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Design optimization of small fishing vessel structures: A case study

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Design optimization of small fishing vessel structures: A case study

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Abstract. The cost of vessel operations poses a significant challenge for fishermen in Indonesia, with 60% - 70% of their operational expenses being allocated to fuel. To address this issue and decrease fuel consumption in fishing vessels, one possible solution is to construct lighter boat designs. Through careful optimization of the construction process and the selection of suitable materials, it becomes feasible to achieve such a lighter design, leading to reduced operational and construction costs. The optimization process involves considering various frame spacing variations, like 400 mm, 500 mm, and 600 mm, and utilizing materials such as mild steel and AH32. Additionally, optimizing the plate thickness ensures that the vessel's stress and deformation remain within the limits set by the rules. As a result of this optimization, a weight reduction of up to 20% is observed.

1. Introduction

One of the primary concerns, particularly for fishermen in Indonesia, revolves around the expenses associated with operating their boats. The reason for this financial burden is that a significant portion, around 60% - 70%, of their operational costs, is allocated to fuel [1]. The situation becomes even more challenging due to the consistent increase in fuel prices in Indonesia, which further escalates the operating expenses for fishermen [2]. To mitigate the impact of rising fuel costs, one practical approach is to design boats with lower resistance, thereby reducing the power required for operation. Achieving this goal entails constructing lighter fishing boats through meticulous optimization of boat construction and the careful selection of appropriate materials. By employing these optimization techniques and choosing suitable materials, it becomes entirely feasible to develop a fishing boat design that is significantly lighter and more fuel-efficient.

Presently, the construction of fishing boats in Indonesia heavily relies on wooden materials. Nevertheless, the accessibility of wood for boat building is progressively dwindling, and not all wood varieties can serve as viable raw materials in traditional boat construction [3]. Consequently, numerous wooden boats are witnessing a decline in their overall quality because of the scarcity of suitable wood types, both in terms of species and size adequacy [4].

In order to achieve the most efficient and effective boat construction in terms of strength and weight, there is a need for research focused on optimization methods and a comparative analysis of different materials used in the process. Several studies have been conducted in this area, exploring various aspects of structural optimization and material selection. For instance, one study delves into the use of genetic algorithms for structural optimization in the engine room [5]. Another research project investigates stiffener optimization in plates utilizing Finite Element Analysis (FEA) with Ansys [6]. Moreover, there are studies that explore structural optimization using evolutionary algorithms, considering multiple variables such as plate thickness, longitudinal & transverse member scantlings, and spacing between members [7].

Furthermore, research has been conducted on material selection with a focus on achieving lightweight designs while considering environmental life cycle assessment [8]. Additionally, there are studies employing genetic algorithms to optimize structural elements such as plate thickness, plate layout, stiffener type, and material selection, all aimed at achieving cost-effectiveness [9]. Lastly, one study is dedicated to the optimization of plate thickness in the hull construction of small fishing vessels previous research [10] solely concentrated on optimizing plate thickness, considering the material's yield strength as the optimization constraint. Unfortunately, the outcomes of that optimization fell short of meeting the deformation limit constraints [11]. To address this issue, the present research seeks to enhance boat construction optimization by incorporating various frame spacing variations and employing two types of steel materials: mild steel and AH32. Moreover, the optimization of plate thickness will now consider deformation limits to ensure compliance with existing rules and regulations. The ultimate objective is to discover an optimal construction that is both lightweight and in full adherence to the required rules and regulations. The novelty of this research lies in its comprehensive approach, considering multiple variables including frame spacing, material types, and deformation limits, with the aim of achieving a lightweight yet fully compliant construction.

2. Method

The optimization method consists of three essential processes. First, the determination of the type of material to be used in the construction. Second, the determination of various frame spacing variations to be applied to the ship's structure. And third, the optimization of plate thickness to achieve the most optimal design. The combination of these three processes is expected to result in a lighter ship construction while still complying with applicable rules and regulations.

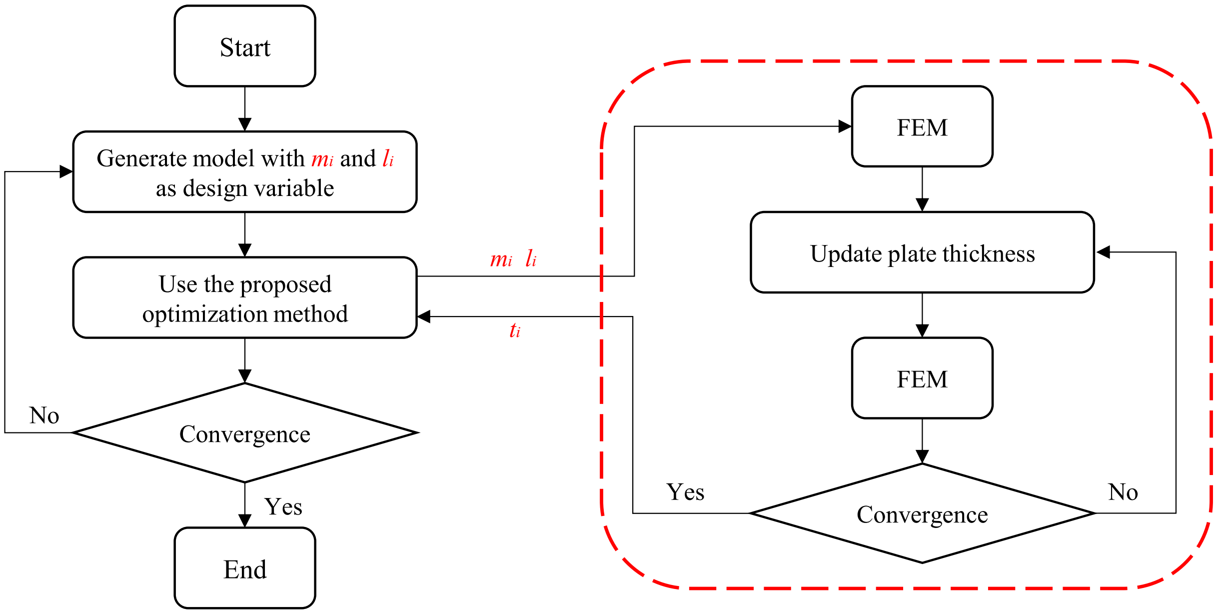


Figure 1. Workflow of optimization process

As depicted in Figure 1, the approach involves a step-by-step application of various types of materials, along with different frame spacing combinations. Subsequently, the focus shifts to optimizing the plate thickness while adhering to predefined constraints. This optimization process is performed iteratively, repeating the defined constraints until the desired state of convergence is attained. By following this systematic method, the research aims to achieve an optimal design for the small fishing vessel, considering both the materials used and the frame spacing variations, ultimately leading to a well-optimized and efficient construction.

2.1. Update of plate material type

In the context of this study, a meticulous material selection process is applied to determine the most suitable plate material, guided by a specific objective function that prioritizes the minimization of construction weight. The shipbuilding industries are driven by a strong incentive to design lightweight vessels due to the manifold advantages it offers. By opting for lighter materials, manufacturing costs are reduced significantly, resulting in enhanced cost-effectiveness. Additionally, this emphasis on lightweight design aligns with the global commitment to reducing carbon emissions, making it an eco-friendly approach. As a result, the integration of optimized plate materials in ship construction not only benefits the industry financially but also contributes to mitigating the environmental impact by curbing CO_2 emissions.

2.2. Update of frame spacing

The design under consideration is intended for a fishing vessel hull with a 5 gross tonnage, where the distance between the frames is irregular, with a maximum of 1000 mm and a minimum of 500 mm. For the structural analysis, a model is utilized that encompasses the main deck, building upon the groundwork laid by previous research [10]. To tailor this model to the specific requirements of the study, additional modifications are made employing Ansys software. These modifications result in the creation of a construction model with varying configurations of frame spacing. Notably, three configurations are examined, as shown in Figure 2, with frames spaced at intervals of 400mm, 500mm, and 600mm, respectively. These different configurations are crucial to understanding how frame spacing impacts the overall structural performance and optimization goals of the fishing vessel.

Upon completion of the modelling process, three construction models were derived, each featuring distinct frame spacing variations. These models will undergo comprehensive analysis using Ansys Static Structural. The final constructed models are as follows:

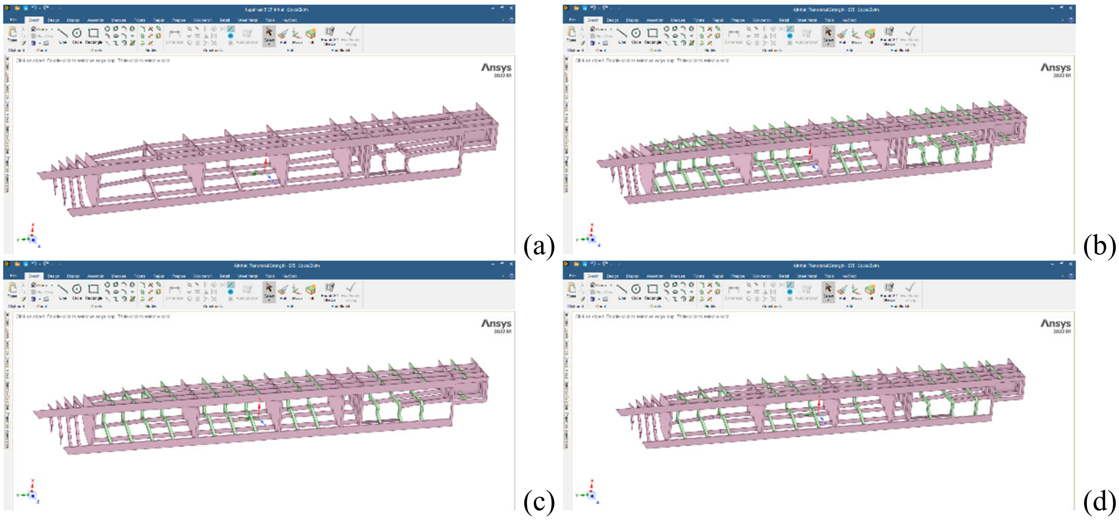


Figure 2. FE models of the fishing vessel (a) Initial, (b) 400 mm, (c) 500 mm, and (d) 600 mm.

2.3. Update of plate thickness

Size optimization is a method employed to enhance the dimensions of an object, aiming for optimal results. In the realm of structural engineering, one application of size optimization pertains to optimizing plate thickness. This process relies on equations that consider the interplay between plate thickness, axial force, bending moment, and stresses [9]. The plate thickness t update process is carried out by using Equations 1 and 2. Equation 1 is derived from the expression of the maximum stress σ^a_{max}, while Equation 2 relates to the maximum deformation w^a_{max}. Following these equations, the recommended optimal plate thickness is determined at step a+1 when the maximum stress reaches the strength limit, σ_{perm}. This iterative process continues until the maximum stress value approaches the strength limit σ_{perm}[12]. Through this iterative approach, the plate thickness is continuously adjusted, ultimately leading to an optimized design where the maximum stress is closely aligned with the strength limit.

$$t^{a+1} = t^a \sqrt{\frac{\sigma^a_{max}}{\sigma_{perm}}} \tag{1}$$

$$t^{a+1} = t^a \sqrt[3]{\frac{w^a_{max}}{w_{perm}}} \tag{2}$$

3. Optimization model

3.1. FEM model

In this analysis, a uniform element size of 22 mm has been employed, resulting in a total of 620,379 elements and producing stress values that tend to converge, as shown in Figure 3. This choice is rooted in several considerations, including the capabilities of the computer, computational time requirements, and the intricate shape of the object under study. Furthermore, the meshing technique adopted is the quadratic tetrahedral mesh. This mesh type is preferred due to its ability to accurately represent and model objects with complex and intricate geometries, ensuring precise and reliable results in the analysis [13].

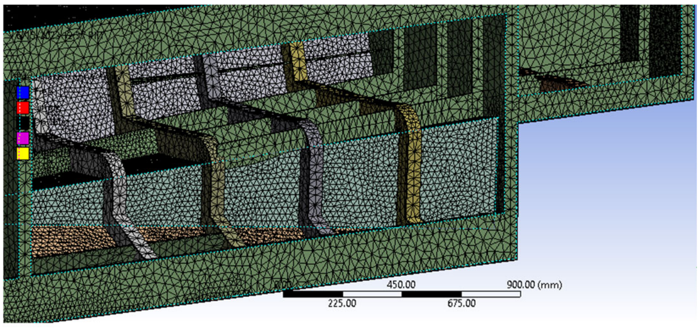


Figure 3. The mesh result for model

3.2. Design variables

This study focuses on three key design variables to optimize the ship's structure: the choice of material, frame spacing, and plate thickness. Specifically, two distinct materials were proposed, MS (Mild Steel) and AH32, with the primary difference lying in their yield strength characteristics as shown in Table 1. Furthermore, frame spacing varies on 400 mm, 500 mm, and 600 mm. Each frame spacing model presents unique structural considerations.

The last variable of interest is plate thickness, a critical factor that significantly influences both the strength and weight of the ship's construction. It's important to note that among these variables, material type and frame spacing are considered discrete variables, while plate thickness is treated as a continuous variable. These design considerations pave the way for a comprehensive optimization process that seeks to strike the right balance between structural integrity, weight efficiency, and performance.

Table 1. Material properties

Material Type	Yield Strength (MPa)	Young's Modulus (MPa)	Density (kg/m^2)	Poisson Ratio
Mild Steel (NS)	235	200,000	7800	0.3
AH32	315	200,000	7800	0.3

3.3. *Design constraints*

To identify the most optimal plate, several constraints must be satisfied initially. The primary constraint is related to the material's strength limit. According to IACS rules, the maximum allowable stress limit is determined by the material's yield strength (R_{eH}), as expressed in Equation 3. This analysis involves the use of a total of 15 plates, as seen in Figure 4. Furthermore, in accordance with the rules outlined by [14], there are constraints governing the deformation limits of a plate. The allowable deformation limits for a plate, whether using steel or aluminum materials, as indicated in Equation 4, are determined by the span or distance between frames (ι) and values provided in Table 2.

$$\sigma_{perm} = 0.8 R_{eH} \tag{3}$$

$$f = \frac{l}{value} \tag{4}$$

Table 2. Values for determination of permissible deflection.

Structural element	Value	
	Steel	Alu
Slamming (shell)	500	700
Shell, Bhd, tank	400	560
Stringer, decks, ramps	200	280

Additionally, the optimization is bounded by practical considerations to facilitate material sourcing and to prevent the plate from becoming excessively thin. Consequently, constraints on the minimum plate thickness and the permissible number of thickness variations are imposed, as described in Equations (5) and (6).

$$t_{min} = 2\,mm \tag{5}$$

$$\text{Number of thickness variations} = 3 \tag{6}$$

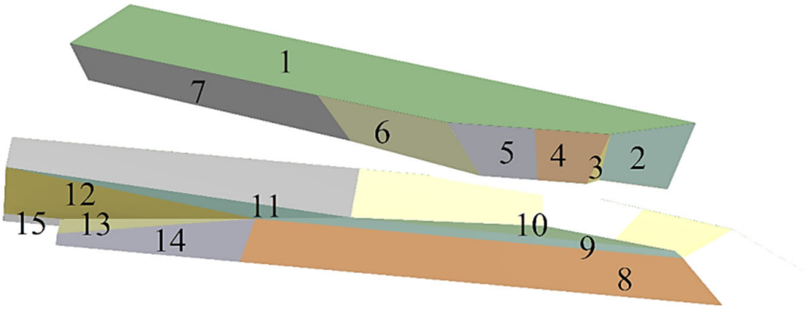


Figure 4. Plate number

4. Results and discussion

In fishing vessels, transverse strength takes precedence over longitudinal strength due to the vessel's relatively short length, which necessitates the use of transverse construction. Consequently, the primary emphasis is placed on ensuring robust transverse strength. Therefore, the results presented below are directly related to the transverse forces acting on the vessel.

When a vessel carries a given load, it experiences tension in response to external forces, including the cargo load and hydrostatic pressure. In the design of ship construction, it is crucial to ensure that the stress occurring in the ship's plates remains below the limit of the ship's material capabilities, particularly its yield strength, as explained previously. Therefore, the constraints associated with structural optimization are closely tied to the properties of the materials utilized in construction.

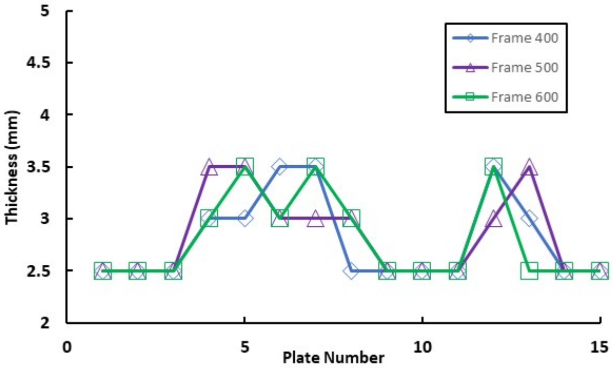


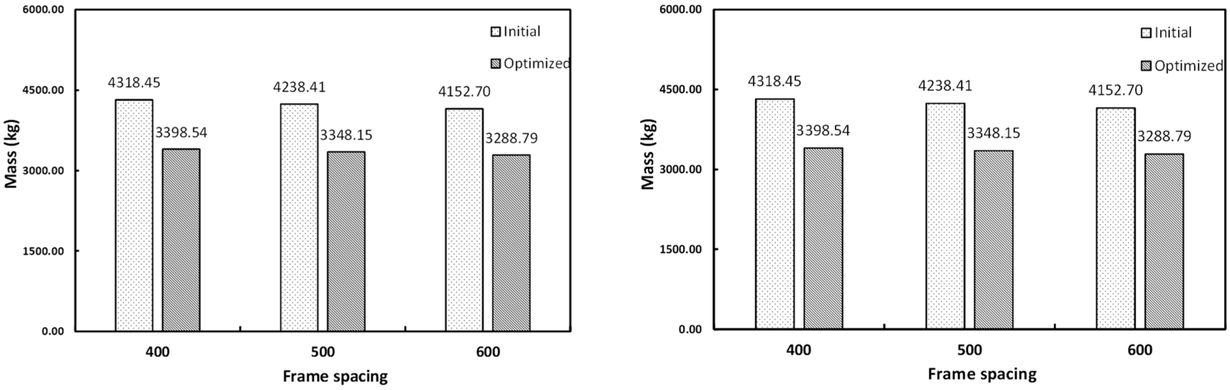
Figure 5. The optimal plate thickness of mild steel & AH32

Figure 5 depicts the results of the optimization process. Post-optimization, the plate thickness does not quite reach the minimum required thickness, despite the von-mises stress levels remaining well below the material's yield strength as shown in Table 3. This phenomenon can be attributed to the presence of deformation limits affecting steel materials with variable frame distances. Interestingly, both AH32 and mild steel materials converge to the same thickness following optimization. From these results, both MS and AH32 show similar outcomes, so there is no significant difference when using either of these materials. This similarity is due to the resulting thickness values being the same. AH32 would have a different impact compared to MS when its stress-bearing capacity is thinner than MS.

Table 3. Max stress & deformation.

Material	Frame spacing (mm)	Initial		Optimum	
		Max stress (MPa)	Max deformation (mm)	Max stress (MPa)	Max deformation (mm)
MS	400	61.86	0.65	93.34	0.99
	500	61.92	0.59	100.60	1.21
	600	62.14	0.66	106.39	1.43
AH32	400	61.86	0.65	93.34	0.99
	500	61.92	0.59	100.60	1.21
	600	62.14	0.66	106.39	1.43

As shown in Figure 6, the optimization results for both mild steel and AH32 materials demonstrate a weight reduction of 21.3% for the 400 mm frame, 21% for the 500 mm frame, and 20.8% for the 600 mm frame. Meanwhile, it's worth noting that an increase in construction mass can provide additional strength [15]. Consequently, When the deformation-to-weight ratio value is smaller, and this value is obtained from the maximum deformation and the total weight produced in various frame spacing variations, it signifies that a relatively minor increase in weight can significantly enhance the structure's strength, resulting in improved overall performance and safety.



(a) (b)

Figure 6. The Hull structure's weight (a) Mild steel and (b) AH32.

Analyzing the deformation-to-weight ratio in Table 4, it becomes apparent that the optimal choice is the 400 mm frame, as indicated by the yellow colour. However, if the aim is to achieve the lightest construction possible, then the 600 mm configuration is the preferred choice. Furthermore, in this construction, the difference between using mild steel and AH32 does not yield a significant impact. This is because the maximum stress that occurs in most frame configurations remains below the yield strength of both materials. Additionally, given that both materials have the same density, the resulting weight remains consistent for the same thickness. Therefore, when considering the cost of material procurement, it is recommended to opt for mild steel, which tends to be more cost-effective than AH32.

Table 4. Strength to weight ratio

Material type	Frame spacing (mm)	Deformation to weight ratio (mm/kg)	
		Initial	Optimum
MS	400	0.00015	0.00029
	500	0.00014	0.00036
	600	0.00016	0.00043
AH32	400	0.00015	0.00029
	500	0.00014	0.00036
	600	0.00016	0.00043

5. Conclusions

Based on the research results of the structural optimization, which considered frame spacing and plate thickness while taking into account yield strength and deformation constraints outlined in the rules, the following conclusions can be drawn to address the research objectives:

1. The optimization results in a weight reduction of 21.3% for the 400 mm frame, 21% for the 500 mm frame, and 20.8% for the 600 mm frame for both mild steel and AH32 materials.
2. Frame spacing exerts an impact on the weight of the construction, resulting in a difference of 80 to 90 kg. In the initial condition, the weight of the construction is 4318 kg for the 400 mm frame, 4238 kg for the 500 mm frame, and 4152 kg for the 600 mm frame.
3. When evaluating the deformation-to-weight ratio, the most favourable combination is the 400 mm frame. However, if the goal is to achieve the lightest possible construction, the 600 mm configuration is a viable choice.

In the future, optimization of frame and stiffener sizes will be needed to achieve a more optimal design. This optimization process involves carefully adjusting the dimensions of the frames and the types and placements of stiffeners within the ship's hull.

Acknowledgements
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