OPTIMISATION OF A HYBRID-COMPOSITE HYDROFOIL USING A GENETIC ALGORITHM TO IMPROVE ITS PERFORMANCES

By

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ABSTRACT

Hydrofoils are a demanding part of the boat in terms of design: their volume is restrained by the hydrodynamic performances' requirements, their structure must hold the load applied on this small volume without breaking or showing too big deformations, their weight and their cost must be controlled and eventually an improved sustainability is an increasingly important criterium. To obtain innovative designs that satisfy all those objectives, the design space is parametrized, and a multi-objective problem is defined. The design space is described by four parameters. Three of them allow to cover the NACA-4 digits series of hydrofoils geometries and the last one is the proportion of flax fibres reinforced composites layers included. Adding this last parameter allows to add a dimension to the design space by considering hybrid composites made hydrofoils to determine if they are a possible solution to improve the designs.

An APDL code is created to model the hydrofoils with the parameters set. This model gives the tip deflection which serves as the structural performance criterium. A surrogate of the structural objective function was constructed with the Kriging basis function. The APDL code also returns the volume occupied by the flax fibre layers and the carbon fibre layers, which is then used to give a weight, cost and sustainability estimate for each hydrofoil. The hydrodynamic performances are estimated using an Xfoil code which determines the lift over drag ratio for each profile shape studied. Based on the literature, the cMLSGA genetic algorithm is applied and its dependency on population sizes tested.

The optimisation process gives results in line with data that can be found in the literature: the sustainability criterium is dominated by hydrofoils built with most layers in flax while structural and hydrodynamic performances are better for hydrofoils with most layers in carbon. It also shows hydrofoils built mainly with flax layers can compete with and dominate carbon made hydrofoils in other directions than the sustainability: they cover a large part of the pareto fronts which consider the cost or the weight. Eventually, this process shows the importance of considering hybrid composites in the hydrofoil designs, not only to improve their sustainability, but also to improve their performances in other directions since 90% of the possible designs given by the algorithm contain both flax and carbon layers.

INTRODUCTION AND BACKGROUND

Due to the rising awareness related to the environmental impact of the composite industry, bio-composites are increasingly studied as a sustainable alternative to E-glass or Carbon fibres reinforced composites [1]. Indeed, not only do they take less energy to produce [1][2] and are easier to recycle [1][3], but they also have a low density, thus high specific properties, and are widely available which allow their cost to be cheaper than carbon [1][4][5][6][7]. Compared to E-glass fibres, their embodied energy and cost can respectively be divided up to six times and two times and their density can reach nearly half of E-glass' [1][2][8][9]. This explains why an increasing number of research has been led on natural fibres reinforced composites and why some have tried to apply them to the maritime industry [10][11][12][13]. Flax is considered to be the natural fibre the most able to replace E-glass considering it has higher specific properties at the fibre scale than other natural fibres while still being more sustainable than E-glass [1][8][14][15][16]. Because appendices production comes with large financial and environmental challenges [17], studying how the inclusion of bio-composites in the building of a hydrofoil can influence its performances has been researched [10][12]. However, even though the results indeed show that flax fibres-built composites are an interesting alternative to carbon or E-glass fibres-made hydrofoils, they still show some disadvantages: they are heavier, thicker, and thus less performant in volume and weight restrained contexts. Thus, the flax fibres reinforced composites properties can be too low to effectively replace carbon or E-glass but they still have advantages compared to these conventional materials such as their sustainability or the fact they allow to reduce damping effects [12]. This is why some studies have examined the possibility to use hybrid composites, composed of natural fibres as well as E-glass or Carbon fibres [18] [19]. Some of these studies have shown that mixing natural and chemical fibres allow to mix their properties and obtain a composite that took the best characteristics from both [18]. Even though [19] showed that the gain in damping properties was at the cost of a sacrifice in tensile properties for E-glass/flax hybrids, the author estimates hybridisation to be more beneficial for carbon/flax hybrids. Few studies dealing with structural applications of hybrid composites have gone out. This report aims to do so by applying carbon/flax hybrid composites to a hydrofoil structure. This would allow to know which type of design set would be most beneficial for different objectives such as its cost, sustainability, weight, and hydrodynamic and structural performances. It would be interesting to know whether the inclusion of flax can result in any feasible design or if it only dominates from the improved sustainability point of view.

The aim of the project is to explore the design space and see at what cost in performances more sustainable designs can be considered.

This aim will be met through two main steps:

- Model the hybrid-composite hydrofoil to assess its performances.
- Use a Genetic Algorithm and link it to this model and interpretate the results with

regards to the different objectives and the weight each objective is given.

The novelty in this study is the inclusion of an optimisation process to explore the design space and objectively determine the adequate flax fibre proportions that would optimise the different objectives. This allows the quantification of the impact the different quantities of flax and carbon fibres will have on the performances of the hybrid-composite hydrofoil.

Firstly, a hydrofoil composed of mixed layers of carbon and flax is modelled using Finite Element Analysis (FEA). This model is then used to estimate and model various performances of each hydrofoil tested. Eventually, a Genetic Algorithm (GA) is linked to the ANSYS Parametric Design Language (APDL) and used to browse the entire design space to discuss the results with regards to the hypothesis made throughout the projec

METHODOLOGY

The first step of the optimisation process is to model all the hydrofoils studied to determine and quantify their performances. This is done using a finite element analysis. The FEA is performed using Mechanical ANSYS 2020.

Input parameters

Choice of the Input Parameters

For each parameter considered, the impact its change can have on the performances of the hydrofoils is evaluated. If the impact is complex (i.e. it has a good impact on some of the performances but a bad impact on others), it is included as an input parameter. Four parameters are selected: the proportion of flax fibres layers compared to the total number of layers and three geometrical parameters (the thickness, the camber, and the position of maximum camber).

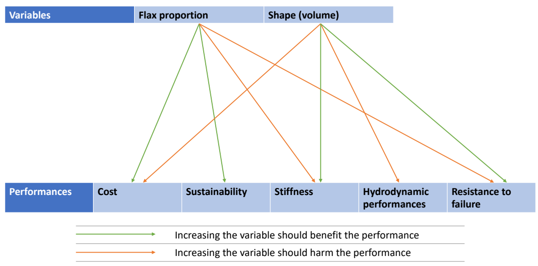


Figure 1 : Selection of the variable parameters

Figure 1 shows how they impact its performances and how complex and interdependent this optimisation problem is.

Inclusion of the Parameters in the Model

The hydrofoils are modelled based on a classical shape usually found on windsurf boards. The profiles considered are NACA 4-digits profiles. The geometries have been defined and parametrised in ANSYS Parametric Design Language (APDL). The materials' properties are then implemented in the model and associated with the adequate layers, before being meshed. All changes between the different solutions possible are implemented into the APDL code so that the use of the GUI would not be required, and the process can be automatised.

Geometry

<u>External shape</u>

The aim is to define the hydrofoils' geometry parametrically so that the genetic algorithm can explore the entire design space. The shapes considered are given by the NACA 4-digits range of geometries. These shapes are defined by three parameters.

These parameters are controlled by four digits included in the name of the hydrofoil e.g. NACA MPXX where:

- M is the maximum camber divided by 100 and goes from 0 to 9.
- P is the position of the maximum camber expressed as a proportion of the camber divided by 10 and goes from 0 to 9.
- XX is the thickness expressed as a proportion of the camber divided by 100 and goes from 01 to 40.

Those three parameters and the range allowed for each allow for 4000 different shapes to be studied. The code needs to obtain the coordinates related to each of these shapes. It is written based on a report written by Ladson C.L. et al. and published by the Nasa on the Computer Program to Obtain Ordinates for NACA Airfoils [20]. Figure 2 shows an example of the profile shapes obtained.

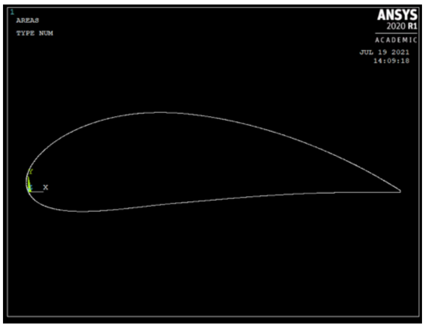


Figure 2 : Example of a hydrofoil profile geometry studied: NACA 6420

Most of the shapes obtained are reasonable solutions to the problem and the parameters used are meaningful which will help the results interpretation. However, the shapes obtained with a thickness inferior to 10% of the chord length give unrealistic shapes and results as can be seen in Figure 3.

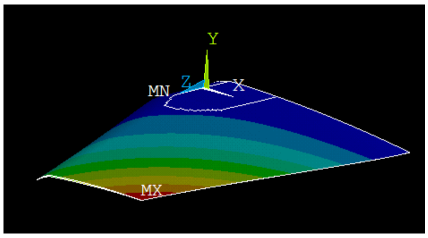


Figure 3 : Hydrofoil 5501, an unrealistic design which gives a tip deflection equal to 640mm

They also cause a bad flow circulation around the hydrofoil which gives low hydrodynamic performances. For these reasons, hydrofoils with a thickness inferior to 10% of the chord length have been discarded from this optimisation study.

<u>Layers' pattern</u>

Then, those shapes need to be divided in the appropriate number of layers which is dependent on the proportion of flax used. The flax layers are centred while the carbon layers are the external layers. Indeed, this has two main advantages: firstly, it increases the second moment of inertia because flax layers act like a core keeping the carbon layers with better mechanical properties away from the centre; secondly, since the impact of water on flax fibres is not yet well described and understood it would give a protective layer around it.

The orientation of the layers is left out of the optimisation process since most of the loading is applied mainly in one direction in this model. However, it is assumed that the impact of this hypothesis on the hydrofoils' performances does not vary sufficiently from one to the other to change the results of the algorithm.

Material Properties

The hybrid composite considered is to be made with epoxy resin reinforced with carbon and flax fibres layers. The material properties required are the layers thickness considered as well as the tensile mechanical properties for each material.

Flax Fibres Layers

The mechanical properties for the flax/epoxy laminate are the means obtained by Blanchard [1] by including several references and experiments to characterize properly most of these properties.

Table 1 Flax/Epoxy composite layers characteristics

Longitudinal Young's Modulus	E_1	25.42	GPa
Transverse Young's Modulus	E_2	4.20	GPa
Shear Modulus	G_{12}	2.01	GPa
Poisson's Ratio	ν_{12}	0.36	-
Longitudinal Tensile Strength	X_t	255.14	MPa
Transverse Tensile Strength	Y_t	24.81	MPa
Longitudinal Compressive Strength	X_c	127.50	MPa
Transverse Compressive Strength	Y_c	85.31	MPa
Shear Strength	S_{12}	39.34	MPa
Fibre Volume Fraction	V_f	43.64	%

The remaining out-of-plane mechanical characteristics are approximated thanks to the rules used by Philips et al. in [21] which gave FEA results in good agreement with experimental results for a carbon/E-glass thick hydrofoil.

The thickness for one layer is obtained from the literature by dividing the mean thickness (4.31 mm) of an 8 layers flax laminate based on 122 specimens [1] which gives 0.539mm. Eventually, the density is obtained using the Rule of Mixtures:

$$\rho = \rho_f * V_f + \rho_m * (1 - V_f)$$

Which gives $\rho = 1264\ kg/m^3$ assuming $\rho_f = 1490\ kg/m^3$ and $\rho_m = 1089\ kg/m^3$ [1]. This value is close to the one obtained by Jeanne Blanchard in [1] when averaging the density of the 122 specimens (1220 kg/m^3).

Carbon Fibres Layers

The carbon fibre laminate used is unidirectional fabric and is 0.5mm thick. Its characteristics are the ones presented as typical values in [22] and are shown in Table 2.

Table 2 : Carbon/Epoxy composite layers characteristics

Longitudinal Young's Modulus	E_1	140	GPa
Transverse Young's Modulus	E_2	11	GPa
Shear Modulus	G_{12}	5.5	GPa
Poisson's Ratio	ν_{12}	0.27	-
Longitudinal Tensile Strength	X_t	2000	MPa
Transverse Tensile Strength	Y_t	50	MPa
Longitudinal Compressive Strength	X_c	1200	MPa
Transverse Compressive Strength	Y_c	170	MPa
Shear Strength	S_{12}	70	MPa
Fibre Volume Fraction	V_f	62	%

The remaining out-of-plane mechanical characteristics are approximated using the same rules than for flax and taking a fibre volume fraction of 0.62. A typical density value is 1550 kg/m^3.

Loading

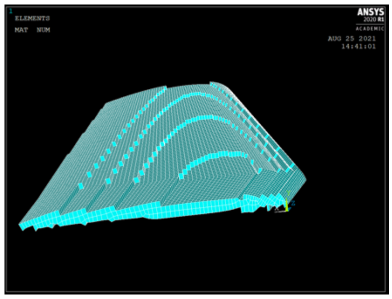
The loading conditions must be representative of real life and coherent to allow to obtain accurate results. Indeed, this project required a simplified but reliable modelling of the load applied on the hydrofoil. In this case, the load is modelled as a pressure applied on half of the hydrofoil. This pressure is calculated as the ratio of half of the total lift produced by the hydrofoil (since only half of the hydrofoil has been modelled due to the symmetry of the system) divided by the planform area of the hydrofoil. For the foil to lift the board, the lift force must be equal and opposite to the total weight of the system, which is estimated equal to 80kg, according to Newton's third law. Most of windsurf board hydrofoils have a tail wing to offer stability. The main wing must produce enough lift to overcome the effect of the tail wing. Since no tail wing is modelled in this project, its effect will be take equal to the one estimated in [10] by considering the respective planform surface areas of both on an existing hydrofoil. This means the main hydrofoil optimised in this study must provide a lift equal to $\frac{P}{0.769}$ where P is the weight of the system. Eventually, the half-hydrofoil modelled is submitted to a pressure equal to $\frac{P*g}{2*0.769} * \frac{1}{A}$ where A is equal to 0.12m^2. As a result, when all the nodal loads are applied on the hydrofoil and summed thanks to the FSUM command, the sum obtained for Fy is equal to the lift the hydrofoil must provide.

Meshing

Meshing Choice

The hydrofoils are meshed with continuum shell elements SOLSH190 which are often used for simulating shell structures with a wide range of thicknesses [23]. In this case, three volumes are defined and then meshed. The two external volumes that are each nc*tc/2 thick are meshed with carbon made elements and the internal part which is nf*tf thick is meshed with flax made elements.

Figure 4 shows the three volumes meshed for the NACA 4420 with 20% of the layers made of flax.



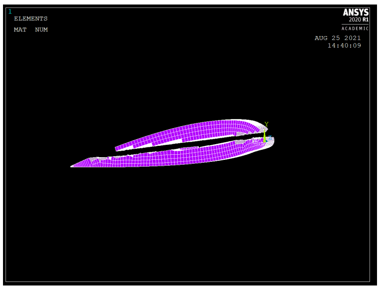


Figure 4 : Flax fibres layers (a) and carbon fibres layers (b) for the NACA 4420 with 20% flax

Table 3 shows the characteristics of the mesh obtained for medium values of camber and position of camber and three different thicknesses.

Table 3 : Mesh Characteristics for the NACA 4410, 4425 and 4440 hydrofoils

Hydrofoil geometry		NACA 4410	NACA 4425	NACA 4440
Number of nodes		51584	106184	167752
Number of elements		40994	94966	156148
Number of warnings		849	793	1393
Including	Aspect Ratio	746	690	466
	Parallel Deviation	103	206	721

	Maximum angle	103	0	412
	Jacobian Ratio	0	0	0
	Warning Factor	0	0	0
Warning elements' contribution		2.07%	0.84%	0.89%

The warnings elements are all on the leading and trailing edges as shown in Figure 5, which is not where the load is applied nor where the maximum stresses and deflection are expected so these results are satisfying.

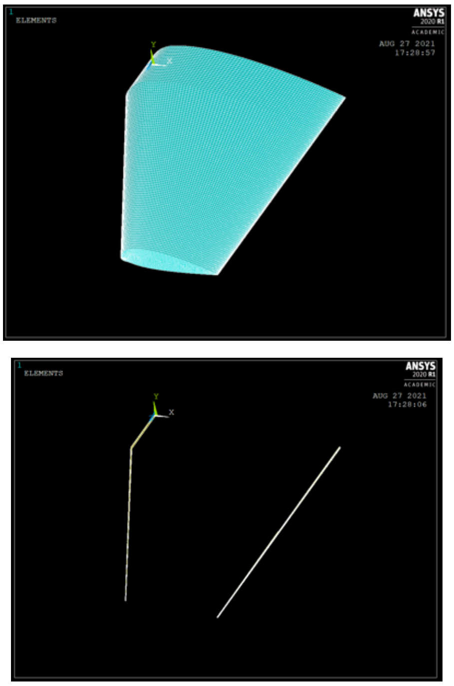


Figure 5 : Warning elements (b) on the mesh of NACA-4410 (a)

Since results are deducted from this FEA model, the meshing quality is an essential part of the study. The optimum mesh size needs to be small enough to capture local effects such as stress fields and yet not too small in order not to require too much computational power, especially considering the number of elements is multiplied for thicker hydrofoils when keeping the same elements size, which is why a convergence study is led.

Mesh Convergence

Because there are a lot of different geometries modelled, not all their meshes could be checked. Firstly, a convergence study is conducted on three hydrofoils (NACA 4410, NACA 4425 and NACA 4440) checking the convergence of the tip deflection for an element size going from 17mm to 4mm. The evolution of the nondimensionalised tip deflection with the mesh size variation is plotted in Figure 6 for each hydrofoil.

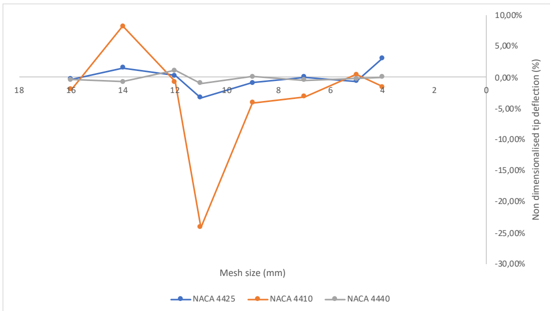


Figure 6 : Dimensionless evolution of the tip deflection with the mesh size for three different thicknesses

This plot shows that the hydrofoil for which the tip deflection varies the most with the mesh size is NACA 4410. Globally, the thicker the hydrofoil, the more converged is the mesh. This is explained by the fact that for thicker hydrofoils the relative size of the mesh compared to the size of the studied object is smaller. Furthermore, the NACA 4410 hydrofoil has a more angulous shape than thicker hydrofoils when adding a camber, which leads to more badly shaped elements. For this reason, the rest of the convergence study is led on NACA 4410. However, based on this plot, it seems that the optimum mesh sizing would be between 8mm, where the curves get closer to a 0% variation, and 4mm, where the curves start diverging again.

For the rest of the convergence study on NACA 4410, three results are studied: the tip deflection, the maximum and minimum stress values and the maximum absolute value obtained when applying the Tsai-Wu failure criterium on the flax fibres and on the carbon fibres. The results for the tip deflection are plotted on Figure 7.

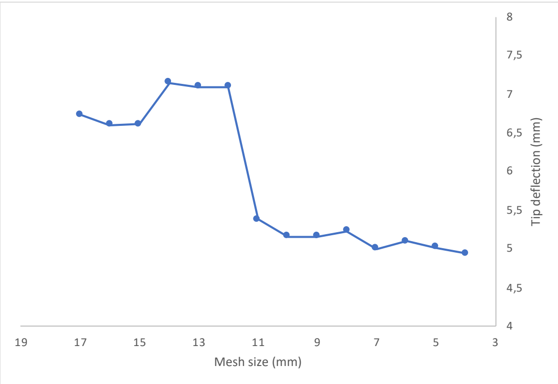


Figure 7 : Tip deflection as a function of the mesh size for the NACA 4410 hydrofoil

The tip deflection curve starts to be stabilized for a mesh size equal to 11mm. Some variations can still be observed but they are less important than those observed for bigger mesh sizes. The plots for maximum and minimum stress and maximum Tsai-Wu criterium values start converging at a similar mesh size.

Eventually, the meshing is conducted by sweeping the volumes with hexahedral elements with a size equal to 5mm which is a good compromise between computation time and accuracy.

Results and Validation

<u>Validation</u>

To validate the methodology applied, the same methodology is applied to a cantilever beam with uniformly distributed load as described in Table 4. The thickness has been chosen to match the thickness of the hydrofoils MP25 set of hydrofoils to have a reasonable number of layers compared to the study.

Table 4 : Validation beam characteristics

Length	L	10	m
Width	l	0.075	m
Thickness	T	0.075	m
Load	Q	98.1	N
Lineic Load	q	9.81	Nm^{-1}
Pressure load	P	13.33	Pa

The moment and load at the point A and the tip deflection are calculated analytically using Euler-Bernoulli beam theory.

The beam is then defined on ANSYS as shown in Figure 8 and meshed with SOLSH190 elements. Because each SOLSH190 element contains the number of layers defined, it is essential that the thickness of the beam only holds one element. For this reason, the mesh size is defined equal to 75mm which is the beam thickness. No elements raised warnings when checked due to the simplicity of the shape compared to the hydrofoil shape.

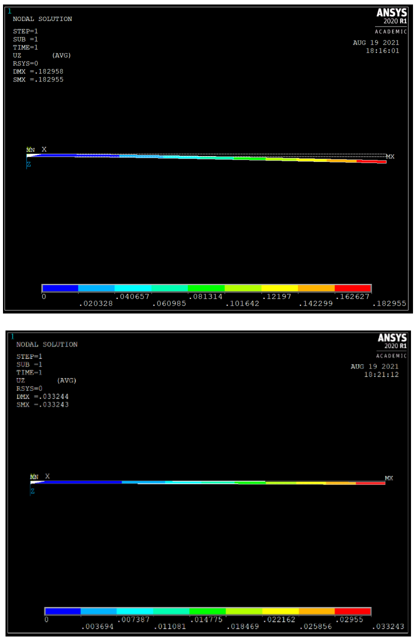


Figure 8 : Tip deflection, as nodal contour plot of the z component of displacement, in the case of a beam made in flax fibres reinforced composites (a) and a beam made in carbon fibres reinforced composites (b)

Table 5 shows the results obtained with the FEA analysis and the error percentage compared to the analytical analysis for the beams.

Table 5 : FEA results, and error compared to Euler-Bernoulli beam theory

	Analytic	FEA	Error
100% carbon	33.219 mm	33.243 mm	0.072 %
100% flax	182.953 mm	182.955 mm	0.001 %

The errors are small enough to consider they should not modify the hydrofoils' ranking in the optimisation process.

Results

A parametric study is conducted for some of the hydrofoils obtained. This has three main purposes: firstly, to check the coherence of the overall results, to check if the code works with random parameters entered and eventually to have a first idea of the tendencies when varying the parameters. This study has been led by studying the tip displacement obtained when loading the hydrofoil with the loading conditions indicated previously.

1. *Tip deflection variation with thickness*

Setting the maximum camber value M at 4 and the position for this maximum camber P at 4 as well, the thickness of the hydrofoil has been increased from 10% to 40% by steps of 5%. This study has been led for three material compositions: an all-carbon fibre, an all-flax fibre and 50% flax fibres reinforced composites. Figure 9 shows the results obtained.

Firstly, as could be expected, the more carbon fibres included in the design, the smaller the tip displacement is. However, this diminution is not linearly linked to the proportion of carbon fibres since the curve matching the 50% flax fibres hybrid composite is not at mid distance from the two other curves. This could be mainly explained by the fact the carbon layers are placed on the outside of the hydrofoil, thus have a bigger impact on the second moment of inertia than the flax layers.

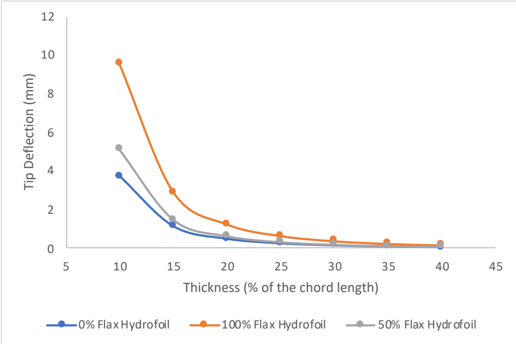


Figure 9 : Tip deflection as a function of thickness for three material compositions for the NACA 44XX set of hydrofoils

Another important piece of information is that to go under a 1mm tip displacement, approximatively 5% additional thickness will be required when going from a 100% carbon made hydrofoil to a 100% flax made hydrofoil. With a chord length equal to 30cm, this means the increase in thickness should be equal to 15mm, equivalent to adding nearly 30 plies of material. Not only will this added plies make a heavier hydrofoil but also decrease its hydrodynamic performances and probably increase its cost due to the added time in manufacturing. However, when considering hybrid composites hydrofoils, these effects are reduced since the increase in thickness required for the same result is approximatively 1%. This shows the importance of considering hybrid composites in this optimisation process.

Eventually, the graph shows that the differences between the different material's configuration decrease with thickness, going from 5.8mm to 0.1mm for this maximum camber and maximum camber position. They could be considered equivalent from a thickness equal to 30% of the chord length. However, these results could vary depending on the camber and position of maximum camber.

2. *Tip deflection variation with camber*

The next study is led by setting the position of maximum camber P at 4 as well but this time varying the camber. The thickness is firstly set at 20% of the chord length and then compared to the same results with a thickness set at 10%. Each time this is studied for both the full-carbon fibre reinforced composite hydrofoil and the full-flax fibre reinforced composite hydrofoil. To ease the interpretation of the results, Figures 10 and 11 show the evolution of the tip displacement as a percentage for each case. For instance, the value at a thickness equal to 2% is the evolution of the displacement between a thickness equal to 0% and a thickness equal to 2% as a percentage of the value of the displacement at 0%.

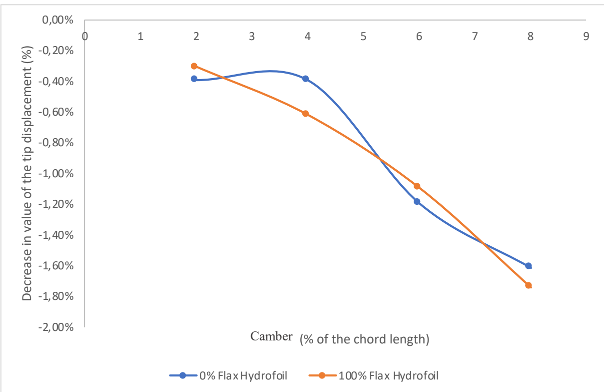


Figure 10 : Dimensionless evolution of the tip displacement with camber for the M420 set of hydrofoils

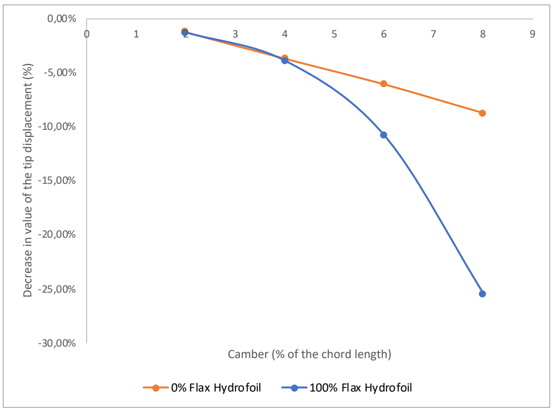


Figure 11 : Dimensionless evolution of the tip displacement with camber for the M410 set of hydrofoils

These curves show that even though increasing the camber allows to minimise the tip displacement, the impact of the maximum camber value on the tip displacement value decrease with thickness. For the smallest thickness studied, it can lower the tip displacement value up to 40% overall whereas adding 30mm to the thickness means it will decrease the tip displacement value only by 3.8%.

Furthermore, whereas for a thickness equal to 20% of the chord length the impact for increasing the maximum camber value is globally the same for both 100% carbon and 100% flax hydrofoils, for a thinner hydrofoil, their evolution greatly differs. Increasing the camber should have a bigger beneficial impact on the 100% flax-built hydrofoils than on the 100% carbon-built hydrofoils, especially for camber values over 0.04.

This study shows once again the complexity of the links between all the parameters, would they be geometrical or related to the materials used, even in a simplified case such as this one with a set position of maximum camber and hydrofoils being either completely carbon made of flax made. Indeed, the impact seen here would vary with a different maximum camber position applied and the proportion of flax included would probably have a non-linear impact such as the one seen previously.

3. *Tip displacement variation with the position of maximum camber*

Finally, by setting a maximum camber at 0.08 and making its position vary from 0% to 8% of the length of the chord for a thickness equal to either 10% or 25% of the length of the chord and for hydrofoils either entirely made with carbon reinforced composites or flax-reinforced composites, Figure 12 is obtained.

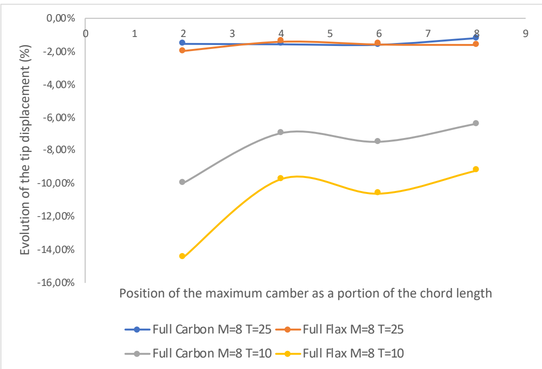


Figure 12: Dimensionless evolution of the tip displacement with camber for the 8P10 and the 8P25 sets of hydrofoils

Moving the camber away from the leading edge of the hydrofoil minimises the tip displacement in all cases considered. However, and for the same reasons than for the camber variation, the impact of varying the maximum camber position is lessened when the thickness is increased. For the thicker foil the decrease is only around 6% overall whereas for the thinner one it can get to 44% in the case of a flax-built hydrofoil.

Furthermore, like for the camber variation case, the impact on the tip deflection is higher for the flax-built hydrofoil than for the carbon-made hydrofoil. However, the curves have this time a similar evolution and do not get further apart when increasing the value studied.

Eventually, an interesting aspect of the curves for the smaller thickness studied is that even though moving the maximum camber point away from the leading edge is beneficial, its maximum impact is for positions closer to the leading edge.

<u>Discussion</u>

These studies show results that could be expected considering the materials' respective characteristics and the hydrofoils' relative shape, which is reassuring about the model. Indeed, increasing the thickness, using more carbon than flax, disposing the carbon layers on the outside of the hydrofoil or increasing the camber do improve the hydrofoil's stiffness as could be expected. Furthermore, they show that all the parameters considered had an impact on the hydrofoil's structural performances, which means they are useful in the optimisation process.

However, these studies also show the complexity of the optimisation problem. Increasing the camber can be a solution for increasing the stiffness of thinner hydrofoils but will not function as well for thicker hydrofoils, not to mention the impact the position of the camber could have on these results. Replacing carbon by flax will not have a linear impact on the tip displacement obtained for a similar thickness, which means the additional thickness required to obtain similar structural stiffness, with all the impacts it has on other performances, is hardly predictable. The complexity induced by these elements makes the evolution of the stiffness with the parameters hardly predictable which is why the optimisation process requires the use of a genetic algorithm.

Furthermore, these studies have only focused on the structural performance of the hydrofoils obtained. The optimisation process would also consider other essential performances for a hydrofoil such as its hydrodynamic performances, its cost, its weight, and its sustainability which add to the problem complexity. These performances need to be assessed for all the hydrofoils considered before launching the optimisation process.

PERFORMANCES ANALYSIS AND DISCUSSION

Hydrodynamic performances

Estimation process

The hydrodynamic performances are mainly dependant on the shape of the hydrofoil. Thus, in this model, the hydrodynamic performances only depend on the three geometrical parameters defined earlier. The hydrofoils' hydrodynamic performances are characterized by the Cl/Cd maximum ratio obtained for all hydrofoils for an angle of attack going from 0° to 15° with 0.25° increments steps. This is obtained by running Xfoil for each NACA-4digits shape considered with a Reynolds number equal to 3.855e6 matching an estimate speed for the hydrofoil's use. Figure 13 shows the program running for a hydrofoil shape.

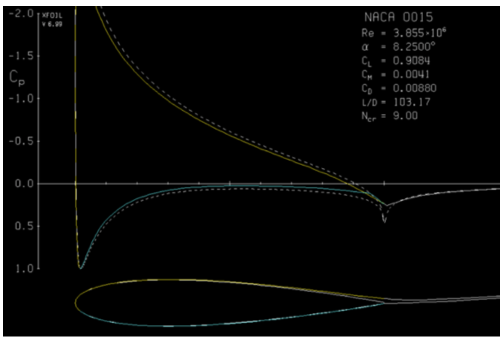


Figure 13 : Flow around the NACA 0015 at an angle of attack equal to 8.25° (Xfoil)

Xfoil software returns different values for each angle of attack considered, including the lift and drag coefficients. A python programme is then written to automatize the process, run the software for all hydrofoils and extract the maximum ratio value for each. This value is stored for all hydrofoils along with the angle of attack matching this maximum value.

Solution and validation

Some of the results obtained are plotted to check the overall coherence and get some first results.

Figure 14 shows the hydrodynamic performances of the hydrofoil decrease when the thickness is increased. The optimum angle of attack also decreases over the range of thickness studied in this case, even though for a thickness over 25% of the chord length, it could be considered constant and equal to 7.

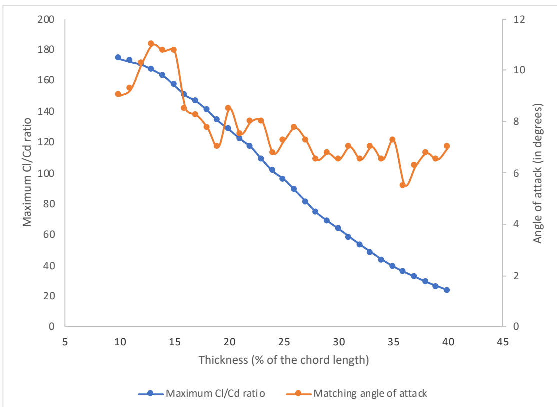


Figure 14 : Evolution of the Cl/Cd ratio and optimum angle of attack for the 52XX set of hydrofoils

The same study is led for a hydrofoil with the same maximum camber, but this time set closer to the trailing edge. Figure 15 shows that moving the maximum camber towards the trailing edge lowers the maximum Cl/Cd ratio attainable for small thicknesses.

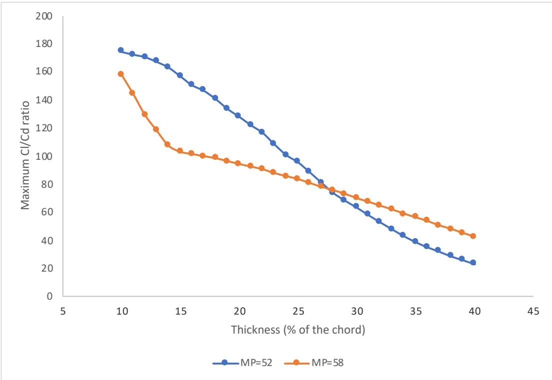


Figure 15 : Evolution of the Cl/Cd ratio for the 52XX and 58XX sets of hydrofoils

However, for thicker hydrofoils, the impact is reversed. The thickness ratio at which the curves intersect varies as a function of the position of the camber studied and of course the maximum camber. Figure 16 indicates that increasing the maximum camber value has a good impact on the Cl/Cd ratio, however this impact is reduced when increasing the thickness and the three curves converge for T>20%.

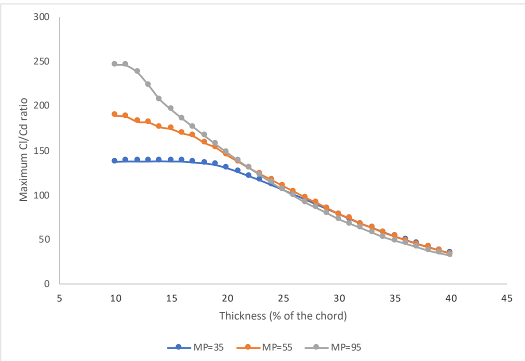


Figure 16 : Evolution of the Cl/Cd ratio for the 35XX, 55XX and 85XX sets of hydrofoils

Other performances estimate

Weight estimate

The weight estimate is based on the volume occupied by each material (Carbon-Epoxy and Flax-Epoxy) in each hydrofoil. This volume is given by the ANSYS analysis as a sum of the volumes of the elements matching the material's number and then multiplied by the density of each laminate.

The total volume of the hydrofoil varies from 2.05E-3 m^3 for the NACA 0010 to 8.22E-3 m^3 for the NACA 0040 which means the lightest half of hydrofoil considered weights 2.6 kg while the heaviest weights 12.7 kg. Considering the importance of weight in marine applications and in the case of performant craft with hydrofoils, it is an important factor to consider during the optimisation process.

This method only gives an estimate of the volume occupied by each material and of the total hydrofoil volume and weight due to the unrealistic tip shape of the hydrofoil and inaccuracy due to the mesh size. However, since in this case the important element is the comparison between the hydrofoil's performances and not the exact value of these performances, it is assumed that the errors are sufficiently close for each case to not impact the results of the optimisation process.

Sustainability assessment

Both the cost and sustainability are assessed based on the weight obtained similarly to what was done in [24]. The sustainability of flax and carbon is assessed based on the embodied energy during primary production and the data is given in Table 6 [2][24][25]. Since both laminates are using Epoxy resin, its part in the sustainability estimate is not assessed, it is not a deciding element of the optimisation process.

Table 6 : Embodied energy for flax and carbon fibres

Material	Embodied Energy (MJ/kg)
Flax Fibres	10
Carbon Fibres	380

The end of life of the materials is not considered in this estimate since the demand for recycled FFC in the UK is still very low [10][26] and thus it is likely no matter the material chosen, it would end in a landfill. Even though flax fibres are biodegradables, the fact they are mixed with epoxy resin makes them equivalent to carbon fibres in their end of life if no mechanical or thermal process is led beforehand. However, if the demand in recycled materials was to change or if the recycling processes were to become more financially and environmentally interesting, which a lot of studies are trying to accomplish [26], this component should be added to the optimisation process.

Using this data, the most sustainable hydrofoil, which has the lowest volume and is made of flax, has an embodied energy value of 26MJ, while the most harmful to the environment has an embodied energy value of 4826MJ.

Cost Assessment

The cost assessment is based on area-based prices which can be seen in Table 7 [24][27]. The area occupied by each material is obtained by dividing its volume by the matching layer's thickness.

Table 7 : Cost of flax and carbon fibres reinforced composites

Material	Cost (£/m^2)
Flax fibre reinforced epoxy composites	49.8
Carbon fibre reinforced epoxy composites	75.5

This means the less expensive hydrofoil's materials would cost 190£ and the most expensive one 1241£. This cost assessment only considers the material cost and does not consider the manufacturing cost. However, since the shapes are similar, the only element that changes from one hydrofoil to another and that can have an impact on its price is the number of layers used. Based on the Advanced Composite Cost Estimation Manual [28], changing the number of layers has an impact on two steps of the manufacturing process (laying the layers and hand finishing) and this impact can be assessed as being equal to:

$$0.1 + N * 0.001518 + 0.000011 * P * N,$$

expressed in hours

Where N is the number of layers applied and P the perimeter of the hydrofoil, in this case equal to 1.48m for all hydrofoils studied. Given that between the thinner hydrofoil and the thicker hydrofoil, the maximum difference in the number of layers applied is 180, this gives an additional time of 20min in the worst case, which is only 1/6th of the estimated manufacturing time for a benchmark hydrofoil [10] and is equivalent to a labour cost of 6.67£ taking a labour rate at 20£/hour. Compared to the values obtained for the materials' cost, this amount is small enough to be dismissed.

Use of the Genetic Algorithm

Choice of the algorithm

Design search and optimisation is the process through which the information necessary to a rational decision making is calculated and processed. It involves postulating a design, analysing it, deciding if the results are acceptable and if not deciding how to change it. Genetic Algorithm are one of the tools used to this purpose, they are inspired on Darwin's theory of evolution and are based on the principle that "if the fittest individuals in a given population mate to form a new generation of children this new generation will be fitter, on average, than the last" [15].

It is essential to choose an appropriate algorithm since, as shown in [15] even though the efficiency of an algorithm on a specific problem will mean a reduction in performance for other optimisation problems, some algorithms can show good results over a wider range of problems than others. The Multi-Level Selection Genetic Algorithm (MLSGA) has different reproduction mechanisms at each level and splits the fitness function between these mechanisms [29]. In this algorithm, the evolutionary fitness does not just depend on the fitness of the individual but can also on the collective of individuals that it is associated with [15].

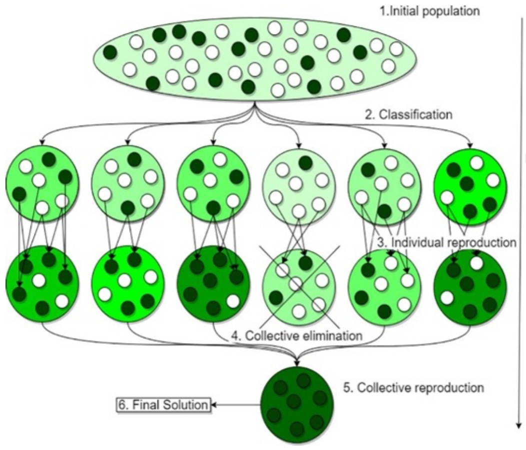


Figure 17 : Mechanism of MLSGA, individual and collective reproduction

The process is illustrated in Figure 17 [30] in which the fourth collective of individuals, which is the one with the worst objective function result is eliminated to be replaced by a collective formed of a copy of the best individuals from each of the remaining collectives.

The algorithm's population size sensitivity when keeping the same number of function calls allowed is assessed. It is lead on several pareto fronts including structural versus weight performances as shown in Figure 18.

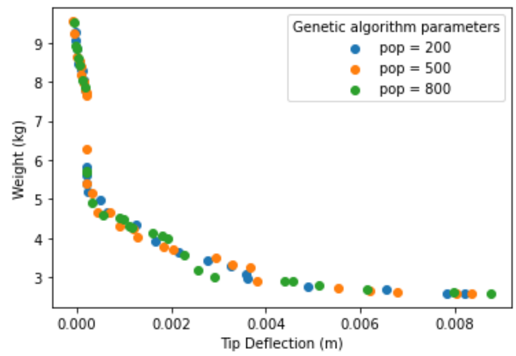


Figure 18: Population size sensitivity evaluation with the weight VS tip deflection pareto front

The algorithm does not show an important sensitivity to population size variation. A population equal to 800 gives a resolved Pareto front and the largest diversity which is why it is chosen to carry the optimisation.

<u>Use of Kriging method to evaluate the structural performances</u>

However, launching the ANSYS model to obtain the precise tip deflection value for each solution studied by the Genetic Algorithm in the design space is too costly and not feasible. A surrogate based optimisation which allows to reduce the time of calculation for costly problems such as a hydrofoil optimisation problem in [31] or a hull-form optimisation in [32] is required. A Kriging model of the tip deflection is thus created.

To check if this method affects the accuracy of the results, the results obtained are tested against values obtained through the ANSYS model for an optimal latin hypercube defined sampling plan. Figure 19 is obtained for a Kriging model which used 40 test points and 10 added points with a model training between each.

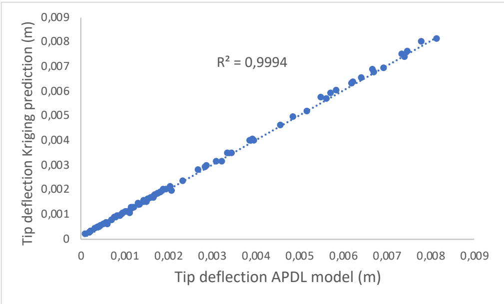


Figure 19: Tip deflection model correlation with Kriging surrogate

The surrogate model shows a low and satisfying mean error value of 2.19%. The maximum error obtained is equal to 12%. High relative error values are obtained for the extremum values of tip deflection. The hydrofoils giving values of tip deflection too high will be removed from the possible solutions because they are considered too weak. The smallest values of tip deflection are reached for the thickest hydrofoils. Considering these hydrofoils will probably be rejected by the algorithm because of their high cost and weight and low sustainability and hydrodynamic performances, this surrogate model is selected.

RESULTS

<u>A various pool of results</u>

Eventually, 800 designs are selected with an average proportion of flax layers equal to 48.7%. The result pool given by the algorithm shows a quasi-uniform distribution in terms of proportion of flax layers, as shown in the histogram figure 20.

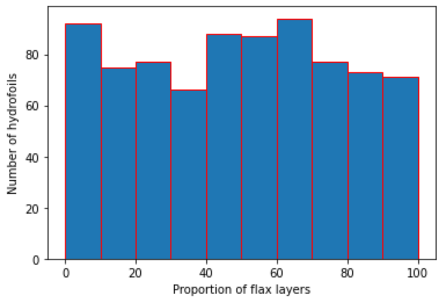


Figure 20: Histogram of the proportion of flax layers in the designs

However, considering flax layers are in the centre of the hydrofoil and are thicker than carbon layers, in terms of volume ratio, histogram in Figure 21 shows the result pool is dominated by hydrofoils composed mainly of flax.

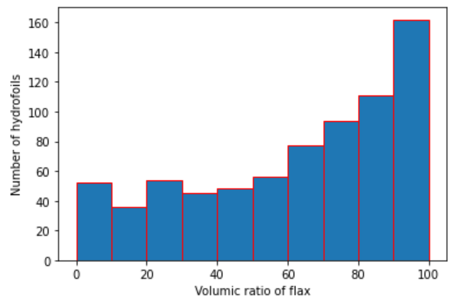


Figure 21: Histogram of the volume ratio of flax in the designs

Table 8 shows the proportion of hydrofoils mainly composed of flax (with more than 50% of the layers being flax) in the pareto fronts opposing each objective to one another. It confirms that for most of the pareto fronts, solutions with more flax layers than carbon layers dominate other solutions. However, when the two objectives considered are the structural and hydrodynamic performances or the structural performance and the weight, the proportion of solutions mainly made of flax falls to 25% and 19% respectively, which shows carbon made solutions still dominate the structural performances.

Table 8 : Proportion of hydrofoils mainly made of flax layers in the pareto fronts studied

	Sustainability	Cost	Structure	Hydrodynamic	Weight
Sustainability		100	83	100	100
Cost	100		75	100	100
Structure	83	75		25	19
Hydrodynamic	100	100	25		100
Weight	100	100	19	100	

Solutions with a tip deflection over 1mm are then considered too weak and removed from the solution set. This gives 614 solutions with an average proportion of flax layers equal to 46.9%. Table 9 shows the results that tend to promote more carbon made hydrofoils than without this constraint.

Table 9: Proportion of hydrofoils mainly made of flax layers in the pareto fronts studied once the weakest hydrofoils have been removed

	Sustainability	Cost	Structure	Hydrodynamic	Weight
Sustainability		100	72	100	66
Cost	100		60	66	70
Structure	72	60		15	11
Hydrodynamic	100	66	15		33
Weight	66	70	11	33	

These results are coherent with carbon and flax properties given that flax has lower cost, density, and embodied energy values than carbon but less good mechanical properties.

<u>Flax largely dominant in terms of sustainability</u>

Those tables confirm the large dominance of flax as soon as the sustainability criterium is involved. Figure 22 shows the repartition of the hydrofoils in terms of weight and embodied energy.

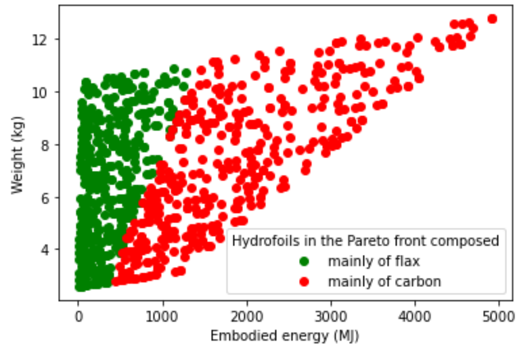


Figure 22: Weight versus sustainability Pareto front

For a same weight, hydrofoils which contain more carbon than flax have a greater embodied energy. This is logical considering the sustainability assessment chosen. However, an interesting and unexpected element is that carbon made hydrofoils are not necessarily lighter than the flax made hydrofoils, even though a structural constraint which eliminates the weakest hydrofoils has been implemented.

Indeed, Figures 23, 24 and 25 show flax made hydrofoils have sufficiently good performances in terms of minimised drag over lift ratio, tip deflection and cost to compete with and dominate carbon made solutions as soon as the sustainability criterium is involved.

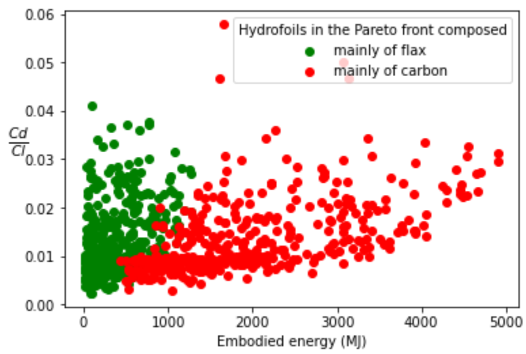


Figure 23 : Hydrodynamic performances versus sustainability Pareto front

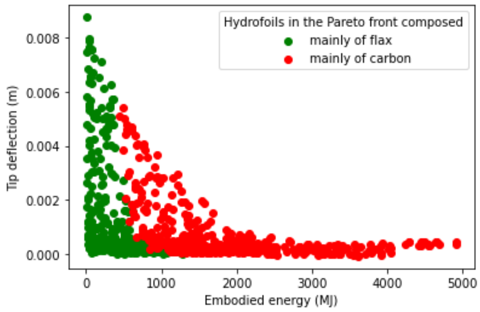


Figure 24 : Structural performances versus sustainability Pareto front

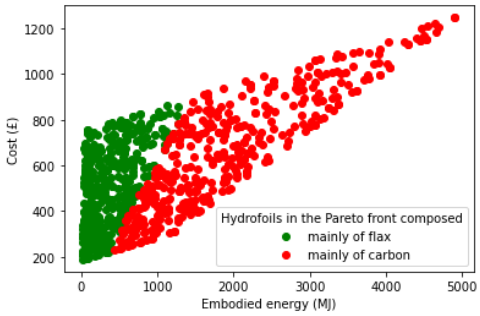


Figure 25 : Cost versus sustainability Pareto front

These graphs are interesting because the lower mechanical properties of flax were expected to lead to thicker hydrofoils when made of flax, which would have had a negative impact on the hydrofoil's cost and its hydrodynamic performances. However, the fact that hybrid composites are considered, which reinforces the structure, and the fact the hydrofoil shape can be optimised to reach good hydrodynamic performances even with a thicker hydrofoil allows to have dominant solutions mostly made of flax despite its lowest mechanical properties.

<u>Carbon dominant in terms of structures, hydrodynamic performances, and weight</u>

Hydrofoils which are mainly composed of carbon fibres still dominate in some directions, in particular structural performances. Figure 26 shows the hydrofoils' performances in terms of the structural and hydrodynamic performances and Figure 27 shows the structural performance opposed to the hydrofoil's weight. In both figures, the hydrofoils which are in the pareto fronts and made with more than 50% of the layers being flax are coloured in green and those which are in the pareto front with more than 50% of the layers being carbon are in red. Both figures show a large predominance of red. This shows that when focusing on maximising structural and hydrodynamic performances or maximising structural performances while minimising the weight, carbon-made hydrofoils remain the best solution. This is coherent with the current state of the market for high-performance hydrofoils for which the weight and structural and hydrodynamic performances are the main objectives considered.

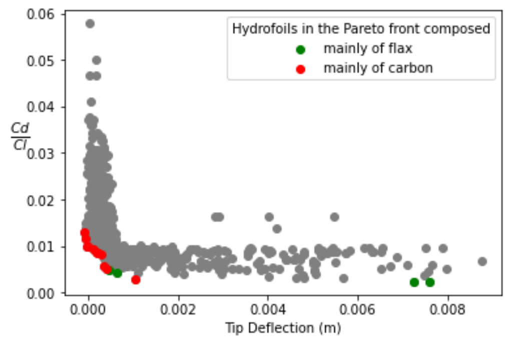


Figure 26: Hydrodynamic versus structural performances Pareto front

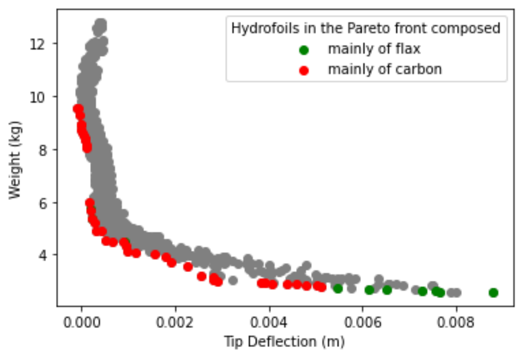


Figure 27 : Weight versus structural performances Pareto front

<u>Hybrid composites essential to have optimum results</u>

Finally, an important result is the large part hold by hybrid composites in the result pool. 90% of the possible hydrofoils to minimise the objectives given has between 5 and 95% of its layers made of flax.

This means most of the optimum hydrofoils found by the genetic algorithm to solve this problem are made of both materials, which properties linked together give better results than the hydrofoils only made with flax or carbon fibres in most objective directions. Table 10 shows the proportion of hydrofoils made of both carbon and flax layers in each of the pareto fronts.

This table confirms the interest in considering hybrid composites to solve the problem of hydrofoil optimisation, especially to maximise structural and hydrodynamic performances. When these performances are considered most of the hydrofoils in the Pareto front are made with both carbon and flax layers.

Table 10 : Proportion of hybrid composites made hydrofoils in the Pareto fronts

	Sustainability	Cost	Structure	Hydrodynamic	Weight
Sustainability		0	16	75	0
Cost	0		89	83	0
Structure	16	89		75	82
Hydrodynamic	75	83	75		83
Weight	0	0	82	83	

The shape optimisation

The mean and standard deviation of the shape parameters among the set of solution are summarised in Table 11.

Table 11 : Mean geometrical characteristics in the constrained and unconstrained cases

		Without structural constraint	With structural constraint
Thickness	mean	24.4	28.3
	std	8.9	7.0
Maximum camber	mean	4.3	4.3
	std	2.8	2.8
Position of maximum camber	mean	4.4	4.7
	std	2.8	2.8

First, these results show the thickness range chosen (between 10 and 40% of the chord length) is adequate since in both cases $mean \pm std$ does not reach the end of the range. Secondly, including a structural constraint leads to keep thicker hydrofoil, which is a logical result. An interesting co-effect is that it also leads to bigger and further placed from the leading-edge maximum cambers overall.

Another interesting element of the shape optimisation is that the hydrofoils with more than 50% of flax layers have an averaged maximum camber 6% higher than those mainly made of carbon and an average position of this maximum camber 12% further away from the leading edge. This can be explained by the fact a higher camber improves the structural performances of the design and moving this camber away from the leading edge can improve its hydrodynamics performances as shown in the parametric studies. This variation of optimum shape with the proportion of flax layers explains why how hydrofoils made mainly of flax, with less good mechanical properties can compete with hydrofoils mainly made of carbon, even for structural performances.

Limitation

The assumptions made to evaluate the different objectives limit the results' interpretation. If one hydrofoil from the set was to be built, the objective values obtained would not be the same than the ones obtained in this model.

The cost, sustainability and weight are based on the volume estimates which are higher than the ones which would be obtained for a real hydrofoil. Indeed, the geometry of the model is thicker at the tip of the hydrofoil than an actual hydrofoil would be. However, since the tip shape is the same for all hydrofoils, this should not have an impact on the ranking obtained.

To evaluate a design's sustainability is difficult for two main reasons. First, the sustainability data can be hard to obtain for the materials. Additionally, the embodied energy chosen in this case represents the sustainability assessment for the production but does not include the design's end of life assessment or the provenance of the materials. For instance, if the design was built in an area with no flax production for instance, the transport environmental cost would lower the design sustainability, which is not considered in this model.

The hydrodynamic performances are only based on the profile shape which does not match the actual hydrodynamics around a foil and does not have an impact on the loading condition of the hydrofoil, which would be the case in reality. Having a more complex load case was too expensive and did not have a great importance since only the tip deflection in the z direction was considered as the structural criterium. However, if a hydrofoil was to be built, its design would require a more precise and thorough load case.

Eventually, the materials properties are based on average of the literature values but do not reflect the standard deviation of these values. For the flax properties, for which data is still limited, including this standard deviation would lower the factor of safety obtained and probably lower the performances expected of these designs.

CONCLUSIONS AND RECOMMENDATIONS

Results

This paper demonstrates the positive impact of an increased utilisation of hybrid composites in the construction of hydrofoils. The shape and material optimisation process leads to better designed hydrofoils with regards to the five main objectives considered: cost, weight, sustainability, structural and hydrodynamic performances. These performances are improved with the use of hybrid-composites in the design since 90% of the possible designs obtained are made of hybrid-composites composed of both flax and carbon layers.

The proportion of flax included in these hybrid composites depends on the prioritisation of the objectives. Hydrofoils designed with mostly flax layers clearly and expectedly dominate other solutions in the sustainability direction. They also show good performances in terms of cost. However, when the hydrofoil's weight, structural and hydrodynamic performances are the main objectives, the optimum designs include more carbon layers than flax.

Even though flax dominates the sustainability criterium and carbon the structural performances, the best designs in all directions are made of a combination of flax and carbon. Additionally, the inclusion of the shape optimisation in the process leads to a quasi-uniform distribution of the proportion of flax layers in the pool of results. Whatever the proportion of flax layers included in the hydrofoil may be, an optimised hydrofoil shape can be found to allow for the design to compete with all other hydrofoils considered.

Thus, to include hybrid composites in the design space is a good solution to start considering an improved sustainability as one of the objectives without sacrificing the other objectives.

Further Work

The current methodology presented can be complemented by further studies in these areas:

- Use of a high fidelity CFD method such as RANS to have more accurate values of the hydrofoils' hydrodynamic performances. It could be used in the building of a surrogate model to be incorporated in the optimization process.
- Include more geometrical parameters to have more realistic hydrofoil shapes, especially for the tip of the hydrofoil. This could be done as a local refinement for non-dominated designs.
- Consider the lay-up configuration more precisely and include the layers' orientation in the process. Include designs with flax layers positioned on the external part of the hydrofoil since that configuration improves further the damping properties.
- Link the hydrodynamic performances to the loading conditions of the hydrofoil and describe the loading conditions more realistically to include other structural criteria in the study than the tip deflection only in the z direction.
- Compare different surrogate construction techniques to the performances of Kriging to predict and evaluate the structural performances in the genetic algorithm.
- Evaluate the performances of other Genetic Algorithms on this problem to check if the one chosen here is the most performant.

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