not been included in the low-fidelity phase. Thanks to the Lo-Fi optimization, we were able to drastically reduce the range of variation of most parameters in the next stage: Hi-Fi optimization using StarCCM+. This phase concentrates its attention on those fine details that require precise results achievable only through tools such as CFD solvers. All optimizations were carried out using modeFRONTIER software as in the Lo-Fi optimization. The logical process is the following:

- The 4 geometric inputs (span, area, flap ratio, and delta) are defined and fed into a Grasshopper node. For each design with different input parameters, a new geometry is created in Grasshopper and passed on to an inner loop node.
- Other 8 inputs (MF and RF span, MF and RF area, lift ratio, MF and RF maximum angle of attack, maximum flap angle) are instead fed directly into an Excel node to obtain speed, flap angle, and angle of attack calculations the operating condition (boatspeed 22kn).
- These three parameters are passed on in vector format into an inner loop node, which runs an internal workflow twice (size of the vector). The internal workflow consists of running a CFD simulation in StarCCM+. The workflow takes the input parameters from the outer project, substitutes them each time accordingly into a macro script file, and runs the simulation in batch mode, taking out as outputs lift, drag, and cavitation bubble values.

For the rudder optimization, the logical process is very similar to the mainfoil. The main difference between the two is that since the rudders angle of attack can be modified manually by the helmsman by modifying the rake of the whole vertical strut+foil system, there is no need for the use of a trailing edge flap as adopted on the mainfoil. Therefore the optimization workflow is simplified and follows the following steps:

- Once again with four geometric inputs (span, area, anhedral angle and delta), fed into a Grasshopper node. For each design with different input parameters, a new geometry is created in Grasshopper and passed on to an inner loop node.
- Geometry is passed on directly to the inner loop, without an intermediate Excel node: in fact, this time we used two pre-defined speeds (8.3 and 18 knots) as inputs, to streamline the process.
- Inner loop runs the CFD simulation and outputs lift and drag characteristics.

The optimization process led to define the final shape of the two lifting surfaces. The last task was to design and integrate the bulbs, which function as attachment point for the struts. Given

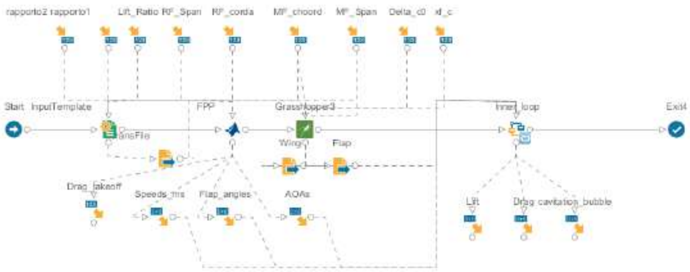

Fig. 1.4: Foils design process

the structural constraints on bulb thickness, in order to reduce the junction drag, a fared surface has to be modelled. It was chosen to adopt a blended bulb, keeping the same airfoil as the wing, scaling it and operating minor modifications. The bulb's main dimensions and position relative to the wing were studied using XFLR5 and Star-CCM+, drawing a comparison with the most common moth foils configurations, keeping in mind the structural issues. Once the final shape was tested and validated, we created the complete wing surface in Rhinoceros, blending the bulb with the wing body. Finally, we performed the engineering of the foil moulds, designed to be made out of aluminium and used with a compression moulding technique. We worked with Rhinoceros and Fusion to create these complex parts. We followed the invaluable advice of our technical sponsor XMTECH shared with us. The foil moulds themselves were then made by XMTECH.

1.3.3 Verticals

For the profile of our verticals, we improved the geometries of the Exploder and chose to vary the chord along the vertical direction. The search for the best airfoil profile began with a preliminary analysis of the most efficient symmetrical NACA profiles, thus defining the key factors: leading edge and thickness and its position.
Using the XFLR5 program, an iterative analysis was conducted, starting from the actual profile and changing one characteristic at a time to find the right compromise. The range of angles of attack considered for the main was fixed at a single angle, while for the rudder it was estimated between -6 to +6 degrees.
Three airfoil profiles were chosen, which we considered to be the most efficient, and we decided to use all of them, varying them along the length of the verticals. Specifically, we decided to have a larger chord near the hull and for the entire area that remains out of the water during flight. This decision was made to provide greater resistance to bending and torsional loads, prioritizing it over the resistance generated in the displacement phase. For the submerged area, we used a smaller chord to reduce frictional resistance while ensuring sufficient thickness.
Together with the structures department, a preliminary analysis was conducted to obtain an optimal range of lengths to avoid excessive bending. In line with last year's choices, a low rake angle was maintained to assist in the takeoff phase and to reduce the risk of ventilation, which would cause a loss of lift and instability.

1.4 Wings and rig

As mentioned in Section 1.1, the main focus last year was on the simplicity of the shapes and ease of navigation; consequently, innovative wings were selected, made for the first time from

flax fiber, with a flat profile and with a moderate inclination of only 13 degrees. However, this configuration introduced some significant challenges: a lower wing, in order to meet the maximum width criteria set by the IMCA's regulations, was considerably shorter and, as a result, generated a lower righting moment compared to a higher configuration. Moreover, the reduced angle of the wings, combined with a lower freeboard of the hull compared to other Moths, prevented the sailor from effectively heeling the boat to windward during the pre-takeoff phases, as this would have led to the partial immersion of the wing itself, significantly increasing hydrodynamic resistance and requiring higher speeds for take off (1.5).
Following the three-year development plan of the project, this year the team was able to shift the focus from stability to enhancing the performance of the hull, benefiting from increased experience with this type of class.

Fig. 1.5: Pre-take off performance with the old wings configuration

1.4.1 Shape design

The reconfiguration of the wings was driven by the need to optimize performance during flight, while simultaneously minimizing hydrodynamic resistance by avoiding contact with the water. The angle of the new wings of BAI-Flying Lina 2.0 was set at 23 degrees, a decision resulting from a meticulous comparative analysis of the inclination angles of different wings from various contemporary Moth models, with particular attention to Mackay's and Manta's models (1.6).

Fig. 1.6: Comparison between the Mackay (Left) and Manta (Right) Moths

The profile of the new wings has been outlined with an 'S' shape (1.7) that is more streamlined towards the bow and gentler towards the stern, thus meeting the sailor's needs for a less pronounced transition towards the stern, facilitating the transition from one side to the other in case of delays in maneuvers.
All the evolution in the design is directly influenced by the needs expressed by the sailors: the

wings now also include a slight rise for the straps, improving ergonomics and facilitating use by the helmsman.

Fig. 1.7: Profile of the New Wings

The new profile of the wings is clearly visible in the following comparative image (1.8), highlighting how the new design favors maneuvers that were previously unachievable due to early contact of the wings with the water's surface.

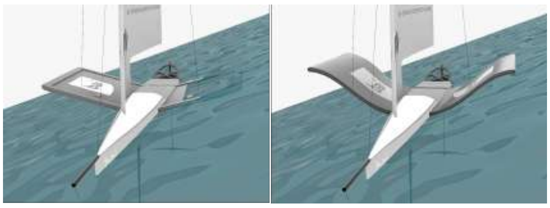

Fig. 1.8: 20° Heeling with old (left) and new (right) wings

1.4.2 The Hydrodynamic Study

The hydrodynamic analysis considered three different longitudinal sections: rectangular, symmetrical, and bearing, which were subjected to CFD simulations aimed at evaluating the ability of a bearing section to contribute to the righting moment in foiling conditions.

The simulations, conducted with Star CCM+, demonstrated that the bearing profile, at high speeds, generates a significantly higher lift than the other configurations, with a slight increase of drag that is practically negligible (1.9). Looking at the wing with the bearing profile, at a

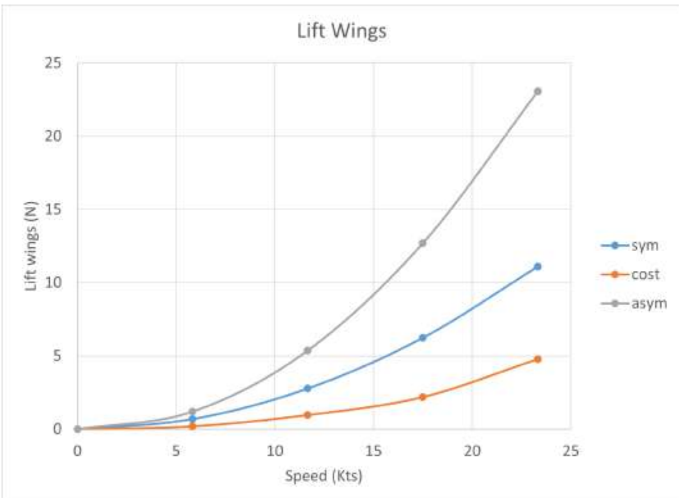

Fig. 1.9: Lift Generated by the wings with different longitudinal sections

speed of 23 knots (apparent), a lift of about 20 Newtons is recorded. Consequently, the impli-

cation of such force can be considered as the addition of an equivalent of about 2 kg on the sailor's side. In more practical terms, thanks to this wing configuration, the necessary ballast that the sailor must counteract to maintain a defined angle of windward heeling is 2 kg less than that required with an uniform profile wing, thus allowing a reduction in overall weight or enabling a lighter sailor to achieve the same results as a heavier one. However, the wing on the sailor's side also generates a certain lift (lower due to the presence of the sailor himself) which creates an opposing moment that partially reduces the beneficial effect just mentioned.
Given the proposed configuration, a complete redesign of the deck would be necessary, despite the marginal effect observed. Consequently, the rectangular section was preferred. However, the analyses have highlighted the crucial role that rigid wings can have in balancing dynamic forces. Therefore, these are expected to undergo further investigations and optimizations, along with a renewed deck design, in preparation for the next Moth of Audace Sailing Team.

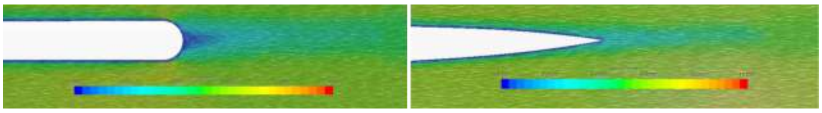

Fig. 1.10: Comparison of the trailing edge of the rectangular section profile (right) and the symmetrical profile (left)

1.4.3 Structural Analysis

Regarding the structural aspect, the decision was made to follow the idea proposed last year, which involves having an external part acting as a load-bearing beam, onto which the rigid central panel distributes the weight, thus dividing the deck into two main parts: external and internal. Unlike the previous version, it was decided that upon completion of construction, there would be a single left-right piece to achieve a more solid structure and reduce the final weight.
Last year's concept involved having the external part composed of a sandwich with an internal recycled PET core (with maximum dimensions of 100x50mm) shaped like an ellipse, onto which the outer flax fiber were laminated, divided into 4 parts for ease of transport: a bow part from right to left, a stern part from right to left, and an outer part on each side (which were later joined to their respective external panels). This year, it was decided to replace the core in the bow and stern parts with a beam made in a 3-layer flax fiber sandwich and a 10mm recycled PET core (manufactured through vacuum infusion), glued to the polystyrene beam and subsequently laminated with flax fiber on top of the polystyrene (which is only used to facilitate the lamination of skins in the design position), adding carbon fiber skins in structurally critical areas for reinforcement. Additionally, slots were prepared to insert the panels of the internal part and thus create a single piece. This results in a significantly lighter structure while still reducing deformations. For the side parts, instead of the beam, carbon tubes from disused windsurfing masts were used, onto which polystyrene was glued to maintain the same final shape as the other parts, and flax fiber was laminated as an external covering.

Last year, the internal panels were made of twill flax fiber sandwich using a 20mm thick aluminum honeycomb core. Problems were encountered with delamination of the skin followed by water ingress into the cells due to excessive curvature of the structure (likely due to

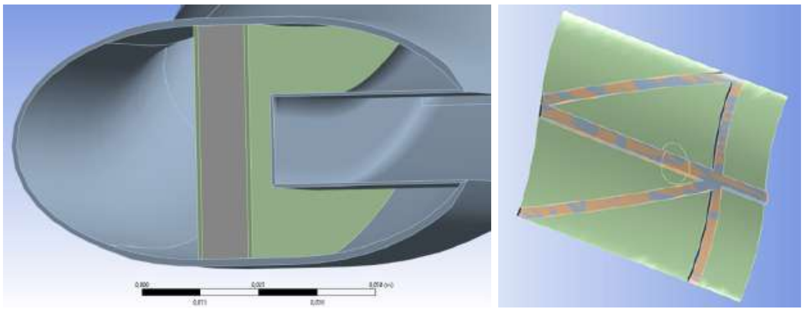

Fig. 1.11: Transversal beam cross section and internal panel

the oversized individual cell dimensions). Therefore, this year, a 10mm recycled PET core was used, with additional beams with 15-20mm cores and an extra layer of UD to increase panel stiffness (despite a slight weight increase). Wooden molds and gelcoat were used to create the panels, onto which flax fiber and PET sandwich infusions were vacuumed.

1.4.4 FEM Analysis

One of the initial design decisions was to avoid using fiberglass in the decks, favoring flax fiber and carbon fiber instead. Therefore, with only 5% by weight of carbon fibers available, it was decided to use it only in the external part of the deck, not on the internal beam. Subsequently, FEM analyses were conducted on individual components of the deck, first to determine the best direction of the various skins, then considering loads increased by 100%, assessing both deformations (ensuring they remain within 50mm) and maximum stresses generated on each skin (ensuring they stay below critical values for each material type). For the central part, the individual panel was validated first without reinforcement beams, and then various beam configurations were tested to find the right compromise between overall weight and maximum deformations. The final configuration results in a maximum displacement of 18mm. Finally, an FEM analysis was performed on all elements, both under design conditions and with a 100% increase in acting forces, with the maximum displacement being below 30mm and stresses below the breaking limits.

(1.12)

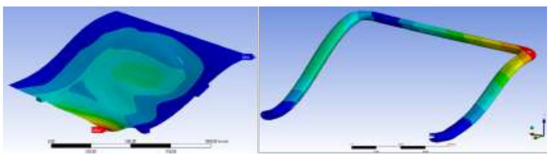

Fig. 1.12: FEM simulation of the internal panel and external frame

1.5 Gantry

Last year, we chose to build a gantry with four attachment points on the stern of the hull. This year, however, we opted for a counter-point gantry configuration, allowing us to also incorporate a foil angle adjustment system directly from the gantry itself. To address the issue of a single tube with two pins, a steel element was constructed to join the two lower screws on the stern of the hull (thus avoiding the need to open and modify the hull structure) with the single adjustment system, which then connects to a carbon tube of the gantry itself via the adjustment system.

1.5.1 Tilting System

The adjustment system was designed using the concept of inserting a C-shaped fitting that connects to the lower tube of the gantry and, through a double nut, is fixed to the screw stemming from the steel element. By varying the position of the nuts, the angle of the gantry relative to the hull can be modified, consequently adjusting the angle of attack of the aft foil directly from the gantry. To allow rotation of the entire gantry without exerting force, two steel L-shaped tabs were built for the upper screws on the stern of the hull to allow connection with the gantry tubes.

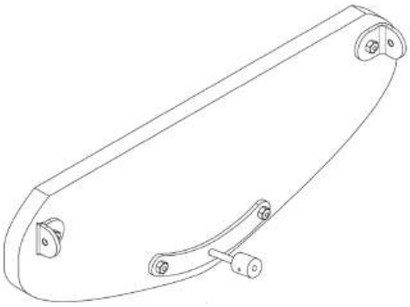

Fig. 1.13: cambia

1.5.2 Structures

The structural part of the gantry consists of five carbon tubes 1.14, sourced from old windsurfing mast tops, joined together with carbon fittings. These fittings are laminated with 3D-printed elements that calculate the shape and angle of the tubes to ensure a perfect connection between the tubes and fittings after gluing. Regarding the sizing of the fittings, FEM analyses were conducted, varying both the number of layers and the layering directions to ensure the necessary structural rigidity based on the expected forces during flight. Additionally, a pivot will be attached to the vertical tube to allow for rudder rotation.

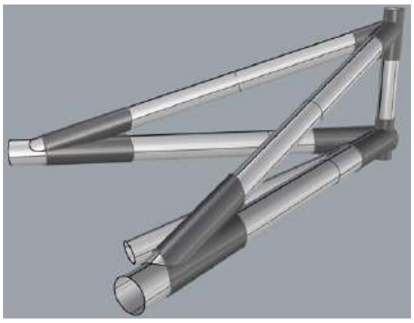

Fig. 1.14: Tubular structure

1.5.3 Fluid Dynamics Analysis

To enhance performance during the displacement phase and facilitate takeoff, a closed structure similar to a casing was developed, enveloping the tubular structures of the gantry and integrating directly with the stern of the hull. This design aims to maintain surface continuity while adhering to the 3cm distance prescribed by class regulations. The configuration was achieved by using the hull mold from the previous year, organically extending the lines of the BAI-Flying Lina hull.

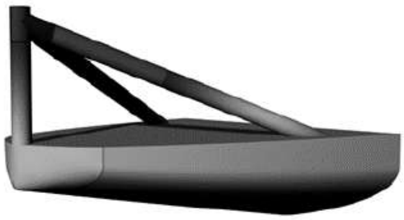

Fig. 1.15: Preview of the closed surface around the gantry's structure

CFD studies conducted with Star-CCM+ demonstrated that this solution significantly contributes to reducing overall hydrodynamic resistance. This is attributed to a reduced boundary layer separation, particularly significant as the BAI-Flying Lina hull, designed for stability, has a wider stern than traditional Moths, leading to pronounced wake formation and intense vortex generation. While the closed surface increases frictional resistance, it greatly reduces wake resistance, resulting in a total resistance reduction of over 15%.

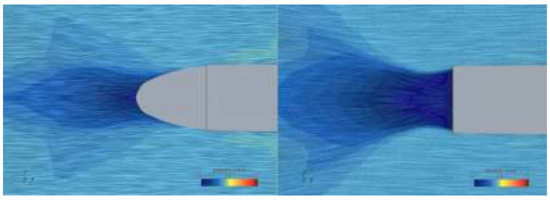

Fig. 1.16: Comparison of the wake generated without (left) and with (right) the closed surface

Numerical tests were conducted at various speeds during the displacement phase, analyzing the flow for both the bare hull and the hull with the closed surface provided by the gantry. Specifically, the latter was analyzed in both the optimal condition where the gantry is fully attached to the stern and the case where separation is allowed as per regulations. The tests were conducted in unsteady conditions using a second-order accurate implicit scheme. A trimmed mesh of approximately 3.5 million cells was employed following a grid-independence study 1.17.

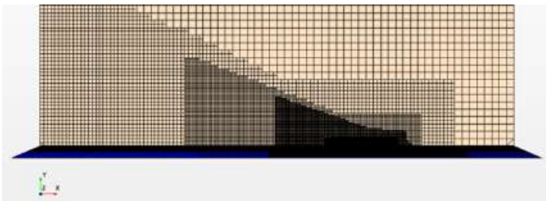

Fig. 1.17: Trimmed mesh for the free surface with special attention to the Kelvin Cone

Chart 1.18 presents the resistance values for the three different configurations in the displacement condition.

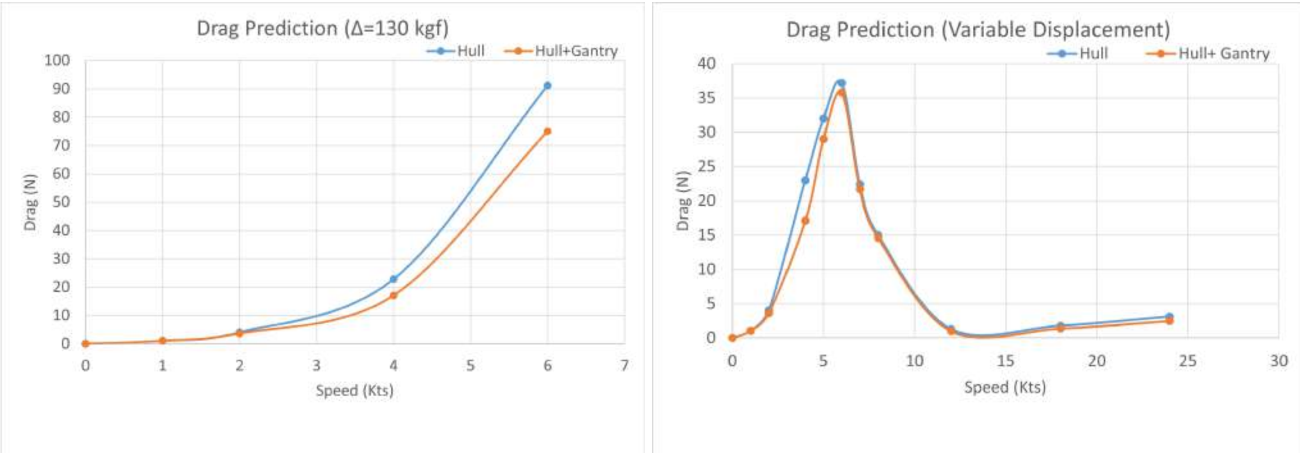

Fig. 1.18: Total Drag in the different configurations(left) and total Drag with Variable Displacement (right)

It's worth mentioning that the results were obtained considering the worst-case scenario where there is always a displacement of 130 kgf: the increase in lift generated by the foils due to higher speeds, leading to a change in displacement and buoyancy, was not considered. The results of the Total Drag in the different configurations underline the effectiveness of the adopted solution. Further analysis in full foiling conditions and in residual displacement were also conducted. In this case, as the speed increases, the lift generated by the foils contributes to the gradual lift of the gantry from the water, thereby reducing its effect. However, even in this more realistic scenario, the presence of the closed surface along the gantry has its benefits. As can be seen from graph 1.18, which represents the resistance of the hull with and without the gantry at varying speeds and displacements from the condition of the hull fully displacing to the condition of the hull fully foiling, the maximum effect of the closed surface is visible at a speed around 4 knots with a drag reduction of over 25%:

Fig. 1.19: Wake generated in air without the gantry's closed surface (left) and with the gantry's closed surface (right)

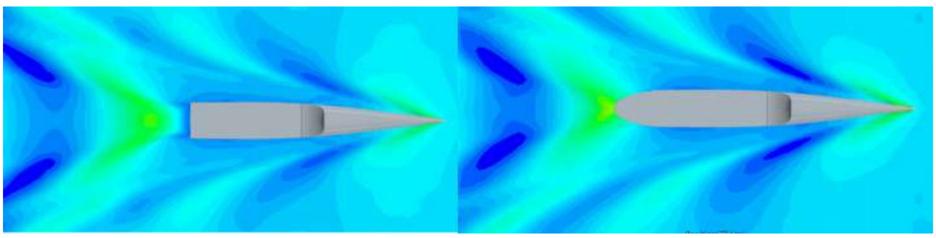

Fig. 1.20: Focus on the waves generated from the Stern without (left) and with the closed surface (right) of the gantry

From these analyses, it is possible to conclude that the closed surface of the gantry allows for a reduction in total resistance. Although the speed necessary for takeoff will remain approximately the same, thanks to the closed surface, it will be easier to reach this speed due to the lower resistance encountered at lower speeds.

1.6 Electronics

1.6.1 Sailing data collection and analysis

The design work, especially for prototypes, relies on many simplifying assumptions due to the type of analysis conducted and the available resources for these analyses. Consequently, it would be very useful to be able to validate (or even refute) the analytical results and design assumptions to improve the design and manufacturing process. To this end, a department has been established to implement electronic sensors for data collection to enable objective analysis of boat performance.

The methods and materials chosen, due to the novelty of the task and the consequent lack of personnel, are those that would allow for the fastest and simplest implementation from a programming and assembly perspective. Therefore, the choice fell on the Arduino ecosystem for its extensive availability of open-source material and general compatibility with other electronic components. The initial sensors to be applied will include a GPS for speed and direction data, accelerometers for impact data, and a gyroscope for attitude; all controlled by a central board that will collect data on an SD card and transmit it via WIFI to an operator on the support dinghy. The entire "package" will be housed in a watertight box approximately 10x10x10cm, with the exact location on the boat to be determined.

Additionally, an ultrasonic or laser anemometer is being developed, which, together with the GPS, would provide real wind data (true wind = apparent wind - boat speed). The anemometer consists of four paired ultrasonic transceiver units, positioned in a cross shape, and a control board that calculates the time between signal emission and reception and compares it with a null wind reference. Having two pairs of sensors allows for both wind direction and intensity measurements. At present, the prototype achieves a resolution of 1m/s, not yet useful for practical purposes, but efforts are underway to improve it.

1.6.2 Flying control system

In addition to data collection, the department is also responsible for developing an electronic flight system for the boat. The system will consist of distance sensors, either ultrasonic or laser, depending on which performs better, placed at the bow, a precision barometer, and the aforementioned accelerometer for additional input and redundancy data. The sensors will provide measurements to the central board, which will then move a servo motor controlling the flap.

The flight system and sensor setup will likely use different central boards for redundancy, although this will entail additional space requirements in an already limited space.

The work mainly involves programming, but since components with existing code libraries have been chosen, the main challenge lies in parsing the obtained data and developing interpretation algorithms to make the data usable. There is also the assembly of components, which, given the choice of components, has its main difficulty in minimizing the space occupied.

1.7 VPP

In the field of racing boats, a VPP (Velocity Prediction Program) is a software program used to predict a boat's performance in different wind and sea conditions. This program considers a number of variables, such as boat design, size, weight, sail type, and weather conditions, to estimate the boat's speed in different sailing situations.

VPPs are important to sailors because they provide valuable information about boat performance and help make tactical decisions during races. Using the data provided by VPPs, sailors can optimize routes, choose the most suitable sails, and adjust sailing strategy to maximize boat performance.

In short, VPPs are crucial tools for racers, enabling them to improve the performance of their boats and achieve better results in regattas.

It is also a powerful tool for the design of any vessel as it allows the overall performance to be evaluated as a single geometric or physical parameter changes.

1.7.1 Goals

To achieve a successful project, given the high complexity of a vessel such as the international moth, continuous compromises in the design phase between all the specific parts are required. Hence the need and desire to develop a development tool that could "predict the future."

Therefore, earlier this year we decided to create the VPP department, to enable us to thoroughly analyze and understand the challenges associated with such an endeavor, with the goal of having a speed prediction program for the construction of the new 2025 boat.

1.7.2 Simplifying assumptions

It is therefore clear how a VPP is as powerful as it is complex, and the goal of writing its own code is far from trivial. To do so then, we decided to start with a simplified version of it and gradually go on to make the model more effective. First, it was decided to develop a static model rather than a dynamic one because a static VPP calculates the boat's performance based on a set of predefined conditions, such as steady wind and flat water, and are often used for planning and preliminary analysis purposes, allowing skippers and crews to assess the potential performance of the boat in different situations.

On the other hand, a dynamic VPP takes into account real variations in wind and sea conditions during a race by using real-time data from wind, boat speed, and sea conditions, continually adjusting its forecasts to reflect current conditions. This type of analysis is extremely useful during a race because it provides more accurate predictions of boat performance in real time, enabling skippers and crews to make informed decisions about race tactics and boat setup, but makes for complications that are unnecessary at this early stage.

In short, while a static VPP provides forecasts based on predefined conditions, a dynamic VPP adapts its real-time forecasts to actual conditions during a race, thus providing more accurate support for race strategy.

However, since we are more interested in a planning tool and not a race strategy one, we chose to go with a static model.

Beyond the evident complexity, essentially a VPP is based on finding equilibrium which ensures that the yacht is moving on a straight course and at a constant speed, height, heel, and trim. The sum of all forces in each of the three main directions is zero, as is the sum of all moments

acting around the relative directions.
These are the equilibrium conditions in all six degrees of freedom for an analysis of a static nature (6 DOF).
Choosing therefore to utlize a nondynamic model, we decided to start from the study of a 3 DOF-only model:

1. Along the direction of motion, where the driving force should be equal to the resistance total.

2. Perpendicularly to the direction of motion in the horizontal plane, where the lateral force of the sail is equal to the lateral force of the submerged body.

3. The heeling moment of the sails is equal to the righting moment of the crew.

We then limited ourselves to these balances, considering the other 3 DOFs satisfied regardless of the input data. This means that we have to imagine the moth that is always at the same flight height, that the pitching moment is always satisfied as well as the yawing ones. We are also considering only the flight phase, thus leaving out all the pretake-off phase which takes place when the craft reaches about 4.3 m/s.
The sail is then considered to be rigid, that is, it does not change shape between upwind and downwind. The only adjustment remains only the sheet angle, which again for simplicity we consider to be such as to initially guarantee an ideal angle of attack of 17° with the apparent wind at any route.
Another fundamental hypothesis, we assume the boat is always sailing at zero roll angle. This is theoretically always possible, as long as the helmsman's weight can guarantee it. We therefore had the program make a check on the feasibility of this assumption at the end of each analysis by comparing the determined heeling moment to the maximum righting moment generated by the helmsman at the toe straps. If ever the equilibrium is not satisfied, we then ask to repeat all the calculations now however by reducing the angle of attack of the mainsail and thus reducing the lift generated, thus simulating the helmsman easing the mainsail.
In order to do this, collaboration with the architecture department was essential, and once they were provided with the CAD of a sail created through measurements on the actual sail, they proceeded to calculate lift and drag coefficients for different angles of attack.

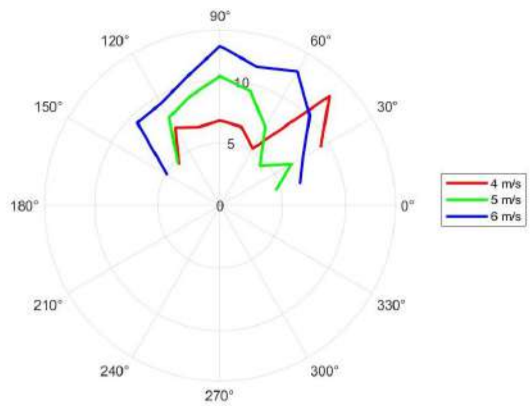

Fig. 1.21: Polar diagram generated by our code

1.7.3 FS-Equilibrium

In parallel with writing our own code, we are also learning how to use FS-Equilibrium, a modular workbench developed from the Fluid Engineering Department of the classification society and maritime advisor DNV GL as a validation system.
The particular quality of this software is its open modular architecture, which allows for setting up any combination of so called force modules. Following the modular structure of the program, there are several predefined modules provided, based on semi-empirical models, but modules can also be defined by the user to include expressions, imported data, for example, from CFD results, or user programmed modules are considered. This characteristic of the program facilitates the creation of an easily structured and flexible model of the forces, parameters and control systems.

2 MANUFACTURING AND COST ANALYSIS

2.1 General description

For the first time, since the creation of our team, the focus of this year will not be the creation of an entirely new boat, the work is going to be indeed centred on the improvement of various important components. The main working areas are going to be:

1. Foils
2. Wings
3. Gantry
4. Spreader
5. Rig
6. Deckhouse

In this report we will discuss only the first three components, in the S2 report there will be more detail information for all the components.

2.2 Foils

This year, for foil and vertical, Compression Moulding was adopted, integrating flax fiber and carbon fiber. The skins were divided into two types: those for the shell and those for the filling. The former, composed of carbon and flax layers, were carefully placed in the molds to ensure uniformity of thickness. After resin catalysis, the pieces were taken out of the molds, checked and refined. The foils required special attention in the laying of the carbon flap skins to ensure an optimal trailing edge, with a coin placed to allow for the connection of the flight control rod. The verticals, built in-house, feature control mechanism inserts made of aluminum and 3D printed plastic. Again, the skins were placed in molds, and the process of extraction, inspection, and finishing was carefully followed. As for the verticals, flax fiber was also used along with carbon, and a the tiller was made from broken carbon tubes. These tubes were cut and fastened together with broken windsurf masts to obtain the new rods. In both cases, the presence of inserts complicated the process, but the production was successfully managed.

Fig. 2.1: Filler plies and shell lamination

2.3 Wings

This year's wings are a one-piece construction and have a curved double-S shape to improve crew ergonomics. The molds are made of a wooden frame and shaped ribs, to the surface of which two panels of okumè plywood are attached. The base of the molds consists of fir wood beams connected by poplar plywood crossbeams, onto which the ribs are mounted. After making the structure of the molds, two layers of gelcoat-treated plywood are applied to facilitate infusion. To avoid bonding problems encountered in the past, a more conservative approach is taken by using flax and PET sandwich wings instead of aluminum honeycomb. Layering includes an outer layer of flax twill and strips of flax UD, with mahogany plywood rectangles added to place cleats and control line deflectors. After the consumables are placed on the surface of the part, the resin is infused, maintaining constant pressure to ensure even distribution. After 36 hours of waiting for the resin to fully catalyze, the panels are cut to size and attached to the hull. Next, the two inner transverse beams, bow and stern, are laminated using PET and wood sections. The beams are shaped to the correct shape and subsequently glued to the panels. For longitudinal beams, sections of windsurfing masts with polystyrene block are used, glued and mechanically embedded in the beams. After assembly, embedding is done on the deck. Polystyrene parts are then prepared to make up the aerodynamic core of the decks, which are trimmed and fitted to the C-section. Next, bands are applied with carbon biaxial and completed with linen twill skins. Finally, the transoms are layered with UD of flax, glass and carbon, and compacted by attaching vacuum bag scraps stretched over the polystyrene and secured with clamps to ensure precise adhesion and strength. Special attention is paid to the vacuum pressure to avoid compression of the polystyrene. In conclusion, the decking construction process includes several stages, from mold assembly to lamination and assembly of the final components, with attention to both the structural strength and aerodynamics of the craft.

Fig. 2.2: Core placement and first fittings on the boat

2.4 Gantry

The new gantry features a tubular support structure made from carbon sticks recycled from other boats, with joints made by 3D printed molds and coated with carbon skins. The lower part of the gantry is composed of a recycled PET core and carbon and linen skins, optimized with CFD for hydrodynamics. A longitudinal slit on the lower part and an insert on the upper part promote water drainage. The gantry is attached to the transom via an adjustable system inspired by the Wasp's gantry, allowing an adjustable rudder pitch angle. Once all components are assembled, the frame is inserted and secured into the lower shell, to which the deck and forward bulkhead are then added, thus completing the component.

Fig. 2.3: Tubular structure with the lower part and closed gantry

2.5 New materials & mechanical test

This year, the materials team worked closely with the structures department to improve the moth wings by addressing weight and strength issues. To reduce weight and simplify construction, they replaced the core with closed-cell polystyrene and laminated the skins on top of it. Although the polystyrene had less efficient shear stress transmission than the core, bending tests showed better results than expected, providing the necessary strength. In addition, polystyrene has lower weight and does not absorb resin, potentially allowing reuse after the component's useful life.

2.6 Cost analysis

The total cost for the components that we did not replace is 5611 SM$. The remaining 4398 SM$ were nearly all spent as described in the following tables:

Table 1: Wings cost

WINGS		**TOTAL COST [SM$]**
MATERIAL	COST [SM$]	261
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	37,5	
Dry fabric glass fibers S Glass	21	
Std. Epoxy Lamination Resin	37,5	
Bio-Based Epoxy Lamination	105	
EPS Standard	5	
Steel All	1,5	
Tacky tape	8	
Vacuum bag	10	
PVC vacuum hose	10	
Brushes	20	
Spiral tube (inf.)	0,5	
Release agent Wax	5	

Table 2: Foils cost

FOILS		**TOTAL COST [SM$]**
MATERIAL	COST [SM$]	3711,05
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	183	
Dry fabric aramid Fibers Kevlar	4,8	
Bio-Based Epoxy Lamination	23,25	
Aluminum All	1500	
Machining (CNC)	2000	

Table 3: Gantry cost

GANTRY		TOTAL COST [SM$]
MATERIAL	COST [SM$]	140,1
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	90	
Bio-Based Epoxy Lamination	17,4	
PLA All	1,1	
3D printing	26,6	

Table 4: Rig cost

RIG		TOTAL COST [SM$]
MATERIAL	COST [SM$]	258,25
Dry fabric carbon fibers Std Modulus CF (i.e. T700)	30	
Bio-Based Epoxy Lamination	2,25	
Steel All	1	
Peel ply	1	
Tiller tube with mechanism and drive shaft	224	

3 SUSTAINABILITY ANALYSIS

"The entire project is accompanied by a sustainability analysis carried out on multiple levels. An LCA protocol is applied with the aim of covering all phases of the project, from the design phase involving material selection, to the construction phase with dynamics related to implementation methods, all the way to waste management and considerations on the 'end of life' of the various boat components. Additionally, there is ongoing research into the development of procedures concerning sustainability certification and a review of scientific literature to remain at the forefront of the marine sustainability sector."

3.1 General description

The main aim of our work is to analyse the environmental impact of the BAI Flying Lina 2.0 refit project. In order to do that, we conducted a life cycle analysis on the materials and methods implemented in the boat's construction by using Marine Shift 360 as a quantitative simulator. Taking most of the experience of the last year, we had the opportunity to improve each stage of the process, from the design one to the final realization itself, trying to maximize the performance while minimizing the environmental impact.
The 2024 refit project's objective is to maintain the hull, the rigging, and the spreader unchanged, and to work on a new design for the wings, the main and rudder foils and verticals, and the gantry. These components have all been taken into account in the LCA analysis, along with their relative mold systems planned for their construction, exception made for the gantry's mold, which has been kept from last year's challenge.

3.1.1 Functional unit

The functional unit describes a quantity standard of a product, in our case it's the cradle to grave impact of Audace Sailing Team's 2024 Sumoth concept refit, BAI Flying Lina 2.0. For our analysis we considered the raw materials in pre-production as the cradle step, while the end of

life of the boat coincides with the grave one.
In terms of quantities, the functional unit used was defined as an estimated 55 kg of boat for a year of usage. We can predict about 60 hours of sailing, split between training sessions and the 2024 Sumoth Challenge regattas. This is only considering the period leading to the competition and the competition itself, after which it becomes much harder to define a proper number of hours spent on the water.
Defining a functional unit allows a fair cross-comparison between different boats with the same function. BAI Flying Lina 2.0 has been designed to be a competitive moth capable to perform fast and efficiently to the finish line. At the same time, it must preserve its integrity for future usage.
We need to precise that some boundaries were set about the energy consumption. Since our labs and headquarters are based in a university building, electricity is drawn directly from its power lines, and it was not possible to isolate the energy intake of our laboratory. We are taking into account only an estimate of the most energy-demanding processes, such as CNC milling and 3D printing. Therefore, we will consider electricity for lightning and computer charges negligible.

3.1.2 Material inventory

The main material used throughout the production of the various components of BAI Flying Lina 2.0 is flax fiber: this is no news from last year. We kept using this kind of fiber because it provides the best balance between mechanical properties, ease in manufacturing and, most importantly, sustainability. We want to emphasize that flax fiber has a negative impact on CO2 emissions, meaning that carbon dioxide is considered as absorbed for its production.
In some components of the boat, we decided to use some less impacting materials compared with last year. We replaced the aluminium honeycomb of the wings' central panels with a recycled PET core. This choice allowed us to also shorten and ease the construction times, as a simpler lamination stage is required to produce the new panels.
We are also reusing full carbon, and carbon and Kevlar rudder sticks and windsurf masts, and used them as structural elements to give more strength where necessary, especially in the gantry and the linear part of the wing's frame. One of these tubes was even found at the bottom of Lake Garda where the Sumoth 2024 will take place. Furthermore, the panels used in the wings' molds are leftovers from Dedalo's (the team's first boat) production. The epoxy resin used throughout all the lamination processes is 30% biobased.

3.1.3 Design phase

Treasuring the experience gained last year, we made some changes to the design of the boat in the process of developing a new method to aim for a more sustainable future, all while endeavouring not to waste the work already done. To move forward, we focused our attention on the new components starting to analyze them immediately from a design stage, using Marineshift360 as an active modelling tool. This process consists in tight cooperation with the design team, anticipating the final construction amounts of the materials and running various simulations with them.
The result involved changes to the aerodynamic shape of the wings and to the foils' mold that has been lightly modified, while the vertical one has been made with aluminium, fully recyclable. Furthermore, we used some optimization software to reduce the weight of some spe-

cific components which benefits both the performance and the sustainability.
We made an estimate of the hours spent on Marine Shift 360 for the design phase and we obtained an energy consumption of 6 kWh which generated almost 3kg of CO_2, based on the Italian energy mix of renewable and non-renewable energy sources. Estimating the hours spent on other software was not credible and, as the graphic in the appendix shows, some processes have a noticeable environmental impact compared to all the other phases of the boat's realization.

3.2 Boat and Elements Lifecycle

The boat and its components have been designed and made to last, so that we can be sailing not only during the foiling week but for a long time to come. The fact that Flying Lina is coming back in its second version is proof of what the team has already done. The key has been to analyze meticulously each material and element of BAI Flying Lina and its 2.0 version.
One of the best ways we found to be sustainable is to look to what has been thrown away but still has potential. We gave life back to some rudder sticks as anticipated, found at the lake or at the beach where they contributed to the waste pollution that damages those ecosystems. We also revive our sails, reviving them from disposal. And lastly, as previously said, we saved some elements from the construction of our first boat Dedalo. This process of transformation took time but has brought incredible satisfactions.
Moving to what is brand new, we considered as extremely important the production of the row materials, their distance from our laboratory and how to dispose them at the end of the boat's life. And to be fair, their costs too. We preferred materials reachable in our region and most of them have null marine eutrophication. Furthermore, we found flax fiber extremely sustainable compared to other fibers and we optimized the ratio of carbon fiber to give more structural support without compromising sustainability.
As previously stated, our goal is to keep sailing with BAI Flying Lina 2.0 for longer than the foiling week. It will be extremely helpful for the trainings in the next years. Once it will not be safe to sail with it, on a pure theoretical hypothesis, the boat can be dismantled and disassembled.
The structures can be mechanically delaminated so that the PET core can be recycled or reused depending on its conditions. The fibers can either undergo chemical recycling treatment to remove resin or be utilized in a process of thermos-valorization to recover energy. Metals from the screws and bolts, or the titanium from the main vertical and main foil conjunction, will be for certain recovered and recycled. Lastly, we are considering that a few elements may be part of our projects for the future boats. More precise details of some recycling aspects are discussed in the respective element's section.

3.3 Wings molds

The major addition in BAI Flying Lina 2.0 is the asymmetrical design of the wings, which we developed after an aerodynamic analysis conducted by our design team. This implies that new molds needed to be created. We were left with two main mold construction options. The first being a polyurethane epoxydic foam mold, machined with a CNC milling machine; the latter being a rib cage frame covered with panels of plywood.
The rib cage mold method derives from a winning design from last year's hull mold. We insisted on replicating the process for the wings' molds with improved attention to sustainability. The wood parts are in fact all modelled by hand. The required shapes to model are obtained via an

image projection. This meant we didn't have to print out and use paper templates.
For the foam mold we would have had to run the CNC milling machine for several hours, resulting in an increased consumption of energy and a higher cost in SuMoth dollars. The shaped mold would then have to be sealed with resin and only then coated with gelcoat to reach a smoother surface for infusion.
We conducted a comparison study of the two different strategies with the use of Marineshift360 and the results showed that the rib cage method is far more sustainable.

3.4 Wings

The main differences between the wings of BAI Flying Lina 2.0 and its predecessor (which we presented for last year's competition) are the new asymmetrical design and the surface reduction. Our goal was to make them lighter and more aerodynamic, without compromising the comfort onboard. With the new standards set by the design team, we focused on assessing the construction process, starting from the choice of materials.
We replaced the polyurethane foam and the aluminum honeycomb with polystyrene foam and a PET composite, choosing them among local suppliers. This also contributed to lighten the boat, improving its performance. The wings are composed by 3 main structural units:

1. The external beams: we had two design options for their construction, the first one was to manufacture them with virgin plastic material (PET), whereas the second one was to adapt some reused carbon fiber tubes, coming from a windsurf mast. Since we had the opportunity, we compared the environmental impact of both possibilities on Marineshift 360. Since the second option showed a noticeable improvement on environmental impact, we chose to reuse the carbon fiber tubes.

2. The transversal beams: the inner c beams are made of reused PET (from a previous boat of ours), whilst the polystyrene used for the outer shape of the component is fully recyclable. The construction system used for these components permitted us to significantly reduce the amount of carbon fiber layers compared to a single core structure type. To shape the polystyrene, we created a 3D printed sanding block from PLA.

3. The main surface of the wings: they are built using two kinds of core; a 5 mm recycled PET and a 10 mm reused PET, the same kind of the one used for the transversal beams.

3.5 Foils

These delicate parts of the moth have been carefully re-designed and improved. The layers of material have been rethought and optimized to reduce the amount of high impact materials whilst retaining the required performance standards.

3.6 Foils molds

Despite the important changes in shape, we managed to reuse last year's mold by a process of reconditioning the old mold adding aluminium, thanks to our supplier. This allowed us to reduce the impact of the production both in terms of costs and sustainability as well.

3.7 Verticals molds

Certainly, an interesting analysis is the one regarding the moulds used to build the verticals. They are aluminium molds used with a compression molding technique to build the verticals. By comparison, we were faced with an alternative: the use of MDF molds. Setting aside for a moment the performance aspects of the two different kinds of mold (the aluminium ones are certainly easier and much less complicated to use), we focused our analysis on the production costs and on the use and end of life stages.
While both mold systems require CNC operations to obtain the desired shape, the aluminium molds are better at retaining the shape and over a long period of time, they can be used much more than the MDF ones. Nevertheless, the MDF ones cannot be reconditioned and modified with a new design. The ones we chose to use, in aluminium, can be reconditioned by our supplier with a small amount of energy and material expense, compared to the creation of completely new molds in either one of the two materials analysed.

3.8 Main and rudder verticals

For these components, the sustainability research was focused on the materials and the construction methods. During the design stage, we cooperated with the structures team to implement sustainable and optimized quantity combinations of materials. We then chose the results which turned out more efficient from a performance perspective and from a sustainability assessment point of view.

3.9 Gantry

The gantry underwent a full revising process during the design state. Great care has been taken on choosing the right materials and using as many sustainable sources as possible. Greater part of the inner structure comes from recovered material from rudder sticks. The conjunctions between the tubes are 3D printed in sustainable PLA plastic and reinforced with reused carbon fiber from previous boats built by the team. The lower shell is built using the same recyclable MDF timber mold as last year. The top closure is laminated on a flat surface to avoid the creation and use of new molds. The skin coating on all the surfaces is achieved through the use of recycled carbon fiber.

3.10 Transport

To transport the boat from our shipyard in Trieste to the competition location at Fraglia Vela Malcesine, we used 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.

3.11 Conclusions

As our goal was to improve our knowledge and applicability of sustainable options in the competitive marine sector, we can happily say we met our expectations this year. The thing we valued the most was producing the best performing sailing boat as best as of our capabilities, while still trying to find the most environmentally friendly material for every specific component. We are aware that a perfect balance between the two targets is hard to find, but we hope to get closer year by year. Surely, many more improvements can be made, as we will point out

in the next section. We hope to further refine our technique in the future.
We would like to enhance that this year the team has hardly worked on comparing all new possible ideas with last year's project, BAI Flying Lina, considered as the base design. Loads of simulations have been carried to find the best plan for each component, both by the design and the LCA team; to identify the most sustainable materials, the simulations were run maintaining constant the material waste and End of Life options. The comparison that needed the most attention is the change in the configuration of the wings, so this will also be found in paragraph 5.
As we encountered a few issues in implementing all our processes in Marineshift360, we put an effort in describing them case by case, trying to be as clear as possible in the explanations. To implement the processes that do not yet exist in the software's database, we run separated simulations to obtain the quantitative of energy absorbed by the operation and the total amount of material used. Such results are taken in consideration in this report, as we believe they are needed for a complete description of our work.

3.12 Actions for a sustainable future

In the pursuit of a sustainable future, we place performance sailing at the forefront of innovation and environmental consciousness. Our pillars are research, reuse, repair and recycle as fundamentals of the circular economy. We care about the resources we have at our disposal, trying to give them a second life while avoiding their abandonment in landfills or in seas.
We find that divulgation is crucial. This year, we relayed on PhD researchers working at the University of Trieste to have a different insight. We had the opportunity to make use of a scientific article which has been written in collaboration with our LCA&Materials Team Department. Hopefully, it will be published in the near future. It is a remastering of a master thesis "A life cycle comparison of several construction alternatives for a performance sailing yacht", work of a graduate at UniTs, and analyzes the study case of "Arca Fondi SGR - Wild Thing". We found that keeping up with the updates on scientific literature on sustainable materials suitable for boats construction focusing on their CO2 emissions is a fundamental part to take into consideration. In the following months, we will take a closer look at completely and easily recyclable materials, as well as bio-compatible substances with no negative effect on the marine environment. Precisely, we are interested in comparing emissions and mechanical properties of peek carbon fibre in relation to generic carbon fiber.
Thinking ahead, shifting the protocol towards the design process, including in it various simulations with the amounts of materials and kinds of construction required during the production. This should be aimed to optimize and combine the performance with the sustainability aspect right from the beginning. A more precise estimation of the construction materials can, based on our experience, drastically reduce the amounts of waste materials. Optimize the creation of waste derived from the lack of production planning is in our opinion a key aspect to be considered.
Another point of discussion should be the Life Cycle Assessment of a component directly related to the amount of time it gets to be used, and to the number of times it is used before it is dismissed.
These cues need further research and time to be evaluated. This will require deep investigation, research, hard work as well as a little creativity.

4 TEAM

4.1 An overview

The inception of the Audace Sailing Team in 2019 marked the beginning of a journey spearheaded by a group of naval engineering students. Their ambition to create something innovative by amalgamating their passion for the sea with theoretical knowledge acquired during their academic pursuits laid the foundation for the team. Over time, Audace transcended its role as a mere hub for sustainable boat design and construction. It evolved into a multidimensional project where students from diverse disciplines, bound by their love for the sea and the environment, converge to work collectively towards shared objectives.
The year 2023 served as a pivotal moment for the team. Having garnered four years of experience in designing and constructing skiffs, the team embraced a new challenge: designing and constructing a moth using sustainable materials. This endeavour, though arduous, proved to be a stimulating pursuit, culminating in the creation of the first BAI - Flying Lina moth.
The team's growing prominence within the university landscape has been evident, with a surge in membership applications each passing year, resulting in a cohort of seventy participating students. This turnover not only facilitated a cyclical rejuvenation but also facilitated the transfer of accumulated knowledge. Consequently, training within the team has assumed paramount importance, benefiting not only naval engineering students but also those from diverse faculties, who engage in novel pursuits, thereby acquiring interdisciplinary skills vital for their future careers.
An additional benefit of this collaborative environment has been the development of soft skills. Teamwork has fostered the cultivation of new friendships and a sense of camaraderie. Moreover, participation in events and conferences has provided invaluable opportunities for honing social and communication abilities, complementing the technical expertise gained through hands-on experiences.

Fig. 4.1: Group picture

4.2 Our internal structure

The onset of this year witnessed a significant reshuffle in roles within the team. As senior members, on the cusp of completing their studies, made way for fresh recruits, a wave of new energy permeated Audace. While the influx of new talent was a cause for celebration, it necessitated an internal restructuring to streamline operations efficiently. Initial efforts focused on imparting knowledge, particularly within the design and construction departments.
Aligned with our objectives for the year, namely, participation in the SuMoth Challenge with BAI Flying Lina 2.0, the initial months were dedicated to comprehensive lessons on sailing, moth dynamics, software utilization for planned modifications, and material science, delving into the mechanical properties of various materials. Subsequently, the focus shifted to researching novel materials and optimization techniques, striving to strike a delicate balance between durability and performance.
Organizational imperatives prompted contemplation of a more intricate structure, with each nucleus specializing in a specific function. Our principal macro groups encompass design, construction, LCA and materials, crew, marketing and communication, social media, and image management.
In response to the aforementioned needs, the design department emerged as the most intricate, delineated into six micro groups: architecture, foil dynamics, VPP (Velocity Prediction Program), CAD (Computer-Aided Design), structures, sensors, and production. Conversely, the marketing and image departments assumed the form of two closely-knit teams, synergizing to fulfill responsibilities towards stakeholders and supporters. Effective communication between these departments has been imperative, underscored by the organization of weekly meetings aimed at meticulously scheduling team commitments and deadlines.

4.3 Board of directors

Similar to elite sports teams, Audace draws inspiration from the concept of coordination. Comprising not only departmental heads but also vice captains, the coordination team plays a pivotal role in harmonizing the efforts of the entire squad.

4.4 Sponsors and marketing

Sponsors have perennially constituted a cornerstone of our endeavor. Since the nascent stages, their contributions have underpinned all activities, spanning from boat construction to event participation. Over the years, our collaboration with the university has deepened, emerging as a cornerstone that bolsters our project through financial support and provision of requisite infrastructure.
However, to sustain our operations, we ventured into private investment avenues. To this end, we delineated various sponsorship tiers, each attracting collaborators based on their level of investment. Audace's ethos, centred around sustainability and performance, guided our selection of sponsors, ensuring alignment with our overarching vision and mission. Presently, our sponsor structure comprises five categories: main (reserved for BAI - Broker Assicurativo Italiano), golden (Esteco and Intesa Sanpaolo), silver (Zurich Insurance Group), sponsor, and supporter.

4.4.1 Main sponsor

The main sponsor has been a financial stalwart since 2022, epitomizing an insurance broker committed to ecological causes. Beyond financial backing, this tier of sponsorship fosters a profound sense of affinity, aligning with our team ethos. Our collaboration transcends financial transactions, culminating in a meticulously crafted brand image, drawing inspiration from esteemed entities such as America's Cup teams. Noteworthy is the integration of BAI branding in our boat nomenclature, along with prominent logo displays on sails and team apparel. Collaborative events and engagements with BAI further reinforce the symbiotic relationship between Audace Sailing Team and its main sponsor.

4.4.2 Golden sponsor

Since 2023, Intesa Sanpaolo has joined as a golden sponsor, providing vital financial backing. As with the main sponsor, Intesa Sanpaolo's branding is strategically integrated into our visual identity, albeit to a lesser extent. Collaborative endeavors, such as the Grand Soleil Cup, underscore our shared commitment to excellence. Concurrently, Esteco, a local optimization software developer, reinforces our technological prowess, having been one of our earliest sponsors. Collaborative efforts with both entities extend beyond financial support, encompassing knowledge exchange and joint initiatives within the university milieu.

4.4.3 Silver sponsor

This year heralds the inclusion of Zurich Insurance Group as a silver sponsor, lending crucial financial support. Positioned between golden and regular sponsorship tiers, Zurich's collaboration mirrors the golden tier in terms of image exposure, while echoing the regular tier in organizational engagement and event participation. Logo visibility on sails and official team attire distinguishes silver sponsors as pivotal allies, following main and golden sponsors in prominence.

4.4.4 Sponsor

Embracing an egalitarian ethos, we refrain from segregating sponsors based on economic or material contributions. Companies within this tier extend material or financial support, albeit to a lesser extent compared to higher tiers. Notable sponsors include:

1. Xm tech (aluminum mold supplier)
2. Seripiave (merchandising)
3. SmartCae (software)
4. Nord Composites (financial support)
5. Trias Chem (construction material supplier)
6. Armare Ropes (rope and rigging supplier)
7. Marlin Yacht Paints (construction material supplier)
8. Rein (financial support)
9. FG CAE Analyst (software training and technical support)

4.4.5 Supporter

Supporters encompass entities offering complimentary or discounted materials, many of whom have been steadfast allies since our inception. Notable supporters include:

1. SO.FA.S (tools)
2. Nl comp (construction materials)
3. Venicemark (display materials)
4. Blukem (financial support)
5. Easycomposites (construction materials)
6. Nmg europe (construction materials)
7. Mekanika (tools)
8. LAMA fvg (custom appendage products)
9. Centro Ottico Triestino (merchandising and eyewear discount)

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Appendix A: MARINESHIFT360 LCA Study

A.1 Introduction

For this year's campaign, we decided to take a slightly different approach to the use of the Marineshift360 tool. From one side, we reported the complete LCA analysis of Audace Sailing Team's foiling moth refit project, assessing the life cycle of the new parts from their production to their end of life. A second simulation has been carried out with the boat components kept from last year's project added to the newly built ones.
As a second objective, we decided to use Marineshift360 as a pure modelling tool, implementing the different design options and reflecting on the obtained results to support the thesis of more sustainable choices right from the beginning of the modelling process.

A.2 Goal of the study

The goal of this LCA study is to evaluate the environmental impacts associated with the entire life cycle of our Sumoth concept refit project from Audace Sailing Team. The assessment aims to identify and quantify the key environmental burdens and hotspots to support sustainable design, manufacturing, and end-of-life strategies for the boat, considering its new components by themselves and added to the parts kept from last year's campaign.
Furthermore, a comparison analysis has been conducted on different components and their construction options. The goal of this analysis is to withstand the theoretical examinations reported in paragraph 3 of this report, helping to decide the most sustainable way of building the new components.

A.3 Scope of the study

A.3.1 Functional Unit

The functional unit for this study is the cradle to grave impact of Audace Sailing Team's 2024 Sumoth concept. The analysis considers the cradle step as the raw materials entering the production process. The grave step coincides with the end-of-life stage.

A.3.2 Assumptions and Limitations regarding the simulations

Before entering the process of analysis, it is important to underline some of the limitations of the study and the assumptions on which is based.
Limitation on the study:
All the values entered in the software are estimated. They are based on the volumes of the single parts, on the design projections and on the densities of the materials themselves. An exception is made for the wings' molds which at the time of the report being completed, have already been constructed.
We would like to notice that there are some consumables that were impossible to quantify: such as the energy consumed by the lights in the labs, the energy used by the computers during the simulations, ecc. On Marineshift360 we accounted for a total of 6 kWh of energy used. The boat's life cycle has been split in two phases:

1. Production: boat and components manufacture and installation, where we indicated the total amount of each material used in kilograms.

2. End of Life: which comprehends the disposal or recycling process of the components.

Regarding workers consumables, these are not factored in the design analyses as it is extremely difficult to predict in total how many people worked on a single component and for how long, given that the production is conducted by students in their free time.

Limitations on the method:

On Marine Shift 360 the energy is modelled on the Italian energy mix of non-renewable and renewable energy sources and measured in MJ.

We would like to keep in mind that the team has worked with a 30% biobased resin in every infusion process mentioned in the report. To implement it on Marineshift 360, we input 2 resin components (biobased and petrol based) in proportion to the total weight of resin used.

Following the indications given by the committee, to implement the 3D printing processes we selected the item "Expert Template" and we used 'Plastic – PVC General' as construction material. This accounted for about 20 MJ of energy. The plastic used in our production processes for 3D printing is, in reality, sustainable PLA plastic.

Assumptions:

It needs to be specified that our lab has in stock large amounts of materials such as polystyrene or flax, as they are also used for other prototypes and projects. As we only need a small portion of it, the lab workers cut only the strictly necessary amounts to work with. Therefore, it is not possible to quantify the real amounts of waste materials created during the production stage. They are nevertheless minimal.

A.4 BAI Flying Lina 2.0 - Life Cycle Assessment

Now we will investigate the MarineShift360 assessments of the new components of our BAI Flying Lina 2.0. Considering that some parts of the boat have been left untouched since last year, we won't cover those units in this section.

Overall, the graphics show that the production stage is generically the highest impact stage, with the second higher percentage of impact procured by the end-of-life processes. We find particularly important to underline that across the various indexes of analysis, the component that constantly resulted as the highest impact one during the breakdown confrontation, is the "Verticals moulds" assessment. This can be expected as the materials and the processes involved in these components' production are quite heavy impact ones. It is nevertheless crucial to underline the fact that these moulds are made to last and to be used several times before they enter the process of end of life. The waste factor amounts to the 8,87% and half of it is due

Global warming – fossil	Global Warming – non-fossil	Mineral resource scarcity	Energy consumption – non-renewable	Energy consumption – renewable	Water consumption	Marine eutrophication
[kg CO2e]	[kg CO2e]	[kg Cue]	[MJ]	[MJ]	[m^3]	[kg Ne]
2 680	-62,11	28,72	33 660	6 450	27,38	0,18

to the construction of the wings and of their mold.

At first glance, the verticals molds had the major impact due to the use of aluminium and the CNC operation. They contributed alone to the 86,58% of the kg of carbon dioxide equivalent emissions.

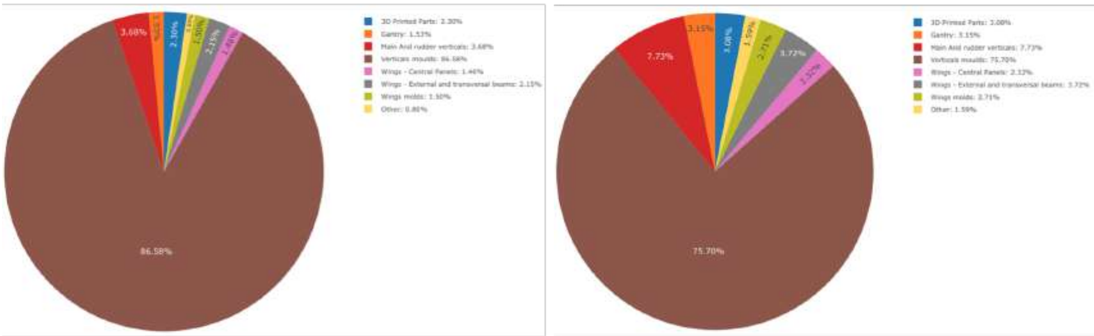
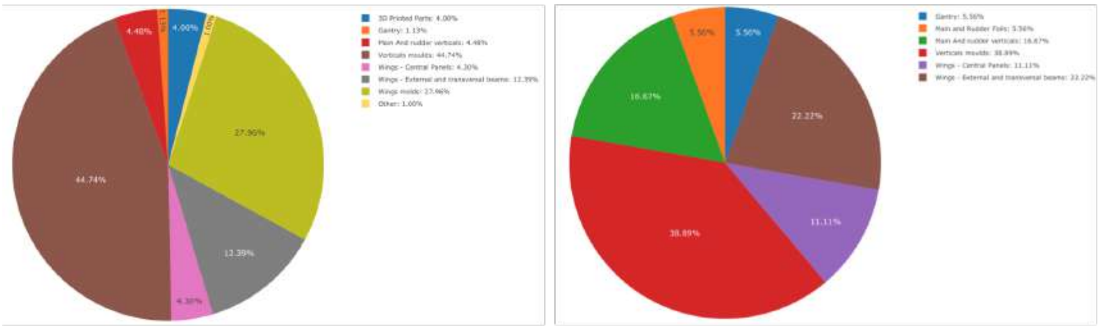


Fig. A.1: Global warming – fossil and Energy consumption – non-renewable



The assessment with negative non-fossil emissions sources was not available on the software. Focusing on the energy consumption of renewables, the quantity of energy requested by the timber of the wing molds is significant and second only to the verticals mold.
A final observation on the marine eutrophication index reveals that a third of the total is due to the construction of wings' central panels and frame. While about another third is due to the vertical molds, because of the use of aluminium. This material had a large impact on the mineral resource scarcity as well. These results confirms that wings and verticals had the greatest impact overall.

A.5 Global impact: the lifecycle of the refit project considering the boat components kept from last year

In this section are reported the results of a global analysis conducted on the project of BAI Flying Lina 2.0, taking into account the components of the boat we kept from last year. To conduct this analysis, we considered the pre-existing parts of the boat as part of the initial production of the boat. The production of the new components is set to coincide with the overall use phase, according to the software's type C scenario.
The graphics show that during the life cycle, the major impacts derive from the production phase of the various components. The older components in the production stage show a higher impact on global warming - fossil, non-renewable energy consumption and mineral resource scarcity indexes; on the other hand, the new components inserted during the use phase have higher impacts on renewable energy and water consumptions.

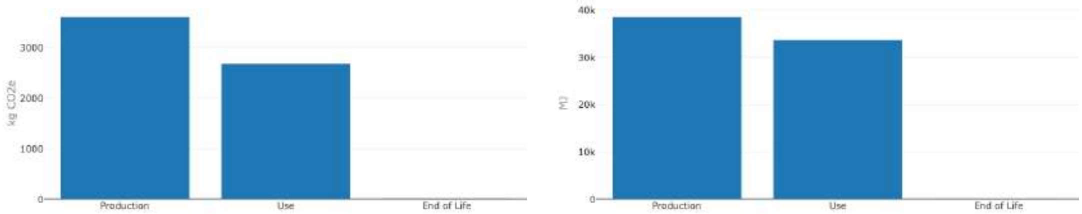


Fig. A.2: Global Warming – fossil and Energy consumption - non-renewable

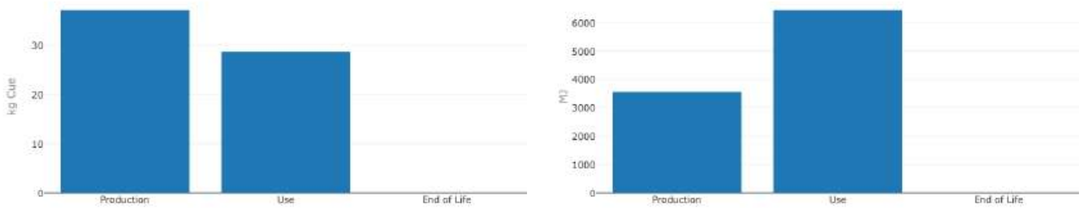


Fig. A.3: Mineral resource scarcity and Energy consumption – renewable

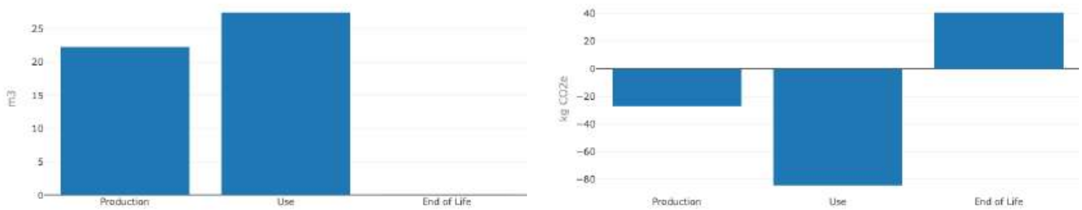


Fig. A.4: Water consumption and Global warming: non-fossil emissions of the whole refitting process of BAI Flying Lina 2.0

It is fundamental to underline that the global warming non-fossil index is negative at -71.14 kg CO2e. This is the net gain between the scores of -27.32 in the production phase, -84.53 in the use phase and +40.7 in End of Life one, in the respective unit of measurement.
Across the different breakdown indexes, the major impact components are the foil moulds and the vertical moulds, which together take up to 89.68% of the fossil global warming chart, 81.03% of non-renewable energy consumption and an impressive 97.09% of mineral resource scarcity. This is caused by the selection of new virgin aluminium as the component of the foil mould and a 30% recycled aluminium for the vertical mould: this decision was influenced by the company provider, and we had to proceed with that. Once again it is important to stress the fact that these components are designed to be used multiple times and over a prolonged period of time.

Discussing waste factor, the average score is 18.12%. The highest relative waste is found in the hull production, as it was an intensive work of lamination, at 24.79%. The other components are overall balanced and contribute to lower the average score. The aluminium moulds do not influence this section as heavily as in the above: there is not a loss of material, and they will be reused in the future.
Looking at marine eutrophication, we can identify once again the foil and vertical moulds as the most impacting at about 20% of the total fraction of the components for each one of them. The other units are nearly balanced. The total equivalent is at 0.38 kg Ne.

A.6 Further comparisons and design choices

A.6.1 Wings moulds

During the design for production stage, we compared the two types of wing molds considered, using Marineshift360. The results clearly showed us that the rib cage system was the best choice in terms of sustainability, adding to the clear benefits expressed in terms of craftmanship and economics.
As a matter of fact, the data below justify our choice in every aspect. The wooden mold was the best option to accomplish our goals. Also, the analysis confirmed that the polyurethane foam is hard to recycle and has a not negligible environmental impact. Furthermore, the foam mold would have required several hours of work with a CNC milling machine, resulting in a higher energy consumption. The graphic below describes a higher consumption of energetic sources from the wooden molds just because it refers to renewable sources. With the use of CNC milling, it would have resulted in the consumption of non-renewable energy.
Also, as the graphics show, the impact on marine eutrophication turned out to be null, and

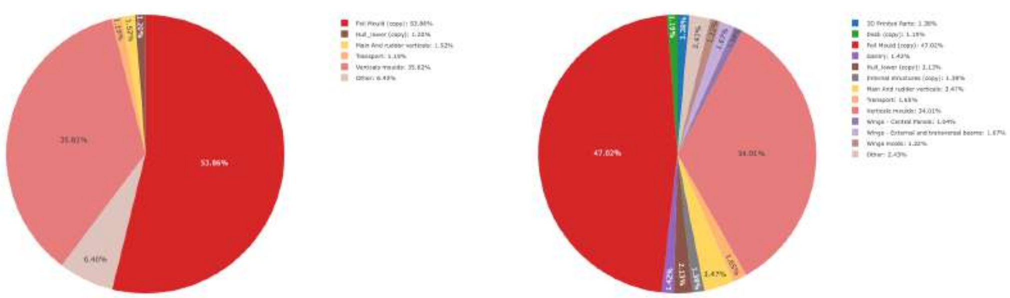


Fig. A.5: Global warming – fossil and Energy consumption - non-renewable

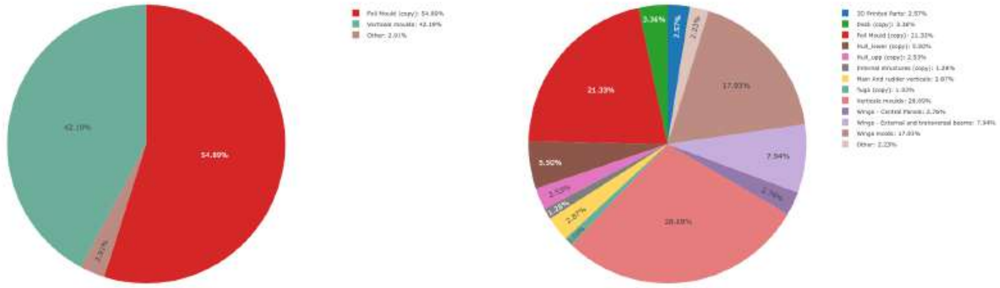


Fig. A.6: Mineral resource scarcity and Energy consumption – renewable

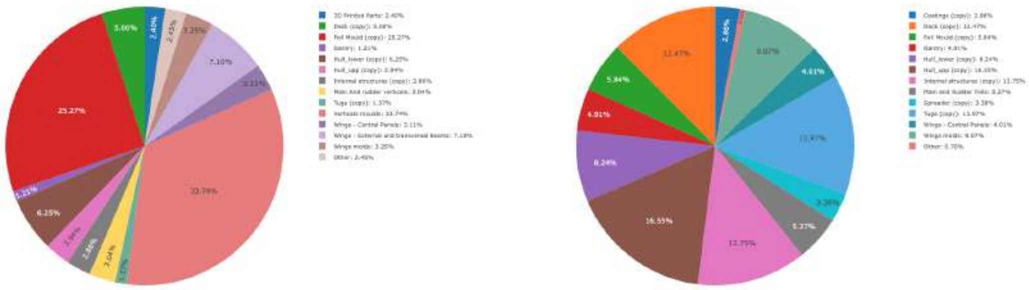


Fig. A.7: Water consumption and Waste factor

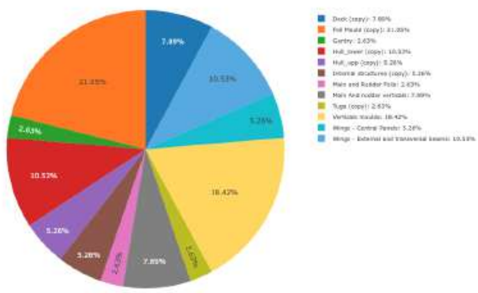


Fig. A.8: Marine eutrophication

Fig. A.9: Global warming – fossil (wings moulds comparison) and Global warming - non-fossil (wings moulds comparison)

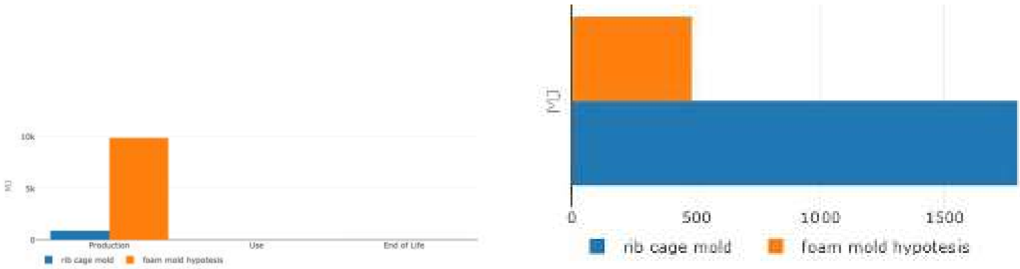


Fig. A.10: Energy consumption – non-renewable (wings moulds comparison) and Energy consumption - renewable (wings moulds comparison)

the water consumption was neatly lowered if using the rib cage mould system. The mineral resource scarcity is lower as well.

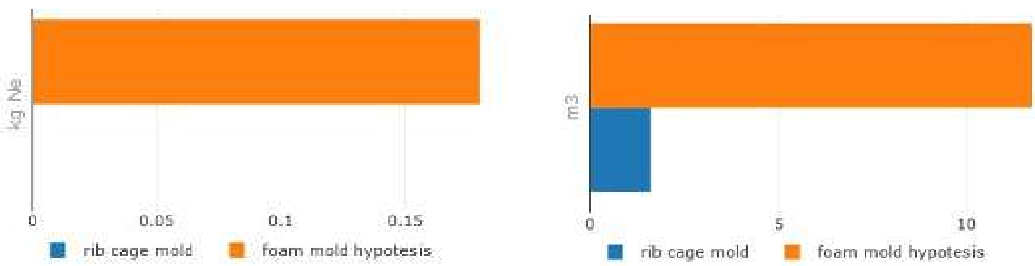


Fig. A.11: Marine eutrophication (wings moulds comparison) and Water consumption (wings mould comparison)

A.6.2 Wings frame: comparison between reused material and PVC

Our first plan was to reinforce the core of the linear parts of the frame with PVC. Since we had the opportunity to reuse some windsurf carbon fiber masts, we made a comparison between these two options to find the best one to enhance sustainability. We implemented 1.5kg of material from the masts as material reused on Marine-Shift 360 and, by comparing the same weight of PVC, the results indicated considerable benefits in the first option, with no surprises. Energy consumption was reduced, and global warming effects as well. The marine eutrophication is diminished, as showed in the graphics below (the orange represents the frame with the reused carbon masts, while the PET option is in blue). The process involving the masts required 130.2 MJ (8.39 kWh) less than the other: it is the equivalent of 130 full battery charges of an average laptop computer. The renewable energy consumption has not changed, while global warming is set on 55.88 kg CO2e, with a saving of 5.84 kgCO2e. The reused masts option reduced the marine eutrophication by a fifth of the total kg Ne.

A.6.3 Foil

With an area of 0.2 m^2, the foil is composed by flax (0.31 kg) and carbon fibers, infused in resin. It was then hand laminated. The carbon intake has been separated into two components, a fraction being Carbon High Modulus (0.059 kg) and the other Standard Modulus (0.123 kg). All its parts have been predicted to be left in a municipal landfill, because they are not easily separable from each other.

Global warming – fossil	Global Warming – non-fossil	Mineral resource scarcity	Energy consumption – non-renewable	Energy consumption – renewable	Water consumption
[kg CO2e]	[kg CO2e]	[kg Cue]	[MJ]	[MJ]	[m^3]
13.12	0.63	0.02	305.36	56.62	0.42

A.6.4 Main and rudder verticals

The input here is a balance of flax fiber and carbon standard modulus. Again, the resin is 30% biobased and the process of lamination has been done by hand with wet layup and compression molding.

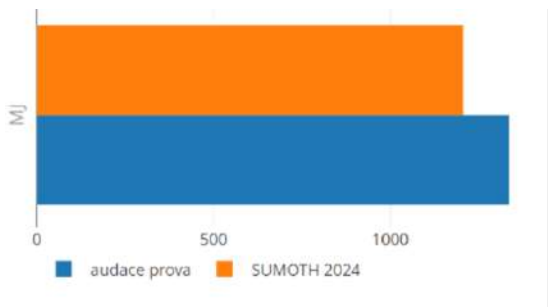


Fig. A.12: Energy consumption – non-renewable (wings frame comparison)

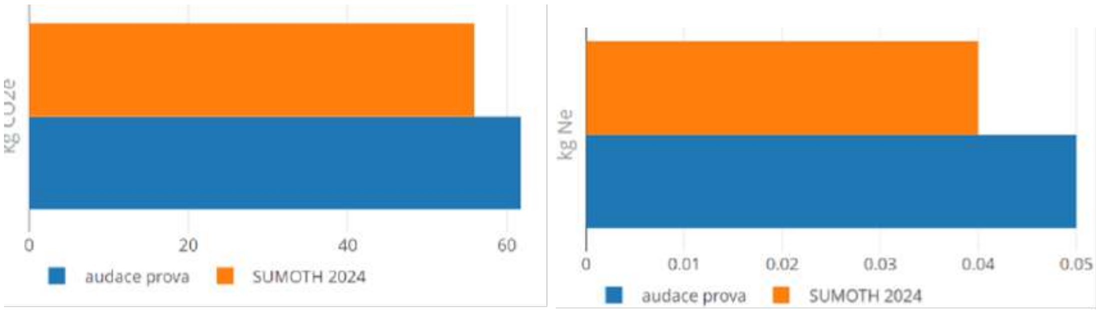


Fig. A.13: Global warming – fossil (wings frame comparison) and Marine eutrophication (wings frame comparison)

Global warming – fossil	Global Warming – non-fossil	Mineral resource scarcity	Energy consumption – non-renewable	Energy consumption – renewable	Water consumption
[kg CO2e]	[kg CO2e]	[kg Cue]	[MJ]	[MJ]	[m^3]
95.58	3.71	0.14	2507.96	287.54	1.51

A.6.5 Rudder control

The rudder control is made by 0.2 kg of Carbon Standard Modulus, infused with 0.15 kg of resin.

Global warming – fossil	Global Warming – non-fossil	Mineral resource scarcity	Energy consumption – non-renewable	Energy consumption – renewable	Water consumption
[kg CO2e]	[kg CO2e]	[kg Cue]	[MJ]	[MJ]	[m^3]
8.71	0.13	0.01	227.39	8.17	0.06

A.6.6 Gantry

The “part dry fibre” section groups all the fibers used in the gantry altogether: Flax, Carbon High Modulus, Carbon Standard Modulus, Recycled Carbon and Fibreglass. In addition to the resin used in all the other components, the construction of the gantry needed also adhesive epoxy. To simulate the core materials, we chose the items of Reused Material, Plastic PVC General and PET foam (recycled). The data processed by the software is the following.

Global warming – fossil	Global Warming – non-fossil	Mineral resource scarcity	Energy consumption – non-renewable	Energy consumption – renewable	Water consumption
[kg CO2e]	[kg CO2e]	[kg Cue]	[MJ]	[MJ]	[m^3]
39.75	3.22	0.06	1021.46	72.78	0.60

A.7 Considerations on End of Life

Clearly, our goal is to reduce the environmental impact as much as possible, without sacrificing the boat's performance. We have worked on the design and the materials selection since last year, and we hope to improve our projects even further in the future.
Moving on to the boat's future disposal, we will focus firstly on reusing components where possible; hypothetically they could be transferred to another training sailing boat. Another option is to adapt some parts to fit a completely new application, as we did with the carbon tube in the wings (which is coming from an old windsurf infrastructure).
The remaining materials will be recycled, if they can be isolated from other substances. Unfortunately, materials such as gelcoat and epoxy resin are challenging to manage; we reached up to local companies who could possibly recycle our resin waste, but they were not able to accept it as the volume is minor to them. Given their reasonable calorific power, we decided to incinerate them.
We selected timber wood as the main constituent of the moulds: besides ensuring good properties, it allowed us to keep a low energy consumption, due to limited use of CNC's related work.
It needs to be highlighted that fossil-energy consumption has been restrained throughout the production stages: indeed, we managed to drastically reduce the amount of CO2 emissions compared to last year, employing mainly sustainable energy sources.