

FOILING SuMoth CHALLENGE

CHALMERS F O R M U L A SAILING TEAM

Foiling SuMoth Challenge Stage 1 - 2024
DESIGN, MANUFACTURING & SUSTAINABILITY

sponsored by





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Introduction

The Chalmers Formula Sailing Team has existed since 2018 and has actively taken part in several competitions across Europe. The team, however, was inactive in 2021. In the fall of 2022, with the initiative of our Team Captain Wilhelm Eriksson, we gathered to build a new organization around the Chalmers Formula Sailing Team.

With a completely new group of students, we were very excited to get the project going again. It was decided that in the upcoming years, the team would take part in the Foiling SuMoth Challenge, in contrast to former participation in the 1001 VELAcup in which the team participated in 2018, 2019 and 2020 (only design stage) with the boat Linnéa. The Foiling SuMoth Challenge is a student competition to design, develop and sail the most sustainable kind of Moth. The competition consists of three stages: Design stage (S1), Manufacturing stage (S2), and the Racing stage (S3). In the 2023 edition of the Foiling week, we made a debut where the team participated only in the S1 Stage. The competition also acted as a place for engaging with teams across the globe and gaining valuable knowledge on the different designs and manufacturing techniques present today.

During the fall 2023, a new recruitment process invited new members to join while others had to leave. This team continued throughout the fall to finalize the design and moved to manufacturing stage with production start in January 2024. This report thereby describes the design concept of our boat as well as the details that entail the manufacturing process.

Report structure

The report begins with background knowledge where the general design of a moth is presented, followed by the preliminary design concept of our moth. The following chapter deals with the manufacturing and economic analysis of the build. Further on, the different materials consumed and the cost for each part are presented. An environmental analysis is then carried out and the results are presented in Chapter 4. The report ends with information about the 2024 team, our current sponsors and a token of gratitude towards the people who helped make this project come alive.



1 Engineering and Design

1.1 State of the art

Before starting the design work a big emphasis was put on a preliminary design study of already existing designs. Early on, requirements of the boat were set to define design parameters of importance and from there guide our design in the right direction for the intended use. The International Moth Class Association (IMCA) rule sets geometrical constraints and gave a good starting point together with a study of already existing designs. Because this project aimed to design a high performance racing dinghy, parameters such as speed, weight and ergonomics were of importance.

1.1.1 Preliminary design study

As mentioned, the rules that apply is the IMCA box rule, which leaves very much freedom of design. A natural first step for the preliminary design study, was to investigate already existing moth dinghies to get a sense of current racing standards. This led us to analyze already market-leading Moths such as eXploder, Swift, Bieker, Aeroscet, Manta, and Mach2.

What we found from the study was a trend in the design philosophy as most brands focused more and more on the aerodynamics of the boat. The hulls are now slender and flat but ropes and lines are also being hidden into the hull and wing to remove aerodynamic drag. Upstream of the sail, the trend is to have a flat foredeck without anything that can disturb the airflow to the sail. There's also a development of the wing bars with aerodynamic profiles to help to create forward power to the boat. Models such as the eXploder now have hull and wing bars integrated together as one, creating a very complex shape with the aim of being as efficient as possible. All the top performing moths are generally completely built using carbon-epoxy materials. Modern moth dinghies have rig and sails with deck sweepers which further increase the importance of a clean upper deck to minimize air disturbance to fully utilize the deck sweeper sail.

As defined in the rules, all moth boats that compete in IMCA competitions use a completely mechanical control system for their foils. The control system has a manual adjustment that controls the flight height and reactivity. The regular IMCA-ruling forbids the use of an electronically controlled system but this is allowed in the SU-Moth competition. Such systems could potentially be a better, more efficient solution as it can be customized in its behavior compared to a mechanical one. But it is also much more complex and arguably less reliable given the wet conditions on a moth and could also weigh more than a simple mechanical system.

Another important part that has seen a lot of development over the years is the foils. Foil design is something that is researched a lot to control cavitation and ventilation effects while optimizing lift over drag to increase the overall performance of the boat. Slim and thinner profiles are seen as stronger and stiffer materials are developed alongside improved manufacturing methods. The use of winglets on the foils has also become popular to reduce the tip vortex which further reduces drag although rounded, unloaded tips are seen as well.

1.1.2 Forces in action

In Figure 1, a simplification of the forces acting on the Moth is illustrated in foiling condition. If 0 degrees of heel is assumed, the aerodynamic forces from the sail contribute to a righting moment around the x-axis that has to be balanced by the weight of the sailor. If sailing with a negative heel angle, the weight of the boat will also contribute to a righting moment. To determine the position of the main foil, wing bars, and mast, a force equilibrium equation summing up the forces and moments acting on the boat in both the horizontal and vertical directions is set up. In the vertical direction, the sum of the forces (buoyancy, gravity, and lift) must be equal to zero as the boat is in equilibrium. Equally, the sum of the horizontal forces (drag, sailforce, and side forces from the sail and foils) must be equal to zero. It is important to get a balanced boat, especially in the longitudinal direction.



Figure 1: Forces acting on the Moth

1.1.3 High performance sailing aerodynamics

As the moth class has been around for a while now, an accelerated development within fluid dynamics has been seen over the last couple of years. Improvements on aerodynamic features such as wings, hull and the implementation of deck sweeper sails. Van Hoorn evaluated the performance of different sail designs by performing computational fluid dynamics on an International Moth as a bachelor thesis 2021 van Hoorn, 2021. More specifically he evaluated the performance of a deck sweeper and compared different designs with numerical simulations.

The use of a squared deck sweeper configuration proved to be more efficient for most of the conditions tested. The idea is to minimize the air leakage between the sail and the hull where the flow tends to separate and create drag by extending the sail all the way down to the deck. To fully utilize the deck sweeper the airflow upstream to the lower part of the sail must be undisturbed as well. Therefore it is crucial to have a foredeck that is as smooth as possible, without ropes, blocks, etc. disturbing the airflow. Therefore, ropes and control systems should to the greatest extent be hidden under deck and fairings to keep the flow attached.

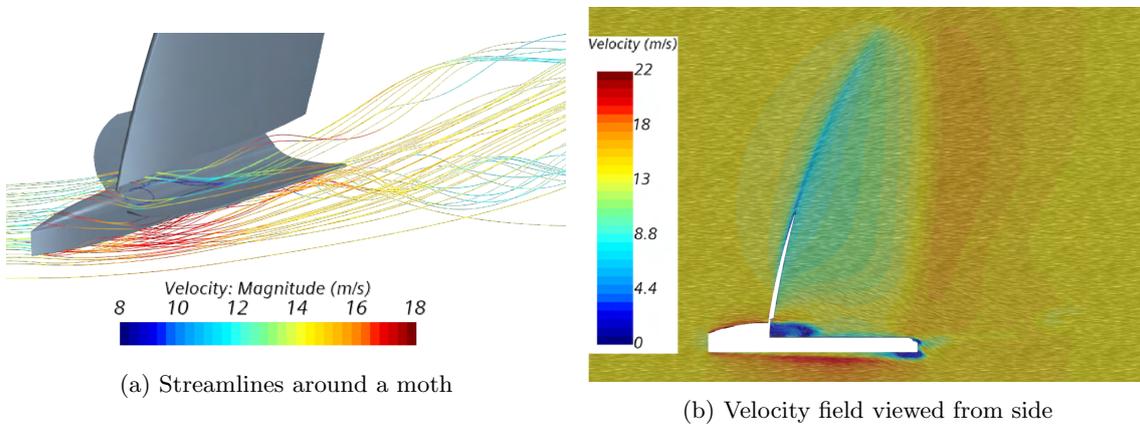


Figure 2: Aerodynamics of a mothvan Hoorn, 2021

1.1.4 Wind analysis

Situated in northern Italy Lake Garda is renowned for its unique weather patterns and surrounding terrains which makes it an attractive sailing destination. Surrounded by mountains of the Southern alps the lakes geography contributes to the local weather phenomena including strong and consistent winds during its long season (Giacomo, 2020).

The two main winds of the region, Pelér and Ora are thermal breezes, a phenomenon commonly observed in regions with contrasting land and water surfaces. Thermal breezes result from the differential heating of these surfaces, which leads to localized temperature variations and the subsequent movement of air. Both of these winds are directed along the elongated shape of the



lake which combined with the towering mountains on either side creates a natural funnel effect channelling wind through its valley and across the water (Laiti et al., 2013).

At night, the rapid cooling of the surrounding mountains cause the air to become cold and dense. As a result, gravity pull this denser air downward, displacing the warmer air. This downward movement, accelerated by gravity, generate a strong and fast-moving wind down the mountains called the Pelér. The narrowing valleys and slipes further amplify this effect, creating a focused and powerful wind that spreads across the surface of the lake from the north (Service, 2004)

As the day progresses and the sun intensity increases, the Pelér gradually loses its driving force due to the equalization of temperatures between the land and water surfaces. As a result, the temperature differential that initially fuelled the Pelér diminishes, leading to a weakening of the wind around midday. This equilibrium state creates a period of calm condition and low winds speeds. However, as the sun continues to heat the land and surpassing the temperature of the water a reversal of the earlier process occurs.

The previous northward flow of wind associated with the Pelér transforms into a southern breeze known as the Ora. This turn of wind intensifies as the temperature difference between the land and water widens, leading to the Ora being the dominant wind from midday until sunset. After which another equilibrium appears and the whole process starts over (Laiti et al., 2013).

The Magnitude of both the Pelér and Ora winds plays a crucial role in determining the appropriate sail size for sailors on Lake Garda. During the early morning Pelér wind, sailors often opt for smaller sail size to effectively navigate the moderate to strong gusts while maintaining control and stability. As the day progresses and the Pelér starts transitioning into the Ora wind, sailors may adjust their sail sizes accordingly. With the Ora Typically delivering more consistent and sustained breezes sailors often choose larger sail sizes to harness the full potential of the wind and maximize their speed and maneuverability on the water (Sails, 2024).

Additionally, the size of the foil correlates with the wind magnitude in the same manner as the sail sizing. As the wind force increases a smaller foil is typically preferred, much like a smaller sail, as sufficient lift is already generated. Conversely, as wind force diminishes, the foil size needs to increase to maintain lift. This is because a certain threshold of lift is required to break free from the water's surface and initiate foiling. Lift is inherently linked to the boat's speed through the water. Therefore, in conditions of lighter wind, either a larger sail to generate more speed or a bigger foil are necessary to produce the needed amount of lift for foiling. However, in strong winds a larger foil may generate too much lift leading to excessive elevating of the hull. Nevertheless, precise sizing of the foil is not always necessary as fine-tuning the foil configuration-based on real-time observations of wind strength, direction and sea state can achieve similar results to some extent.

1.2 Design

Our design process has been closely intertwined with the actual construction, rather than completing the design before starting the manufacturing phase. Throughout the project, we have extensively researched various forums dedicated to home-built moths, drawing inspiration and discovering innovative design solutions as construction progressed.

The primary reason for this approach is the extensive effort invested in securing sponsors to finance the project. Additionally tasks, including CAD modeling, simulations, and calculations, were undertaken voluntarily by the students, without direct guidance from professors.

This approach has been particularly vital in accurately estimating the amount of materials and resin required for the composite work, as well as in achieving a perfect fit for the various components. Instead of relying on simulations or extensive calculations, we based our material usage on rough estimations during the design phase. These estimations were adjusted along the way as the construction progressed and further research into specific parts was conducted.

1.2.1 Hull Design

The hull's main functions are to provide buoyancy, act as mounting point for mast, rudder, foil, and deck hardware, as well as enable low take-off speed. Therefore, moth hulls are generally slender

in order to minimize resistance at low speeds.

The hull was designed using a parametric approach where a general section was defined with a set of parameters. These parameters were described by functions of the longitudinal coordinate which combined with the section definition made up the surface of the hull. The profile selected for the midship section was a U-shape with a small flare to have lower draft and some initial stability.

This was done in the program CAESES because of its easy integration with SHIPFLOW, a CFD software for ships. This was used to get estimates of resistance and wave pattern at an early stage to aid the shaping process. Wave height for draft=0.15m, speed=4kn.

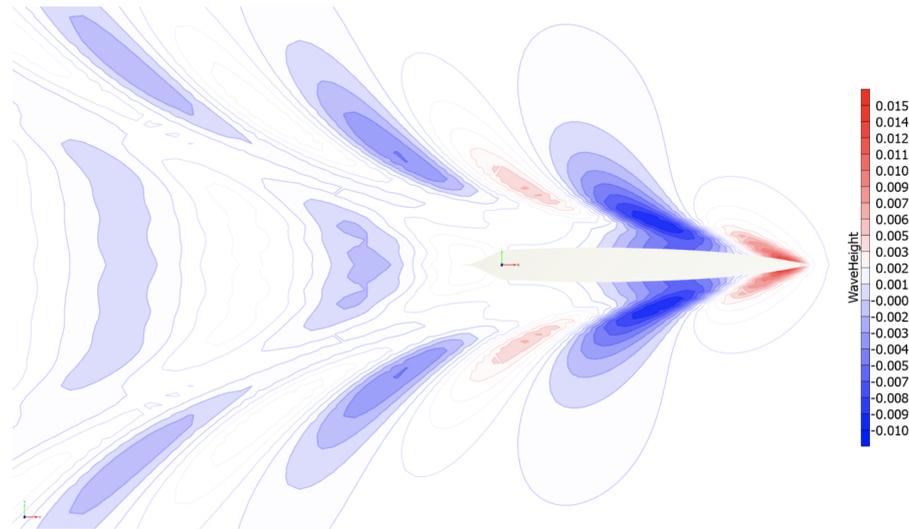


Figure 3: Hull wave analysis

1.2.2 Internal structure

Since we have a slender hull form the transverse stresses are negligible compared to the longitudinal stresses. The longitudinal stresses are carried by the hull and the deck combined. Transverse bulkheads provide resistance against racking along with dividing the hull into two watertight spaces. A stiffener running along the bottom of the deck provides additional bending stiffness. The foil-box and the control channels integrated into the hull provide additional structural rigidity. The foil-box transfers most the weight of the hull and the down-force on to the foil in an even manner by increasing the contact area. Transverse and cross ribs are placed beneath the deck to provide additional stiffness when the sailor put their weight on the deck during maneuvers.

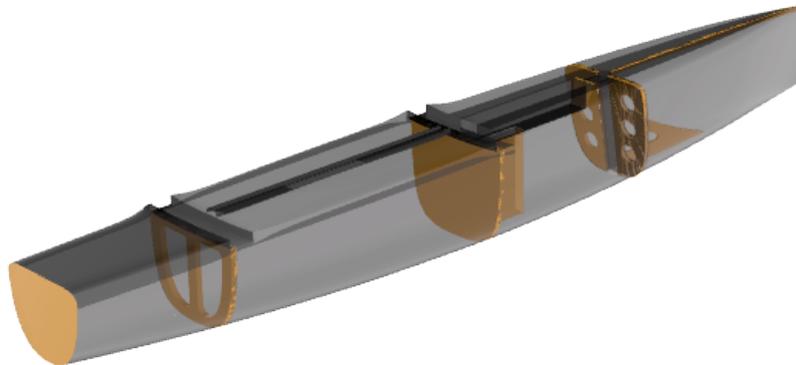


Figura 4: Primary Strengthening Members

The bulkheads are positioned in areas having higher stress concentration. Bulkheads placed beneath the wing-bars assist the distribution of the weight of the sailor and the forces off the wings into the hull form. Bulkhead positioned with the mast distributes the load from the mast to the hull. The three bulkheads combined ensures that the hull is sufficiently stiff. Weight is of high importance, in all means of transport. This is however much more critical in a foiling craft. Material removal in two of the bulkheads makes the hull lighter with a negligible decrease in strength.

Pounding forces are dealt with here with the help two longitudinal stiffeners. The deck stiffener and the hull stiffener running along the center-line ensures that sufficient rigidity is provided without having to use a full bulkhead. The hull stiffener doubles as a mast bracket providing extra support to the mast and reducing the stress concentration.

1.2.3 Gantry

The purpose of gantry is to connect the rudder with the hull and facilitate control, stability and customization to the boat, and in turn to the sailor.

The design objective was simple - a gantry which was light in weight and endured high loads from the rudder. Now, it is to be noted that the loads, being vector in nature, can be very dynamic and therefore really hard to predict. They majorly depend on boat speed, wind direction, sailor input and design characteristics as a whole. The loads can be broadly classified into hydrodynamic, foiling, steering and aerodynamic in nature. On the prima facie, we can deduce that the structure's cross section and material has to be such, that it can endure tension (due to foiling), compression (due to sudden change in direction), shear (lift and side force), bending and torsional loads (due to steering).

In accordance to the (Federation, 2015), the gantry is limited to 500 mm extension from the transom and during the moth evolution several different types of designs has existed. Earlier a tube based design was most common since it is easy to manufacture and an efficient structural design. More common today is a gantry with a surface following the lines of the hull to be more streamlined. However, there is a rule preventing the gantry from lengthening the waterline (Federation, 2015). In practise this means that a 30mm gap between the gantry and the hull is enforced. To ease the manufacturing process a traditional tube based design was selected. This also enabled the use of up cycling hockey sticks to make the design more sustainable and reduce the expense in the sumoth budget.

Another aspect to consider was the shape of structure and its mounting to the hull. Looking at the nature of loads, a triangulated structure was chosen as it ensures 'zero' Degree of Freedom. The

gantry is mounted to the hull by stud bolts laminated into and extending out from the transom. Ideally the bottom tube would be adjustable length to allow for a changeable AoA of the rudder foil. To account for this and implementing a more basic solution is to instead shim the upper or lower mountings if AoA needs to be increased or decreased respectively.



Figura 5: Conceptual design of gantry

1.2.4 Foils

As first-time participants in Stages 2 and 3 of the SuMoth Challenge, the team was provided with loaned foils. However, modifications were necessary to address damages and implement improvements for optimal performance. These foils are production-grade, but they possess certain manufacturing defects that makes them unsuitable for being sold on the market.

1.2.5 Foilbox

There are a handful of commercially standard solutions in the moth class today on how to fit the main-foil. To be able to adapt foils from different manufacturers, an adjustable solution was preferred to be able to control the AoA on the foil. the lower part of the box is designed to fit inserts that can be custom-built to fit different shapes and profiles of the mast. The mast is secured with a stud bolt pointing up trough a longitudinally cut out slot in plate at the top of the foilbox and held in place with a nut and washer on the top of the foilbox. The angle can be adjusted by loosen the nut and angle the foil, sliding the stud bolt. The box is made slightly oversized on the top to allow for different manufacturer and might need shims for a tight fit.

1.2.6 Wings and rig

Throughout the project, the wings have been at the center of discussion. Initially, it was considered to have wings integrated with the deck. However, as we are restricted by a cost cap, the wings were concluded to be built with the lowest possible impact on our SM\$ budget by utilizing bio-materials. This changed the first concept with integrated wings to a frame design with soft wings instead.

Functionality and performance The main purpose of the wingbar is to support the loads from the sailor and the rig. It disperses the loads and forces generated by the mainsail out to the sailor. Therefore a rigid construction is of high importance to minimize flex and torsional movements. The wing bars were given a curved shape with the aim to improve ergonomics and boat handling. It was also argued to gain aerodynamic performance with the use of a deck sweeper. However, that was never evaluated or confirmed with CFD simulations due to lack of time. According to the



IMCA class rule, the total width of the boat must be within 2255mm. The Moth is sailed with a heel, thus to get maximum leverage the wing should have an angle relative to the horizontal plane of the hull. Because our wing is curved, a triangle can be drawn. The length of the hypotenuse then equals the leverage to the sailor while sailing. In other words, angled wingbars help to provide righting moment.

Wings We landed in a removable wing design where the wingbars are made of laminated wood covered by a soft wing sewn from used sail cloth recovered from a damaged sail. The wingbars have a square cross section of 45 by 45 mm and have a single continuous bend spanning the maximum width of 2250 mm. Many previous designs, as well as ours last year, used a double bend with the motivation that it was more ergonomic for the sailor. However, after discussions with local sailors it was discovered that the single bend design was the more ergonomic option with a larger platform allowing for easier maneuvering. The use of the maximum span is standard for the moth class as a wider beam allows for higher righting moment allowing larger forces from the sails increasing speed.

1.2.7 Rig

The IMCA allows a maximum sail area of $8.25 m^2$. In favour for the SU\$-budget, a second hand rig was opted for. From subsection 1.1.4 and subsection 1.1.3, a decksweeper sail with the maximum sail area was desired, although budget and availability played a part in the ultimate choice of rig.

1.2.8 Control systems

For a foiling Moth the lift from the foil is dependent on the velocity meanwhile the down force generated by the boat is not. This makes it necessary to regulate the lift from the foil, so the foil stays under water and the hull stays out of water. The decision was made to implement a mechanical system to ensure the boat's compliance with the IMCA rules. Thus the boat will not utilize any electronics to control the ride height.

To control the lift a wand type arrangement will be used as a form of sensor, see figure 6. The system consists of a wand connected to a stiff rod, which in turn links to a bellcrank connected to the flap on the foil. On the stiff bar a offset screw is added to ensure adjustments in the system.

When designing the lift control system we decided between a pulling or pushing system. The pulling or pushing focuses on the stiff rod connecting the wand to the bellcrank. Both of these systems are commonly used in competitive Moth sailing but lately more have gone to choose a pullrod system. The benefit of the pullrod is that it eliminates the risk of buckling, allowing for a thinner rod saving on weight and material usage (Boman, 2020).

Our acquired foils was produced for a pushrod system. Therefore changing to a pull system meant that we have had to change the linkage between the pullrod and the bellcrank. Commonly used is a reversion linkage before the adjustment screw which allows to keep the main vertical untouched. The problem with this system is that it takes up space above deck, increasing the risk for tangle with the other control lines. See figure 7 Our decision was instead to change the bellcrank coupling in the main vertical. By moving the pivot point backward on the mast we could reverse the bellcrank allowing us to use a pullrod from the wand and a pushrod down to the mainfoil. See figure 8 We chose to reverse the linkage this way as it meant less parts to produce as well as more free space above deck.

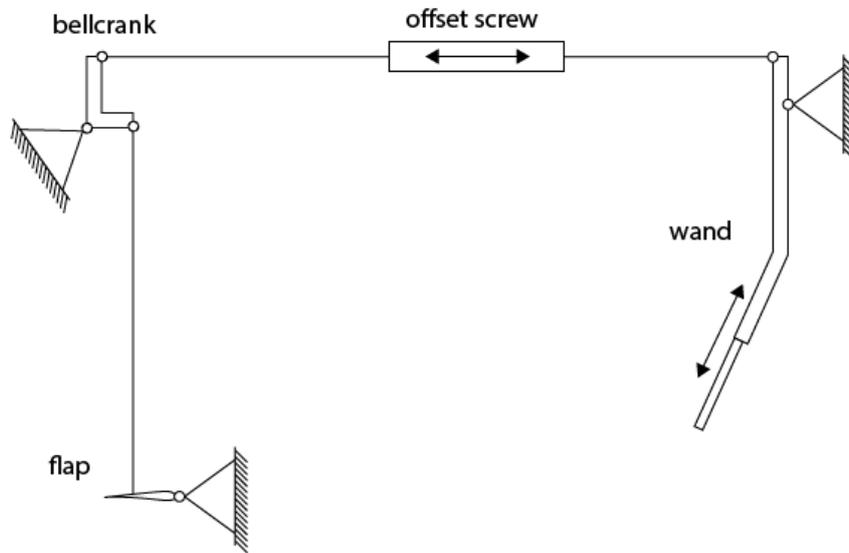


Figura 6: Sketch of wand control system

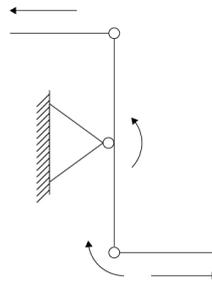


Figura 7: Reversion linkage

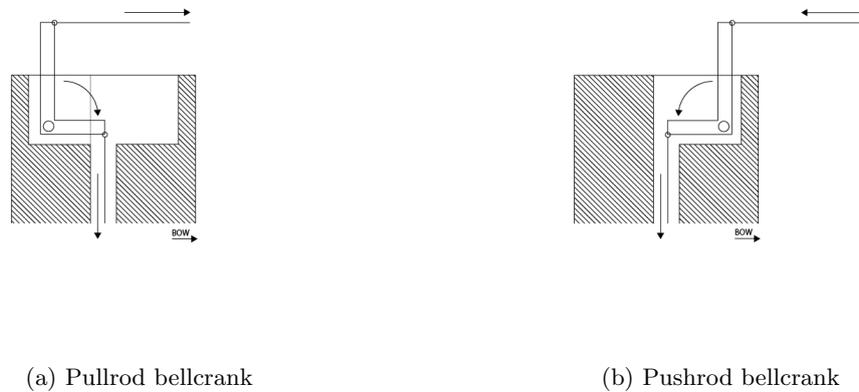


Figure 8: Difference in bellcrank pivot

1.2.9 Material choices

From early on it the clear choice was to use composite materials for the project to reflect what is most currently used by the industry. This is also dependent on the mold concept being an optimal trial for composite materials mixed with large scale 3D printing. Since the time frame for a normal plug mold setup is long and typically expensive bringing a faster alternative that could be used in prototyping composite parts industry wise could come with great benefits, not just by shortening the timeframe but also being an eco friendly alternative since the molds can be melted down and recycled.

For the fibers we went with BCOMP ampliTex™ 300 g/m² which is a good balancing point in the BCOMP lineup between rigidity and weight together with BCOMP powerRibs™. Using flax fibers instead of carbon greatly reduces the impact on the environment. Smith Smith, 2023, concluded in a previous study that one Ply of ampliTex™ 300 g/m² together with 1 Ply of powerRibs™ offers comparable bending strength and stiffness to the baseline carbon while reducing weight, however the study is based on a "non structural" part and therefore without core. Since extra rigidity is needed in the hull and deck in the form of core, a layup of two skins as a sandwich construction is needed to close in the core. On all areas without core powerRibs™ are placed to give the stiffness needed. Carbon fibers will be used to stiffen up critical areas of high load. The carbons used in the build is cutting-machine excess mostly containing unbranded mixed seize pieces of BX, QX and some mixed UD fibers.

The choice of core is also made with sustainability in mind, however, it might not appear so at first glance. The goal for the core was to have light thin sheets spread out in areas of high stress as well as positions where bulkheads where to be glued in to ensure a flush waterproof fit with high surface area. The core that was chosen was A Diab 80 kg/m³ virgin PVC Core. The reason for this specific core is the resin uptake. Having a denser virgin core is from a baseline comparison of carbon footprint worse than a lighter non-virgin core, however when taking resin consumption into account the situation changes. According to calculations made with MS360 represented in Table 1 using a virgin core which takes less matrix to fill gives a lower carbon footprint. This comes down the the resin having a high carbon footprint and since the higher density virgin core drinks less it gives lower carbon emissions than a comparable non-virgin core. Summarizing using the 5 mm 80 kg/m³ core gives a lighter and more environmentally friendly end product.



Table 1: CO₂ and weight calculation comparison of different core materials.

Product	Resin (kg/m ²)	Dry weight	Resin weight (kg)	Total (kg)	CO ₂ Footprint
5 mm PVC core 60 kg/m ³	1.08	2.7193002	9.78948072	12.50878092	53.71 kg
5 mm PVC core 80 kg/m ³	0.87	3.6257336	7.88597058	11.51170418	48.43 kg
5 mm rPET core 80 kg/m ³	1.2	3.6257336	10.8772008	14.5029344	54.79 kg

For resin two locally produced epoxys from Nils Malmgren AB (NM) was used. "NM Infusion 665" together with the "NM Hårdare 650 M" curing agent for infusion purposes as well as "NM Laminering 635" with the curing agent "NM Hårdare 650 B" for wet laminations. These are BIO-resins with a bio content of 33% produced just outside Gothenburg with good mechanical properties. However a test made together with Nils Malmgren AB gave the matrix to fiber properties of 60:40 on a test pice of ampliTex™ 300 g/m² which is i substantially higher resin consumption than spec. The probable cause of this is not properly drying the fibers beforehand. As a release agent for infusion parts, we where gifted a opened can of an unknown realease agent believed to be MARBOCOTE 227 which had expired 2013 but was said to still work. If not used it would have been thrown away and was therefore the clear choice.

1.3 Molds

A vacuum infusion or pre-preg manufacturing solution was preferred to enhance the quality of the laminate by maximizing the fibre to matrix ratio. To allow for a vacuum infusion of the hull and deck, a negative mold design was required. Several concepts were evaluated, including a strip built negative mold similar to the team's open mold concept the previous year. Such a mold would be favorable for the SU\$-budget as it is built completely using wood, but was argued to have a longer build time. In the light of making the process faster and easier, the option to 3D-print the mold was evaluated.

1.3.1 Large scale 3D-printing

In 2022, Melker of Sweden, together with RISE, printed a full scale prototype of a kayak using wood fibre reinforced recycled plastic (Bioinnovation, 2022). With the foiling moth being sensitive to weight, directly printing the hull would result in a heavy boat. While Melker made a prototype of their final product, we wanted to explore the technology as a tool to manufacture a lightweight composite hull.

Large scale 3D-printing comes with some challenges and limitations. With the help from a local company, Circlab, the molds could be printed using a ABB robot equipped with a KFM extruder, capable of printing 20kg/h. The robot allow parts with maximum dimensions 6x2x2m. The extruder can print most materials with a meltpoint between 150-200 degrees Celsius. Typical material, PLA for example, with a melting point around 150-180 degrees Celsius has a glass transition temperature (T_g) around 55-60 degrees Celcius, that is the temperature at which the materials soften and potentially loose it's shape. Although materials with higher (T_g) exists, they are more prone to warping during print. Surface finish is another limitation that had to be considered in the design process.

With experience from Circlab, the best surface finish was achieved using a PLA with their smallest 6mm nozzle. With the ability to produce custom filament, cellulose fibres were added to the PLA, making it a wood-plastic composite (WPC) with 20% fibre content. Higher fibre content was found to create a porous end material.

The design process involved small-scale prints to verify design ideas and print settings. In total, five iterations were done and throughout the process the print-time and material consumption was reduced, resulting in approximately 50% cost savings from the first prototype to the final product.

The first concepts consisted of five separately printed segments for both the hull and the deck, held together with a wood frame. They where modeled solid in CAD and imported to a slicing software to customize the prints with a custom infill. Although different infill patterns could

be optimized to minimize material consumption and increase strength, it was slow to print and demanded a lot of material, making it expensive to produce in full scale. Instead, the next concept was designed as a shell. It also utilized a wood frame, along with external wooden bulkheads to reinforce and stiffen the printed shell. Small flanges were added to the sides to increase its torsional and longitudinal stiffens further. This proved to be faster to print while being rigid enough with the external bulkheads. All concepts where printed standing, i.e. bow up.

In the final design, the deck and hull mold where merged together and printed at once in vase-mode, which means the printer-head prints one continuous single layer at the outlines of the part, see Figure 9. Compared to previous concepts with multiple parts, the deck and hull where merged, making a connected, circular path for the printer. This makes for a smoother more time-efficient print with less parts. Due to the height constraint of the robot, the mold was split and printed in two parts, bow and stern. This also allowed the parts to fit in a car, making transportation convenient.

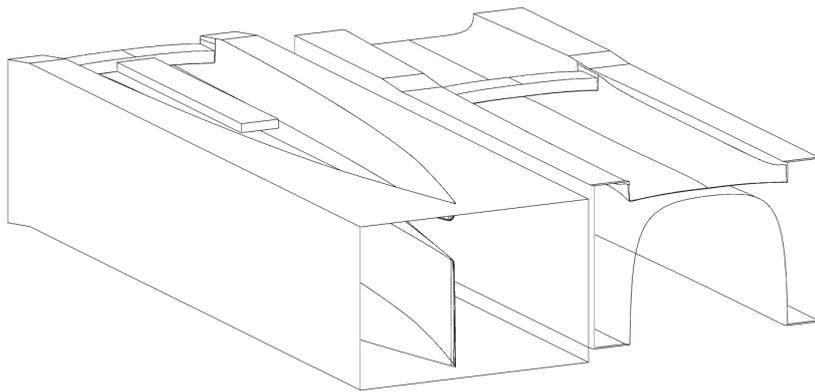


Figura 9: 3D-printed mold design

Figure 9 shows the final mold design with deck and hull connected together and split in two parts. The print is done standing, with the the split midships on the baseplate and the bow and stern up respectively.



2 Manufacturing and cost analysis

2.1 General description

The focus throughout the process has been to choose materials and manufacturing methods to balance weight, strength, and sustainability.

2.2 Hull & deck

2.2.1 Infusion

For the hull and deck, the 3D printed molds were used. To be able to produce industry-like and lightweight parts the choice to do infusions on both these parts were made. The process could be argued to be less environmentally friendly since it requires more single-use plastics but helped to avoid oversaturation of the flax fibers.

2.2.2 Resin

In the tests with our NM it was concluded that the flax drinks roughly 60:40 to its own weight. This aspect was used when calculating the amount of resin for each part. For purchasing of resin a rough overhead of the areas with the planned layup was used together with estimations or true values of what all different materials in said layups were to consume. For the carbon, a 40:70 mix was used for calculation purposes. For the rest of the resin consumption calculations, the manufacturing spec was used.

2.2.3 Layup

The materials choice for the layup of the hull and deck follow the same narrative, Using BCOMP ampliTex™ 300 g/m² fibers for the bulk of the hull together with BCOMP powerRibs™ which not only helped the structure, but also minimizing the amount of single use plastics & consumables during the infusion of the hull and deck. Both the hull and deck consist of two layer sandwich designs with the outer skins of BCOMP ampliTex™ 300 g/m² and the core being a virgin PVC 80 kg/m³ from Diab in 5 mm sheets.



Table 2: Hull Layup

Hull & Deck superstructure					
Type	Item	SM\$/unit	Unit	Quantity	Price
Material					
	BCOMP ampliTex™ 300 g/m ²	0	g	3320	0
	BCOMP powerRibs™	0	g	1094	0
	Diab 80 kg/m ³ PVC Core		g	40	
	BX 1600	200	g	200	40
Processing					
	NM Infusion 665	25	g	9480	237
	NM Härdare 650 M (Hardener)	25	g	3320	83
	Releaseagent Expired 2013	50	l	0.2	10
Production					
	Bag	2	m ²	24	48
	Tacky tape	8	m ²	4	32
	Peelply	5	m ²	5	25
	PVC vacuum hose	1	m	10	10
	Input line	1	m	6	6
	Infusion Mesh	10	m ²	2	20
	Bonding agent	15	kg	0.4	6
Total					517

2.3 Core

For the core we went with a higher density virgin PVC core form Diab in 5mm sheets of 80 kg/m³. The motivation for the higher density core is related to it's resin uptake being lower than using a lower density core. By using the higher density virgin core, we can therefore accomplish a stiffer, lighter, and less resin-consuming end product that also produces a lower carbon emission, see Table 8.

2.4 Gantry

Manufacturing of the gantry is best performed using a "jig" to hold the tubes in the correct locations and angles while doing the lamination. The ambition is to build this jig with materials that has been left over from earlier stages in the build. Since visual defects and resin spill etc has no effect on the function of the jig. The circular tubes and hockey sticks are cut into the correct lengths and prepared, and then assembled together by a wet lay-up of carbon fibre and epoxy resin. Below is a preliminary plan for amount of materials needed. The carbon tubes are store bought as one unit with length 2 meters with outer diameter 16 mm and wall thickness 1 mm.



Table 3: Materials used for manufacturing of the gantry and the associated costs

Gantry					
Type	Item	SM\$/unit	Unit	Quantity	Price
Material	Carbon tubes	80		1	80
	Hockey stick	0			0
	Epoxy resin	15	kg	0,1	1.5
	Carbon fibre	150	kg	0,1	15
Production	Brush	2	#	1	2
	Peel ply	5	m^2	0.1	0.5
Total					99 SM\$

2.5 Foilbox

The foilbox is one of the components that is susceptible the highest loads and thus it is motivated to use carbon fibre for this part. Due to its complex geometry, it is difficult to perform an resin infusion on the layup. Hence, this part is done as a wet lamination then a vacuum is applied such that the excess resin and air is removed for maximum strength. The foilbox is mounted into its mounting hole by structural glue. The glue used is Sika Adekit A 140 (Sika, 2024), a two component epoxy adhesive passed its expiration date. This glue is used for multiple parts on the hull and every application is difficult to measure the amount used. Therefore the total glue usage will instead be specified under the hull manufacturing to ensure a correct measurement as the sum of all contributions.

Table 4: Materials used for manufacturing of the foil box and the associated costs

Foil Box					
Type	Item	SM\$/unit	Unit	Quantity	Price
Material	Carbon fibre	150	kg	0.15	22.5
	Epoxy resin	15	kg	0.18	2.7
Production	Tacky tape	8	rolls	0.15	1.2
	Vacuum bag	2	m^2	0.5	1
Total					27.4 SM\$

2.6 Internal structures

Even though carbon fibre laminates were considered for constructing bulkheads, we came across already infused glass fibre sheet from Aston Harald Composite that they had left over. Thus by upcycling the material, contribution is made in making the hull even more sustainable. The longitudinal ribs on the deck also uses cut-out from the glass-fibre sheet, but with additional carbon lamination to provide extra stiffness between the kingpost and forestay attachment in the bow. A hockeystick acted as a tunnel for the pullrod, from the bowsprit through the kingpost connecting to the deck.



Table 5: Materials used for manufacturing of the internal structures and the associated costs

Internal structures					
Type	Item	SM\$/unit	Unit	Quantity	Price
Material	Glass-fibre plate, upcycled	0		1	0
	Hockey stick	0			0
Production	Brush	2	#	1	2
	Bonding glue	15	kg	0.3	4.5
Total					6.5 SM\$

2.7 Foils

As described in subsection 1.2.4, the team was provided with loaned foils, which required addressing damages and implementing improvements for optimal performance. Additionally, the control system needed to be implemented for the foils. As of the current writing moment, this work remains pending.

2.8 Wings

As mentioned previously the wings are made up of wingbars laminated with wood, epoxy and carbon/glass fiber and a soft cover sewn from a sail cloth. The wood is a knot free pine from just outside of Gothenburg. It was chosen for its superior strength to weight ratio while also being moderately stiff as well as local availability (Thomasson, 2018). A trial was made laminating with regular wood glue but that did not result in a satisfactory stiffness so a regular lamination epoxy was used instead.

The wingbars are made of 8 layers of pine glued together in a single continuous bend. No mold was necessary as wood blocks mounted to a work table was enough to shape the wood.

Table 6: Materials used for manufacturing of wings and the associated costs

Wings					
Type	Item	SM\$/unit	Unit	Quantity	Price
Material	Pine	0	kg		0
	Lamination epoxy	15	kg	1	15
	Sail cloth, upcycled	0	m^2	8	0

2.9 Rig

The final rig set-up is not fully planned yet

2.10 Control system

Not manufactured yet The control system is mainly constructed out of carbon fibre to keep the weight of the system down. Since most of this material is new we have tried to cut down on the usage. Using the pullrod system per example is one way that meant we could use a rod of a smaller diameter opposed to if we had gone with a pushrod system.

Some of the parts for the control system have been able to be sourced second hand or up-cycled. Examples are the bowsprit created from an old hockey stick, and the outer part of the wand which we were able to source second hand.



2.11 Deck layout

Not fully planned and not manufactured yet

The deck layout mostly follows the standard within competitive moth and follows the IMCA rules. For the sustainability part we plan to solely use second sorting hardware which otherwise would be scrapped as it could not be sold.

2.12 Total cost SM\$

Table 7: Total SM\$ calculation

Total Costs	
Hull and Deck Superstructure	517
Gantry	99
Foilbox	27.4
Internal Structures	6.5
Molds (20h print time)	400
Borrowed Foils	400
UFLP Main Vertical	1500
UFLP Main Horizontal	500
UFLP Rear Vertical	1500
UFLP Rear Horizontal	500
Deck Hardware & Ropes <i>Estimate</i>	1200
Control Systems <i>Estimate</i>	265
Upcycled Rig & Sail <i>Estimate</i>	1500
Wings	15
Total (SM\$)	9429.9



3 Sustainability analysis

3.1 General description

The integration of bio-based materials, such as flax fibers, in the hull construction represents a strategic shift towards sustainable practices in composite material selection. This sustainability analysis aims to evaluate the environmental impact and resource efficiency of incorporating flax fibers alongside bio-based epoxy and PVC core in the composite manufacturing process. By assessing the life cycle implications of these material choices, this study seeks to quantify the overall sustainability benefits and environmental footprint of the composite structure, contributing to a more eco-conscious approach in marine engineering.

3.2 Boat and elements life cycle

The boat's life cycle calculations were conducted using MarineShift360 LCA software. The results are presented in Appendix B.

3.3 Foils

The foils originate from the foil loan program, indicating that they are production-grade but have defects making them unsuitable for the market. By repairing and integrating them into this project, we ensure they are not simply discarded. Moreover, these foils will continue to be used by future teams in upcoming SuMoth Challenges, which maximize their lifespan and value.

3.4 Wings

The wingbars are constructed from locally sourced knot-free pine, chosen for its strength-to-weight ratio and minimal transportation emissions. Initially attempted with wood glue, the final lamination uses regular epoxy for necessary stiffness.

3.5 Rig

The final rig set-up is not fully planned yet

3.6 Materials

This subsection describes the materials used for the glue, fibers, and core.

3.6.1 Glue

Through our sponsor Sika, we received glue and sealant for our boat. All glue used to glue in the bulkheads and in the hull and deck marriage was done with Adekit A140, a structural epoxy glue that had just expired and could therefore not be sold.

3.6.2 Fibres

During last years competition in Garda, the team received overdue material from Iridium sailing team and their build which they in turn received as left overs from the build of the 11th Hour Racing IMOCA 60.

3.6.3 Core

Today there is a growing range of recyclable core materials on the market. Recyclable PET is a common material for components manufactured with sustainability in mind. Although there's ongoing research on recycling, given the complexity of separating thermoset composites, including epoxy, is a complex and challenging process the component is challenging to recycle and the process



is expensive. In Table 8 the resin consumption for recycled PET and a standard PVC core material is presented.

Klose et al., 2023 argue that the recycling of thermoset polymers, such as epoxy resins, is a challenging and complex process due to their cross-linked molecular structure, which limits their reprocessability without compromising on mechanical properties. Conventional recycling methods, including chemical, mechanical, and thermal treatments, face obstacles such as high energy consumption, hazardous waste generation, and reduced material quality. For instance, chemical treatments involve breaking down thermosets using strong catalysts, while mechanical recycling results in lower-quality recycled materials suitable only for low-value applications. Thermal recycling methods like pyrolysis and waste-to-energy conversion also pose environmental concerns and require significant energy inputs (Klose et al., 2023).

In light of employing a bio-based epoxy variant that exhibits a 20% reduction in CO₂ emissions relative to conventional epoxy, it is not to be forgotten that it is a CO₂-heavy product and that the inherent challenges associated with the recyclability of epoxy polymers persist. A strategic emphasis has been placed on minimizing resin consumption within the design framework to address this predicament, notably exemplified by the meticulous selection of core materials. While initial considerations may incline towards utilizing a recycled PET core, its propensity for resin absorption presents a notable drawback. A comparative evaluation between a recycled PET core and a conventional Divinycell PVC core underscored the paramount importance of reducing epoxy utilization, leading to the preferential adoption of the PVC core characterized by a lower resin consumption rate of 0.87 kg/m³ in contrast to rPET's 1.2 kg/m³. Integration of these quantitative metrics into the Life Cycle Assessment (LCA) tool Marine Shift 360 revealed a discernible disparity in the total CO₂ footprint for core and resin amalgamation, with PVC registering 11.5 kg and rPET recording 14.5 kg.

Material	Density (kg/m^3)	Resin consumption (kg/m^3)	Total CO ₂ (kg)
rPET	80	1.2	55
	60	1.4	60
PVC	80	0.8	48
	60	1.4	53

Table 8: Resin consumption of different core materials and densities and total CO₂ footprint for core and bio-epoxy.

In Table 8 it can be seen that the rPET core consumes more resin than the PVC core and that the higher densities corresponds to a lower consumption. From calculations, the lower density foam corresponded to a higher total weight due to its higher resin consumption. The closed cell foam has a porous surface that will fill up with resin and since the lower density foam is coarser, more resin will get stuck in the creases. Based on this we performed an LCA study the core material comparing the two cases.

3.7 Actions for a sustainable future

For a more sustainable future in yacht design, it is crucial to gain widespread interest across the entire sailing community towards embracing innovative materials and designs. By working together, the adoption of these sustainable materials holds the potential towards a more environmentally conscious and ethically responsible era in high-performance racing. This initiative prompts the crucial inquiry; how can regulations be structured to integrate these materials, ensuring fairness and equity among all competitors?

Composites that are used mainly for these types of high-performance boat come with a load of challenges for the future. Many of them connected to difficulties with recycling, as composites per definition is a mix of materials. So, the challenges for the future are booth how to lower the impact during the beginning of the life cycle by using recycled materials or materials with less



impact during the manufacture. But also, to find ways during the end of the life cycle to reuse or recycle the composites.

Klose et al., 2023 explain the advancements in creating biodegradable plastic. One advantage of biodegradation over thermal recycling is that it doesn't produce pollution or hazardous waste materials or require a high energy input. With the epoxy on the market today it's not possible to recycle composites in any other way than thermal recycling, even though the reinforcing material is recyclable or biodegradable. That means there is a huge potential to get the same advantages of biodegradation also in composites by developing a biodegradable epoxy.

However, this presents a significant challenge, as the composites must still meet all requirements and maintain their characteristics despite the stresses they may endure under the demanding conditions on a boat throughout its entire lifespan. And that's only possible if investments are made in research on this type of material.



4 Team

The team, representing Chalmers University of Technology from Gothenburg, Sweden comprises of students with varying levels of experience in sailing, ranging from newcomers to seasoned sailors skilled at handling tall ships and maneuvering foiling boats. Predominantly composed of master's students from the Mobility Engineering program which brings together the Automobile, Marine and Aerospace Engineering together, the team also includes undergraduates with a Mechanical Engineering background. Everyone in the team shares the common goal of creating a competitive boat for the SuMoth Challenge 2024.

All work has been carried out voluntarily and in an extracurricular capacity, in addition to regular studies. In other words, the students have not received any academic credits for their efforts.

4.1 Team members

Team Captain:

Wilhelm Eriksson

Team Manager:

Olof Wranne

Team Members:

Aditya Barman

Alexander Krokstäde

Arvid Sörfeldt

Basil P Thomas

Edwin Ghasemi

Emma Wendt

Nils Helgesson

Otto Lettevall Forsgren

Pontus Nilsson

Simon Holmgren

Tova Källarfelt



4.2 Sponsors





4.3 Acknowledgments

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A big thanks to **James Tomlinson** from Iridium SuMoth for generously providing us with flax composites and for actively engaging in progress-sharing throughout our journey.

And lastly, thank you to the staff at **Chalmers FUSE** and students from **T-RAX**, the makerspace on campus. Thank you for your dedication to the project and for helping out with everything from 3d-printers to event arrangements.



References

- Bioinnovation. (2022). Sverige först i världen att 3d-printa kajak i ett stycke – öppnar för biobaserad och cirkulär tillverkning av stora föremål. <https://www.bioinnovation.se/nyheter/sverige-forst-i-varlden-att-3d-printa-kajak-i-ett-stycke-oppnar-for-biobaserad-och-cirkular-tillverkning-av-stora-foremal/>
- Boman, A. (2020). Design of a flight-control system for foiling dinghies with a t-wing and individual flaps. <https://search.ebscohost.com/login.aspx?direct=true&db=ir01625a&AN=cst.20.500.12380.301921&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds>
- Giacomo, M. (2020). Lake garda's winds: The ora, pelèr and balin: Sport. <https://360gardalife.com/en/magazine/lake-garda-winds-ora-peler-balin/>
- Federation, I. S. (2015). <http://moth-sailing.org/wp-content/uploads/2015/02/Att-10-141228-Moth-Class-Rules-2015-DRAFT.pdf>
- Klose, L., Meyer-Heydecke, N., Wongwattanasat, S., Chow, J., Pérez García, P., Carré, C., Streit, W., Antranikian, G., Romero, A. M., & Liese, A. (2023). Towards sustainable recycling of epoxy-based polymers: Approaches and challenges of epoxy biodegradation. *Polymers*, 15(12). <https://doi.org/10.3390/polym15122653>
- Laiti, L., Zardi, D., De Franceschi, M., & Rampanelli, G. (2013). Analysis of the diurnal development of the ora del garda wind in the alps from airborne and surface measurements. *Atmospheric Chemistry and Physics Discussions*, 13, 19121–19171. <https://doi.org/10.5194/acpd-13-19121-2013>
- Sails, N. (2024). International moth speed guide. <https://www.northsails.com/blogs/north-sails-blog/north-sails-international-moth-speed-guide>
- Service, N. W. (2004). Atmospheric controllers of local nighttime temperature. https://www.weather.gov/source/zhu/ZHU_Training_Page/winds/nighttimeinfluences/Nighttime_Influences.htm
- Sika. (2024). Adekit a 140-1. <https://industry.sika.com/en/home/advanced-resins/sports-and-leisure/composite-resin-systems/adhesives-for-compositesystems/adekit-a-140-1.html>
- Smith, S. (2023). A feasibility analysis of natural composite alternatives in high performance sailing vessels.
- Thomasson, B. (2018). Om olika träslag och deras lämplighet för kanotbygge. <https://www.thomassondesign.com/bygga/materialfakta/traslag>
- van Hoorn, P. (2021). High-performance sailing aerodynamics an investigation of the international moth class.