RAFALE3
TEAM ETS MONTRÉAL

École de technologie supérieure

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SuMoth Challenge 2022

Stage S1 - Design Report

Abstract

This report covers the design, fabrication, and lifecycle analysis of Rafale 3, the third and current sailboat of team Rafale-ETS. It will cover the design as have been presented in earlier editions and the modifications made when applicable, as well as the fabrication process of the pieces previously presented as well as the modifications we made to these pieces and the new pieces made since then. This edition will be the last presenting Rafale 3 as this boat, after many hiccups, is finally able to be present on the start line of the race. The team will start on a new design, Rafale 4, this summer. The loosening of the COVID-19 restrictions and recruitment efforts allowed the team to gain several valuable new members which contributed greatly to our ability to bring the boat to the start line this time.

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1. ENGINEERING AND DESIGN

1.1. Hull

The design of the hull is strongly based on an eco-thinking. The hull can be considered as one of the biggest parts of the project and its design has a huge impact the sustainable aspect of the boat. Sustainable development has deeply influenced the design choices in order to reduce the environmental impacts of the materials and processes at each step of the project's life cycle.

1.1.1. Conceptual Design

Most of hulls are typically thin to minimize lift-out hydrodynamic drag and in-flight aerodynamic drag. To ensure best performance and stability, the team chose to utilize the maximal dimensions allowed by the IMCA rules. Past experiences on Rafale 1 have shown that larger hulls are more stable and allow the team to have a better impact on the limitation of lift-out dragging. To prevent under sizing the hull its volume has been treated with special care.

Instead of choosing a circular section for the hull shape, as is usual on the state-of-the-art moths, it was decided to adopt a "U" section shape. This type of design slightly increases the wet area but results in increased form stability and capacity to plane. For the rest of the hull, straight lines were preferred, when possible, to ease the design and manufacturing.

1.1.2. Reverse Engineering

Due to the current team's lack of experience, we've decided to base the design of the hull on a reverse-engineering of the Waszp hull. The Waszp is a one-design foiler which is class-legal under the IMCA. Its simplified design makes it easy to model and an attractive and acceptable starting point for our hull. By using the Creaform Go!SCAN3D platform, the team was able to carry out a 3D scan of a Waszp hull. The resulting CAD model was used as starting point for the geometry of Rafale 3 (Figure).

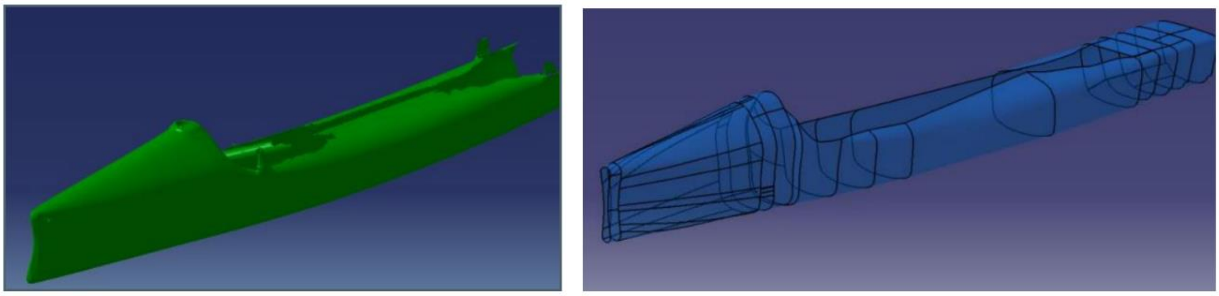


Figure 1: Scanned Waszp hull, point cloud (left) and CAD model (right)

This allowed the team to quickly produce a shape without extensive knowledge and experience in moth's hull architecture. This solution provided us a good way to start in a field not taught at local universities. The quick choice of this method also gave more time to the team to focus on how to reduce the environmental impact of the final product.

1.1.3. Symmetrical Mould

One of our big challenges in the design of the hull is the manufacturability. The past team's projects, Rafale 1 and Rafale 2, were made using lateral female split moulds, obtained by using male plugs. Each plug represents hundreds of kilograms of machined medium density fibreboard (MDF). This means that each mould needs its own lamination process. However, those processes require an important amount of energy and materials which is unreasonable for a project aiming to promote sustainable manufacturing techniques.

A popular alternative is to use fairing and sanding to make male plugs and obtain our half-hulls from those. It is a popular process, but it does not provide the accuracy offered by a CNC machine. To retain that accuracy but also reduce the amount of material and machining require our team came out with a new idea. The idea of forming both hull sides from a single symmetrical mould was born (Figure).

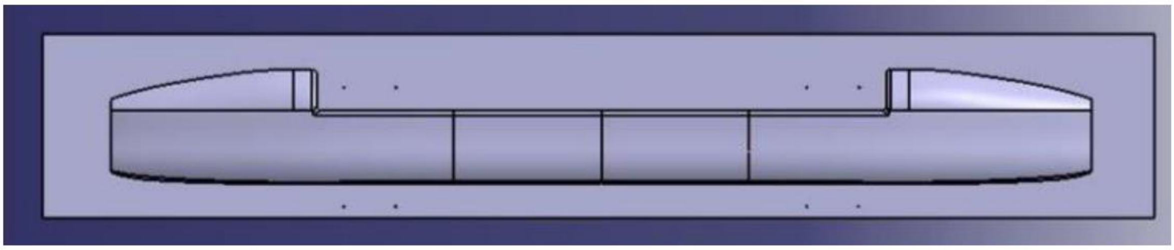


Figure 2: Symmetrical mould for making Rafale 3's hull.

This mold allows us to make both half-hull shells by using a traditional vacuum-assisted resin infusion process, one after the other. To form the transom in-situ with the rest of the shell, we positioned an insert on either side of the half hull shells (Figure). This adaptation was done to avoid tear-out failure as found in Rafale 2, which featured a glued transom.

The mould of Rafale 3 was made by using pinewood, which is reusable, recyclable and even compostable.

In addition to offering the same surface accuracy as conventional methods, the process presented distinguishes itself by eliminating the need for two laminated moulds and one machined plug. Therefore, the symmetrical mould concept presented is an innovation on both the economical and environmental fields. Unfortunately, the literature doesn't offer much information on this, or similar, process. But our discussions with sailing experts revealed that the concept had been applied in the Americas' Cup to reduce production costs. This leads us to believe that Rafale 3 features one amongst the first composite sailboat hull made from a single symmetrical mould.

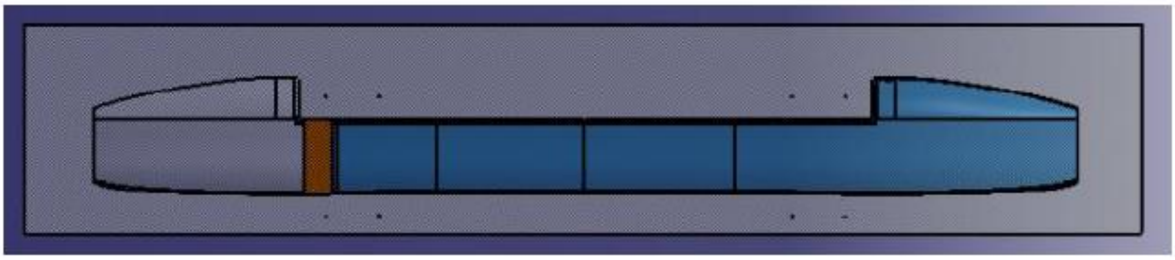


Figure 3: Port hull shell as made inside of the symmetrical mould.

1.1.4. Bulkheads

Most hulls integrate the bulkheads as an internal structure. It improves strength and resistance of the hull. Indeed, while the hull resists longitudinal loads and make the boat watertight, there wasn't any solution to resist transversal loads applied by the mast, foils, and wings. That's the role off the bulkheads. Skillfully positioned in areas of high stress concentration, they lead to a better distribution of the load to the rest of the structure (Figure).

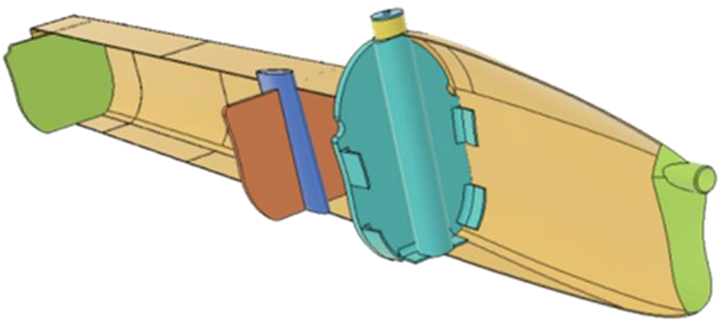


Figure 4: Bulkhead positioned in the hull to reinforce zones of high loads.

1.1.5. Material Selection

As mentioned before, the main objective in designing the hull is to provide a model which tends to maximise recyclability and minimise environmental footprint and impacts. The team has adopted an eco-friendly look for the material selection as well. Although composite sandwich panels are notoriously difficult to fit to these criteria, they were an essential choice to ensure product functionality. Recyclability and energy consumption were the primary drivers of fibre, matrix, and resin selection.

1.1.5.1. Resin

To account for recyclability and environmental impact, conventional thermoset resins (epoxy and polyester) were ruled out since they are a product of the petrochemical industry. Bio-sourced resins are an interesting choice, due to their recyclability which their fossil-based counterparts don't have. Unfortunately, this process still does not feature the recyclability sought after by the team.

Even if thermoplastic resins are recyclable and constitute a well-known choice, they are usually inaccessible to student teams. In fact, processing them typically requires high temperatures and heavy machinery which the team doesn't have. The Elium resin made by Arkéma stands out in this category since it can be infused in liquid form and polymerize at room temperature. Besides, it presents a good compatibility with basalt fibre (see below) and the methacrylate glue used to bond the hull elements. This product was a natural choice for the team. With this acrylic-based resin and glue, optimal bonding and recycling was ensured.

1.1.5.2. Fiber Reinforcement

Due to their high environmental impact, carbon fibres were avoided. A promising solution could be to use natural fibres derived from hemp or flax. However, they were ultimately rejected due to their incompatibility with the Elium resin. Due to being made out of molten volcanic rock, basalt fibres are less energy-hungry than carbon fibers and have properties similar to S-glass. One of our partners, local company Texonic, helped the team by providing them taffeta woven basalt to serve as fibre reinforcements for the hull.

1.1.5.3. Core Material

Balsa and cork were proposed as core material because they are popular bio-based infusible core materials. They where however avoided due to their incompatibility with the chosen Elium resin. By searching for a solution while keeping the eco-conception concerns, the team decided on a PET foam made from recycled water bottles. Produced by Armacell, this material is specifically designed for composite applications.

1.1.5.4. Wrapping Film

For finishing the hull, a vinyl wrapping film was chosen over the more traditional gel coat finish allowing Rafale 3 to feature a smooth watertight finish without compromising the recyclability of the rest of the hull.

1.1.6. Structural Analysis

To dimension the hull, team had to pursue a structural analysis. Forces acting on the hull were determined using static analysis. The sums of forces and moments were assumed to be zero for the boat travelling forward at constant speed. Free-body diagrams (FBD's) for takeoff and steady flight are given in Appendix B. The resulting equations are presented below. The team was able to compute the loads acting on the hull, based on design targets and literature values. The results for each mode, liftoff and steady flight, are compiled in Table and Table.

$$\Sigma F_x = P_{sail} - 2D_{verticals} - D_{main\,wing} - D_{rudder\,wing} = 0$$

$$\Sigma F_y = P_{sail} - P_{daggerboard} = 0$$

$$\Sigma F_z = P_{main\,wing} + P_{rudder\,wing} - W = 0$$

$$\Sigma M_x = M_W - M_{sail} = 0$$

Table 1: Liftoff Load Calculations

Descriptif	Symbole	calcul	valeur	unité
Poids skipper+bateau	W_{Tot}	(Mb+Ms)*g	1275,3	N
Moment de redressement	MR	W_{tot}*L_{large}	1434,7	N.m
Moment de gîte	MG	à l'équilibre MR=MG	1434,7	N.m
Portance foils total	P_{foils}	à l'équilibre W_{tot}=P_{foils}	1275,3	N
Répartition poussé foil principal			0,7	-
Répartition poussé foil gouvernail			0,3	-
Portance foil principal	P_{foil-p}	0,7*P_{foils}	892,7	N
Portance foil gouvernail	P_{foil-g}	0,3*P_{foils}	382,6	N
Portance voile maximal	P_{voileY}	0,5*2*ρ_{air}*$V_{min}^{2*}S_v$	91,0	N
Poussée anti dérive	$P_{derives}$	à l'équilibre $P_{derives}$=P_{voileY}	91,0	N

Table 2: Steady flight load calculations

Descriptif	Symbole	calcul	valeur	unité
Poids skipper+bateau	W_{Tot}	(Mb+Ms)*g	1275,3	N
Moment de redressement	MR	W_{tot}*(L_{large}/cos(θ))	1526,8	N.m
Moment de gîte	MG	à l'équilibre MR=MG	1526,8	N.m
Portance foils total requise	P_{foils}	Wtot*cos(θ)	1198,4	N
Répartition poussé foil principal			0,6	
Répartition poussé foil gouvernail			0,4	
Portance foil principal	P_{foil-p}	0,6*P_{foils}	719,0	N
Portance foil gouvernail	P_{foil-g}	0,4*P_{foils}	479,4	N
Portance voile maximal	P_{voileY}	0,5*2*ρ_{air}*$V_{max}^{2*}S_v$	1655,8	N
Poids résultant de la gîte		W_{Tot}*sin(θ)	436,2	N
Poussée anti dérive	$P_{derives}$	P_{voileY}-436,2	1219,6	N
Trainée dérives	T_{shaft}		négligeable	N
Trainée foil principal	T_{foil-p}		240	N
Trainée foil gouvernail	T_{foil-g}	Calcul par logiciel de CFD	160	N
Portance foil principal	P_{foil-p}		1054	N
Portance foil gouvernail	P_{foil-g}		702,7	N

1.1.6.1. CFD Validation

Results of the structural analysis were compared with those of the CFD. The analysis is presented on Table. This CFD validation ensured the team that the hydrofoils were capable of greater lift than required for static stability. This provides a margin of error with respect to speed and weight predictions.

Table 3: Load predictions based on FBD and CFD

	Pré-décollage		En vol	
	PFS	CFD	PFS	CFD
foil principale	892,7	1062	719	1054
foil gouvernail	382,6	455,15	479,4	702,7

1.1.6.2. Shroud loads

Shrouds and forestay maintain the mast in place and are tensioned for optimal rig performance. The hull must be able to support these forces easily. Tension values were obtained from the team's mast supplier (Ikual):

- ⇨ Shroud tension: 1600 N (each)
- ⇨ Forestay tension: 2000 N
- ⇨ Resulting mast step pressure: 5200 N

1.1.6.3. Transom loads

Transom loads were calculated based on the appropriate FBD, provided in Appendix B. The corresponding equation are given below.

$$\Sigma F_x = F_{B,x} - F_{A,x} - T_{foil,g} = 0$$

$$\Sigma F_y = F_{B,y} - F_{A,y} - F_C = 0$$

$$\Sigma F_z = -F_{B,z} + T_{foil,g} = 0$$

$$\Sigma M_{B,x} = -F_{A,y} * H_{coque} + F_C * H_{foil} = 0$$

$$\Sigma M_{B,y} = F_{A,x} * H_{coque} - T_{foil,g} * H_{foil} = 0$$

Points A and B represents the two joints between the hull and the rudder gantry. They are critical load paths. Forces were computed assuming maximum flight speed combined with a lateral rudder load of 1000 N, as per studies conducted for Rafale 1 and 2, see papers by M.Prudhomme and C.Chamberland in the bibliography. Results are given in Table.

Table 4: Computed transom loads

Descriptif	Symbole	calcul	valeur	unité
Effort latéral (changement direction	F_C	admis	1000	N
Trainée foil gouvernail	T_{foil-g}	CFD	160	N
Trainée dérives	T_{shaft}	Négligée	0	N
Portance foil gouvernail	P_{foil-g}	CFD	702,7	N

Force en B sur x	F_{B-x}	$F_{B-x}=F_{A-x}+T_{foil-g}$	750	N
Force en B sur y	F_{B-y}	$F_{B-y}=F_C+F_{A-y}$	4687,5	N
Force en B sur z	F_{B-z}	$F_{B-z}=P_{foil-g}$ à l'équilibre	702,7	N
Force en A sur x	F_{A-x}	$F_{A-x}=(T_{foil-g}*H_{foil})/H_{coque}$	590	N
Force en A sur y	F_{A-y}	$F_{A-y}=(F_C*H_{foil})/H_{coque}$	3687,5	N

1.1.7. Laminate Selection

Sandwich panels are the structure of choice for modern production Moths [6-9]. Those made using a liquid moulding process (wet layup or infusion) are generally composed of a 5 mm-thick foam core and 150 gsm woven or unidirectional carbon fibre. As seen in Material Selection, the materials chosen were basalt/Elium for the skins and PET foam for the core. Woven plies were oriented at 0/90 degrees to resist flexure and 45/-45 degrees to resist torsion. The ply sequence is given in Table .

Table 5: Hull fibre ply sequence

Ply no.	Material	Thickness [mm]	Orientation [deg]
1	Basalt	0.35	0/90
2	Basalt	0.35	45/-45
3	Armacore	10	0
4	Basalt	0.35	45/-45

Ply 1 corresponds to the tool-side and outermost ply. The hull is thus composed of a 2-ply outer skin and single ply inner skin. This was justified through discussion with naval architects and boatbuilders behind Ikual, Onefly, Northern Light Composites and F101. The same reasoning was used for the bulkhead laminates. One additional ply was used to compensate for local in-plane compression loads. The Table show the sequence for those.

Table 6: Bulkheads fibre ply sequence

Ply no.	Material	Thickness [mm]	Orientation [deg]
1	Basalt	0.35	0/90
2	Basalt	0.35	45/-45
3	Armacore	10	0
4	Basalt	0.35	45/-45
5	Basalt	0.35	0/90

1.2. Hydrofoil Wings

A foiling moth without its hydrofoil wings is no more a foiling boat since they are critical parts that enable the boat to fly over water. Since the team knows that Rafale 3 will surely be heavier than most of the competitive moth sailboats, it has been decided to design relatively large wings that ensure takeoff at low speeds.

Each vertical section, called shafts herein, has it own wing thus constituting the complete hydrofoil subsystem (See Figure 7). The hydrofoil on the rudder is a single part wing and is manually managed by the skipper, by moving the rudder itself. The one on the daggerboard is made of two parts, one moving and the other no, managed automatically by the wand system. The flap is the trailing edge portion of the wing and induce lift depending on the flight mode case.

1.2.1. Needs analysis

Theoretically, takeoff signifies the beginning of foiling, then the boat continues progressively to reach a steady flight and then it ends with gentle deceleration and return of the boat to floating on water. Realistically, accidents can happen leading to the catapulting of the boat forward (nose down) or sideways (capsizing). Those extreme cases provide load cases and precious information for the design process of each component of the subsystem.

Figure 5 : Left to right: takeoff, steady flight, capsize and nosedive.

It is necessary to note that the lift forces provided by the wings are considered normal to their surface. The consequence is that a heel angle is required to counteract the sail's moment and to improve the overall lift to sail at a constant flight speed. In addition, the mass is estimated to 40kg for the hull and 80kg for the sailor equivalent to a total weight of 1178N that should be constantly lifted by the foils. Finally, a safety factor has been established on the lift forces and the different slight profiles are characterised in Table 7.

Table 7: Foiling input and targets for each flight case

Targets	**Flight Cases**	
	Lift Off	**Steady**
Crew mass (Kg)	80	
Boat mass (Kg)	40	
Total weight (N)	1178	
Speed	6.5 knots (3 m/s)	20 knots (10.2 m/s)
Daggerboard Lift Distribution (%)	70	60
Rudder Lift Distribution (%)	30	40
Heel Angle (°)	0	20
Safety Factor	1.2	1.2
Target Daggerboard Lift (N)	1058	901
Target Rudder Lift (N)	353	601

1.2.2. Concept Generation and Evaluation

For the wing, three criteria are used to ensure achieving the target lift-off speed and enabling modification of the wings during manufacturing. Those criteria are the manufacturability, the thickness and the efficiency that corresponds to the best of lift coefficient of drag, or Cl/Cd at Reynold's number in the range [200 000-400 000] for the lift-off flight case.

The first step has been to investigate multiple wing profiles, choose four amongst them using airfoiltools.com and compare their proprieties as shown in Figure 6 and Table 8.

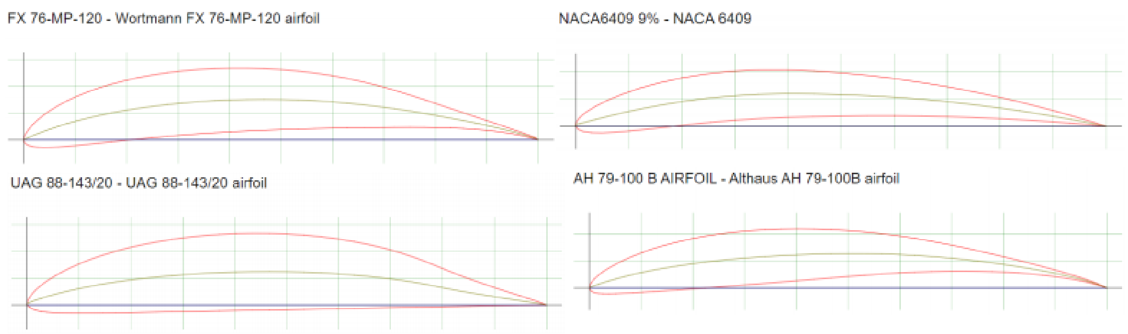


Figure 6: Hydrofoil wing profiles

Table 8: Hydrofoil wing profiles specifications

Foil Profile	Reynold's Number	Max. Cl/Cd	Angle of Attack (deg)
FX 76-MP-120	200 000	85.9	8
	500 000	147.3	5.25
NACA 6409	200 000	87.1	6
	500 000	122.4	5.5
UAG 88-143/20	200 000	55.1	9.5
	500 000	127	6.25
AH 79-100 B	200 000	100	6.25
	500 000	148.3	4

These data allowed to estimate the wingspan by assuming a simplified rectangular airfoil with a fixed chord length. To overcome the lack of data for specific airfoils with a lift coefficient (Cl) and an arbitrary flap engaged, a safety factor increased from 1.2 to 3.5 with the lift coefficient has been used. For the chord length and the flap location on the fin, industry standards were used. All the estimations for the calculations and the conceptual design allowed the team to calculate the span of the fin and rudder wing as follows in Table 10 and Table 9.

Table 10: Wing parameters

Parametre	Assumption
Flap Engaged Factor on Cl	1.5
Root Chord Length (cm)	12
Flap Axis Location - X (% Chord)	75
Flap Axis Location - Y (% Thickness)	50
Profile Scaling Point - Z	Flap Rotation Axis Location

Table 9: Wingspan estimates

Wing	Range (cm)
Daggerboard	50-75
Rudder	40-60

Finally, the best profile was chosen using the CFD analysis Star CCM+ of our sponsor Siemens. It consists in modeling the wings and running the simulation with a convergence criterion of 10^{-4} while using the steady state $k - \varepsilon$ turbulence model given the same wingspan, wing tapering and optimal angle of attack. The steady flight test has been used to see which one had the highest lift to drag ratio as drag would become more important at higher speed and limit top speed.

The NACA 6409 airfoil profile was kept and used throughout the rest of the design process. Table 11 illustrates the results for each.

Table 11: Airfoil performance results using STAR-CCM+

Airfoil Type	Lift (N)	Drag (N)	Cl	Cd	Lift/Drag
FX 76-MP-120	1087.54	276.45	0.72780	0.09363	3.933
NACA 6409	1272.50	215.48	0.85219	0.05517	5.905
UAG 88-143/20	1009.12	202.73	0.11557	0.11557	4.977
AH 79-100B	1275.15	218.48	0.85318	0.05475	5.836

1.2.3. CFD Analysis and wing geometry

The selection of the shape completed, further CFD analysis with CCM+ was done. The first step was to improve the model by refining the meshing especially along the leading/trailing edges of the airfoil and at the shaft junction. At the wingtip, a conic volume mesh was added to capture the effects of wingtip vortices. Behind the airfoil, an increase to the box volume allowed to model the wake and flow separation properly. The other steps consisted of expanding the control volume and changing the turbulence model to $k - \omega$ for more realistic and less conservative results.

With this new model, the airfoil's angle of attack, flap deflection and wingspan have been parametrized. Tests were run in this order to determine first the wing's most efficient angle of attack for lift-off conditions, then the optimal flap deflection angle for maximum lift at lift-off conditions, and finally the ideal wingspan necessary to achieve our target lifts at both lift-off conditions and steady flight conditions as well as the upward flap deflection.

Those tests required a few hours to run but, since geometry was parametrized, enabled the study of multiple cases/iterations using a rough range for desired values at first and then refining the step size with the closest target values. Once all values were recorded for each iteration, the parameters closest to giving the target flight values was kept and the results are presented in Table 12.

Table 12: Optimal wing parameters for target lift and speed

Wing	Best Angle of Attack (°)	Ideal Flap Angle for Lift-Off (°)	Span for Lift-Off (cm)	Steady Flight Upward Flap Deflection (°)
Daggerboard	4.8	-42.25	89	15
Rudder	4.8	N/A	60	N/A

The resulting values for wingspan ended up being higher than the estimates since those did not take in consideration the shaft's flow disturbance and the wingtip vortex losses. They were also high but highly optimized and likely more efficient than most industry wingspan. Table 14 compares the target and modeled lift forces and Table 13 compares the estimated, modeled and industry standard wingspans.

Table 14: Hydrofoil wings target and modeled lift forces

Wing	Lift-Off Target Lift (N)	Modeled Lift-Off Lift (N)	Steady Flight Target Lift (N)	Modeled Steady Flight Lift (N)
Daggerboard	1058	1061	901	1052
Rudder	353	406	601	612

Table 13: Hydrofoil wings estimated and modeled wingspan

Wing	Rough Estimates Range (cm)	Modeled Dimensions (cm)	Industry Standards Range (cm)
Daggerboard	50-75	89	75-90
Rudder	40-60	68	50-70

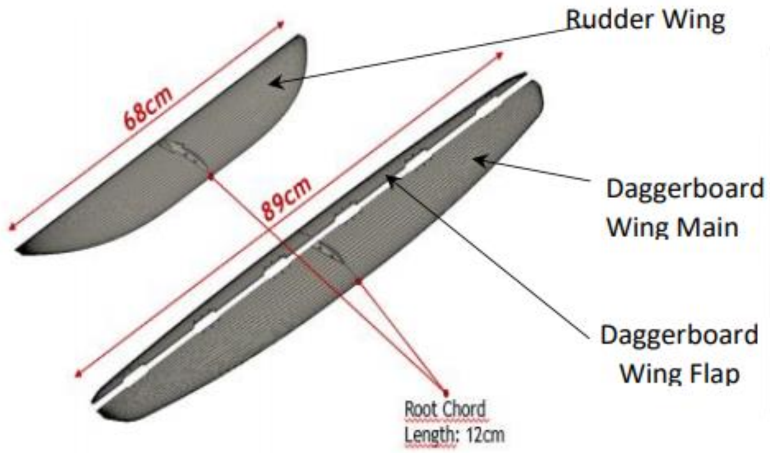
For the daggerboard wing, the main element and the flap are linked together machined hinges and an off-the-shelf steel rod inserted into each hinge to act as the axel and allow rotation to generate more lift. The geometry as been designed to optimise wing and flap area while reducing vortex losses a the wing tip. This has been done by scaling the cross-section of the airfoil from the axis of rotation of the flap. The airfoil was reduced by 10% over the first 90% of the wingspan, and then by 20% of the original base chord over the last 10% of the wingspan.

It was then verified by CFD analysis that confirmed it should be able to generate a force of 1061N for the take-off and 1050N of lift in stable flight.

For the rudder wing located at the rear of the boat, the geometry consists in a single element with the same aerodynamic profile, although the scaling is different. The scaling was done so that at 40% of span, the profile is reduced from the center of the trailing edge until it reaches 20% of the original chord.

It was then also verified by CFD analysis confirming it should be able to generate the target lift of 416N for the takeoff and 612N for the stable flight, giving sufficient lift considering the safety factors.

Figure 7 here shows the shapes of the modeled wings and the CFD flow visualisation.



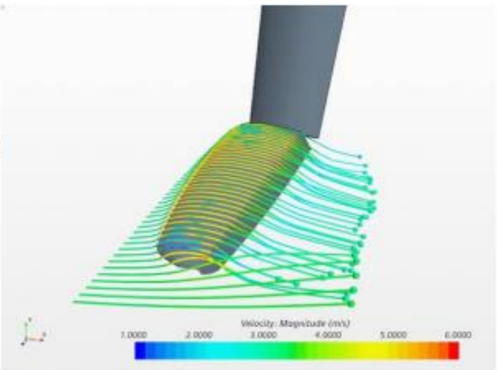


Figure 7 : Wing design embodiment (left) and CFD streamline visualization (right).

1.3. Daggerboard and Rudder Vertical Section

1.3.1. Load Cases

During takeoff and foiling the vertical sections need to provide a stiff platform for maximum performance and must have enough strength to avoid failure in case of nosedive or capsize. Those specific cases were modeled to allow for designing the components for the right loads. All loads were calculated based on the design target listed in Table 15.

Table 15: Rafale 3 design targets.

Crew weight	80 kg
Boat weight	40 kg
Sail area	8.25 m^2
Maximum speed	10.3 m/s

Nominal loads, occurring at takeoff and while foiling, were calculated by a static FBD analysis for each shaft modeled as vertical cantilever beams and design targets provided the input forces.

Extreme loads, occurring with nosedive or capsize, were calculated by modeling shafts/wings as flat plates moving through water at maximum speed and consequently maximum drag.

For both case, forces were computed assuming a 70:30 vertical stabilizer to rudder load distribution at takeoff and 60:40 when foiling. The results are summarized in Table 16. For the extreme loads, values obtained were extremely high due to the model that should have been using a dynamic safety factor of 1.5 rather than the flat plate according to the designer of the Exocet.

Table 16: Vertical sections load cases

Nominal Load

Mode	Lateral Shaft Load (N)	Vertical Wing Load (N)
Takeoff	749	824
Cruising	467	664

Extreme Load

Mode	Lateral Shaft Load (N)	Vertical Wing Load (N)
Capsize	17,463	0
Nosedive	0	9630

1.3.2. Conceptual Design

For ecological, economical, and time reasons, moulds from the previous boat of the team, Rafale 2, were reused. This choice made the design challenge mainly structural with the material challenge of using the best available material to maximise stiffness and strength while minimizing weight.

With generous donations of high-end industry grade materials such as rolls of prepreg carbon fiber and sheets of structural foam as listed in Table 17, the team tried to follow the modern moth shafts choices.

Table 17: Daggerboard and rudder materials

Name	Supplier	Type	Applications
8HS/5320	ÉTS	Satin prepreg carbon fiber	- Provide a stable outer skin layer - Bear loads (~10%)
UD/5320	Boeing	Unidirectional prepreg carbon fiber	- Make up the bulk of the skins - Bear loads (~90%)
UD/977-2	Bombardier		
Corecell™ M	Gurit	Structural foam	- Stabilize skins to avoid buckling - House part of the wand mechanism

Stiffness and strength, respectively critical for performance during nominal use and extreme cases, were evaluated by transverse deflection at the tip and failure analysis. For the strength failure analysis, three composite failure criteria were essentials: maximum stress, Tsai-Wu and Hashin. With safety factors based on axial root stress and properties from the datasheets, effective properties of laminates could be computed using Matlab. A stack of 8 laminates, each with varying ply schedules, which define material type, ply count, and ply orientation, were gathered in Table 18.

Table 18: Laminate schedules concept

Laminate	Ply schedule	t [mm]	E_x [GPa]	E_y [GPa]	G [GPa]	υ	ρ [kg/m^3]
L_s0	$[00\ 8HS]_2/\pm[00/25/00\ UD]_6$	5.7	108.1	17.6	10.4	0.68	1601.8
L_s1	$00\ 8HS/\pm[00/25/00\ UD5320]_5$	4.5	110.6	15.1	10.7	0.71	1603.1
L_s2	$00\ 8HS/\pm[00/25/00\ UD5320]_4$	3.7	109.6	16.1	10.6	0.70	1602.6
L_s3	$00\ 8HS/\pm[00/25/00\ UD5320]_3$	2.8	108.1	17.6	10.4	0.68	1601.8
L_s4	$00\ 8HS/\pm[00/25/00\ UD5320]_2$	2.0	105.3	20.3	10.1	0.64	1600.3
L_s5	$00\ 8HS/\pm[00/25/00\ UD977]_3$	3.7	101.8	15.2	9.4	0.72	1602.6
L_s6	$00\ 8HS/\pm[00/25/00\ UD977]_4$	4.8	102.8	14.0	9.5	0.74	1603.3
L_s7	$00\ 8HS/\pm[00/25/00\ UD977]_2$	2.6	99.9	17.4	9.2	0.69	1601.4

1.3.3. Structural Analysis

Structural analysis for composite laminates is not as simple as for metal parts. The results must be criticized and well understood. That's the reason why it is safer to realise both mathematical modelling in Excel and finite element analysis in Abaqus in addition to the fact it reduces running time for finite element analysis.

1.3.3.1. Mathematical Model

The mathematical model used represents shafts as cantilever beams with an effective length of 0.7m, a fixed support at the base, a hollow shape, a constant skin thickness because the loads should be mostly carried by the skins. With those assumptions and with the profile dimensions and section properties computed in CAD, the tip deflection was then computed with the De Lannoy's tip deflection model for hollow wings with constant skin thickness, see bibliography.

$$\delta_{tip} = \frac{WL^3}{EI_{root}} \frac{1 + 2\lambda}{(1+\lambda)(13+35\lambda)}$$

- W: total load [N]
- L: length [mm]
- E: effective skin stiffness [GPa]
- I_{root}: moment of inertia at the root [mm4]
- λ: taper ratio (tip chord/root chord)

Then for the failure analysis, the model has been completed by modelling the roots as rectangular sandwich. Extreme loads were converted to local force and moment per unit width. By computing safety factors for each case using classical laminate theory, to laminates were deemed most promising for FEA validation: L_s3 and L_s5 presented in Table 19

Table 19: Rudder and daggerboard possible laminate schedules

Laminate	Tip deflection under nominal load [mm]		Safety factor under extreme load					
			Max stress crit.		Tsai-Wu crit.		Hashin crit.	
	Takeoff	Cruising	Nosedive	Capsize	Nosedive	Capsize	Nosedive	Capsize
L_s3	20.5	21.4	167	1.5	137	1.4	166	1.5
L_s5	18.0	18.8	203	1.7	161	1.5	191	1.7

1.3.3.2. Finite Element Analysis

To correctly model the shafts three steps were necessary using separately the CAD model in Abaqus two times and then assembling them as a sandwich part.

- The first model represented the core following the linear elastic isotropic assumption. A volume meshed using a combination hex elements and wedge elements in areas of high curvature and the properties of Corecell™ M were used.
- The second model represented the laminate using composite layup feature. Surface meshed using rectangular elements and the properties of the laminate L_s3, then L_s5 were used.
- The third model, assembly of those two models, represented the sandwich composite. A tie constraint was used to couple the meshes.

Then boundary conditions and loads were applied:

- Nodes at the top and bottom of the hull-shaft interface were fixed to simulate the reaction forces at the daggerboard case.
- The vertical wing load was modelled as a shell edge load along the skin tip.
- The lateral shaft load was modelled as a pressure acting on one half of the immersed part of the skin.

Finally, each model was solved for each load case and laminate. The results needed were the maximum displacement U for tip deflection and the maximum axial stress, S11 as an input to the failure analysis (with classical laminate theory). Like the mathematical model, those results, presented in Figure 8 and Table 20, were deemed acceptable and used for further studies.

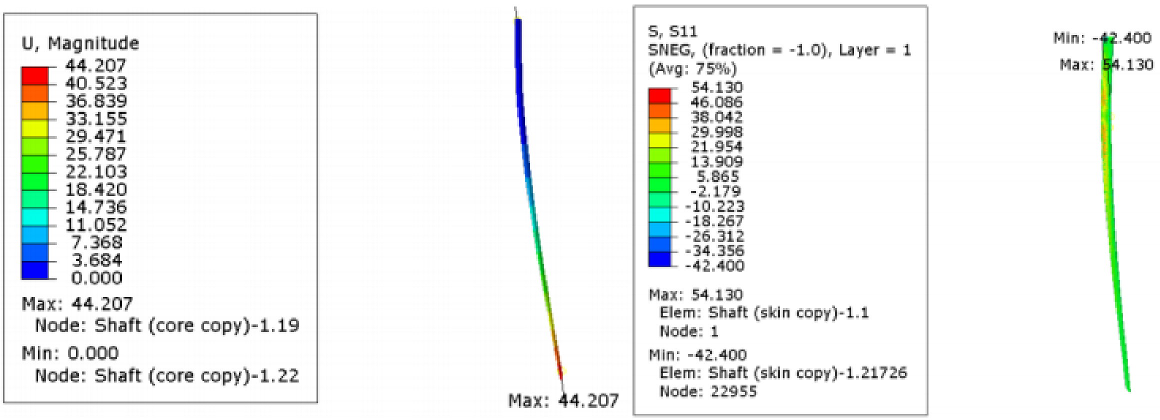


Figure 8 : Sample FEA results for tip deflection and root stress

Table 20: Finite element analysis of L_s3 and L_s5

Laminate	**Tip deflection under nominal load [mm]**		**Safety factor under extreme load**					
			Max stress crit.		Tsai-Wu crit.		Hashin crit.	
	Takeoff	Cruising	Nosedive	Capsize	Nosedive	Capsize	Nosedive	Capsize
L_s3	44.2	48.2	207.6	1.4	194.9	0.9	200.6	1.4
L_s5	39.9	43.7	208.6	1.8	226.8	1.3	203.2	1.7

1.3.3.3. Physical testing

After modelling, practical testing were done using a 2 in x 6 in sample of each laminate, laid-up and cured. This final step revealed a demoulding warping effect for the sample made of L_s5. This effect was attributed to the 8HS/5320 and UD/977-2 prepregs having different resin systems, each having their own cure rate and shrinkage. As a result, L_s3 was chosen as the optimal laminate.

1.3.4. Material Choices

As explained before, each shaft was made of three main components: the skin, the core, and the inserts. The skin provides structural integrity by transferring axial and transverse loads between the wings and the hull, the foam core ensures local buckling and wrinkling resistance while remaining lightweight and water-resistant and the inserts fix the wings in place. Their different roles explain the different materials used.

The skin is the laminated layer of carbon fiber on the outer surface of the shaft. Two different fibers are used. Satin-woven are intertwined fibers are used at the outermost layer to provide a protective shell that can resist local indentations and delamination. Then, non-woven unidirectional fibers packed densely are used for the rest of the skin to provide maximum stiffness

The core in Corecell™ M occupies the volume enclosed by the skin. In the daggerboard core a channel houses the vertical pushrod of the wand mechanism.

The inserts, made of aluminium, occupy the volume enclosed by the skin at the very tip of each shaft. They feature a pair of tapped holes for the bolts fixing the wings in place

1.4. Wing and Rudder Structure

1.4.1. Wings

The wings of Rafale 3 were inspired by those of the Waszp and everything designed for has to be mirrored to account for a moth's 2 wings. Also, one might think that a wing only consists of the wing itself, but it is much more, such as brackets to keep it in place or anything that is attached to it that is not related to the main purpose of the wing but essential for the rest of the boat such as the pads to hold the cleats, which are mounted on the wings.

The main part of the wings is the wing structure itself that supports the skipper. It thus must be stable and strong. The wing structure is made of 2 hollow carbon tubes with open ends that drain down and 1 hollow carbon tubes with closed ends to avoid any accumulation of water inside of the structure. To connect the 3 tubes, 2 plastic elbows were designed to be 3D printed. Once the 5 components fitted together, a fiber wet lay-up would be done over the joints to ensure they stay in place and to reinforce the corners of the structure. To then connect the wings to the hull, brackets with holes were designed to be attached to the hull and allow the installation of the wing with pins.

The compression bars were added to design to absorb the compression force produces by the sail and the rig's tension. Carbon fiber was chosen as the material for its low density yet high mechanical strength. An insert has been added to the ends of the compression bars so that the wings and the bars themselves don't support all the force applied to them by the pin holding them to the wings and the hull. These inserts are stainless steel cylinders that were designed to fit into each tube. Stainless steel was chosen as a material because it has a high resistance to corrosion and can take on large quantity of strain.

It was decided to design a secondary set of wing supports to obtain a better distribution of charges by improving their repartition. These supports are blocks, positioned under each wing's arm, just ahead the attaching system, the brackets presented above. These blocks are also useful to maintain the wings in the wanted inclination and facilitate the wings' installation process.

The trampoline for the boat were manufactured by Max Marine and are essential to our design because it's one of the surfaces the skipper rests on while sailing. The cover the internal area of the wing structure, they let water pass through and are much lighter than a hard surface. Two of the sides of each trampoline are folded and bonded to create tubes that lets a wing's structure pass through. The other two sides have small openings to let a rod pass through. This rod lets the trampoline be lashed to mounting points on the hull and to the remaining side of the structure and allows setting the right amount of tension for it. The trampoline is lashed using a rope.

For the trampoline hooks, or lashing points on the hull, the design is quite simple, it consists of carbon strips with holes that are equidistant to each other. Hooks made from rope are be inserted in the holes. The type of rope was chosen to make sure that they are strong enough to absorb all the tension from trampoline. The hooks are positioned on the boat in a way that allows the trampoline to be attached with enough tension.

To hold the wings in place, the teams designed mounting brackets made of carbon fiber, for its lightness and strength. They were designed to be a bit over 3 inch wide and 2 inch deep. 4 holes would be drilled to keep each bracket in place on the hull and additional holes would be made to allow for a pin to secure the connection between the wings and the brackets. However, when the team did their first nautical tests, these brackets broke. As a replacement, new aluminium brackets where designed. The tube used to make the previous brackets had the perfect dimension, so the same bracket design was used.

For the connection between the compression bars and the wings, another set of brackets were designed. These consist of 3 components. They consist of two carbon fiber plates and one 3D printed component. The 3D printed component replicates the shape of the wing so that they would fit perfectly together. The carbon fiber plates have a triangular shape with a rounded top and a hole for the pin holding the compression bars to the wings.

The final component of the wings are the pads which support the cleats for the rigging. The design was kept simple, it is a carbon plate with a foam core and 1 L shaped bracket. This is quite enough to hold 3 cleats per wing.

1.4.2. Rudder Structure

The rudder structure holds the rudder in place and allows the connection between the rudder and the tiller. For this moth the rudder structure was, at first, designed out of 5 distinct elements: 6 carbon tubes, 2 3D printed connectors, 2 carbon plates, 1 screw connector and 4 clevises.

The 3D connectors were designed with holes so the tubes would fit inside the connectors themselves. However, after 3d printing them, it was noticed that they were quite bulky. Thus, 2 other connectors where designed and printed, this time with extrusions that would fit inside the tubes and 1 hole to hold the vertical tube.

The 2 plates were designed so that the first half of the plates was parallel to the boat and the second half in perfect alignment with the tubes of the structure. Three holes have been added, 1 to connect the plates with the boat and 2 to connect the plates with the clevises holding the tubes. The thickness of the plates was dictated by the size of the slot the clevises. It was also planned that 2 insert would be added to the holes for the clevises. The diameter of these holes was thus based on the outer diameter of the insert.

The pin holding the rudder must be inserted into the rudder structure so that the bearing in the extremity of the vertical carbon tube can absorb some of the force of the rudder. The rudder structure acts as a recipient for this pin. Its inner diameter must be wide enough to hold the pin and allow some movement of the latter so that the rudder can move to control the height of the boat when foiling.

Once the rudder structure was assembled, the team realized that since there was no movement allowed for the structure itself, an enormous amount of stress was applied to it, making it a weak point. To solve that problem, the horizontal carbon tube was cut in 2 and a insert was added to allow some movement of the rudder structure and relieving some of the stress applied to it. The following Figure 9 shows the fully assembled rudder structure. As such, the final rudder structure is made up of 7 distinct elements: 7 crabon tubes, 2 carbon plates, 5 clevises, 2 plain bearings, 2 3D printed connectors, many screws and this insert.

Figure 9: The finished rudder structure

1.5. Wand System

1.5.1. Design

The wand system was designed as a series of bar linkages with sliders and pivots. Links were positioned relative to one another to provide maximum motion sensitivity. The sizing of each link was determined using multibody position analysis in Fusion 360. For simplicity, three positions were considered: takeoff, default flight and high flight. At takeoff, the wand is nearly parallel to the hull and must press the flap down to increase the lift of the main wing. At default ride height, the wand should be at its default angle of 45 degrees and flap angle should be zero. If the flight height increases past this point, the flap must rise to decrease the lift and allow the boat to fall back down.

Table 21. Design objectives for wand system

Position	Ride height (m)	Wand angle (deg)	Flap angle (deg)
Takeoff	0	10	45
Default flight	0.7	45	0
High flight	0.8	55	-15

Since the optimal length of each link is difficult to determine analytically and can vary as a function of wind and sea state, the system was made as adjustable as possible. Since no team members have moth sailing experience, the adjustments were designed by reverse-engineering those of commercial moths, photos of which are available online. Three adjustments were designed: wand length, gearing and offset. The wand can telescope in and out so that the 45-degree default setting can be tuned to different ride heights.

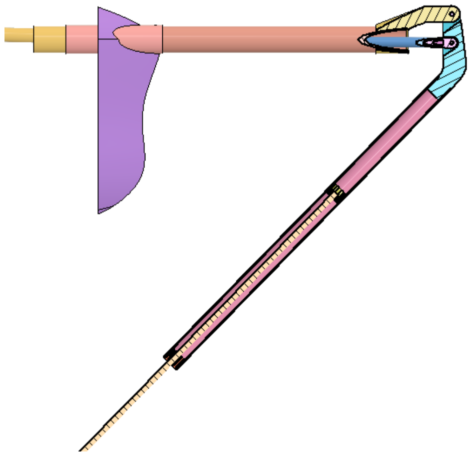


Figure 10. Cross-section of wand showing telescoping mechanism.

The gearing is the motion ratio between the wand and flap. With higher gearing, a given change in wand angle will result in a higher change in flap angle. Gearing is controlled by adjusting the position of the horizontal pushrod relative to the bell crank. Offset is the absolute position of the flap given the default wand angle. It is adjusted by changing the length of the horizontal pushrod.

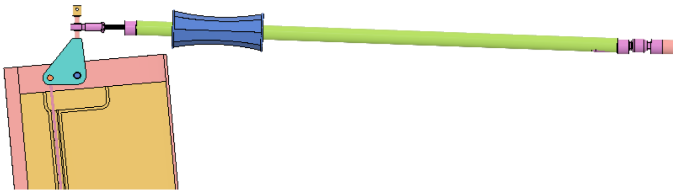


Figure 11. Wand bell crank with adjustable gearing and horizontal pushrod with adjustable rod end.

1.5.2. Dynamic model

Since wand action is highly dynamic, a time-dependent model is required to fully capture its effect on flight stability. As a first step to this complex process, a single degree-of-freedom (DOF) model was constructed to analyze the effect of wand angle on ride height (or heave). Foil lift was expressed as a function of heave through wand action, keeping boat speed and pitch constant. After linearization (assuming small oscillations in the linkages), the resulting system is analogous to a block on a spring oscillating in the vertical direction. In this analysis, the ride height is under proportional control: the change in lift is purely proportional to the change in ride height. A consequence of this is that the system is undamped—if disturbed, it will oscillate forever without coming back to rest. Since stability is the primary function of the wand system, the present model does not fully capture the physics at play and cannot be used as a design aid. In its next design cycle, the team will concentrate on developing a 2-DOF model capturing both heave and pitch to hopefully capture the stabilizing effect of the wand.

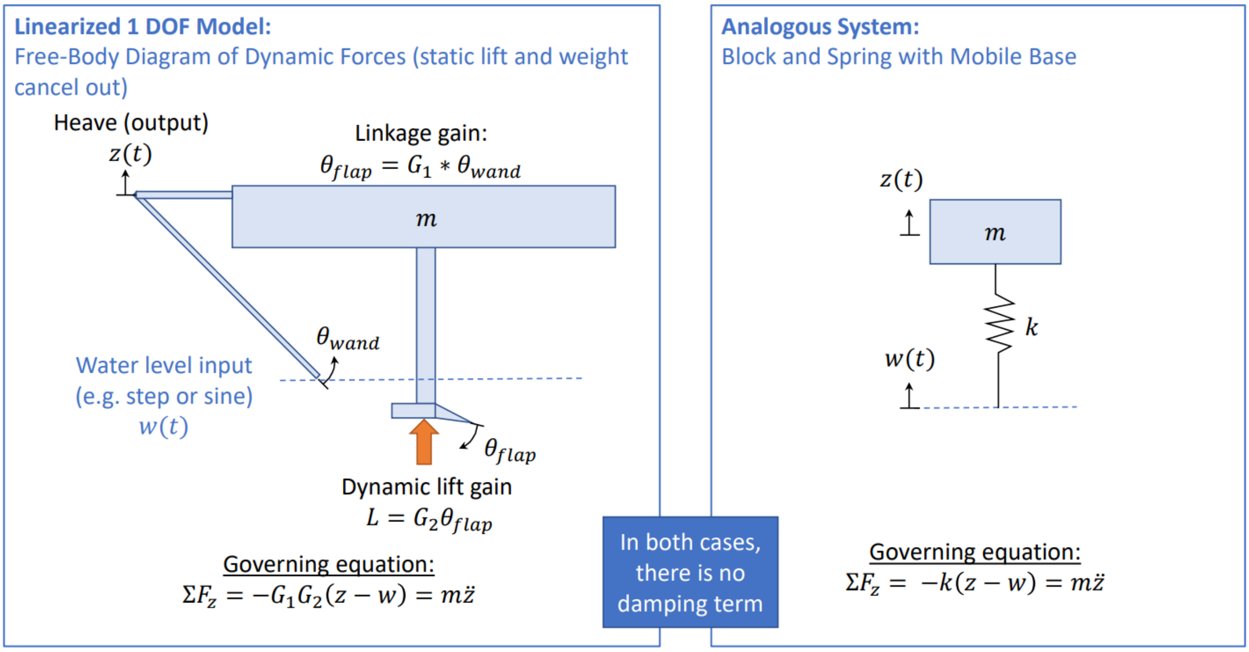


Figure 12. Single DOF model of the wand's effect on ride height

1.6. Tiller

Contrary to a classic tiller system, the moth's tiller has two distinct functionalities that the rudder blade fulfils, steering the boat and tilting the wing to control foiling. Its design is therefore more complex and requires the existence of two distinct tiller movements for the skipper. Documents about the subject and the accurate inner workings of it are not readily available on the internet so the engineering and design have been done by analyzing pictures and videos such as the video "Moth Tutorials - 1. Rigging" by International Moth Class Association. The tiller is visible at around the 8th minute of the video. (International Moth Class Association, 2014, 7'50"-9').

The first functionality, and the easiest, is to control the horizontal movement of the rudder blade to steer. It consists in an assembly of 3 parts between the skipper's hand and the rudder blade. These parts are shown on Figure 13 where the tiller extension is in yellow, the tiller itself is in orange and the rudder head is in red. The skipper holds and moves the tiller extension from front to back, transmitting the movement to the tiller by a universal joint into a horizontal, rotational movement. The tiller transmits this movement to the rudder head by a tight fit, which makes the rudder move to steer the boat.

Figure 13: Moth under sail showing the tiller assembly

The second functionality is much more difficult to design. In addition to a pushing movement, used to steer, the skipper can also rotate the tiller extension in their hand. This rotation is transmitted by the universal joint to the tiller where it is converted in a horizontal movement inside of it. This conversion is possible because of the transmission of the rotation between the tiller's external tube and an aluminium threaded element leading its helical movement in a threaded plastic cylinder. This plastic cylinder then pushes an aluminium pin which leads to a rotational movement of the rudder around the x axis, or in the bow to stern vertical plane of the boat, due to the contacts with the rudder structure and the rudder's extension. In both contacts points, two bearings have been added to dampen the movement. The Figure 14 shows the schematics for this tiller assembly.

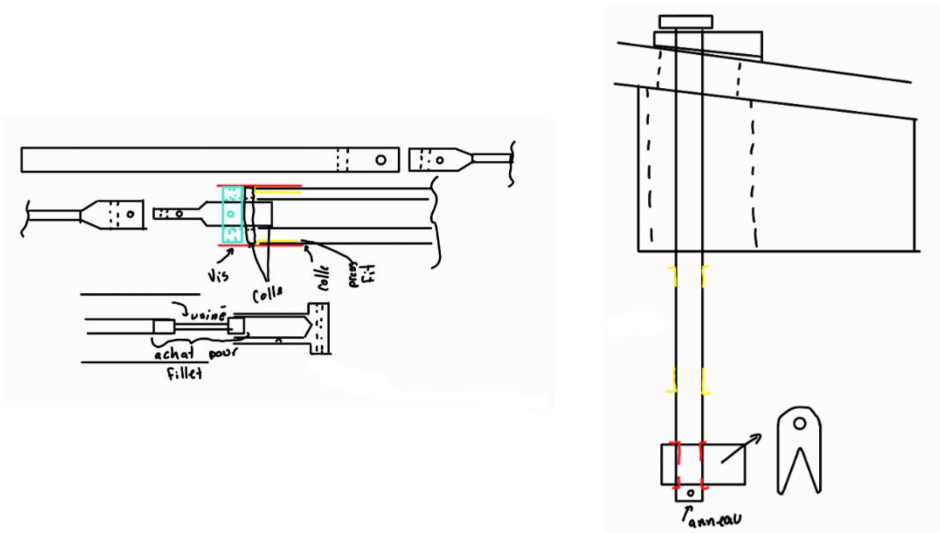


Figure 14: Tiller assembly schematics

1.7. Rig

For the fittings and the rigging, we were greatly inspired by what is already done in the industry for our system. We had organized and planned the fittings beforehand using drawings and lists of parts and ropes required for each section, vang, Cunningham, and others to make sure nothing is forgotten.

The Figure 15 here shows the rigging layout, followed by the lines used in Table 22 and the fittings listed in Table 23. The letter on each fitting shows where it goes in the rigging.

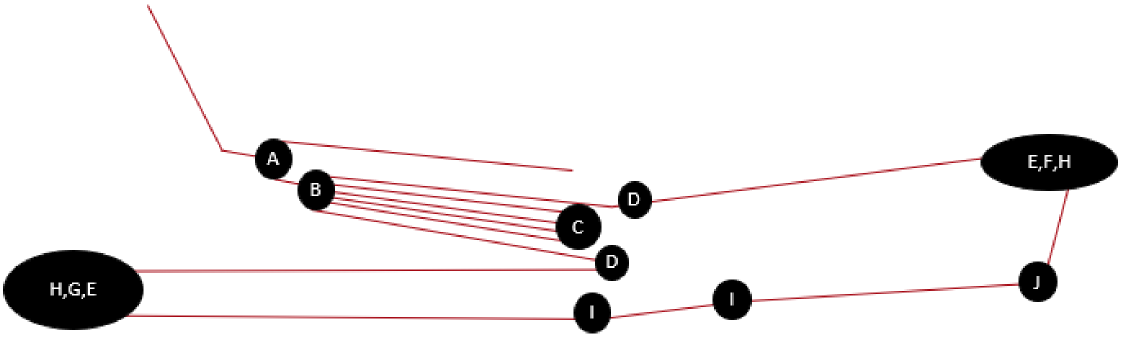


Figure 15: Rigging layout

Table 22: Line types and lengths

Section	Type	Longueur	Répétition	Longueur tot	Commentaire
a	Marlow D12 78 4mm Red	650	1	650	
b	Marlow D12 78 4mm Red	700	1	700	
c	Marlow Excel Control 4mm Rec	500	6	3000	
d	Marlow Excel Control 4mm Rec	400	2	800	
e	Marlow Excel Control 4mm Rec	3000	24	72000	

Table 23: Fittings list

Point	Type	Qtée	Commentaire
A	Harken 25mm Wire Block	1	
B	Harken Fly 18mm Soft Attach Triple Block	1	
C	Harken Fly 18mm Soft Attack Double Block	1	
D	Harken Fly 18mm Soft Attach Single Block	2	
E	Harken Micro Cam-Matic Cleat	2	
F	Harken Micro Fairlead Green	1	
G	Harken Micro Fairlead Red	1	
H	Ronstan Bushing 7mm	2	

The anchor points of the backstay for the mainsail sheet are two one-loop Ropeyes pad eyes arranged separately on each side of the deck. The two inserts were fit from the inside of the hull before gluing the 2 hull halves together.

After careful consideration and a study of feasibility, we changed our initial plans for the locations of the cleats for the various adjustments (vang and others) on the boat to unclog the already very limited space on the deck of the boat. The initial plan was to install the cleats on angled blocks, as far forward as possible from the deck of the boat. Their new location is on carbon fiber pads on top of the front tubes of the wings, parallel to the angle of the win. The pads' structure has been reinforced by an L-shaped carbon fiber piece that bonds it to the wing tube.

When installing the various fitting and rigging parts on the boat, we had to modify the location of the vang pulleys to lighten the charge of the one loop Ropeye pad eye initially installed to accommodate the vang and Cunningham pulleys. Therefore, we added another Ropeye one loop pad eye just above the first one to install the downhaul pulleys. We have also added an eyelet in the edge of the sail to be able to have a functional headline since the eyelets already present in the sail were too far back compared to the boom headline giving our moth a sail that was too hollow.

Another problem encountered when installing the cleats for the various adjustments, vang, and others, is that they are mounted a little too low on the pads to allow them to be used without problems. When jotting the ropes in the cleats, the lines hit the outer tube of the wing before the rope can be properly inserted between the teeth of the cleat.

1.8. Electronics and Data Acquisition

To be able to improve the designs from one edition to the next, a lot of data is required. Usually this data is obtained manually, by sailing the boat, looking at it's structure afterwards, interviewing the skippers on how the boat sailed and so on. These ways of obtaining data work, but the data acquired like this is not precise. Thus, it was in the team's goals to produce a data acquisition electronic system to go with Rafale 3, usually referred to as Rafale 3's embedded system, or ES, and allow the collection of more precise navigation data that could then be compared with the data from future editions to be able to compare different boats on the same metrics. This section details how this system has been designed for Rafale 3.

1.8.1. The Goals of the Embedded System

As mentioned in the introduction, the general goal of the embedded system is to collect as much data as possible about the behaviour of the boat in the water. This includes data such as the orientation of the boat in space, its GPS position, the wind speed and direction and force vectors in its structure and it's rigging. Not all these data source have been added to Rafale 3's system, the reasons for which are detailed in the Known Shortcomings and Missed Goals subsection.

When planning Rafale 3 in 2019 it was decided to create an embedded system that would have orientation data, from an IMU (accelerometer and gyroscope combo), position and speed data, from a GPS and wind speed and direction, from an ultrasonic anemometer. It was also planned have a display on board to show the speed and direction to the skipper and to make a wireless link from the boat to the shore as well as a piece of software to be able to monitor in real time the behavior of the boat. The collection of force vectors for the structure and rigging was put to the side early because the hull design was already in an advanced state and incorporating these sensors would require some major modifications. As a reminder, at the time the boat was planned to sail in the summer of 2020.

The electronics section of team Rafale-ETS has mostly consisted of one person since 2019, so the progress has been slow and interrupted by COVID as well. As such some of the original goals from 2019 had to be moved to Rafale 4 over time. The goals for the embedded system on Rafale 3 are now to collect only the orientation (IMU) data and the position and speed (GPS) data, as well as establish a link to shore. More details as to why the other goals have been moved are found in the Known Shortcomings and Missed Goals subsection.

1.8.2. Parts and Modules

Because this was the first real foray into electronic systems for the team, this embedded system has been designed in a way that would allow for rapid prototyping and reduce potential problems. To do so it was decided to build the system entirely with off the shelf modules.

The base of the system is a Raspberry Pi 3 B+ that the team already owned following some previous experiments. This is a powerful embedded computer running Linux, allowing the system to be written for a known platform in an easy to debug language.

The orientation data sensor that got chosen is a BNO085, the updated version of the BNO055 IMU, on a breakout board. This sensor was chosen because it directly computes the orientation and acceleration values into known formats which removes the need to write software to handle the raw data, speeding up implementation.

The GPS module chose is a ZED-F9P based Raspberry Pi Hat (addon board). It was chosen for its ability to handle RTK positioning, which the team wants to implement in the future to enable very precise GPS positioning up to centimeter level. For Rafale 3 it is used only as a standard GNSS GPS receiver.

The shore communication technology of choice is the LoRa system, using a pair of LoRa-E5 based development boards as premade modules. This choice and its problems are discussed in the Sending Data to Shore subsection.

All the modules are connected to the Raspberry Pi via its serial busses. The GPS module is connected via the Pi's pin connector to the internal Serial interface (USART, /dev/ttyS0 on the linux system) and the I2C interface on address 0x42 (Unused for Rafale 3, but available for configuring the module). The BNO085 IMU module is connected to the same I2C interface as the GPS but on address 0x4B. Finally, the LoRa-E5 module that is connected to the system is connected via USB, opening a USB serial port to communicate with using the AT protocol. The other LoRa-E5 module is likewise connected via USB, but to a laptop on shore, running a software to be able to receive the data sent by the embedded system.

1.8.3. Programming the System

As the embedded system is built on top of what is effectively a linux computer, the decision was made to program the system in python to allow for fast prototyping, testing and for members that don't already have programming skills to learn on an easy-to-use language.

The architecture of the python software has changed a lot during the development of Rafale 3's system so for the sake of shortness only the current architecture will be detailed.

The backbone of the embedded system, software wise, is the MQTT protocol and the Mosquitto MQTT broker made by Eclipse and freely available for use. Every sensor and software module of the system is built as an independent python script that register either as a publisher or a subscriber on one or multiple MQTT topics to Mosquitto. Mosquitto then handles redistributing the data on the different topics to the modules that needs it.

The python software is composed of the following 4 modules and a script to start them all together:

Module	Associated hardware	Description
imu (imu.py)	BNO085	Handles reading data from the IMU and sending it to the “orientation” MQTT topic.
gps (gps.py)	ZED-F9P	Handles collecting and parsing the gps data provided as NMEA strings and sending it to the “speed” and “position” MQTT topics.
shore_com (shore_com.py)	LoRa-E5	Handles reading the data from all the available MQTT topics and sending it over to the LoRa receptor on shore.
database (database.py)	-	Reads the data from every available MQTT topic and saves it into a file based local MongoDB style database using Mongita.

Table 24: Embedded system python modules.

1.8.4. Power Usage

One of the main challenges with an embedded system installed on a sailboat that has otherwise no electrical power source or consumer, is providing power for long enough to allow the system to gather significant data, while keeping the system light and small.

The first step to designing a power supply for any electronic system is calculating the total power draw of the system, at the rated voltages and consumption (amperages) of each module. The following table presents the different module as well as their theoretical maximum power draw and the total maximum power draw of the system.

Module	Consumption (mA)	Operating Voltage (V)	Power (mW)
Raspberry Pi 3 B+	1500 *	5	7500
BNO085 IMU	45.5	3.3	150
ZED-F9P GPS	130	3.3	429
LoRa-E5 mini	111	3.3	366
		Total:	8445
Total consumption at battery voltage:	2283	3.7	

Table 25: Power consumption of the Rafale 3 embedded system.

** Note: The Raspberry Pi computer can consume up to 2500 mA depending on the computing load put on it, but the python software does not load the Pi very much, as such we don't expect to need anything more than 1500mA, probably even a lot less.*

To allow for a decent amount of time to collect data, and not run out of power mid race, the system would require to be running somewhere from 4 hours to 8 hours without interruption or physical access. This means that the battery used should sustain the maximum power draw expected, for at least 4 hours and ideally 8 hours. Multiplying the total consumption at battery voltage by the number of hours of desired run time yields the amp-hours ratings we should be looking for in a battery. These are $2283mA * 8h = 18.26Ah$ and $2283mA * 4h = 9.13Ah$ respectively. This means the battery should have between $10\,000\,mAh$ and $20\,000\,mAh$ of rated capacity. The best solution for such a battery is to use a ready-made power pack like those used to charge cellphones. Standard LiPo cells don't come in the desired capacities and require additional circuitry to charge and supply power while a power pack with these capacities is easy to find and only needs a USB cable to both power and charge. The last consideration for the battery is the physical size, which guided the choice towards the smallest $10\,000\,mAh$ power pack we could find, the Anker PowerCore 10000. The team will have 2 of them to allow for quick swap of a discharged battery with a charged one if needed since the capacity of the PowerCore is on the shorter 4 hours theoretical range.

1.8.5. Sending Data to Shore

Probably the most complex goal of the Rafale 3 embedded system is sending the collected data to a station on shore. The team chose to use LoRa for this due to the very long range supported by this technology. The LoRa-E5 mini and LoRa-E5 development board were chosen as a pair to communicate together. The LoRa-E5 mini as the emitter on Rafale 3 and the LoRa-E5 development board as the receptor, plugged into a computer on shore. These modules were chosen amidst the integrated circuit shortage due do COVID, partially due to availability and partially due to them looking like powerful LoRa boards. However, these boards have a major flaw, that the team only discovered when trying to make them work, and that is that they are only able to do point to point communication in a test mode. This works for the needs of the system to some degree but is far from the intended use of the modules. As such, the LoRa shore communication module is still being worked on as of the writing of this report. The system can send some data through it and the hope is to have it working properly using this test mode before the races.

By itself, sending data to a station on shore doesn't do much and so a visualisation software is on the works in parallel with the embedded system itself. This software is designed to be able to present all the sensor data that gets received through the LoRa link as a list, as well as show the boat's position on a map and its orientation on a 3d model. Eventually it will also display the different forces applied on the boat when the force vector sensors are added to Rafale 4. Sadly, the only actual programmer of the team left in January 2021 and that has put this software on hold, so for Rafale 3 the team is working on a command line tool that can at least display the incoming data as a table.

To ensure that the collected data can still be extracted from the system in case of the LoRa failing or not being ready on time, the system will have a web interface that will allow for downloading all the data saved on board in a few clicks by connecting to the Raspberry Pi's Wifi access point. This web interface will also allow to monitor the system's status and data in real time from a cellphone or a computer.

1.8.6. Known Shortcomings and Missed Goals

There are a lot of shortcomings with the design of the Rafale 3 embedded system. This section will detail the ones the team have encountered thus far and what has been done to mitigate them if anything.

The first shortcoming is the lack of wind data, an essential data point for a sailboat. This missed goal is due to the team not being able to find a decently affordable, small anemometer in time. The MQTT based design of the system as well as the system's WiFi access point will allow for a fast and easy integration of wind data as soon as an anemometer is found. This is now planned for Rafale 4 as of the writing on this report.

The second shortcoming is the absence of an onboard display. This missed goal is also due to the team not being able to design a display on time. Having an onboard display has been pushed back to Rafale 4, but the design of the embedded system allows for an easy integration of such an external display. For Rafale 3 the display will be replaced by a web interface available when connecting to the Pi's WiFi access point.

The third shortcoming is the LoRa connection. This edition's design for the shore connection taught a lot to the team in what to do and what not to do. The mitigations in place for this problem are detailed in the Sending Data to Shore subsection above. This edition's system will be used as a platform to evaluate the LoRa capabilities and decide if, going forward, the system will continue using LoRa, probably with a proper gateway instead of a point-to-point system, or if another technology is more adapted. Some of the key points under evaluation are the data throughput needed and the actual needed range, which could be a lot smaller than the range LoRa provides, and thus enable other technologies to be used such as WiFi or Cellular (LTE and/or 5G).

The fourth shortcoming is the visualisation software. The loss of the team's programmer made this a missed goal for Rafale 3. There isn't much that can be done to mitigate the absence of this software except to recruit multiple programmers for Rafale 4 to ensure it can be made for the next edition.

The fifth shortcoming is the power supply and consumption of the system. While the power supply described in Power Usage works fine, the system has not been designed for power efficiency. The Raspberry Pi B 3+ is a somewhat power-hungry device and the system is using only a small portion of its capabilities. As such, the physical backbone of Rafale's embedded systems for Rafale 4 and the following boats will be redesigned to reduce power consumption by a lot.

The sixth and last shortcoming is the mechanical placement of the system on board Rafale 3. When the embedded system started being worked on, a lot of the hull and the mechanical systems of Rafale 3 where already designed, and there hasn't been a good effort to integrate the embedded system mechanically properly. This prevents the system to be in an ideal location along the hull and will have an impact on both the data collected and the transmission of said data to shore. For Rafale 4, the placement of the embedded system will be designed into the boat from the start which will prevent this for future editions.

1.8.7. Future perspectives

This edition's embedded system, with it's MQTT backbone and the Raspberry Pi's ability to act as a WiFi access point, has been designed to be easily expanded upon, in a modular fashion. The idea behind this structure was that modules that are external to the box containing the Pi would connect to and work with the system in the same way as modules that are inside the box. This means that a sensor on top of the mast would connect to the Pi's WiFi access point and gain access to Mosquitto and the MQTT backbone directly to send its data. A display on the boom would do the same thing, but instead subscribe to a few MQTT topics to be able to display them. This will accelerate the development of the next editions' systems.

Provision for a few future projects have already been made into the design of the current embedded system, on top of the goals that have been pushed back. The following paragraphs will outline them and what has already been designed into the system for each one.

The first one is data analysis and replay, to allow for comparing between race sessions and our next generations of moths. The provisions for this were made by making sure the current system has a way to save and keep its collected data, explaining the existence of the database software module. The shore connection should play into that as well, allowing for saving the navigation data off the boat in real time.

The second project is the inclusion of strength vector sensors, and really any new or delayed sensor module. Adding new sensors has been made easy by the MQTT backbone like mentioned at the start of this section, and this has been designed explicitly as to enable us to design some removable testing sensor modules, that can be put on the boat for test sails, and then removed for the races to prevent hindering performance. Such removable sensor modules would measure non navigation type data that is more useful to qualify new materials and methods than to racing itself, such as hull flexing, or vibrations in certain parts of the boat.

The third project is the automation of the flying height. The embedded system would control the flap on the daggerboard's foil to keep a stable flight height, selectable by the skipper with some kind of device, most likely on the tiller's hand hold. However, doing this will require a lot of navigation data in a variety of sailing conditions to be able to develop a good control model. To start gathering this data at the earliest, the embedded system was designed with an IMU as one of its critical components, on top of the database capabilities doing double usage with collecting data for this and general data analysis and replay.

2. MANUFACTURING AND COST ANALYSIS

2.1. General description

To create and assemble Rafale 3, several parts had to be manufacture in house by the team, and a few where also outsourced when the team did not have either the expertise, the equipment, or the time to manufacture them. The parts presented in this chapter are the infused basalt fiber hull, and its mould, the machined carbon fiber hydrofoil wings, the sailboat's wings and rudder structure assemblies, the wand system, and the tiller.

2.2. Hull

2.2.1. Symmetrical Mould

Figure 16 shows the pinewood mould used to manufacture the hull. This 17-foot-long mould doesn't fit into the CNC machines the team has access to in ÉTS. The mould had to be made by an external company. The block of pinewood was machined and coated with Duratec 707-002 surface primer. To obtain a mirror finish, the primed surface has then been sanded and polished.

Figure 16: Symmetrical pinewood mould coated with Duratec

2.2.2. Inserts

Inserts presented in Figure 17 were used to make the transom in the mould. The inserts were made by hand-cutting layers of wood. They underwent the same priming and polishing as the mould itself. Inserts were positioned using dowel pins.

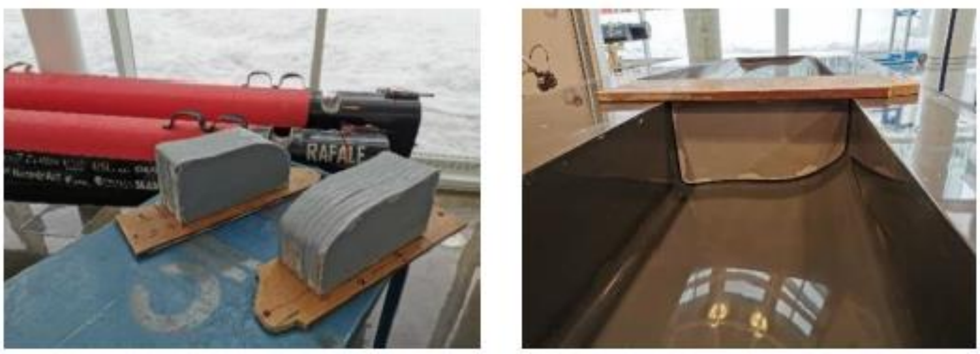


Figure 17: Mould inserts for making the transom

2.2.3. Core Forming

Sheets of PET were cut and thermoformed to match the mould surface as seen in Figure 18. The first step of the process was to heat the sheets to 190°C (above their glass transition temperature) for 5 to 7 minutes. They were then malleable enough to manually be pressed in the mould and take the mould's shape. Once in the mould, the sheets could cool down and become rigid again. To ensure thorough resin penetration in both skins, the foam core was dotted with 3 mm holes at 5 cm intervals.

Figure 18: Thermoformed hull core sheets

2.2.4. Bonding Flanges

To glue the hull shells together, it was necessary to create a sufficiently wide bonding surface. For this purpose, a 3 cm monolithic flange was planned around the shell contour: a method originally developed for Rafale 2. This process would also add extra flexural rigidity to the finished hull. The team decided to make the flanges in-situ, during the infusion of the hull. MDF planks were fastened along the mould parting line to create the flange shapes.

2.2.5. Lamination

Each ply was hand cut from a 48-inch roll of woven basalt. The width of the roll relative to the hull length meant that a single 45-degree ply did not span the entire surface. As a result, two plies had to be juxtaposed with an overlap for adequate load transfer. Based on the following formula, a 20 mm overlap was used. Indeed, the minimum theoretical overlap is equal to the ply thickness t divided by the joint angle θ. The joint angle is computed from the resin shear strength S and the fibre longitudinal tensile strength F_{1t}, see paper by L. Chevallier in the bibliography.

$$\theta = \sin^{-1}\left(\frac{2S}{F_{1t}}\right)$$

$$L_r = \frac{t}{\theta}$$

The Figure 19 here shows the dry basalt sheets in the mould.

Figure 19: Lamination process of dry basalt fibre

2.2.6. Infusion

The infusion apparatus is illustrated in Figure 20. First, the process begins by positioning the insert. Then, by using silicone caulking between the insert and the mould to seal the join. The cut basalt fiber plies and the core are then stacked, according to the specified sequence. At this point, the bonding flange boards are fastened. The laminate is then covered with peel-ply and flow mesh. The next step is to carry out the vacuum bagging. Then, the laminate is dry compacted at full vacuum. Once compacted, resin is feed through an inlet while drawing reduced vacuum at the outlet (20 inHg to avoid resin vaporization). The part is finally demoulded when cured, 24h after full impregnation. To use only one mould, this process was carried out twice, placing the transom insert once on each side of the mould, to make both hull halves. Figure 21 shows the resin being feed through the half hull in the mould, under vacuum.

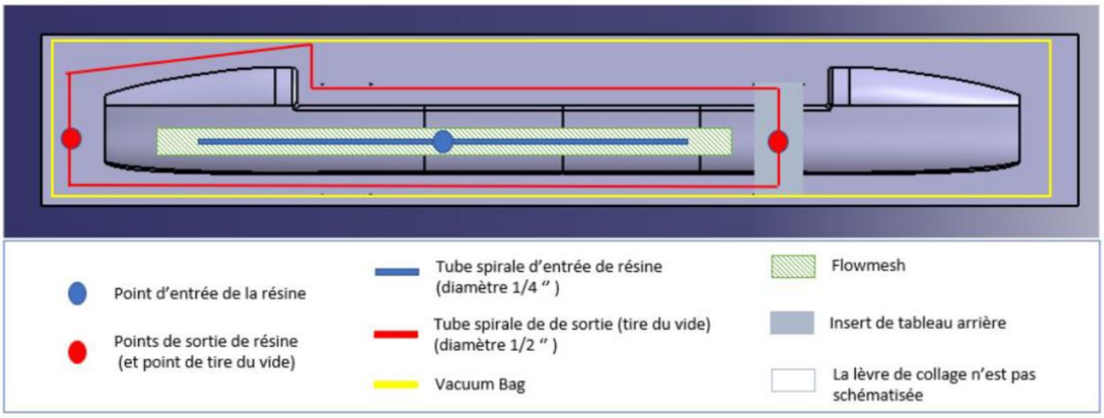


Figure 20: Schematic of the infusion process of the starboard hull shell

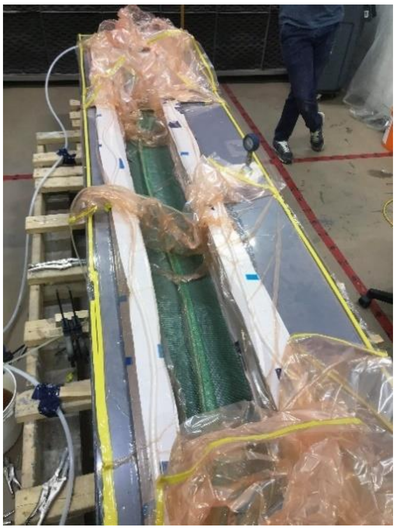


Figure 21: Elium resin being injected into the starboard hull shell

2.2.7. Hull fairing

Although the infusion of each hull half was completed successfully, notable surface waviness resulted in the need for fairing the hull. This waviness was caused by inadequate compaction of the outer skin against the mould surface. This was caused by the thermoformed core panels resisting the vacuum pressure, mostly in areas of high curvature such as the deck corners. To smoothen the surface, epoxy fairing compound was applied and sanded. This process inevitably compromised the recycling potential of the hull, as epoxy is a thermosetting material and cannot be thermoformed into a new shape.

Figure 22: Surface waviness resulting from inadequate fibre compaction

2.2.8. Bulkheads

The bulkheads were cut from a basalt/PET sandwich panel infused on a flat aluminum tool plate. The contours were trimmed by hand using a printed outline of the hull sections. They were glued to the inside of the hull with MMA structural adhesive.

2.3. Hydrofoil wings

2.3.1. Lamination

To make the composite stock material, 12 in by 39 in rectangular plies were cut from the remainder of the roll of prepreg carbon fibre used for Rafale 2. The sheets were aligned, stacked, and compressed in a 0/0/45/0/0/-45 ply schedule. A debulk was performed after the first ply layup and that of every ply sequence. The resulting slab was consolidated under vacuum for 24 hours. A frame of square aluminum tubes was placed around the slab to prevent corner rounding during consolidation. It was then cured in an autoclave. The cure cycle was obtained from the material data sheet and verified in the Raven cure simulation software.

2.3.2. Ultrasonic Testing

Before machining the wings out of the slab, structural integrity was verified using non-destructive ultrasonic testing. This test was carried out to detect internal delamination which will interfere with the ultrasonic wave. A single-element 2.25 kHz probe was used to scan 360 individual points on the face of the slab. Each the response of each scan was analyzed using a MATLAB script. No indication of delamination was reported.

2.3.3. Machining

The hydrofoil wings were machined in a 3-axis CNC mill equipped with a dust collection system. The CAD model was imported into Mastercam to generate the toolpaths. Since both faces of the wings are curved, two machining setups were required. In the first setup, the top faces of the wings were machined directly from the slab which was secured in the mill. Minimal clamping force was applied to avoid distorting the slab which would result in inaccurate wing profiles.

Figure 23: Clamped slab with contoured rudder wing (bottom) and surfaced daggerboard wing (top)

Once the top faces were complete, the wing contours were hand cut to separate them from the slab. To clamp the curved surface of the wings, a work-holding jig had to be made. This jig was machined out of the aluminum slab used to secure the carbon fibre slab in the first setup (this part was previously a rudder plug for Rafale 1). The jig included curved beds for each part and tapped holes for step clamps. Figure 23 above shows the wings being machined and Figure 24 shows holding jig with a wing mounted.

Figure 24: Aluminum work-holding jig with the main daggerboard wing mounted using step clamps

2.3.4. Assembly and Finishing

The machined wings had rough finish and a regular step-like pattern resulting from staggered tool passes. Both these features were eliminated by applying a layer of epoxy clear coat, sanding and polishing to a near-mirror finish. The flap hinges were CNC machined by a professional supplier and anodized to avoid galvanic corrosion between the aluminum and carbon fibre. The main wing was assembled using bolts and MMA adhesive.

2.4. Wings and Rudder Structure

2.4.1. Wings

To build the wings, a wet lay-up was done with carbon ply sock to keep the elbows in place and make the corners stronger. Before doing the lay-up, about 7 inches of plastic wrap was added at each extremity of the elbow to avoid resin getting on the tubes of the wings. Once everything was in place the assembly was bagged and kept under vacuum for at least 48 hours. After everything cured, the assembly was debagged. Finally, a hole on each side of the wings were drilled to allow a pin to pass and connect the wings with the holding brackets on the hull.

2.4.1.1. Compression bars

The 2 compression bars were cut from a long carbon tub to the right length. Then a hole was drilled at each end for a pin to attach them to brackets at the base of the mast and brackets on the wings

2.4.1.2. Wings holding brackets

The holding brackets to hold the wings to the hull were, at first, fabricated by using Prepreg ply 20: $\left[[8H5\,\infty]/[UD\,\infty/45/90/{-45}]_2\right]_5$. The ply was placed on an aluminium square tube that was polished and cleaned with acetone and Zyvax cleaner. Once everything was set it was slow cooked in an oven. Finally, 6 holes were drilled per brackets: 4 for the screw to keep it in place and 2 to attach the wings to the hull with a pin.

However, as explained before the brackets broke during the first test. Thus, they were replaced with 3x3 aluminum tube cut at 2 inch long and the top side removed. Also, where cut where made it was sanded to make it nice and smooth and the carbon brackets were used as templates for the six holes to make sure the alignment does not change.

Two access ports were cut into the hull in the form of an ellipse of 3 inches by 3.5 inches. One port was situated at the back of the hull and the second one closer to the front, on the deck. Also, 2 covers were made of a laminate of 2 sheets of carbon fiber. These can be screwed into place with 6 screws. These were made so we could install nuts to be able to screw the brackets into place. These nuts were glued using M1-30 glue.

To add support to the holes in the brackets 8 washer were cut in a FR4 sheet with a hole saw. Then, they were sanded on both sides to have a smooth surface for gluing. Before gluing, masking tape was applied to any surface that wasn't involved in the gluing process. Once the wings, hull and brackets were assembled the washer were glued and it was done as such to ensure that the alignment of the holes of the wings and brackets stays the same. Afterwards the masking tape was removed and any excess glued was removed from the rest of the surface.

2.4.1.3. Brackets compression bar: for connection between CB and wings

The brackets for the compression bars were made in 3 steps.

First was the preparation of the materials. The right template was cut out of a paper sheet, a woven fiber plate with the right thickness was chosen and the templates were glued on it using AirTac.

Secondly, the plates for the brackets had to be cut out of the carbon plate. It was first roughly cut with a grinder, then a sandblaster was used to smooth out the edges. Afterwards, $3/16$ inch holes were drilled into the plates with a drill press. Before passing to the gluing step, the necessary area on the plates and the 3D printed component needed to be either sanded or covered in masking tape. Finally, the sanded surfaces were cleaned so no particles are left.

The final step was to glue the 3 components together. First, glue was applied to the surfaces and the structure was assembled, kept in place using clamps and an insert was added in the holes to assure the right alignment and everything was laid on a plane surface, so everything is straight

2.4.1.4. Inserts

To reinforce the critical points on the wings and the compression bars, inserts were added. Even though the dimensions very between the wings and the compression bars, the manufacturing steps are identical. The inserts are fabricated in 3 vital steps: marking, drilling, assembly, and gluing.

First, the inserts had to be covered with 5 layers of masking tape so that they would fit and not move inside the tubes. Then, they were inserted into the tubes. Once inserted, the wings and compression bars were installed on the boat. Since the holes for the pins were not perfect circles the excess space of pin holes in the brackets had to be filled with molding clay. The pins were slowly removed, so that the molding clay stayed in place, then the inserts were put into place and were held in place with clamps. Once the inserts were in place, the wings were removed and held upside down, vertically, so that the center of the holes could be marked with a punch.

For the drilling step, the marks were used to align the insert in the vice. Then a pointed drill was used to start the hole, a ¼ inch hole was drilled over it and a ¼ reamer was used to make sure the hole was the right size, and the circumference was clean.

Finally, everything was assembled, and the inserts were glued. However, before gluing, 6 layers of demolding wax was applied to the pin so they would be removeable after the glue had set. The insert needed to be sanded and tape on the inside, and the outer surface of the tubes also needed to be taped to prevent the glue going everywhere. M-20 glue with glass beads was prepared for the gluing process. The glue was applied to the inside of the tube and on the outside of insert. The insert was inserted into the tube, the excess glue was removed, the holes were cleaned, and the masking tape was removed. Finally, the wings were installed on the boat with the pins to ensure the right alignments of the inserts.

2.4.1.5. Pins:

The pins are made from 4 stainless steel pins in which 1 hole were drilled at each end. These holes were created to hold 2 metal rings with a line connecting them in order for the pins to stay in place and prevent losing them.

2.4.1.6. Additional brackets

The additional wing holding blocks were made from scrap materials. First the team had to resize each of the 4 pieces (2 per wings). Then holes were drilled. Once the wanted inclination had been measured, a hole saw was used to make the top of the block a concave shape to allow the wings to fit into the brackets. Some adjustments had to be done to obtain a better position for the wings. Finally, the brackets were screwed to the and glued using M1-30 glue.

2.4.1.7. Trampoline hooks

The trampoline hooks are composed of carbon strips and dry loops. A total of 40 holes were drilled in the carbon strips to make place for the hoops. Each hook was spliced 3 times to make them strong enough for the charges applied to them. The hooks were made by pulling the fishing rope in the hole in the strip, then measuring 3,5 cm, applying masking tape to the loop, so that the hook itself does get drench in resin and can no longer be open and used. The excess of rope was pulled apart on the other side of the strip.

When the preparation was done, resin was poured over the pulled apart part of the hooks then the hooks and the strips were bag and put under pressure for at least 48h to assure the strips and the hooks are now one. After that, everything was unbagged, the excess of pulled apart rope was cut using a Dremel and the strips were placed in a vice to keep it steady.

Finally, the strips were glued using M1-30 glue to the hull with the right measurement to be able to attach the trampoline with enough tension in them.

2.4.1.8. Cleat shelves

The shelves are each made up of a carbon fiber plate with foam core, that was cut to the desired dimensions. A "L" shaped bracket was also made using carbon fiber. Once both were completed, they were glue together. Before assembling it to the wings, a clear coat was applied on the pieces to protect the carbon from the environment. Once that dried, the surface was sanded and so was the surface where it was to be glued on the wings. After everything was cleaned, the assembly was glued to the wings using M1-30.

2.4.2. Rudder

2.4.2.1. Rudder Structure

Carbon plates were infused using a 3D mold to give them a perfect curve, to serve as the fixations for the rudder structure unto the hull. The Pro-set epoxy and carbon fiber of 1 ply and laminated at 0° and 45° were used for the infusion. Once the infusion was done, the plate was removed, and 2 templates were glued onto it using Airtac. With a grinder, the plates were roughly cut and a Dremel was used to sand it and get the perfect shapes. After that, the 3 necessary holes were drilled into it to make place for 2 inserts. The 2 inserts were cut and sanded to the right length. Finally, the templates were removed, the plates were washed, and 2 holes in the hull were drilled so the plates could be screwed to the boat.

The 6 carbons tube needed to make the structure were cut to the desired length. Using a 3D printed jig as seen on Figure 25, the carbon tubes and the 2 connectors were assembled. Then the 3D printed connectors were glued to the tubes using M1-04.

Figure 25: Rudder structure being assembled on its jig

The 4 clevises were positioned on the plates and the assembly was screwed on the boat so that the clevis could be glued to the rudder structure in the right position as shown in Figure 26. Then, the tubes were glued to the clevis while positioned in the jig and screwed into the bottom tube's adjustment screw.

Figure 26: Rudder structure being assembled on the transom

Once everything was cured, the tubes were cleaned and sanded to prepare for the infusion of the connectors. Then, laminated 45° and 0° carbon ply were cut with a length of 30 cm for compression ply. The Pro-set epoxy resin was mixed and the 45° ply was wetted and applied on the structure in alternance with the 0° ply. Then the whole structure was bagged, and epoxy was infused under vacuum into the plies. This process is shown in Figure 27.

Figure 27: Rudder structure reinforcement process

On each side of the plates holding the structure to the hull, 2 rubber washers were added to make the distance between the hull and the plates wider and better aligned with the tubes of the structure. 2 plain bearings were also press fitted into the vertical tube that is holding the rudder.

2.5. Wand System

The wand system is a custom assembly of mostly off-the-shelf parts. Pushrods were made from off-the-shelf carbon fibre tubes cut to length and fitted with off-the-shelf aluminum rod ends. Complex parts such as the wand elbow and crank were 3D printed in PET plastic filament reinforced with short carbon fibres. Pivots were made from cut stainless steel rods.

2.6. Tiller

2.6.1. Tiller Extension

The tiller extension has been obtained by recycling the one from the catamaran Rafale 2, catamaran built by the team for a previous competition, and adapting its length to Rafale 3. Two holes have been drilled into it to screw the universal joint with nuts and bolts.

2.6.2. Universal Joint

To have a rigid and solid universal joint, the choice has been made to buy a ready-to-use universal joint made for moth boats. Four holes have been drilled to connect it to the tiller and the tiller extension with screws.

2.6.3. Inner Carbon Tube

This tube was glued with methacrylate glue with glass beads to a semi-threaded rod, bought and machined to the wanted good diameter on the non-threaded side. This rod, with a plate head, is the one described in the design part which moves with a helical movement into a threaded plastic cylinder that was machined for this purpose.

2.6.4. Translation Blocking System

To avoid the translation of the inner tube, 4 components have been added to the outer carbon tube. A plain bearing was bought and machined so the outer diameter of the head was slightly smaller than the outer diameter of the outer tube. It was press fitted into the outer tube. A small cylinder was machined using a plastic rod with an inner diameter slightly smaller than the outer diameter of the inner tube et and outer diameter equal to the bearing. It was glued to the inner tube with methacrylate glue with glass beads. The bearing and the small cylinder block the first translation.

A thin carbon tube was reinforced using a wet lay-up, 4 holes at equal distance were drilled into it and it was glued to the outside of the outer tube, so that it is proud of the end of the outer tube. To block the second translation a second small cylinder was machined with 4 holes drilled on its circumference and 4 screw where screwed in the carbon tube and the second cylinder to keep the latter in place. This whole assembly can be seen in Figure 28.

Figure 28: Tiller translation blockage system

2.6.5. Tiller to Universal Joint Connector

The difference of diameter between the intern tube and the universal joint led to the need for an additional connection. A cylinder was machined in an aluminum bloc for this connector. On the universal joint's side, two holes have been drilled for the joint to be screwed on. The other side was simply bonded to the tiller with a quick set methacrylate glue mixed with glass beads to avoid galvanic corrosion between aluminium and carbon.

2.6.6. Rudder Head Extension

The connection between the rudder and the tiller required four parts. Three of them were 3D printed and one was a carbon tube with a wet lay up to reinforce it. Amongst the 3D printed parts, one is for the lower connection and the two others for the higher parts, to support the carbon tube and to create a pin head support. All parts have been bonded to the rudder by resin infusion and 2 plain bearings have been added in the lower part with a press fit. The finish of the assembly consisted in applying a clear cote after infusion and sandblasting the parts to improve the surface finish.

2.6.7. Rudder pin

The rudder pin was obtained from a long aluminium rod machined to obtain a flat head and consequently block its downward translation when inserted. The upward translation was blocked by drilling a hole at the lower end of the rod and inserting a ring into it.

2.7. Materials

This part presents is a non-exhaustive list of the principal materials used for manufacturing and their engineering characteristics. A lot of parts in Rafale 3 are made of composites structures. Three sets of materials were used according to the desired properties for the laminates: two sets of fibres/resin as Carbon/Epoxy and Basalt/Elium and one type of carbon prepreg.

2.7.1. Fibers

2.7.1.1. Carbon

Carbon fibers are used mainly for the critical parts and in different forms:

- Ready-to-use, like all the tubes used for the rudder structure, the wand system, the tiller, the wings and as plates out of which have been cut different parts that were then glued to form pieces such as holding brackets. This form is useful for standard shaped parts.
- Semi-finished products like prepregs for the rudder and daggerboard or for some brackets. The advantages of this form are the quality, the homogeneity, the processability, the strength characteristics and the appearance. The main disadvantage is the conservation time and temperature due to the shelf life of the thermoset that as begun it reticulation. In addition, the heat cure at minimum 270°F and the costs are also important. The infusion of prepregs is a long and rigorous process that need to be well prepared and organised.
- Dry fibers like in resin infused reinforcements for the rudder structure, the wings, and the rudder, or as lay-up reinforcements. They are used in woven or non-woven form. This form is easy to use for small touch ups and bigger pieces with hard shapes alike. The infusion process, when used, can be cumbersome and requires a good level of technical ability.

The problems with carbon fiber are mainly the price, the durability aspect (petroleum origin, recyclability, energy efficiency) and the toxicity. The toxicity is a critical element to know because it requires taking precautions when manufacturing and to have good work conditions such as a ventilated sandblasting room and PPE (gloves, particle mask, glasses, and industrial suit).

2.7.1.2. Basalt

Basalt fibers are used for the bigger parts such as the hull. Even if their properties are less impressive than carbon fibers, they are suitable for most parts of the boat. Their advantage is that they are natural and recyclable fibers made from the melting and the grinding of volcanic rocks. They are cheaper than carbon fibers and there are an inert and non-toxic material. They also have interesting mechanical properties similar or better than glass fibers and offers a good chemical, thermal and humidity resistance not negligible for a boat. Its higher elongation failure and flexibility than carbon explain its use to produce parts like the hull which will sustain impact loads and small deformations. Basalt fibres are disadvantaged by a poor interface adhesion with resins, making them hard to use with a lot of resins and their energy hungry production process.

2.7.1.3. Manufacturing considerations

Both fibers, when used in their dry fibers form, need to be handled with care to keep the weave in place and have the best spacing between the fibers for a good infusion of the matrix. Many other kinds of fibers, synthetic or natural, exist and could be used. The choice was made not only from the mechanical properties of the fiber mediums, but also from the availability of the materials (recycling, donations, already owned by the team), the manufacturing resources (knowledge, machines, tools), the costs and the competition’s challenges.

2.7.2. Resins

2.7.2.1. Elium

The Arkema Elium resin system was the resin of choice for the bigger parts of Rafale 3 such as the hull. It paired well enough with the basalt fiber and is recyclable, so it covered our needs for a more environmentally friendly solution. It has properties similar to standard epoxies and is infusible at room temperature which allowed to team to use it without a need for any extra equipment and expertise.

This resin seemed to not play well with a lot of demoulding agents, and the team ended up using Teflon stick on sheets, or Teflon tape to cover the surfaces and ensure proper release for most pieces made with Elium.

2.7.2.2. Epoxy

Epoxy was used for a few different tasks. The filling compound of choice for fairing the hull was epoxy based because of the known and easy to use nature of it. Epoxy was also used for the lay-ups used to bond together carbon fiber tubes for multiple structures such as the wings and the rudder structure to make sure the bond with the resin used when the premade tubes where made, was strong. Epoxy was also used, with glass beads, as a glue for inserts to ensure a strong bond to the composite pieces.

2.7.2.3. Clear Coat Epoxy

A clear coat epoxy was used as a finishing coat for most composite parts to prevent damage and offer a nicer surface.

2.7.3. Other

2.7.3.1. PMMA glue

PMMA glue was used to bond together most parts that did not need a fiber lay-up reinforcement, including the bulkheads inside of the hull and the attachment strips on deck for the trampoline. This glue was chosen for its very good holding properties.

2.7.3.2. Aluminium parts

A few parts such as a lot of inserts, the daggerboard hydrofoil wing’s flap hinges and the new wings brackets have been machines out of aluminium. This material was used for it’s availability, lightness and load bearing capabilities.

3. SUSTAINABILITY ANALYSIS

3.1. General description

The goal of this study is to analyse the environmental impact of Rafale 3. Concerned with environmental impacts, Rafale's team wants to design a cleaner foil to be part of an eco-design initiative. To achieve that, environmental aspect needs to be included as soon as we develop the design phase to attain the most reasonable balance between the environment, speed, and manufacturing cost. To ensure that, we used the software MS360 from Marine Shift specialized in life cycle assessment for boats.

3.1.1. Functional unit

The functional unit clarifies the quantitative aspects of the function of the product. Its definition is fundamental because it will be use as a reference if an environmental comparison with other foil moth is done. The functional unit will ensure that the product is being compared with similar quality of service. It follows those essential questions:

Table 26: Fonctional unit design questions

WHAT?	HOW MUCH?	HOW WELL?	HOW LONG?
Rafale 3	1	To be the fastest without dysfunctions	During the Foiling week

Therefore, the functional unit for our life cycle assessment is "Navigate as fast as possible one Rafale 3 during the Foiling week without dysfunctions**.**"

3.1.2. Hypothesis

Some parameters or steps in the life cycle of the foil can be neglected due to the lack of information or, if those steps will have too little influence on the study:

- **Screws & bolts:** The mass of these parts is lower than 1 % of the total mass of Rafale 3. Moreover, screws and bolts are made of recyclable materials: steel and aluminum. Thus, their impact is not included in the analysis.
- **Consumables:** It is challenging to estimate the impact of consumables because it will mainly depend on the part we are building and who is doing it. In addition, MS360 is not precise enough to allow us to include consumables like tape, paper, plastic bag, wood, etc. However, the team is completely aware of the environmental impact of this part. Particularly for the work done with composites materials and the used of plastic bags. Research are being carried out to reduce the use of consumables for Rafale 4.
- **Packaging:** When the packaging is made of carboard, we assume it was recycled at the end of life.

3.2. Boat and elements lifecycle

To calculate the environmental impact of Rafale 3, we decided to separate the main parts of the boat. Thus, 7 parts were distinguished:

- Foils
- Hull mold
- Hull
- Rigging & Pulley
- Sail
- Shafts
- Wing bar
- Tiller and Shaft structure
- Trolley

Then tree other external parts were added. It is the design phase, the transport phase and the trolley needed to transport Rafale 3. The details of each of these parts are developed in the following parts of the report.

The life cycle analysis includes raw materials as well as transport and end-of-life phase. The use phase is not included for Rafale 3 since it is a foil operating with the wind and, therefore, it does not require any other resources to move. Regarding the energy required for manufacturing, the energy that was required for the design of the boat on Catia was included through the Design phase. The lights in the room could have been included, but since the boat was built in a school, the crew did not have full control of the lights and did not have access to the information needed. However, when the MS360 software allowed it, the energy required for machining operations was included.

3.3. Design

On average, a fully equipped desktop computer uses 200 watts per hour. Knowing we spent approximately 1 500 hours on the conception of Rafale 3, we consumed 300 kWh.

Item	kWh
Electricity – Renewable - Hydro	300

Table 27: Rafale 3 design process's energy consumption

3.4. Foils

3.4.1. Material

Item	kg	m^2	Packaging weight (kg)	Road distance (km)
Dry Carbon fiber	10	-	-	-
Resin – Epoxy	1	-	1	-
Prepreg-paper one side / plastic one side	-	45	-	-

Table 28: Hydrofoil materials

Foils are made with out of shelf-life carbon, and which has been upcycled from Rafale 2. Also, the resin used is an excess from Rafale 2. Therefore, the packaging of the fiber and road distance are not included.

3.4.2. CNC Operation

Electricity Source	Material	Electricity (KWh)	m^2
Hydro electricity	CNC – Carbon Fiber	780	45

Table 29: Hydrofoils' CNC energy consumption

Because foils are made with out of shelf-life carbon upcycled from Rafale 2, the area has been divided by two (because this option doesn't exist in MS360 we divided by two to be as most realistic as possible). The CNC operation is made by us at ÉTS.

3.4.3. Curing process

Electricity Source	Temperature (°C)	Time (hrs)	Oven size (m^3)	Electricity (KWh)
Hydro electricity	150	7	3	85.15

Table 30: Hydrofoils' oven curing process's energy consumption

Curing the hydrofoils was done by the company Stelia Aerospace in an autoclave oven.

3.4.4. End of life

Item	Material Waste	Packaging	Material
Dry Carbon fiber	Average – Landfill municipal waste	-	Average – Landfill municipal waste
Resin – Epoxy	Average – Landfill municipal waste	Average – Recycling	Average – Landfill municipal waste
Prepreg-paper one side / plastic one side	Average – Landfill municipal waste	-	Average – Landfill municipal waste

Table 31: Hydrofoils' end of life per material

Because of the prepreg carbon fiber, the foils can't be recycled.

3.5. Hull mold

We made the decision to design a symmetrical mold that allows construction on both sides of the hull: starboard and port. This solution makes it possible to reduce the quantity of materials necessary for the construction of the boat.

Most of the time, molds are constructed of MDF (Medium Density Fibreboard) as it is inexpensive and easy to machine. Unfortunately, it's challenging to recycle it, which is why we have preferred a more environmentally friendly solution: pine wood.

3.5.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Timber – Pine wood	346	0	25

Table 32: Rafale 3 hull mould materials

The pine stock was machined by *Modèlerie Montréal* with a 5-axis machine for a high-performance result. We did not consume any plastic or cardboard to transport the hull. It was just surrounded with blankets.

3.5.2. CNC Operation

Electricity Source	Material	Electricity (KWh)	Area (m^2)
Electricity – Renewable - Hydro	CNC – Timber	714,35	1

Table 33: Rafale 3 hull mould's CNC energy consumption

3.5.3. End of life

Item	Material Waste	Packaging	Material
Timber – Pine wood	Recycling – Timber	-	Recycling – Timber

Table 34: Rafale 3 hull mould's end of life solutions

The hull mold was recycled by Kruger in Montreal. Precisely, it was incinerated with energy recovery. Because wood is a clean energy and renewable, the impact of the combustion is therefore neutral. However, the mold could have been recycled by making other parts for the boat with this wood reducing the used of other materials; therefore reducing the environmental impact of Rafale 3.

3.6. Hull

The hull is made of basalt fiber, recycled PET and Arkema Elium thermoplastic resin. This resin has been considered in the simulation as a “bio resin” which allows the recycling process. Indeed, the Elium resin is 100 % from petrochemistry but it is recycled. However, MS360 does not allow us to choose an option “recycling – resin” for the life cycle assessment. Therefore, we simulated a “bio resin” to obtain a final result closer to reality. This part is fabricated by a lamination infusion process.

3.6.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Core – PET Foam (recycled)	2.5	0	600
Dry fibers – Basalt fiber	15	1	40
Resin – Epoxy Bio Resin	10	1	60

Table 35: Rafale 3 hull materials

- The PET core is made near Toronto at 600km.
- The basalt fiber is woven by Texonic.
- The Arkema Elium is given by the CDCQ (Quebec Composites Development Center – CDCQ).

3.6.2. Foam thermoforming

Electricity Source	Temperature (°C)	Time (hrs)	Oven size (m^3)	Electricity (KWh)
Electricity – Renewable - Hydro	150	1	3	51.83

Table 36: Rafale 3 hull core thermoforming energy consumption

The core is thermoformed, but this option does not exist in MS360, therefore we replaced it by an oven cure option.

3.6.3. End of life

Item	Material Waste	Packaging	Material
Core – PET Foam (recycled)	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste
Dry fibers – Basalt fiber	Average – Landfill municipal waste	Average – Recycling	Average – Landfill municipal waste
Resin – Epoxy Bio Resin	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste

Table 37: Rafale 3 hull end of life by materials

Technically, the hull can be recycled at the end of its life. But because industries capable of recycling composite materials are practically non-existent these days, there is no option in MS360 to simulate it.

3.7. Rigging & Pulley

3.7.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Rope – Polyester (virgin fiber)	0,47	0,1	270
Standing Rigging – Stainless	0,37	0,1	270
Equipment – Reused	1,17	-	0
Dinghy block (plastic and stainless)	0,17	0,1	270
Plastic Injection Moulding – PP	0,13	0,1	270
PET filaments reinforced with 20 % carbon fiber	1,5	-	-
Casting Fitting – Aluminium (0% recycled)	0,09	0,5	270

Table 38: Rigging materials

All ropes and dinghy blocks come from Max Marine, but a portion of the dinghy blocks is reused from Rafale 2. Moreover, PET blocks (reinforced with 20 % carbon fiber) have been manufactured by a 3D printer at ÉTS. Therefore, packaging and road distance are not included for this part.

3.7.2. End of life

Item	Material Waste	Packaging	Material
Rope – Polyester (virgin fiber)	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste
Standing Rigging – Stainless	Average – Recycling	Average – Landfill municipal waste	Average – Recycling
Equipment – Reused	Average – Landfill municipal waste	-	Average – Landfill municipal waste
Dinghy block (plastic and stainless)	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste
Plastic Injection Molding – PP	Recycling – Plastic	Average – Landfill municipal waste	Recycling – Plastic
PET filaments reinforced with 20 % carbon fiber	Average – Landfill municipal waste	-	Average – Landfill municipal waste
Casting Fitting – aluminum (0% recycled)	Recycling – aluminums	Average – Recycling	Recycling – Aluminums

Table 39: Rigging end of life per material

If ropes and dinghy blocks are undamaged at the end of the competition, we can think of reusing them for Rafale 4. However, because we are not convinced this solution will be chosen, we still decided to simulate the landfill option at the end of life. Also, parts made of plastic and aluminum can be easily recycled.

3.8. Sail

3.8.1. Material

Item	Final quantity (kg)	Packaging weight (kg)	Road distance (km)	Air distance (km)
Sailcloth – Mylar	2	6	100	5500

Table 40: Sail materials

The sail was bought used from a French sailor based in La Rochelle. Therefore, this part was sent to us by plane.

3.8.2. End of life

Item	Material Waste	Packaging	Material
Sailcloth – Mylar	–	Average – Landfill municipal waste	Average – Recycling

Table 41: Sail end of life

Mylar is not a recyclable material. However, we are planning to upcycle the sail to build bags and accessories as the French brand “727 Sailbags” does. Unfortunately, the option to upcycle into other objects doesn’t exist in MS360 so we simulated “recycled” to have an equivalent impact.

3.9. Shaft

Shafts, or the vertical sections of the rudder and daggerboard, are built with an old mold used from Rafale 2, thus its impact is unincluded in the simulation. Both of shafts are made with prepreg carbon fiber upcycled from Rafale 2 and so the area has been divided by two (same as for the foils).

3.9.1. Material

Item	Quantity (kg)		m^2	Packaging weight (kg)	Road distance (km)
Core – Corecell Foam	0.5		-	0.5	130
Dry Carbon fiber	3	-	-	-	
Prepreg-paper one side / plastic one side	-	12	-	-	

Table 42: Shafts materials

The shafts are made with 2 prepreg carbon fiber skins upcycled from Rafale 2 and a Corecell foam machined by the company Gurit. Therefore, packaging and road distance are not included for the fiber.

3.9.2. CNC Operation

Electricity Source	Material	Electricity (KWh)	m^2
Electricity – Renewable - Hydro	CNC – Foam	303,99	12

Table 43: Shafts' CNC energy consumption

Because shafts are made with prepreg carbon fiber upcycled from Rafale 2 the area has been divided by two.The CNC operation is made by us at ÉTS.

3.9.3. Curing process

Electricity Source	Temperature (°C)	Time (hrs)	Oven size (m^3)	Electricity (KWh)
Electricity – Renewable - Hydro	150	7	3	85.15

Table 44: Shafts' oven curing energy consumption

The shafts had to be cured in an autoclave oven.

3.9.4. End of life

Item	Material Waste	Packaging	Material
Core – Corecell Foam	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste
Dry Carbon fiber	Average – Landfill municipal waste	-	Average – Landfill municipal waste
Prepreg-paper one side / plastic one side	Average – Landfill municipal waste	-	Average – Landfill municipal waste

Table 45: Shafts end of life by material

Because of the prepreg carbon, the shafts can't be recycled.

3.10. Wing bar

For the manufacture of wing bars, we also used dry carbon fiber to reinforced bends, but we could not simulate it in MS360. We included its mass to the option "Composites CFRP" to be closer to reality.

3.10.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Fitting – Composites CFRP	4	1	430
Resin – Epoxy Resin	0,2	-	-

Table 46: Wing bars materials

- Carbon tubes were bought at DragonPlate Carbon Fiber located in the USA.
- The resin is given by the CDCQ (Quebec Composites Development Center – CDCQ) but its packaging and transport have not been calculated for Wing bars because it was already included in the part "Tiller and Shaft structure" and we used the same can of resin.

3.10.2. End of life

Item	Material Waste	Packaging	Material
Fitting – Composites CFRP	Average – Landfill municipal waste	Average – Recycling	Average – Landfill municipal waste
Resin – Epoxy Resin	Average – Landfill municipal waste	–	Average – Landfill municipal waste

Table 47: Wing bars end of life by material

3.11. Tiller & Rudder Structure

Like for the wing bars, we used dry carbon fiber to reinforced bends. Therefore, we add its mass to the option "Composites CFRP".

3.11.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Fitting – Composites CFRP	0,5	0,8	430
Resin – Epoxy Resin	0,2	1	60

Table 48: Tiller and rudder structure materials

- Carbon tubes were bought at DragonPlate Carbon Fiber located in the USA.
- The resin is given by the CDCQ (Quebec Composites Development Center – CDCQ) located just outside Montréal.

3.11.2. End of life

Item	Material Waste	Packaging	Material
Fitting – Composites CFRP	Average – Landfill municipal waste	Average – Recycling	Average – Landfill municipal waste
Resin – Epoxy Resin	Average – Landfill municipal waste	Average – Landfill municipal waste	Average – Landfill municipal waste

Table 49: Tiller and rudder structure end of life by material

3.12. Trolley

To facilitate the shipping and transport of Rafale 3 we also manufacture a trolley.

3.12.1. Material

Item	Quantity (kg)	Packaging weight (kg)	Road distance (km)
Metal – Aluminium (0% recycled)	4,38	0,5	20
Timber - Plywood	6,49	0,5	20

Table 50: Trolley materials

Materials have been bought at Montreal and is assembled with screws and bolts.

3.12.2. End of life

Item	Material Waste	Packaging	Material
Metal – Aluminium extrusion profile (0% recycled)	Recycling – Aluminums	Average – Landfill municipal waste	Recycling – Aluminums
Timber - Plywood	Recycling – Wood	Average – Landfill municipal waste	Recycling – Wood

Table 51: Trolley end of life by material

Aluminum and Plywood are two materials easily recycled.

3.13. Transport

The boat will travel to Italy by plane, and we also assume that 12 members of the Rafale team will go from Montreal to Italy by plane for the competition. Rafale 3 weight is slightly over 40 kg, but to transport it, a wooden box has been used. Therefore, we estimate the weight at 50 kg. Similarly, we have estimated the distance by plane between Montreal and Milan is 6 142 km. For transport through the road, by adding the distance to get to Montreal airport and the distance to get from Milan airport to the site of the competition, we calculate a total of 150km.

3.13.1. Logistic

Type	Type	Weight (t)	Distance (km)
Road	Freight, Lorry 7.5-16t	0.05	150
Air	Freight, Aircraft, Unspecified Flight	0.05	6 142

Table 52: Rafale 3 transport to the site of the competition

3.13.2. Passenger

Type	Type	Passengers	Distance
Road	Road car	12	150
Air	Air long haul flight	12	6 142

Table 53: Team transportation to the site of the competition

3.14. Actions for a sustainable future

Rafale 3 was designed to be environmentally friendly. However, improvements are always possible. For this edition, much of the work has been done on the hull. It was purposely designed symmetrically to allow construction of both sides of the hull: starboard and port from the same mould. This solution makes it possible to reduce the quantity of materials necessary for the construction of the boat. In addition, the mold was manufactured in a material more environmentally friendly: pine wood. Usually, molds for boats are made of MDF (Medium Density Fibreboard) which are economical and easy to machine. Unfortunately, it’s challenging to recycle it. So that is why the pine wood mold was chosen.

Work was also done to ensure that the hull itself is more sustainable. Indeed, the hull of Rafale 3 is made of basalt fiber, recycled PET and Arkema Elium thermoplastic resin. The Elium resin is 100 % from petrochemistry but it is recyclable. So, technically, the hull can be recycled at the end of its life. But because industries capable of recycling composite materials are practically non-existent, it will be hard to do so.

Thus, for Rafale 4, the team wants to build a boat with even less impact. To this end, work is underway on the use of other natural fibers and organic resins. Fibers such as flax or hemp are particularly studied by the team as they are renewable, natural, and recyclable. This work is important and necessary since these materials are certainly more interesting from an ecological point of view, but they are heavier, more difficult to work, and less resistant. Also, work on the compatibility between resin and fiber is necessary. Added to this, the challenge of using a bio-sourced and recyclable resin is big. The team is currently looking for a more environmentally friendly alternative to thermoplastic resins. New resins made of pine resin for example are currently being tested in laboratories to see if their use would be relevant on a boat such as Rafale 4. The combination of a new natural fiber and a bio-sourced and bio-degradable resin would allow Rafale 4 to reduce drastically the environmental impact of the hull mold, foils, shafts, and wing bar.

The desire to make the mold for the hull more ecological is also present. Although currently the mold is made of wood, a natural material, other less energy-consuming options are sought for. For example, the use of a 3D printer for certain parts and for the mold itself would make it possible to use recycled and recyclable plastics, allowing its reuse to make new parts.

To these works are added small gestures that can help reduce the overall impact of the boat. For example, using recycled metals would be a step forward in reducing the impact of the boat. Also, designing parts of the boat so that they can be easily disassembled would facilitate its recycling. Efforts can also be made when designing the boat such as avoiding the use of many consumables like tape or plastic bags or using recycled packaging would have a slight impact. Similarly, continuing to source from companies close to the assembly site is a good solution to reduce its carbon footprint and support the region’s industries.

4. MARINESHIFT 360 LCA

4.1. General results

Thanks to the simulation on MS360, we can observe the environmental impact of Rafale 3:

- **Global Warming:** 1 132,99 kg CO2 equivalent. It is corresponding at 7 237 km driven by an average passenger vehicle.
- **Mineral resource scarcity:** 3,65 kg Copper equivalent
- **Energy consumption:** 57 970 MJ. It is corresponding to 0,8 home.
- **Water consumption:** 40, 58 m3
- **Marine eutrophication:** 0,2 kg Nitrogen equivalent.

The life cycle assessment of Rafale 3 reveals us that the production step is the most significant. This is coherent because it includes the impact of the raw materials and its production. The boat is functioning with the wind's power, thus it as no impact during its usage phase. For more details, graphs are available in appendix A.

To analyze more precisely the results, we compare the environmental impact of every main part of the boat. This will help us to highlight strengths and weaknesses of Rafale 3.

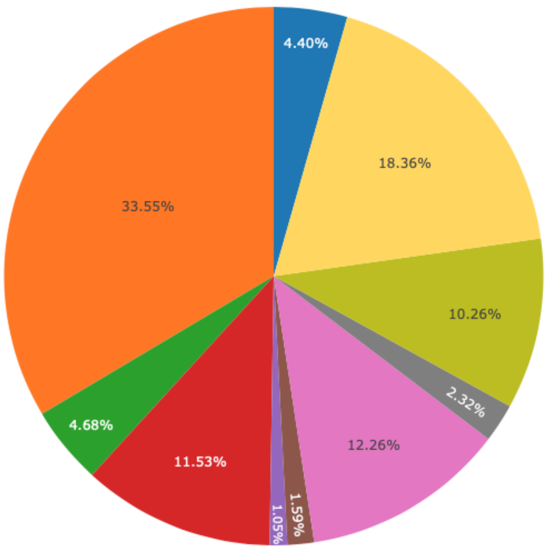


Figure 29 : Global warming - fossil

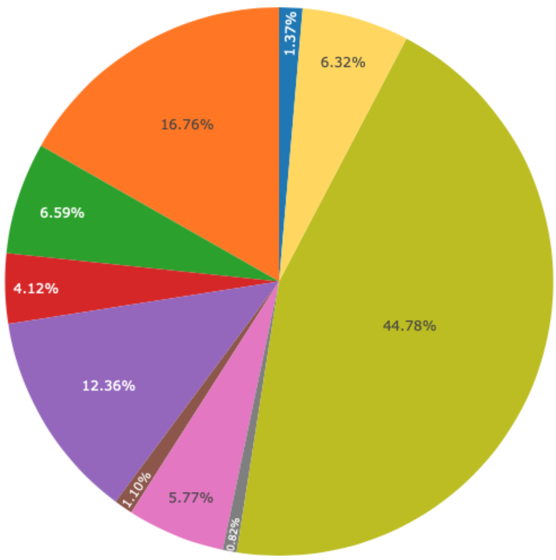


Figure 30 : Mineral resource scarcity

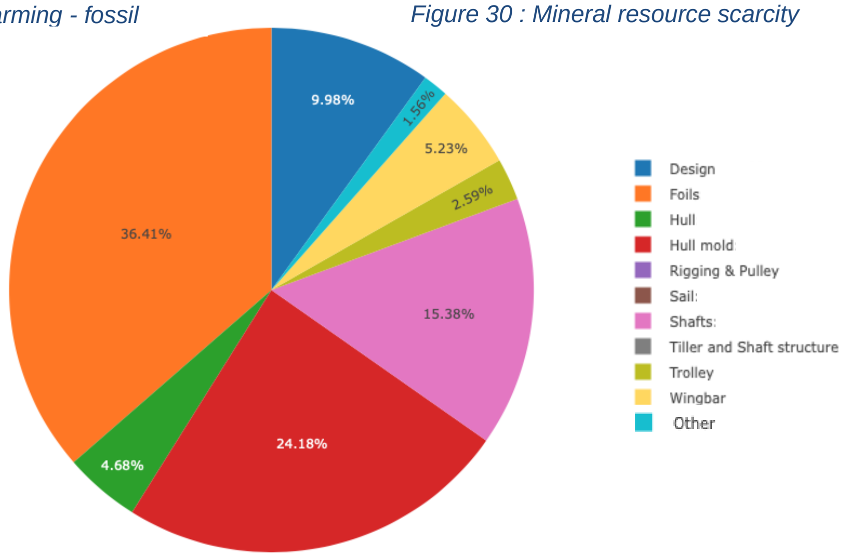


Figure 31 : Water consumption

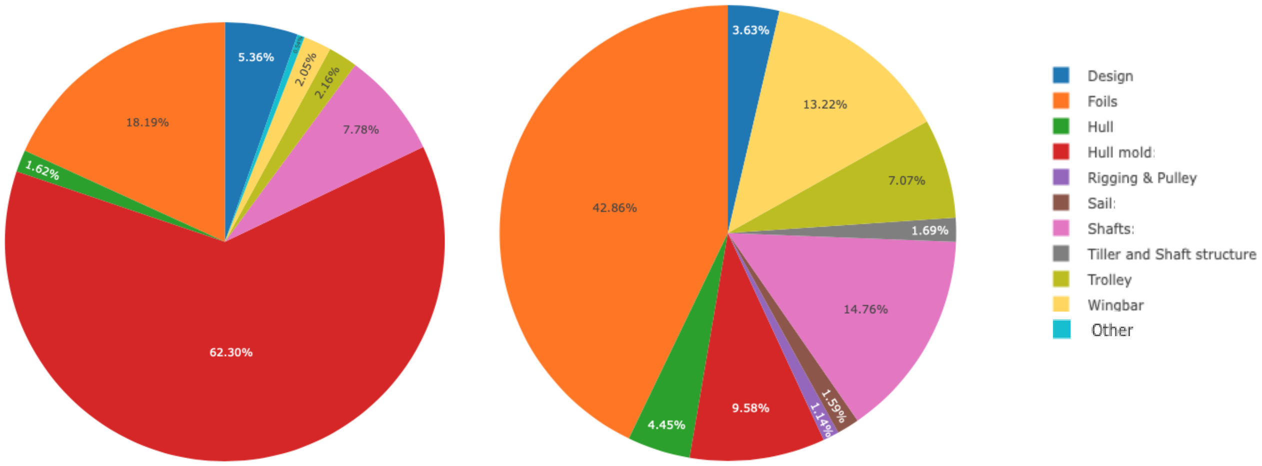


Figure 32 : Energy consumption renewable (to the left) and non-renewable (to the right)

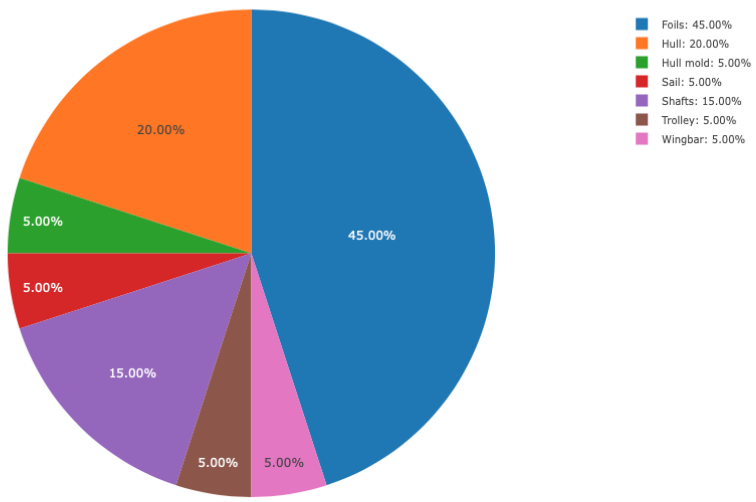


Figure 33 : Marine eutrophication

It can be noticed that the wing bars, shafts, and foils represent most of the impact of the boat because they were made with carbon tubes, prepreg carbon fiber and Epoxy resin which are admittedly very light and resistant, but they cannot be recycled. The use of such materials was necessary to obtain a competitive boat. Indeed, most of the effort concerning the eco-design was made on the hull of the boat. By this choice, other elements of Rafale had to be very light, but resistant, so that Ralafe 3 could be lighter. Aware of the impact of the use of carbon fiber and thermoplastic resin, the team is currently working on the use of bio-sourced and recyclable fiber and resins. However, it is important to precise that foils and shafts were made using excess fibers and resin from the previous boat: Rafale 2. This decision allowed the reuse of materials that would have been destined to be discarded.

Although the hull mold is made with pine wood, given its weight its impact is quite significant on the Energy consumption part. This impact is due to the energy used to incinerated with energy recovery. However, this impact is relative because wood is a clean energy and renewable, the impact of the combustion is therefore neutral. Despite is weight, the hull has a light impact. This is because it was made of basalt fiber, recycled PET and Arkema Elium thermoplastic resin. This resin is 100 % from petrochemistry but it is recycled which allows the recycling process of the parts.

The trolley also has a significant impact compared to other part of Rafale 3 on the mineral resource scarcity. It is because it's made of aluminum. However, theses tubes will be recycled or reused for the construction of the next Trolley for Rafale 4.

Members of the team are particularly concerned by the environment; therefore, we want to build a moth with reduced impact and still performant and resistant. This life cycle assessment will help us to build Rafale 4 thanks to the highlighted of strengths and weaknesses of Rafale 3. Actions and ideas are currently being researched and are explain in section 3.14 of this report.

4.2. Transport results

As you can notice, we did not include the part "Transport" in the simulation due to issues with the simulation on MS360. Indeed, because Canada and Italy are far away if we directly include environmental impact of the transport in the simulation it would completely distort the result. Therefore, we separate the impact of those parts:

- **Global Warming:** 7 923,84 kg CO2 equivalent.
- **Mineral resource scarcity:** 14,93 kg Copper equivalent
- **Energy consumption:** 118,50.10^3 MJ
- **Water consumption:** 5,45 m^3
- **Marine eutrophication:** 0,02 kg Nitrogen equivalent.

4.3. Rafale's origin

To go into the life cycle assessment in depth, we also analyzed origins of Rafale's materials:

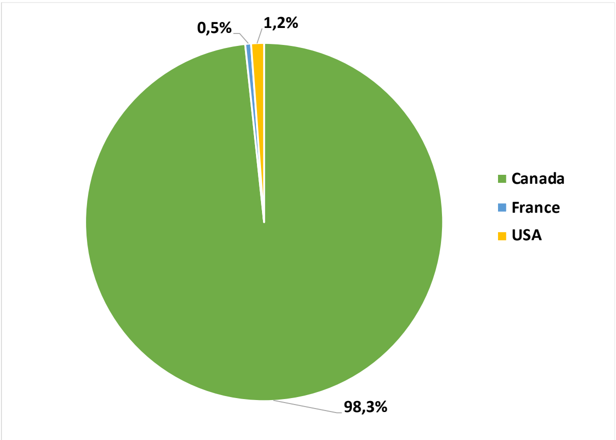


Figure 34: Rafale 3 materials' source countries

As we can see on this graph representing the distribution between the mass (kg) of Rafale 3 and the origin of its materials, most of it comes from Canada. Team members are making a point to work with Canadian companies to participate with local economy. In addition, this proximity will reduce the transport distance, and therefore the impact on the environment.

4.4. Budget Sumoth dollar

To prove the team's environmental commitment, a budget based on the fictitious currency of Sumoth dollars was simulated. As a result, the maximum budget of $10,000 was not exceeded because the cost of Rafale 3 is $7,968 as indicate in the table below.

Boat part	Material and Processes	Amount	Unit	Price	Unit	Cost
Foils	Prepreg carbon fiber	10	kg	150	$/kg	1500
	Prepreg Cure	7	h	40	$/h	280
	Machining CNC	20	h	40	$/h	800
	3D printing	10	h	20	$/h	200
	Resin – Epoxy excess from Rafale 2	1	kg	25	$/kg	25
Hull mold	Pine wood	346	kg	0	$/kg	0
	Machining CNC	30	h	40	$/h	1200
Hull	Resin – Epoxy	5	kg	25	$/kg	125
	Dry Balsalt Fibers	15	kg	0	$/kg	0
	Liquid thermoplastic Resin Arkéma Elium 1880	10	kg	15	$/kg	150
	Plastic - Wrap	1	kg	10	$/kg	10
	Recycled PET foam (Armaform)	2,5	kg	0	$/kg	0
Riggin & Pulley	Rope - polyester (virgin fiber)	0,47	kg	20	$/kg	9,4
	Equipment upcycled from Rafale 2	1,17	kg	0	$/kg	0
	Standing Rigging – Stainless	0,37	kg	30	$/kg	11,1
	Dinghy block (plastic and stainless)	0,17	kg	10	$/kg	1,7
	Plastic Injection Moulding – PP	0,13	kg	10	$/kg	1,3
	Casting Fitting – Aluminium (0% recycled)	0,09	kg	10	$/kg	0,9
	PET filaments reinforced	1,5	kg	20	$/kg	30
Sail	Mylar bought used	1	pc	0	$/pc	0
Shafts	Prepreg carbon fiber excess from Rafale 2	3	kg	150	$/kg	450
	Prepreg Cure	7	h	40	$/h	280
	Core – Corecell Foam	0,5	kg	20	$/kg	10
	Machining CNC	1	h	40	$/h	40
Wing bar	Carbone tube	4	kg	300	$/kg	1200
	Trampoline Nylon upcycled from Rafale 1	1	pc	0	$/pc	0
	Resin – Epoxy	0,2	kg	25	$/kg	5
Tiller & Shaft structure	Carbone tube upcycled	0,5	kg	300	$/kg	150
	Resin – Epoxy	0,2	kg	25	$/kg	5
Trolley	Plywood	6,49	kg	0	$/kg	0
	Aluminium tube	4,38	kg	10	$/kg	43,8
Vacuum bagging	Tacky tape	5	roll	8	$/ro	40
	Vacuum bag	50	m2	2	$/m2	100
	PE vacuum hose	50	m	1	$/m	50
	PVC vacuum hose	50	m	1	$/m	50
	Breather	50	m	3	$/m	150
	Peel ply	50	m	5	$/m	250
	Brushe	25	brush	2	$/br	50
	Spiral tube (inf.)	50	m2	1	$/m2	50
	Fiber scissors	5	pc	5	$/pc	25
Release agent	Cleaner	2	L	100	$/L	200
	Sealer	2	L	100	$/L	200
	MMA	5	kg	15	$/kg	75
	Release	2	L	100	$/L	200
						$7968,2

Table 54: Sumoth $ breakdown for Rafale 3

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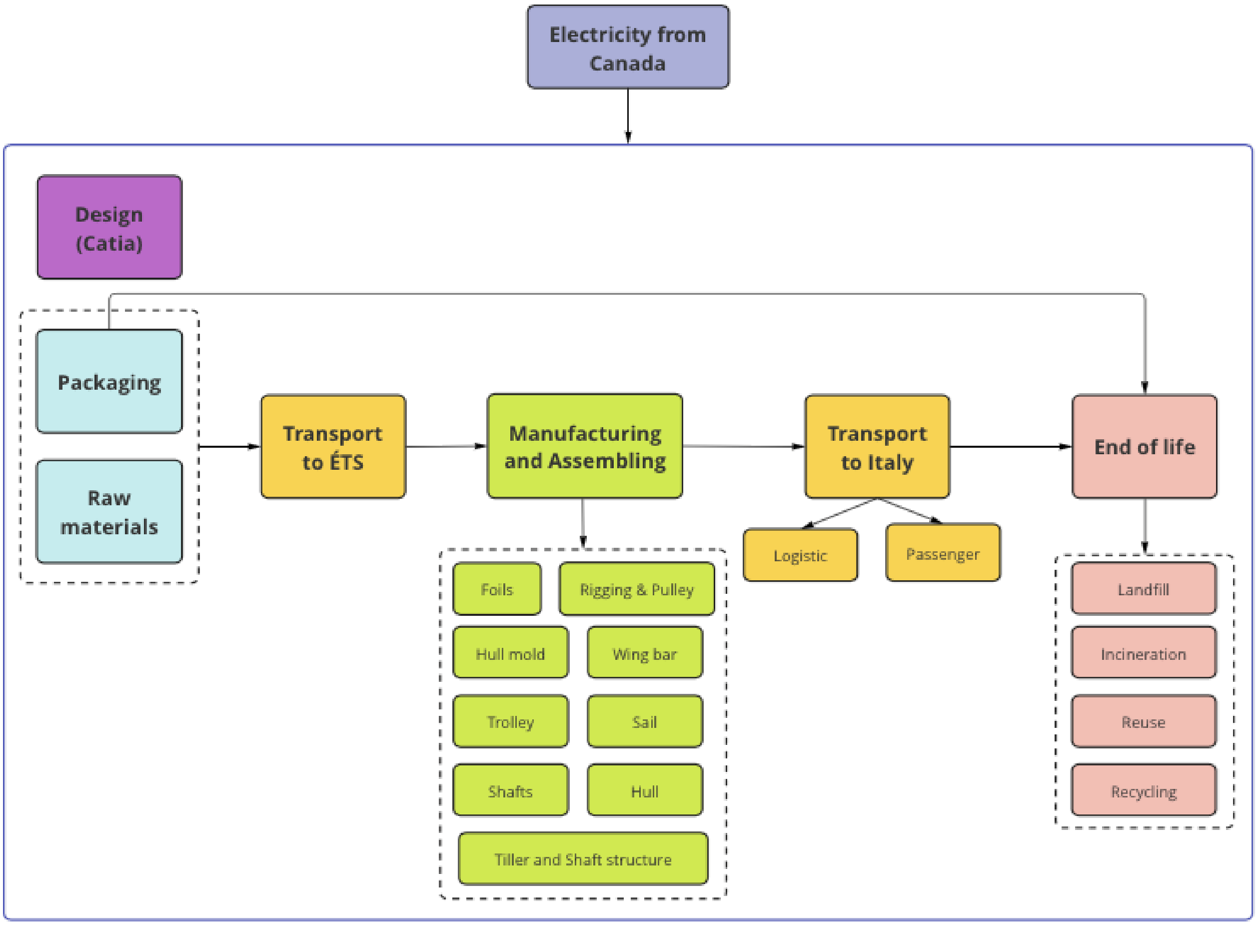
A. APPENDIX A - MS360 LCA

A.1. Boat lifecycle assessment discussion

To realize the life cycle analysis of Rafale 3, only the MS360 software has been used. It was considered by the team members to be the most suitable and easy-to-use software for an analysis of a foil. The sections separated by type of material or part of the boat make it easy to locate. However, when unconventional choices are made for the choice of materials, we may find ourselves limited by the software. Indeed, since the materials are essentially stored by part of the boat, it was not always possible to find the material used in the good part of the software. Also, some materials are not yet available on MS360. For example, Prepreg carbon is not available, so it is necessary to find unconventional ways to successfully simulate its impact. However, despite these challenges, the software remains very effective for the life cycle analysis of Rafale 3 and the results are generated in very clear and understandable ways

A.2. Boat lifecycle assessment scheme

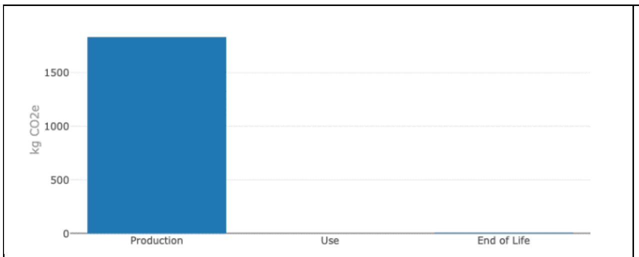
To illustrate the elements evaluated on a full assembly, a scheme has been created.



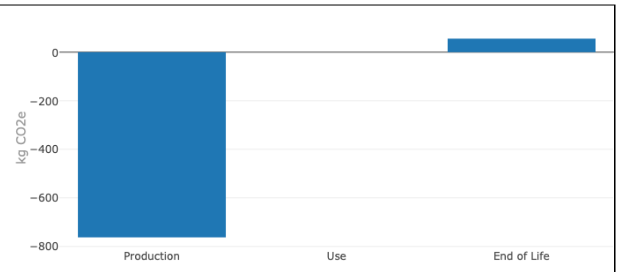
A.3. Overall results & CO2 equivalent impact

Detail of results from Marine Shift 360 are available in the table and figures below.

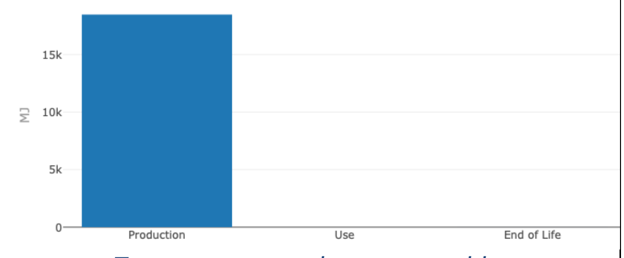
Assessment	Global warming - fossil (kg CO2e)	Global warming - non-fossil (kg CO2e)	Mineral resource scarcity (kg Cue)	Energy consumption - renewable (Mj)	Energy consumption - non-renewable (Mj)	Water consumption (m3)	Marine eutrophication (kg Ne)
Design	80,888799	3,14959575	0,049313343	990,9642402	1179,286819	4,0516014	0,003106067
Foils	616,5975589	13,67372061	0,606073055	3360,368081	13922,35414	14,76282107	0,079162523
Hull	84,26220254	2,421632486	0,241285016	299,4383516	1434,241094	1,892728742	0,006376338
Hull mold	212,058128	-795,9395025	0,153769657	11512,45044	3113,904582	9,812178589	0,009180196
Rigging & Pulley	16,3762029	0,522504896	0,219322784	25,46744682	325,9993784	0,18553908	0,00067967
Rigging & Pulley	2,922204613	0,139409728	0,232082107	9,539804851	42,60204291	0,031730515	0,000117848
Sail	29,03160807	0,208027271	0,037964325	16,08671085	514,8833745	0,142421672	0,000475907
Shafts	225,2442347	5,548842	0,211039241	1437,781359	4794,831923	6,242923182	0,025375325
Tiller and Shaft structure	42,54681516	2,049628076	0,030889161	47,83015532	550,1974319	0,272576775	0,001218309
Trolley	188,7231587	-10,92446303	1,633190802	399,8681477	2295,644339	1,047843942	0,004550563
Wingbar	334,6441388	16,37020948	0,229517575	377,999497	4294,118149	2,113343207	0,009616683
FINAL TOTAL	**1833,3**	**-762,78**	**3,64**	**18477,79**	**32468,06**	**40,56**	**0,14**



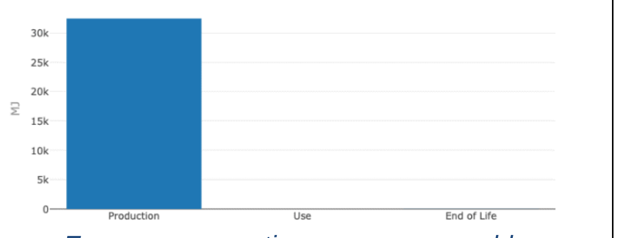
Global warming - fossil



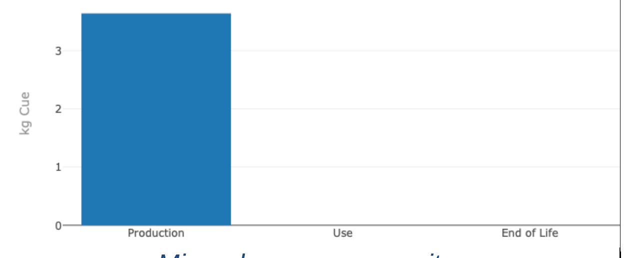
Global warming - non - fossil



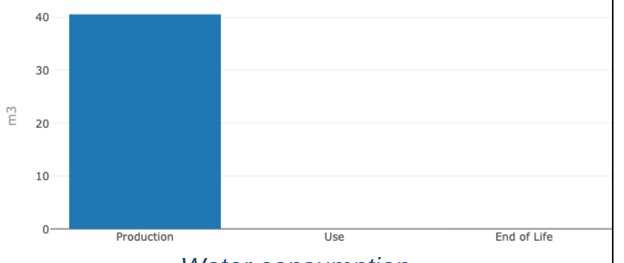
Energy consumption - renewable



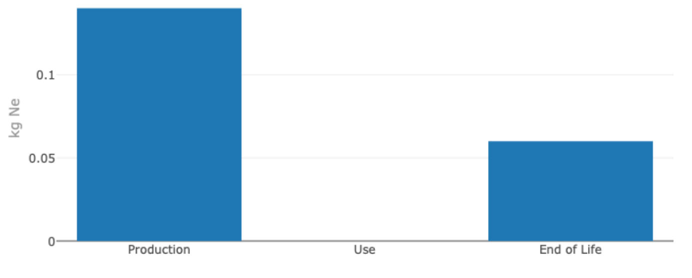
Energy consumption – non - renewable



Mineral resource scarcity



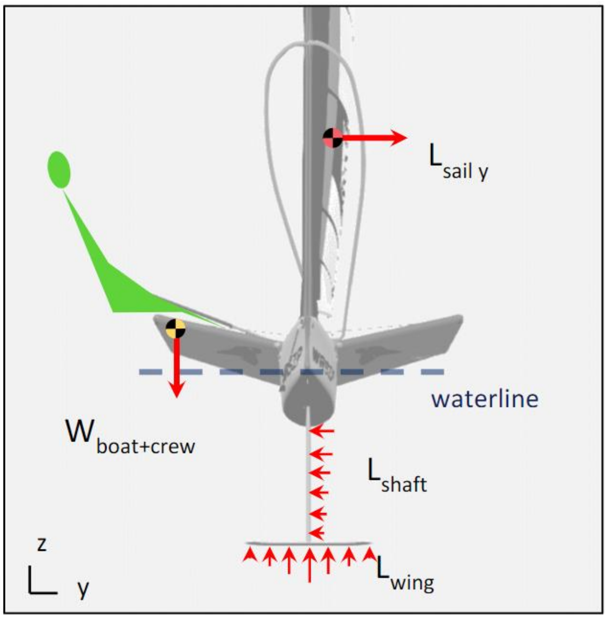
Water consumption

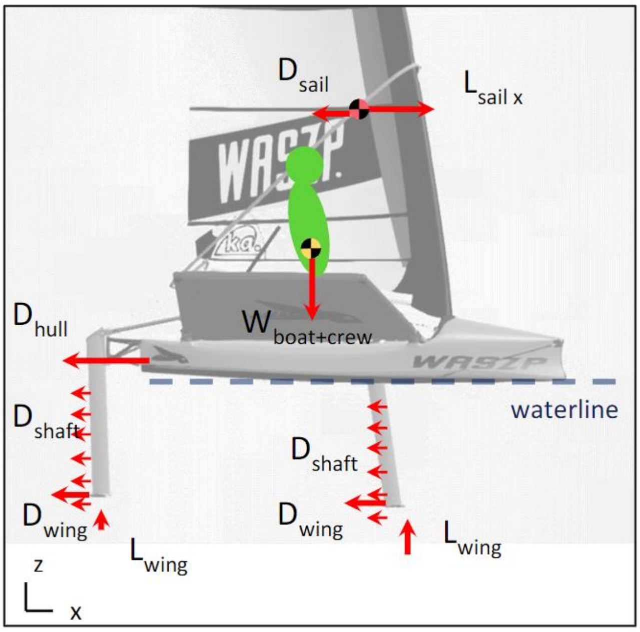


Marine eutrophication

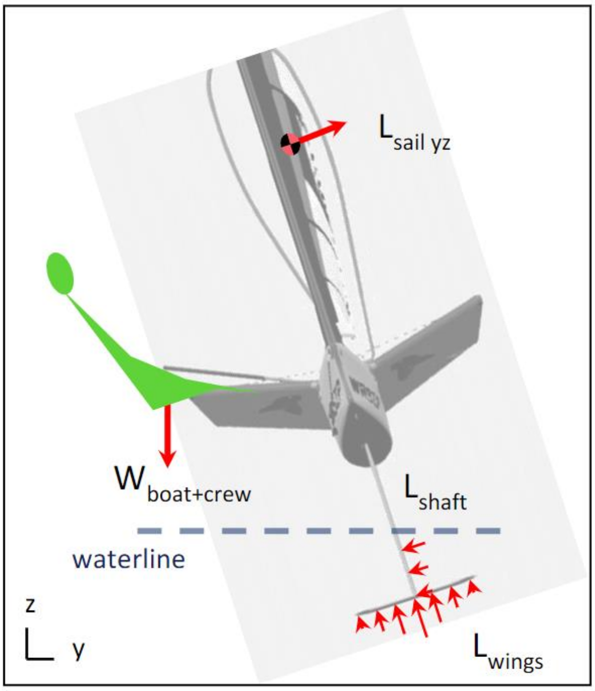
B. APPENDIX B- Free-Body Diagrams

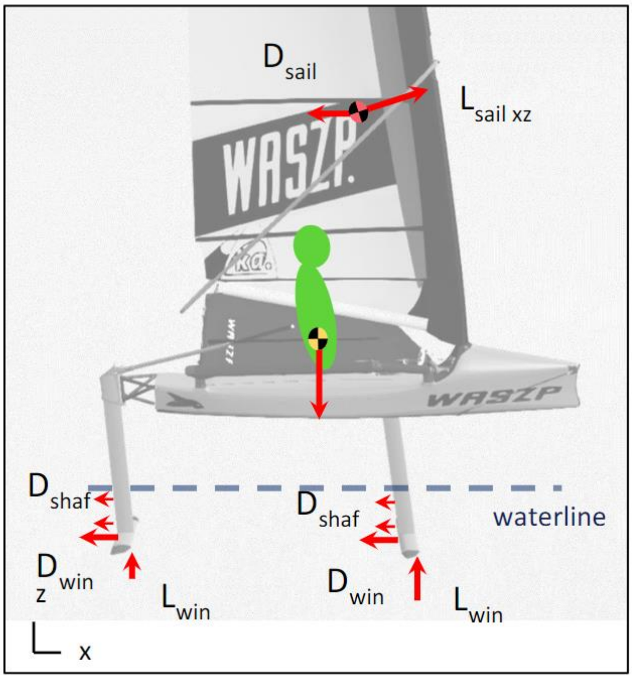
B.1. Boat at takeoff



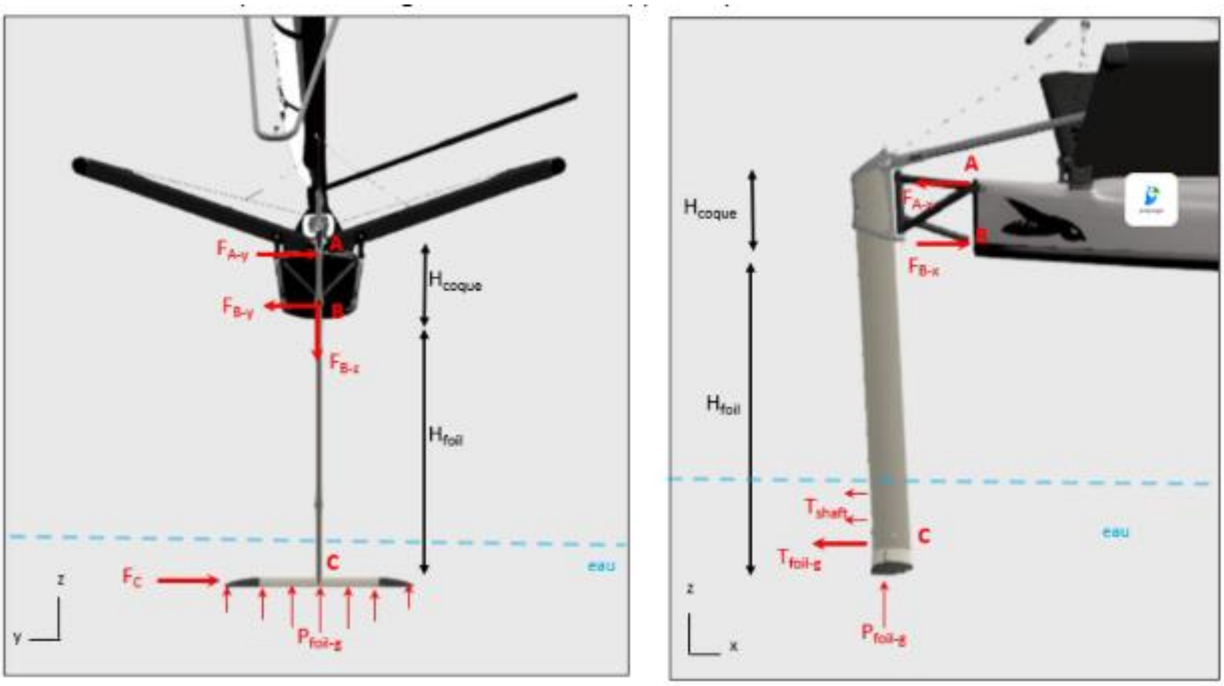


B.2. Boat in steady flight





B.3. Rudder system showing forces applied to the transom



C. APPENDIX C - Embedded System Source Code

The source code for the embedded system is too big to present directly as an appendix but it is publicly available on the team's GitHub account at https://github.com/Rafale-ETS/MothHub .