Topology optimization of a solar-powered boat

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Abstract. To reduce climate change effects caused by the marine industry's uncontrolled emissions, the proposal of a technique that implements topology optimization to boat design can help boatyards and governments to reduce CO_2 emissions. Boats are responsible for approximately 3% of the world's total CO_2 emissions and making lighter boats is a great way to reduce this contribution. Until now, the works that use topology optimization do not take into account some specifications of marine design, such as balance. This work solves the compliance minimization problem subject to a volume constraint and a new COG (center of gravity) constraint to respect the primary boat equilibrium project to avoid rework. A reference solar-powered boat is considered as a baseline design. The power required by the boat is used as a measure of CO_2 reduction for comparing the baseline and the optimized designs. This is done via hydrodynamic analyses before and after optimization.

Keywords: Topology Optimization, ship design, boat design, Naval Architecture.

1 Introduction

The naval industry has been responsible for 2.89% of total anthropogenic emissions in 2018 year according to the fourth IMO (International Maritime Organisation) Greenhouse Gas Study [1]. No wonder this high result, as the locomotive of global commerce, the maritime industry has a protagonist role in anthropogenic changes on our planet. This number sets an alert. Most of this CO_2 comes from fuel consumption because most of the cargo boats use diesel as fuel. To decrease CO_2 emissions, efficient, clean energy-powered boats need to be designed. Nevertheless, this energy transition needs to be followed by a low-cost solution because of the competitive scenario that embraces this industry.

The first intuitive solution is to produce clean energy boats and substitute diesel ones. Nevertheless, this new energy technology needs to be supported by new designs, capable of producing lighter boats. Topology optimization can be a great ally in this task. In the past decades, this optimization method has produced many design solutions for aeronautics, cars, tractors, civil engineering, medical equipment, and so on. Despite that, naval architecture doesn't pay proper attention to the technique. Until now, only a few academic works about the theme, all in the past 5 years. Furthermore, almost all of them are on leisure boats such as Leidenfrost [2] and Macuso [3], and just one, from Islam [4], about optimization in oil tanker bulkhead and still just about a very small part of the boat, without considering some core specifications that involve the naval architecture, as stability and hydrostatics. Besides this, Leindenfrost [2] presents a technique to avoid problems when the design domain is set as solid and set up the boundary conditions using a quasi-static load case. This work concerns the topology optimization of a solar-powered boat for a university competition and it is the first step toward structuring a method to solve the problems quoted.

In section 2 the methodology is described, the boat chosen 2.1, and the software 2.2, optimization method 2.3 and boundary conditions 2.4 are explained. In section 3.1, the first analysis of the whole boat is presented such as the benchmark for comparison. Finally, at 3 the numerical results are presented.

2 Methodology

The objective of this work is to compare the results of topological optimization with a baseline design. The reference value for comparison is the power necessary to maintain the maximum velocity of the boat. With this value, it is possible to calculate the proportional reduction of CO_2 emission. To achieve this, it is necessary to reduce the boat draft, so his wetted area. The boat draft is reduced by reducing mass. Therefore, topology optimization is applied herein to maximize structural stiffness with a mass constraint.

2.1 The boat

The boat chosen to be optimized is Floki. This is a solar-powered trimaran, designed by the PoliNáutico team, a university competition guild, for the DSB (Brazil's Solar Challenge). The part of the boat that is optimized is the structure of the principal hull. Floki was chosen because of the availability of CAD archives, and project reports, which facilitates the process. The boat's principal attributes are 6 m of length overall, 0.14 m of draft, 271,9 kg of displacement, 0.85 m of breadth, 0.4 m of pontoon, and a maximum velocity of 6 knots. His lines can be seen in figure 1 and figure 2.

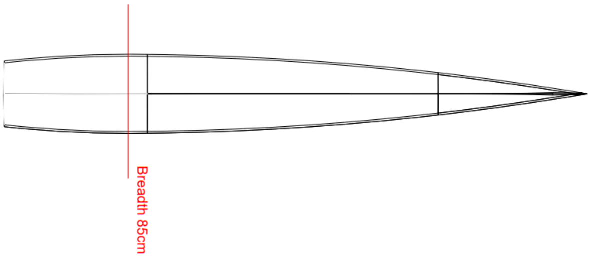


Figure 1. Breadth

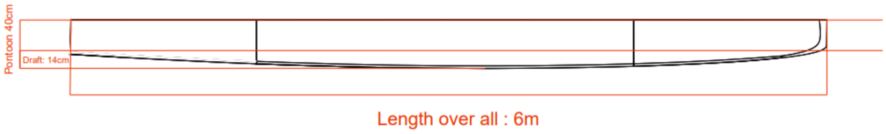


Figure 2. Pontoon, draft, and length overall

2.2 Computational Setup

This work was done using three software, Rhinoceros 3D, MaxSurf, and Altair Inspire. The first one was for CAD file adaptations, preparation and results interpretation. The second was for boat analysis such as stability, curve of areas, hydrostatics and hydrodynamic data. The last one was for finite element analysis and optimization.

2.3 Optimization Problem

Altair Inspire uses the density-based method by employing the SIMP (Solid Isotropic material penalization method) approach, Sigmund [5]. For the objective function, the minimization of compliance (C) was chosen eq. (1). A volume constraint eq. (3), applies to all the objects, and COG (Center of gravity)eq. (4) constraints. The variable θ_i corresponds to the pseudo-density applied by the SIMP method, and varies eq. (5) from 0 to 1, where 0 is void and 1 is solid.

$$Min : C = \frac{1}{2}U^t FU \tag{1}$$

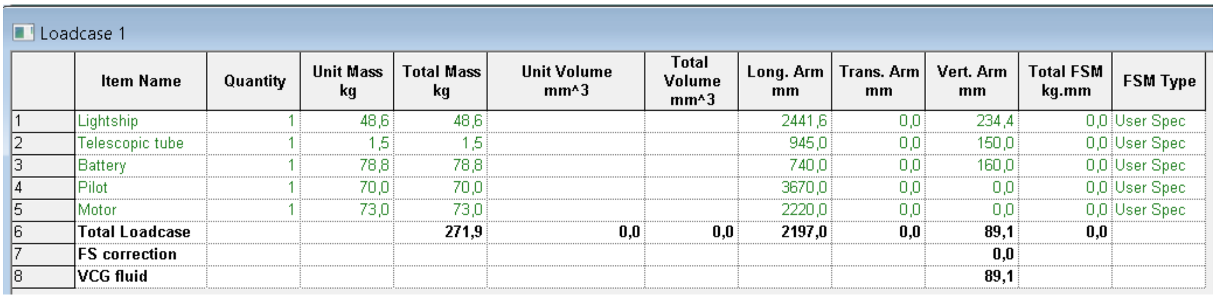
$$s.t. KU = F \tag{2}$$

$$\sum_i \theta_i \leq V_0 \tag{3}$$

$$x'_j = \frac{\sum_i x_{ij}\theta_i \mu v}{\sum_i \theta_i \mu v}, j = 1,2,3 \tag{4}$$

$$0 < \theta_i \leq 1 \tag{5}$$

Where C is the structural compliance, U is the vector of structural displacements, K is the global stiffness, and F is the vector of strengths. It is important to explain why the COG constraint is necessary. As previously mentioned, a boat is a complex system and one of the factors that contribute to this complexity is the equilibrium. Once a first project of a table of weights is designed, it is very complicated to change the mass distribution. Floki's weight table is shown in figure 3 and figure 4. To maintain the same stability and prevent re-work, it is necessary to apply the COG constraints, so the optimization version will have the same COG as the standard version. This is the most significant novelty of this work, as the other available works in the literature did not consider this important boat specification. In a bigger project, where many heavy parts of the boat will be optimized, it is wise to consider a global COG constraint, with both design and nondesign domains as part of the constraint.



Loadcase 1

	Item Name	Quantity	Unit Mass kg	Total Mass kg	Unit Volume mm^3	Total Volume mm^3	Long. Arm mm	Trans. Arm mm	Vert. Arm mm	Total FSM kg.mm	FSM Type
1	Lightship	1	48,6	48,6			2441,6	0,0	234,4	0,0	User Spec
2	Telescopic tube	1	1,5	1,5			945,0	0,0	150,0	0,0	User Spec
3	Battery	1	78,8	78,8			740,0	0,0	160,0	0,0	User Spec
4	Pilot	1	70,0	70,0			3670,0	0,0	0,0	0,0	User Spec
5	Motor	1	73,0	73,0			2220,0	0,0	0,0	0,0	User Spec
6	**Total Loadcase**			**271,9**	**0,0**	**0,0**	**2197,0**	**0,0**	**89,1**	**0,0**	
7	**FS correction**								**0,0**		
8	**VCG fluid**								**89,1**		

Figure 3. Floki weight table

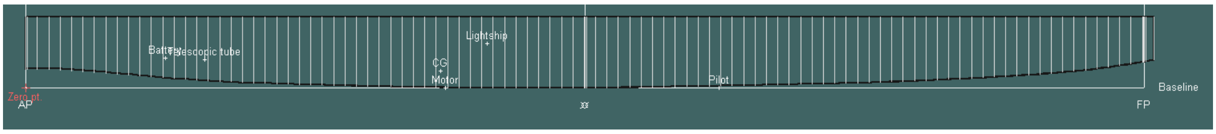


Figure 4. Graphic example

2.4 Load Case and Hydrostatics

The loads on a boat can be classified by the level of structure they affect. There are four levels of structure: hull girder, hull module, principal member, and local member. In this work, were considered external hydrostatic pressure and internal loads because they act on the four levels of structure as defined by Hughes [6]. Also according to Hughes [6], the loads can be classified by how they vary with time, which can be: static, quasi-static, and dynamic. This work will only consider the static and quasi-static loads, which can be modeled as static. Two extreme load cases were selected: sagging and hogging. Sagging and hogging are two pure bendings that implicate a deformation of the hull in the longitudinal direction as present in figure 5 They occur when a wave, passing through the boat, acquires a wavelength with the size of the boat and an amplitude equal to the pontoon of the boat. In these conditions, the buoyancy force is concentrated on the extremes of the boat resulting in a bending moment. Besides sag and hog, the internal loads: battery, pilot, motor, and propulsion weights were also added. Graph 6a and 6b present the buoyancy, weight, and the resultant of their sum. With these boundary conditions, the total draft of the boat was 14 cm and the total wetted area was 3364138 mm² as figure 7 shows.

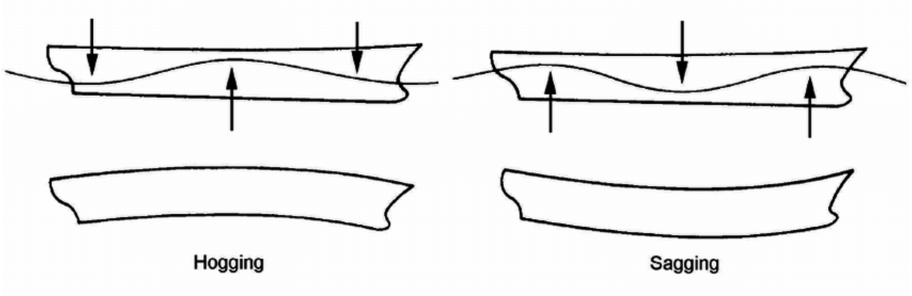
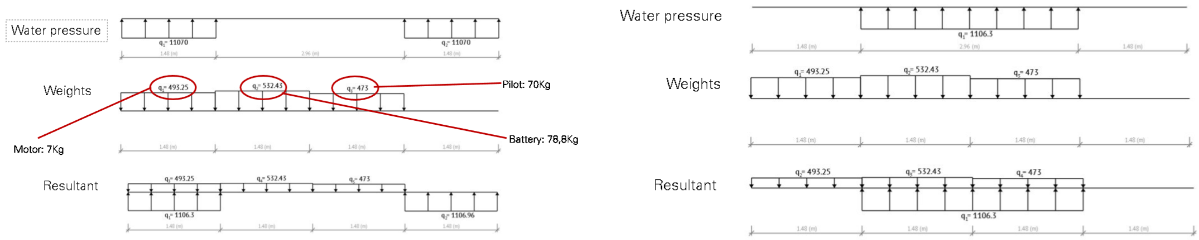
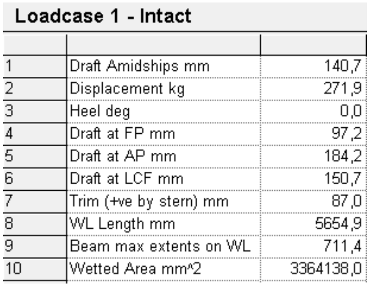


Figure 5. Hogging and Sagging



(a) Sag graph (b) Hog graph

Figure 6. Loanding Cases



Loadcase 1 - Intact

1	Draft Amidships mm	140,7
2	Displacement kg	271,9
3	Heel deg	0,0
4	Draft at FP mm	97,2
5	Draft at AP mm	184,2
6	Draft at LCF mm	150,7
7	Trim (+ve by stern) mm	87,0
8	WL Length mm	5654,9
9	Beam max extents on WL	711,4
10	Wetted Area mm^2	3364138,0

Figure 7. Hydrostatic analysis

Also, an Inertia Relief boundary condition was applied. This condition is a software tool to simulate objects that did not have supports. As is specified on Altair's help website [7], "with inertia relief, the applied loads are balanced by a set of translational and rotational accelerations. These accelerations provide body forces, distributed over the structure in such a way that the sum total of the applied forces on the structure is zero´´.

2.5 Element size convergence

To obtain the best result and the computational costs low as possible, a finite element convergence test is needed. In figure 8 is possible to see the mesh with a 0.04 m element size and in figure 9 a 0.08 m mesh, on these sizes the displacement remains almost the same. Nonetheless, it is possible to see that the element mesh shown in figure 9 is not exactly symmetrical, which is undesired for boat analysis. The computational cost for the 0.04 m element size mesh was not considerably high, therefore, this mesh was chosen.

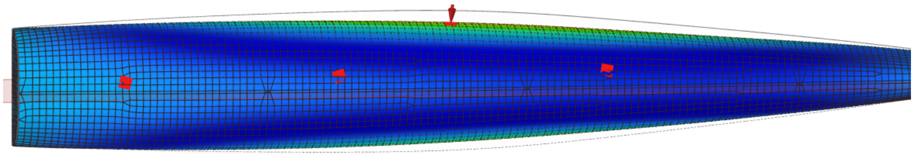


Figure 8. 0.04 m element mesh size

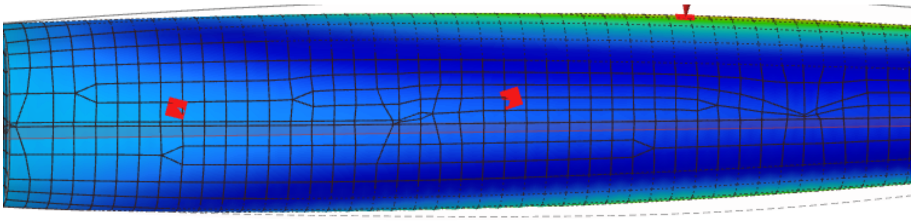
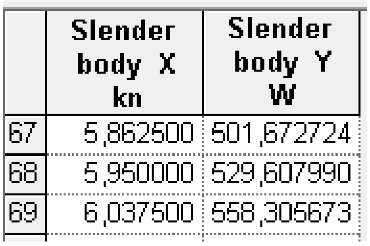


Figure 9. 0.08 m element mesh size

3 Numerical results

3.1 Hydrodynamic analysis of the baseline design

To measure the power reference value for comparison proposed in section 2, a resistance prediction method and the efficiency of the mechanical system need to be defined. The prediction method chosen was the Slender Body method because the boat fits on the method's coefficient limits that can be checked on the MaxSurf Resistance User Manual [8] and the efficiency of 55% as the boat project report. The boat navigates at a 6-knot velocity, so the power for this velocity with 14 cm of draft was 558,3 W as figure 10 shows.



	Slender body X kn	Slender body Y W
67	5,862500	501,672724
68	5,950000	529,607990
69	6,037500	558,305673

Figure 10. Power x Velocity table

3.2 Optimized design and hydrodynamic analysis post-optimization

The results of the optimization setup are shown in figure 11 and interpreted on Rhinoceros 3D as shown in figure 15. The proposal is to design a structure that is capable of handling all the primary stress, leaving to the hull, only the function of being watertight. So, on the weight table, the mass of the hull is changed to the mass of the topology optimization solution, which corresponds to 30% of the original mass resulting in 14,6 Kg. The new weight table is shown in figure 16 and the new hydrostatic analysis in figure 17. As shown in figure 17 the draft changed to 12,8 cm. Redoing the hydrodynamic analysis, with the same setup, the new power needed to navigate at 6-knot is 524,3 W as shown in figure 18, a 6.1% less energy, which implicates the same amount of less carbon dioxide emissions on the atmosphere.

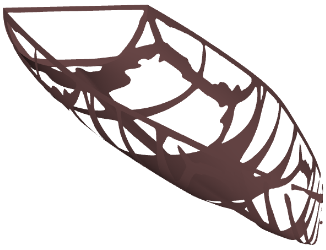


Figure 11. Topology optimization solution obtained via Altair Inspire - Isometric View

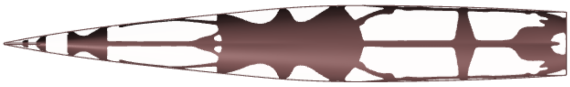


Figure 12. Topology optimization solution obtained via Altair Inspire - Plan View

Figure 13. Topology optimization solution obtained via Altair Inspire - Profile View

Figure 14. Topology optimization solution obtained via Altair Inspire - Body Plan View

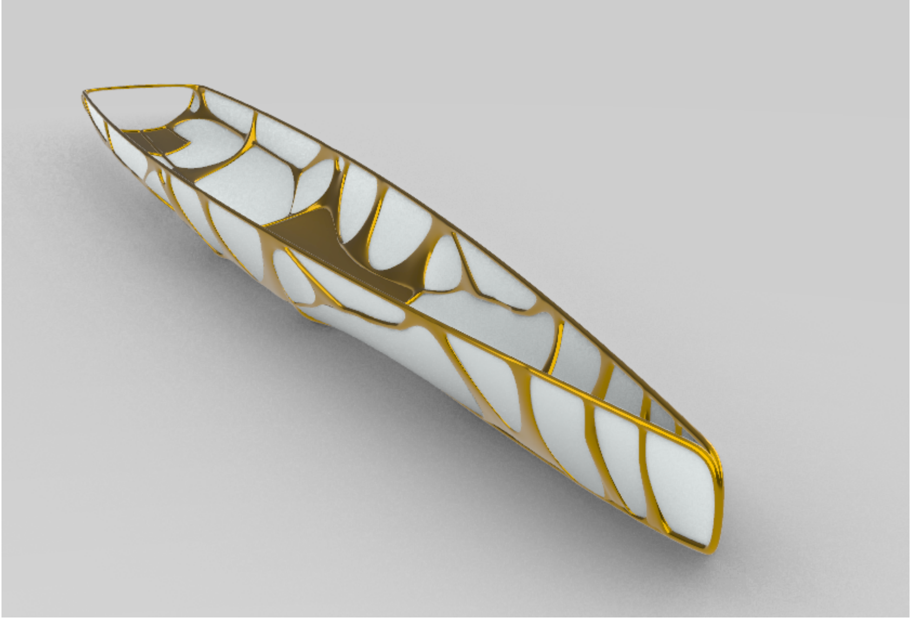
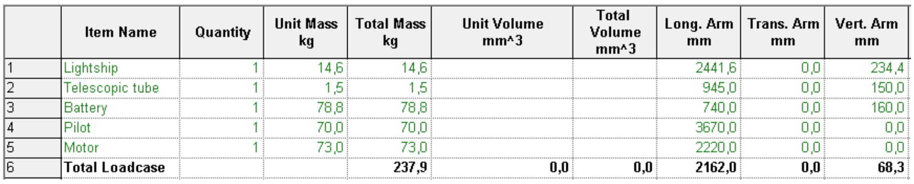
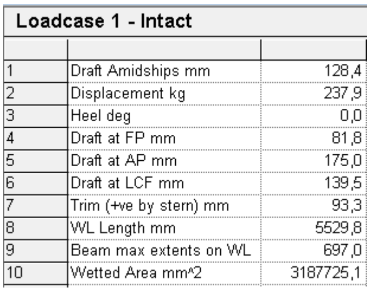


Figure 15. Interpretation of the topology optimization solution



	Item Name	Quantity	Unit Mass kg	Total Mass kg	Unit Volume mm^3	Total Volume mm^3	Long. Arm mm	Trans. Arm mm	Vert. Arm mm
1	Lightship	1	14,6	14,6			2441,6	0,0	234,4
2	Telescopic tube	1	1,5	1,5			945,0	0,0	150,0
3	Battery	1	78,8	78,8			740,0	0,0	160,0
4	Pilot	1	70,0	70,0			3670,0	0,0	0,0
5	Motor	1	73,0	73,0			2220,0	0,0	0,0
6	**Total Loadcase**			**237,9**	**0,0**	**0,0**	**2162,0**	**0,0**	**68,3**

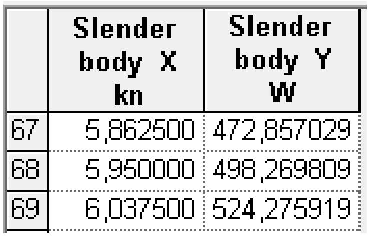
Figure 16. New weight table



Loadcase 1 - Intact

1	Draft Amidships mm	128,4
2	Displacement kg	237,9
3	Heel deg	0,0
4	Draft at FP mm	81,8
5	Draft at AP mm	175,0
6	Draft at LCF mm	139,5
7	Trim (+ve by stern) mm	93,3
8	WL Length mm	5529,8
9	Beam max extents on WL	697,0
10	Wetted Area mm^2	3187725,1

Figure 17. Hydrostatics of the optimized design



	Slender body X kn	Slender body Y W
67	5,862500	472,857029
68	5,950000	498,269809
69	6,037500	524,275919

Figure 18. Hydrodynamic of the optimized design

4 Conclusions

A COG constraint is necessary to maintain the balance of the optimized boat. Furthermore, a global COG constraint would be more accurate to maintain the original design equilibrium. It is possible to conclude that topology optimization can lead to lighter and less fuel consumption boats. The result of this work is just a small part of the whole potential of the technique. The possibility to optimize other structural parts and the capability to produce stiff structures that lead to bigger boats are other examples of how this technique could be applied to reduce the total amount of CO_2 anthropogenic emissions.

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