

Study on optimal design of hatch cover via a three-stage optimization method involving material selection, size, and plate layout arrangement

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The rising prices of materials for ship construction is one of the primary problems faced by global shipbuilding industries. A potential solution is to reduce the material cost through a structure optimization technique. In this study, the plate material and stiffener types, plate thickness, and plate layout are optimized in order to minimize the cost of materials. The genetic algorithm (GA) is a popular optimization technique for determining design variables. However, the GA is not suitable for dealing with continuously changing design variables, such as plate thickness. Hence, this study proposes a three-stage optimization method that consists of the optimization of plate material and stiffener types, plate thickness, and plate layout. The first and second stages are part of an integrated process called the hybrid GA, which starts with the plate material and stiffener-type selections, and then performs plate thickness optimization. The hybrid GA is effective in simultaneously determining design variables with different characteristics, such as the first - and second-stage problems. The last stage is layout optimization in which the plate material and stiffener types handled in the previous stage are considered to have been decided, thereby resulting in minimal effort during this stage.

Keywords: Three-stage optimization, Material selection, Plate layout, Optimal design

1. Introduction

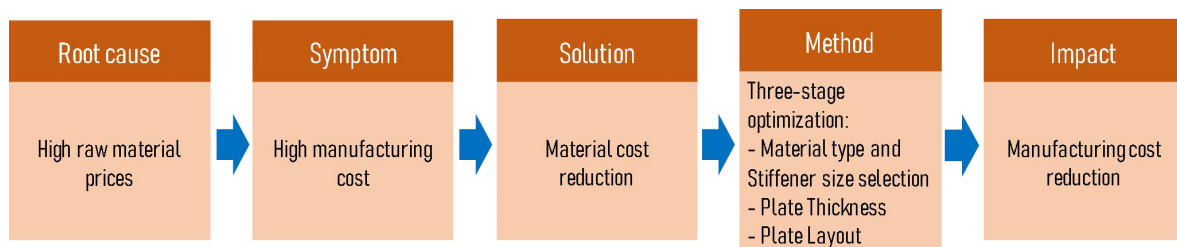
High manufacturing costs due to rising raw material prices are one of the major challenges facing the shipbuilding industry (Putra et al. 2019). Comprehensive research on structural optimization that reduces material costs is required to solve this problem. In order to develop novel solutions to this problem, a literature survey related to hull structure optimization is performed. Over the last 20 years, ship structural optimization has focused on handling stiffener size, plate thickness, and frame spacing, as listed in Table 1. Heretofore, no comprehensive ship structure optimization study has been found that combines material selection and plate layout placement. Therefore, this study treats plate material type and plate layout placement as design variables and aims to create a more optimal design.

Automotive and aircraft industries use material selection as one of optimization processes. (Poulikidou et al. 2015) conducted research on material selection by applying a material selection process to reduce the weight of materials and considered the environmental life cycle in the design of automobile parts. Kaspar et al. (2016) reviewed product, manufacturing process, and material information, and applied it in an integrated manner to the material selection process. Tawfik et al. (2016) reduced the weight of the hatch cover by changing the material from steel to composite without using optimization methods. (Yang et al. 2017) succeeded in creating automotive parts that are more prone to remanufacturing by improving the material selection process in the early stages of fuzzy design. In addition, Mehmood et al. (2018) presented a comprehensive review and critical analysis of Ashby's approach to MEMS material selection studies. The shipbuilding industry does not currently apply the material selection process to the hull structure. Therefore, this is an opportunity for a deeper study of optimization techniques in the shipbuilding industry. Since the plate layout has not been studied so far, this study is the first to examine the structural optimization in the shipbuilding industry by selecting the material type and combining the plate layout.

Table 1. Previous studies

Authors, Year	Method	Objective
Kitamura et al., 2000	Genetic Algorithm	Optimize the plate thickness, stiffener type, and frame spacing of a ship's engine room
Rigo, 2001 and Caprace et al., 2010	Module Oriented Approach (LBR-5)	Optimize the dimensions of longitudinal and transversal members, plate thickness, and spacing between members
Shin et al., 2006	Multi-objective Genetic Algorithm	Optimize longitudinal and transversal members of tankers
Kong et al., 2006	OPTSHIP (Optimization framework)	Reduce vibration with change in the plate thickness and stiffener size
Kong et al., 2008	Genetic Algorithm	Optimize plate thickness and stiffener size of ship structures
Papanikolaou et al., 2010	Parametric optimization through NAPA and POSEIDON software	Decrease oil-outflow probability and increase cargo carrying capacity
Ringsberg et al., 2012	Parametric optimization	Optimize the waveform dimension of the corrugated shell plating
Pajunen and Heinonen, 2014	Linear response surface	Minimize the weight of a stiffened plate via optimized plate thickness
Sekulski, 2014	Genetic Algorithm	Optimize plate thickness, stiffener size, stiffener number, and frame spacing of hull structures
Um and Roh, 2015	Sequential quadratic programming	Optimize the stiffener size and plate thickness of the hatch cover for minimizing weight
Shin and Ko, 2017	Evolution Strategy	Optimize waveform dimension to minimize minimized the weight of corrugated bulkheads for chemical tankers
Liu et al., 2019	Two-stage optimization	Optimize a ship's prow via topology and size optimization
Putra et al. 2019	Hybrid Genetic Algorithm	Optimize plate thickness, stiffener number, stiffener size, and stiffener spacing of stiffened plate

The target structure in this study is a part of a ship and is called a hatch cover because of the simplicity of its modeling and the weak constraint conditions in classification rules. This is also partly because it is composed of plates and stiffeners with suitable areas, which will be optimized by adhering to the restrictions specified by the class regulations. In addition, the requisite function of the hatch cover is to prevent water from entering the hold. Thus, reinforcement of hull strength is not required. The hatch cover is placed on the hatch coaming via rubber so that the longitudinal bending deformation and torsional deformation of the hull are not transmitted to the hatch cover. Therefore, the optimization process will not affect the safety and strength of the ship. Furthermore, the fabrication cost of the hatch cover is 5–8% of the total shipbuilding cost (Ha 2011). Hence, the proposed optimization can reduce the manufacturing cost of a ship by reducing the material cost of a hatch cover.

**Figure 1.** Hierarchy of study

In summary, the objective of this study is material cost reduction in order to combat high manufacturing costs. It proposes an optimization method by selecting plate material types, stiffener types, plate thickness, and plate layout, as depicted in Figure 1. The optimization method used in this study is called three-stage optimization. It involves selection of the plate material and stiffener-type via a genetic algorithm in the first stage, size optimization in the second stage, and layout optimization in the third stage. The plate material type selected in the optimization process is the most economical, but is in alignment with the applicable rules. Furthermore, reduction of the mass of the material is achieved by selecting the stiffener type, determining the plate thickness, and attaining an optimal plate layout arrangement. The selection of the stiffener type and determination of the plate thickness aim to reduce the weight of the structure while conforming to the applicable rules. In addition, the determination of the plate layout arrangement aims to optimize the welding positions in accordance with the optimal plate thickness.

2. Optimization method

Typical goals for design optimization include maximizing the efficiency of the object or minimizing the production cost of the object. An optimization algorithm is an iterative procedure that updates the design variables and compares several solutions until it arrives at an optimal solution. Advances in computer development have enabled optimizations as part of computer-aided design activities.

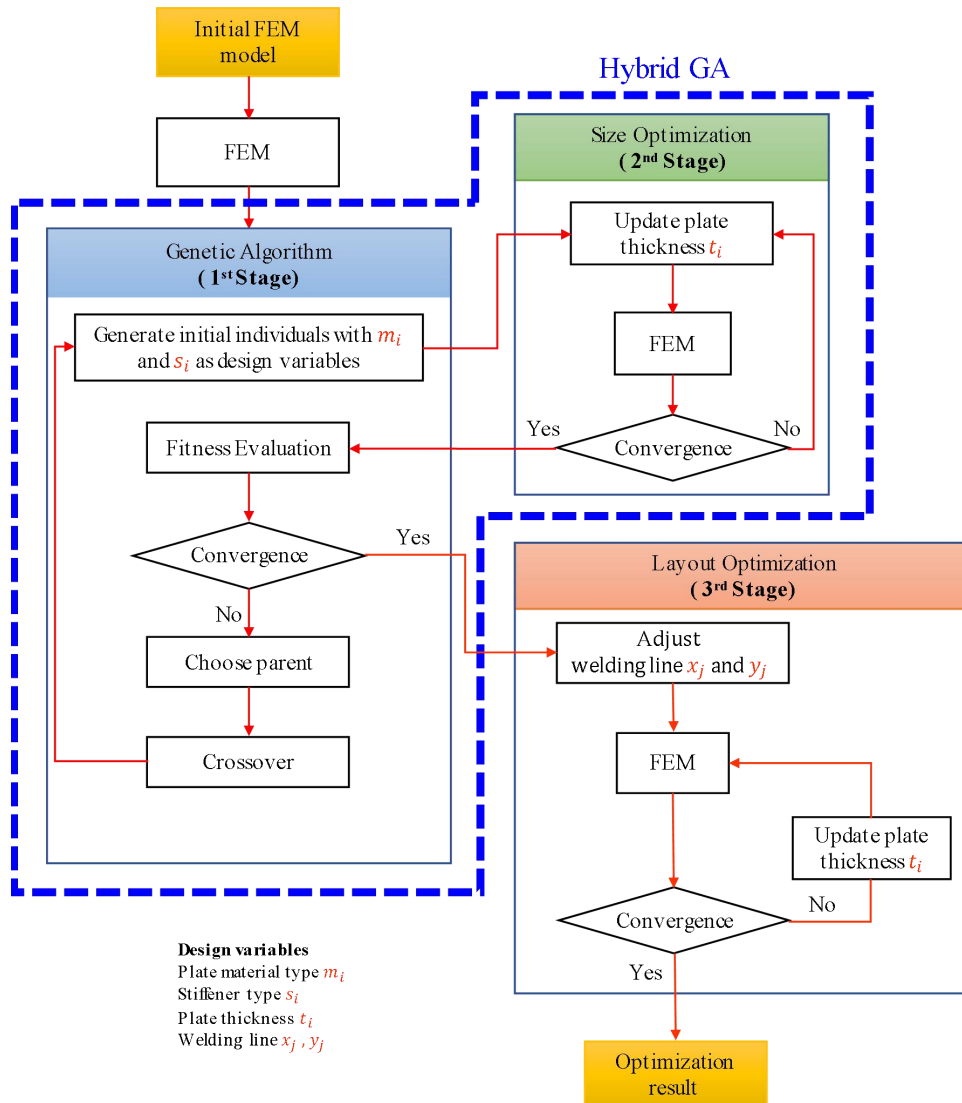


Figure 2. Three-stage optimization

The two distinct types of optimization algorithms that are extensively used today are deterministic and stochastic algorithms (Francisco et al. 2005). Deterministic optimization methods, including sequential quadratic programming (SQP), have been widely applied for constrained optimization to obtain optimal solutions within a reasonable amount of computational time (Edgar et al. 2001). Alternatively, stochastic optimization methods, including genetic algorithms and simulated annealing (Edgar et al. 2001; Welsh 2007) are suitable for complex nonlinear and discontinuous problems, where the deterministic optimization might fail to produce an optimal solution.

The GA is considered a good optimization method because it can determine all design variables with reasonable accuracy and stability. However, it has a long computational time. Therefore, this study proposes a three-stage optimization method to remedy the weakness of the GA. The proposed method combines material selection, size optimization, and layout optimization. The first stage begins with material selection that includes the choices of the plate material and stiffener types using the GA. Once the candidates for plate material and stiffener types are selected, size optimization suitable for them is performed in the second stage. In the first and second stages because there is a combination of different optimization methods, namely the GA and size optimization, this optimization process is called the hybrid GA. The processes of the first and second stages are repeated until the minimum fitness value is reached. The output of the hybrid GA in the first and second stages is sent to the third stage, namely, the layout optimization. Layout optimization works by adjusting the welding line arrangement that aims to minimize the material cost by decreasing the thicker plate area and increasing the thinner plate area with the material types determined in the previous stage. The three-stage optimization process is depicted in Figure 2.

The GA can consider the first, second, and third stages jointly as a one-stage optimization. However, it is not recommended to include the plate thickness and the positions of the welding lines in the design variables of the GA because handling the continuous design variables is not a strength of the GA. In order to eliminate this drawback, the second and third stages are introduced.

2.1 Genetic Algorithm and Material Selection

The natural selection principles of biological organisms are incorporated into the GA to determine the optimal solution naturally. This means that the GA collects the population of solutions and applies selections, reproduction, and mutation strategies. Randomness is an important aspect of the GA, and thus the results are different even if the algorithm is rerun with the same process. This is why the GA is referred to as a non-deterministic algorithm.

In general, the GA process consists of an important step including population, selection, crossover, and mutation. The process does not yield an optimal solution but a set of solutions or individuals called the population. In the selection process, stronger individuals in the current generation are picked up and become parents. They play important roles in creating the next generation. Several advantages of each parent are combined to produce new offspring, and this step is termed as crossover. The mutation process randomly changes chromosomes to create new solutions that do not exist. Subsequently, the GA combines individuals from the current generation to produce new individuals or solutions, and this step is the key to the evolution process in reproduction. The concept of selection is inspired by the principle of natural selection wherein the strongest individuals survive and weaker individuals terminate, which is also known as survival of the fittest (Futuyma 2014).

The GA was selected as the most suitable optimization method to solve the material selection problem in a previous study (Sen and Yang 2011). It developed a solution based on an objective function, including minimizing mass and material cost, and was also adaptable to multi-objective problems, including the determination of Pareto frontiers (Papanikolaou et al. 2010b). The material selection process determines the best option between the material properties and the constraint of the design requirements. Figure 3 illustrates the strategy used in the material selection process for a hatch cover using the GA optimization method. In the design requirement part, it is necessary for the material to satisfy the constraint and objective function, which is defined in the following section. Furthermore, the mechanical and physical properties of the material are obtained from

supplier data sheets or manual search. Integration of the material data and the design requirements creates rank, which is used to determine the most suitable material.

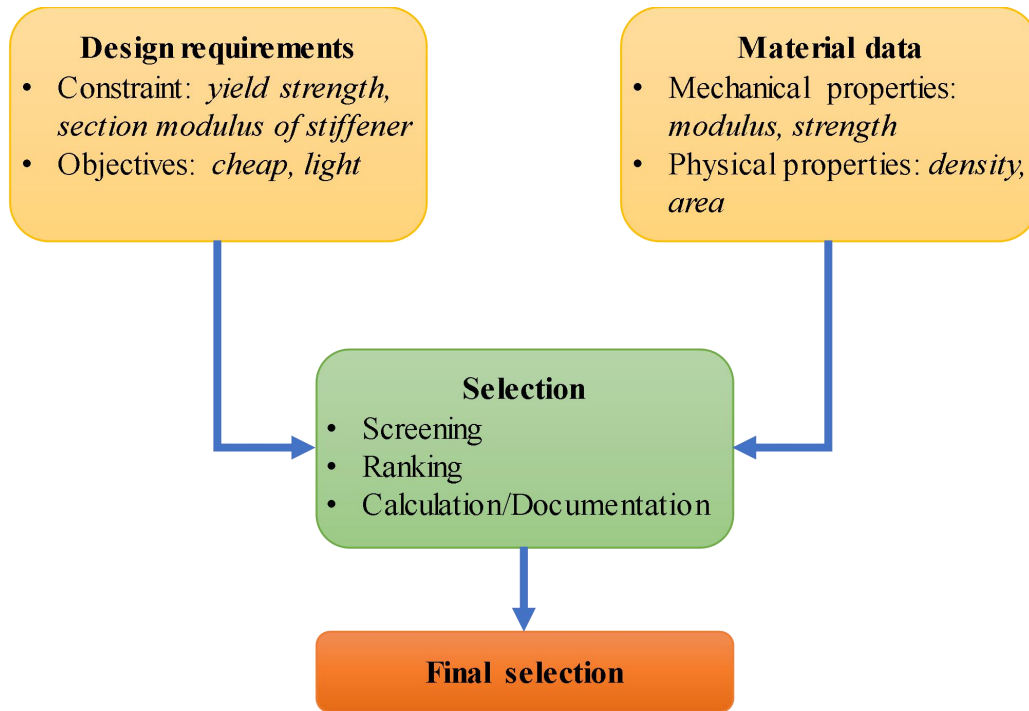


Figure 3. Material selection process

The material selection process is applied in this study to select the plate material and stiffener types based on the desired objective function, which minimizes the cost of the materials. Shipbuilding industries are encouraged to design lightweight ships to reduce manufacturing costs and CO₂ emissions. The material candidate corresponds to a rank and screening based on predetermined criteria. The rank process is performed using the following equations (Ashby 2012):

$$\frac{Mass_1}{Mass_0} = \frac{\rho_1}{\rho_0} \cdot \left(\frac{\sigma_{y,0}}{\sigma_{y,1}} \right)^{1/2} \quad (1)$$

$$\frac{Cost_1}{Cost_0} = \frac{C_1 \rho_1}{C_0 \rho_0} \cdot \left(\frac{\sigma_{y,0}}{\sigma_{y,1}} \right)^{1/2} \quad (2)$$

Here

- σ_y : Yield strength (N/mm²)
- ρ : Mass density (kg/m³)
- $Mass$: Mass (kg)
- C : Material unit price (¥/kg)
- $Cost$: Material cost (¥)
- $*_0$: for Original material
- $*_1$: for Substitute material

Equations (1) and (2) represent the mass and material cost saving ratios derived from material substitutions based on a scaling law by the strength limit designed for plates. Calculation is performed based on the material

ranking before arriving at the final choice. The sample problem to obtain the rank of material by material substitution for weight saving is provided in Table 2 and Equations (3) and (4). A steel panel under bending loading is replaced by aluminum to save weight or cost. The panel strength must remain unchanged. The maximum potential weight and cost savings can be calculated as follows:

Table 2. Material properties

Material	Material unit price (¥/kg)	Mass density ρ (kg/m ³)	Yield stress σ (MPa)
Steel	3,700	7,860	320
Aluminum	25,000	2,710	248

$$\frac{Mass_1}{Mass_0} = \frac{\rho_1}{\rho_0} \cdot \left(\frac{\sigma_{y,0}}{\sigma_{y,1}} \right)^{\frac{1}{2}} = \frac{2710}{7860} \cdot \left(\frac{320}{248} \right)^{\frac{1}{2}} = 0.39 \quad (3)$$

$$\frac{Cost_1}{Cost_0} = \frac{C_1 \rho_1}{C_0 \rho_0} \cdot \left(\frac{\sigma_{y,0}}{\sigma_{y,1}} \right)^{\frac{1}{2}} = \frac{25000 \cdot 2710}{3700 \cdot 7860} \cdot \left(\frac{320}{248} \right)^{\frac{1}{2}} = 2.65 \quad (4)$$

Here, the subscripts “0” and “1” refer to steel and aluminum, respectively. A ratio of 0.39 is obtained on the basis of Equation (3) to determine the rank of material for weight saving. Therefore, the possible weight saving is 61% by substitution steel by aluminum. On the other hand, Equation (4) illustrates that the material cost becomes 2.65 times larger when aluminum is selected instead of steel.

2.2 Size optimization method

The plate thickness was optimized after the plate material and stiffener type were selected in the first stage. The output from the previous stage does not have to be reconsidered (Kitamura et al. 2011). In other words, in the second stage, size optimization will be processed in cooperation with design variables determined at the first stage. The plate thickness is updated based on the equations expressing the relationships between bending moment, axial force, plate thickness, and stresses. Equations (5), (6), and (7) recommend the plate thickness at step $a+1$, in which the maximum stress σ_{max}^{a+1} , buckling stress σ_{bc}^{a+1} , and shear stress σ_{sh}^{a+1} reach the constraint stress values σ_c under the assumption of unchanging moment and axial force.

$$t_{\sigma_{max}}^{a+1} = t^a \sqrt{\frac{\sigma_{max}^a}{\sigma_c}} \quad (5)$$

$$t_{\sigma_{bc}}^{a+1} = t^a \frac{\sigma_{bc}^a}{\sigma_c} \quad (6)$$

$$t_{\sigma_{sh}}^{a+1} = t^a \frac{\sigma_{sh}^a}{\sigma_c} \quad (7)$$

$$t^{a+1} = \max (t_{\sigma_{max}}^{a+1}, t_{\sigma_{bc}}^{a+1}, t_{\sigma_{sh}}^{a+1}) \quad (8)$$

The maximum thickness among the three candidates is used at step $a+1$, as depicted in Equation (8). There is a discrepancy between the assumed and the FEM stress values in the process, and several iterative calculations are performed until convergence is observed. It is expected that the use of the approximation equations decreases the computation time without recreating the FEM model.

2.3 Layout optimization

The hatch cover is composed of several plates, including the bottom, top, and girder plates. The bottom and top plates are formed by joining multiple plates, as depicted in Figure 4, where the red lines indicate the butt-welding lines. In this study, the top and bottom plates were composed of 4 plates. Moreover, different material types and thicknesses can be selected for the plates. The purpose of this layout optimization is to reduce the cost of the top and bottom plates. By reducing the masses of the plates under the given arrangement, the material costs incurred will be reduced.

The concept of layout optimization involves adjusting the longitudinal and transverse welding lines, in order to minimize the plate volume by reducing the area of the thick plate member so that the area of the thin plate member becomes larger. In order to determine the best welding lines, the minimum thickness necessary to satisfy stress constraints is calculated for each element. As previously explained, the thickness value is determined by the largest value of the approximation equations. The positions of the welding lines x_1 , x_2 , y_1 , and y_2 and the thicknesses of the plates are determined based on the element thicknesses of the plates, such that the total cost is minimum. In this study, the layout of the plates is limited to A-type and B-type, as depicted in Figure 4. In the A-type layout, the welding line exhibits three design variables (i.e., x_1 , y_1 , and y_2), where x_1 and x_2 are identical positions or maintain only a line. In addition, in the B-type layout, the design variables are x_1 , x_2 , and y_1 , where y_1 and y_2 correspond to the same positions or maintain only a line. Finally, the plate thickness is determined based on the element with the largest thickness in a welding line boundary. Further, the total cost is calculated based on the volume produced.

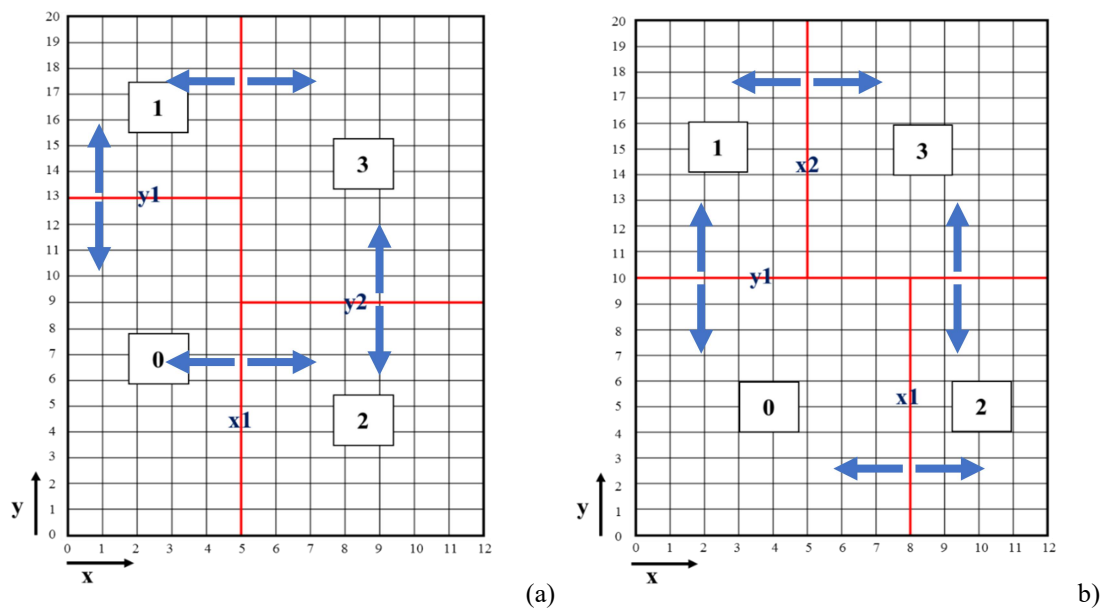
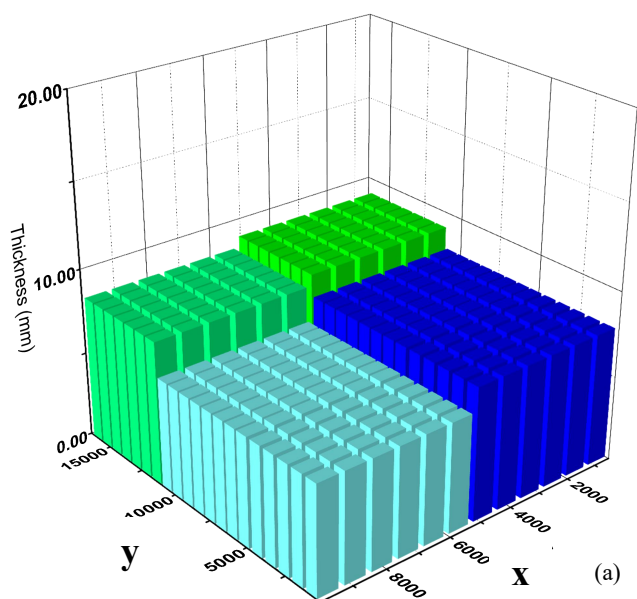
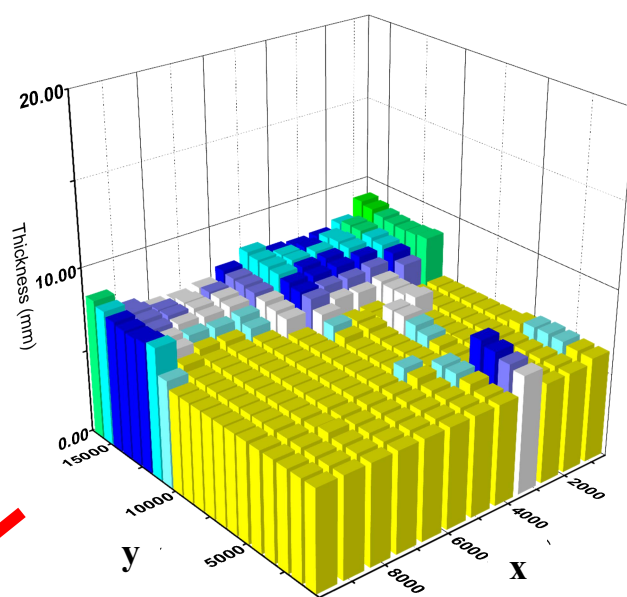
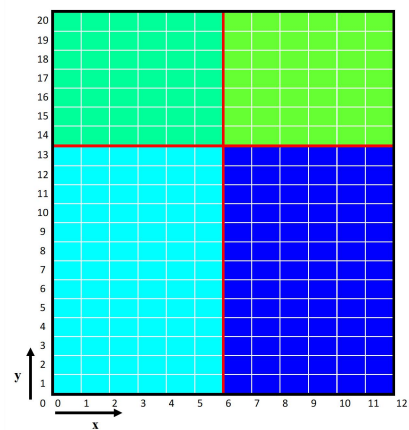


Figure 4. Plate layout configuration (a) A-type layout, (b) B-type layout

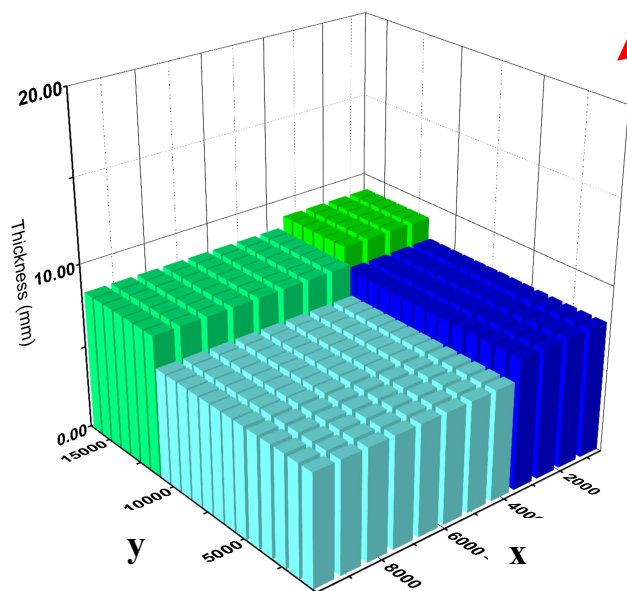
This optimization method needs to be verified to ensure that the process runs well and produces optimal results. Figure 5 presents an example of a plate arrangement composed of 4 plates prior to optimization. The stress is analyzed via finite element analysis with a uniform load on the surface of the plate and clamped condition on all sides. The updated thickness of each element is obtained from the produced stress value so that the welding line can be adjusted to minimize the plate volume by reducing the area of the thick plate in order to increase the area of the thin plate. The result of plate layout optimization exhibits a decrease in plate volume. The minimum cost can be obtained by shifting the objective function from the weight to the cost.



(a) Before layout optimization (Volume: 1.182 E+09 mm³)



(b) Calculation of thickness for each element



(c) After layout optimization (Volume: 1.174 E+09 mm³)

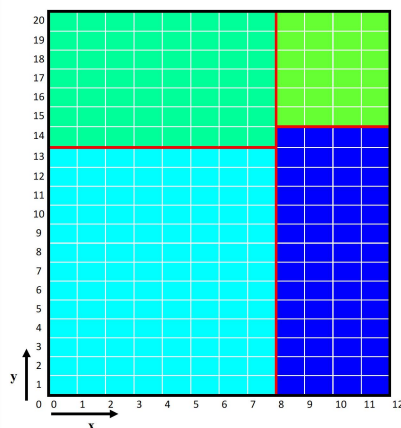


Figure 5. Layout optimization process

3 Case study

3.1 Model

Most commercial ships, including container ships, bulk carriers, and general cargo vessels, use hatch covers to protect their cargo from seawater. There are three basic configurations of hatch covers: folding covers on general cargo ships or bulk carriers, side-rolling covers on bulk carriers, and lift-away covers on container carriers or general cargo ships. Recently, folding covers are being widely used because they do not require a large storage area during the unloading cargo. This type of hatch cover is handled by hydraulics that can reduce loading and unloading time. Folding-type hatch covers comprise a top plate and bottom plate with a stiffener attached inside the plate, as portrayed in Figure 6. The folding-type hatch cover was selected as a testing model for the optimization process to verify the proposed method. The hatch cover is composed of plates and stiffeners and is restricted via class regulation, so it is suitable as an optimization model. In order to decrease the computational burden, hatch cover A is selected for the optimization process. Hatch cover A is composed of the top plate, bottom plate, longitudinal girder plates, transversal girder plates, and stiffeners attached to the top and bottom plates, as depicted in Figure 7. Shell elements are used in the FEM model to expressing the plates and girders, while beam elements are used to express the stiffeners.

The data for the initial design of the hatch cover and material data is provided in Table 3. The load on the hatch cover consists of lateral pressure, as provided by the IACS Common Structural Rules. Figure 6 illustrates the boundary condition of the hatch cover with support points. The symmetric boundary condition is considered as half of the hatch cover is modeled. Moreover, u , v , and w denote the longitudinal, transverse, and vertical displacements, respectively. Furthermore, θ_x , θ_y , and θ_z denote the angular displacements around the x -, y -, and z -axes, respectively. The initial design of the hatch cover is composed of two types of materials, namely MS and HT32.

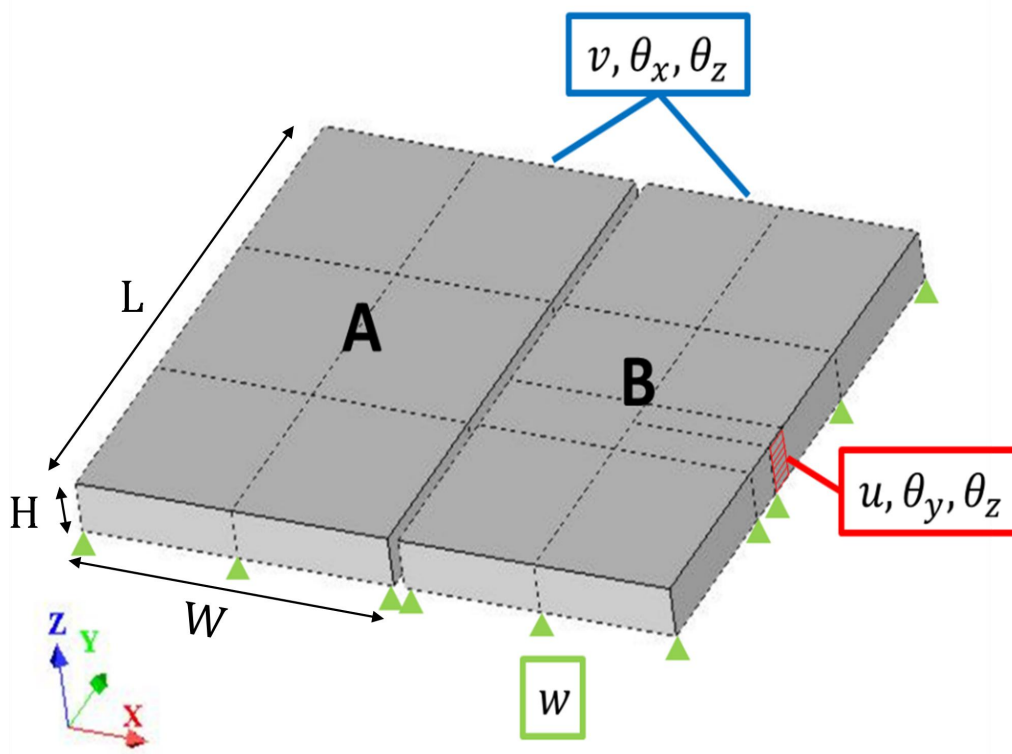


Figure 6. Hatch cover design and boundary conditions

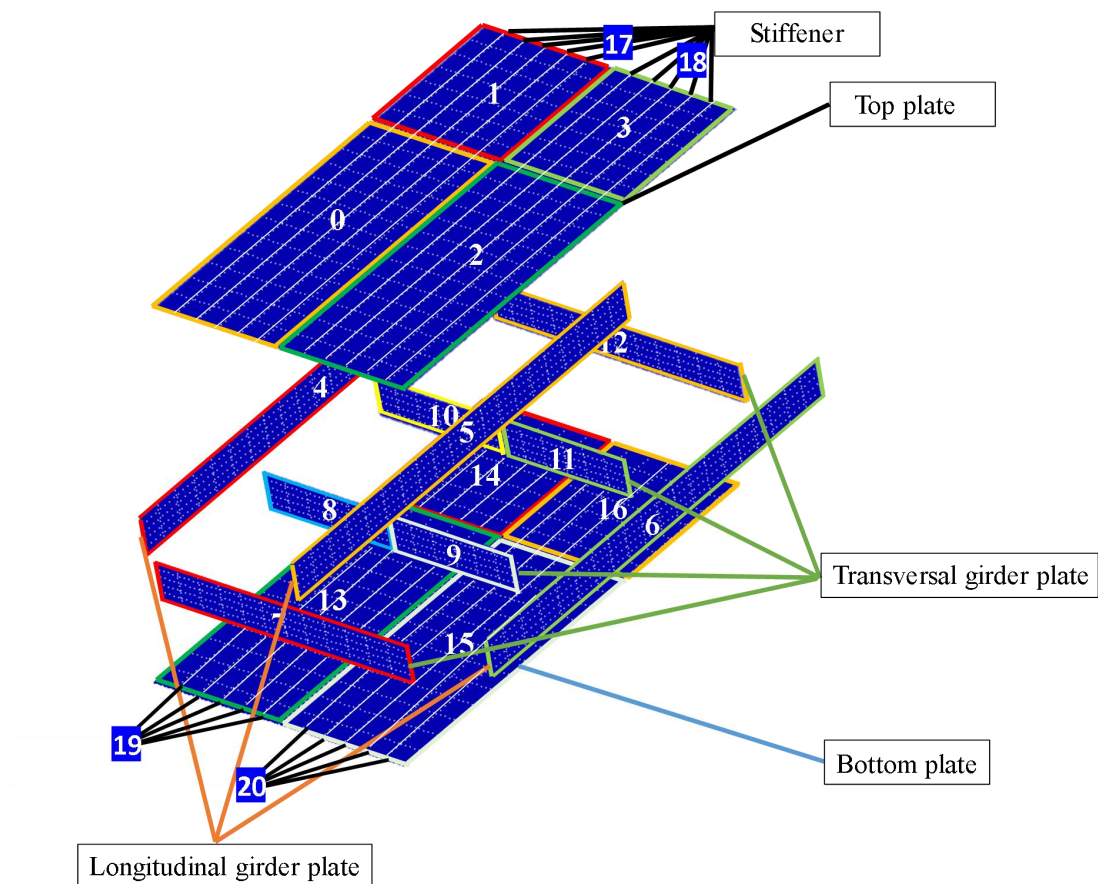


Figure 7. Part of hatch cover A

Table 3. Initial data

Item	Unit	Initial design
L (length)	mm	14137.5
W (width)	mm	12300.6
H (height)	mm	1059.5
Load	N/mm ²	0.0343
Material	-	MS, HT32
Density	kg/m ³	7800
Stiffener (Top plate)	mm ²	1362 (Type 2)
Stiffener (Bottom plate)	mm ²	2736 (Type 6)

3.2 Design variables

The design variables to be determined through 3-stage optimization method are the thickness and material type for Plate 0–Plate 16, stiffener type for Stiffener 17 ~ Stiffener 20, and the positions of the welding lines. One from MS, HT32, and HT36 was selected as the material type for Plate 0–16, and one from type 1–6 is chosen as the stiffener type for Stiffener 17 ~ Stiffener 20. The material properties of the plate and Stiffener-type description are listed in Tables 4 and 5, respectively. The positions of the welding lines are determined by deciding x_1 , y_1 , and y_2 for the A-type layout and x_1 , x_2 , and y_1 for the B-type layout, as illustrated in Figure 4.

The design variables are segregated into discrete and continuous variables. Examples of the discrete variables are standard sizes and materials, such as the plate material and stiffener type in this study. On the other hand, the plate thickness is considered a continuous variable, assuming any value between two specified values. Although the positions of the welding lines are essentially continuous variables, their positions are limited to the edges of the element.

Table 4. Material properties of plate

Material type	Young's Modulus (N/mm ²)	Density (Kg/m ³)	Poisson Ratio	Yield Strength (N/mm ²)	Material Price (¥/kg)	Material cost saving
MS	200,000	7,800	0.3	235	60	1
HT32	200,000	7,800	0.3	315	80	1.15
HT36	200,000	7,800	0.3	355	90	1.22

Table 5. Stiffener type descriptions

Type	Size A × B × T1/T2 (mm)	R1 (mm)	R2 (mm)	Cross Sectional Area (mm ²)	W (Kg/m)	I (cm ⁴)	Z (cm ³)	Yield strength (N/mm ²)
1	100 × 75 × 7	10.0	5.0	1187	9.32	674	72.5	315
2	125 × 75 × 7	10.0	5.0	1362	10.70	1110	97.2	315
3	100 × 75 × 10	10.0	7.0	1650	13.00	860	96.2	315
4	125 × 75 × 10	10.0	7.0	1900	14.90	1420	130.0	315
5	150 × 90 × 9	12.0	6.0	2094	16.40	2490	181.0	315
6	150 × 90 × 12	12.0	8.5	2736	21.50	3060	230.0	315

3.3 Objective function

Based on the shipyard needs, the primary objective is to decrease the material cost of the hatch cover. The material cost can be reduced by selecting the most economical material type and optimizing the plate thickness, as shown in Equation (9).

$$\min f_2(A, t, l, C) = \sum_{i=0}^{n-1} A_i L_y \rho C + \sum_{j=0}^{m-1} t_j l_x L_y \rho C \text{ [¥]}, \quad (9)$$

where,

- n : stiffener number
- m : plate number
- A_i : cross-sectional area of the stiffener (mm²);
- L_x : width or length in x-direction (mm);
- L_y : width or length in y-direction (mm);
- ρ : material density (kg/mm³);
- t_i : plate thickness (mm)
- C : material price (¥/kg)

3.4 Constraint

The constraint conditions follow the recommendation of *IACS Common Structural Rules* for hatch cover design (IMO 2012). Six constraints are applied as follows:

$$\delta \leq 0.0056 \cdot l_{max} \text{ [mm]} \quad (10)$$

In Equation (10), δ denotes the deflection limit and l_{max} denotes the greatest span of the primary supporting members.

$$\sigma_{max} \leq 0.8R_{eH} \text{ [N/mm}^2\text{]} \quad (11)$$

$$\sigma_{sh} \leq 0.46R_{eH} \text{ [N/mm}^2\text{]} \quad (12)$$

In Equation (11), σ_{max} denotes the maximum stress on the structure, and R_{eH} denotes the yield strength of the material, which corresponds to 235 N/mm² for the MS, 315 N/mm² for HT32, and 355 N/mm² for HT36. In addition, in Equation (12), σ_{sh} denotes the shear stress on the structure.

$$\sigma_{bc} \leq 0.8\sigma_{C1,2} \text{ [N/mm}^2\text{]} \quad (13)$$

where,

- σ_{bc} : compressive stress (N/mm²);
- σ_{C1} : critical buckling stress (N/mm²);

$$\sigma_{C1} = \sigma_{E1} \text{ for } \sigma_{E1} \leq \frac{R_{eH}}{2}$$

$$\sigma_{C1} = R_{eH} \left(1 - \frac{R_{eH}}{4\sigma_{E1}}\right) \text{ for } \sigma_{E1} > \frac{R_{eH}}{2}$$

$$\sigma_{E1} = 3.6E \left(\frac{t}{1000s}\right)^2$$

- E : modulus of elasticity (N/mm²);
- t : net thickness (mm),
- s : stiffener spacing (m),
- σ_{C2} : critical buckling stress (N/mm²);

$$\sigma_{C2} = \sigma_{E2} \text{ for } \sigma_{E2} \leq \frac{R_{eH}}{2}$$

$$\sigma_{C2} = R_{eH} \left(1 - \frac{R_{eH}}{4\sigma_{E2}}\right) \text{ for } \sigma_{E2} > \frac{R_{eH}}{2}$$

$$\sigma_{E2} = 0.9mE \left(\frac{t}{1000s_s}\right)^2$$

$$m = c \left[1 + \left(\frac{s_s}{l_s}\right)^2\right]^2 \frac{2.1}{\psi + 1.1}$$

- s_s : length of the shorter side of plate panel (m),
 l_s : length of longer side of plate panel (m),
 ψ : ratio between the lowest and highest compressive stress,
 c : 1.21 when plating is stiffened by the secondary stiffener.

$$t = F_p 15.8s \sqrt{\frac{p}{0.95R_{eH}}} [\text{mm}] \quad (14)$$

$$Z \leq \frac{1000l_s^2 p}{12\sigma_a} [\text{mm}^3] \quad (15)$$

where,

- F_p : factor for combined membrane and bending response (1.50 in general),
 s : stiffener spacing (mm);
 p : pressure (N/mm²);
 l : secondary stiffener span (mm)
 σ_a : allowable stress (0.8 R_{eH}) (N/mm²)

In Equation (14), t denotes the minimum thickness of the plate of the hatch cover, which is not less than 1% of the stiffener spacing or 6 mm, whichever is greater. Furthermore, in Equation (15), Z denotes the required minimum section modulus of the stiffeners.

4 Results and discussion

In order to reduce material costs, this study proposes three-stage optimization starting with running the hybrid GA in the first and second stages, followed by layout optimization in the third stage. The hybrid GA is run by combining the GA optimization method for the material and stiffener-type selections and the size optimization method for plate thickness determination. The GA parameters used in this optimization process are listed in Table 6. The material and stiffener types are selected through a natural selection process with the objective of minimizing material costs.

Table 6. GA parameter

Parameter	
Population number	50
Elite number	10
Selection	Tournament
Mutation	5%

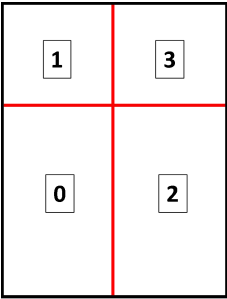
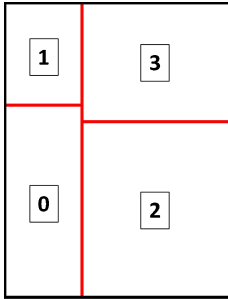
Table 7 presents the results of the proposed three-stage optimization method. The first stage consists of the plate material type and stiffener-type selection process, in which the MS is mostly selected as the plate material

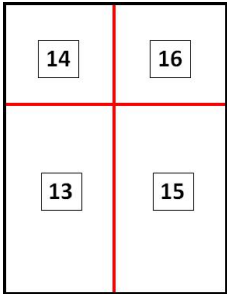
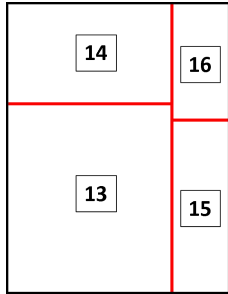
type because it is the most cost-effective material type based on the values shown in Table 4. The results of material selection indicate that the process is the most economical according to the objective function, which minimizes material costs and is consistent with the majority of the cost saving values listed in Table 4. HT32 and HT36 materials were chosen for plates 6, 7, and 9. One reason is that the initial design did not satisfy the constraint conditions at these girder plates. Therefore, these plates need to increase their thicknesses and/or to change their material types. The other reason is the influence of other plates connecting them. If MS is used for these girder plates, they become very thick and very stiff so that they act close to the clamped boundary conditions to the upper and bottom plates, thereby resulting in large moments and large stresses along the connecting edges of the top and bottom plates. Hence, HT32 and HT36 material types are selected to reduce the thickness. This results in additional support for the stress relaxation of the top and bottom plates with larger areas.

For stiffener selection, the results of the GA optimization method illustrate the changes in the stiffeners from type 6 to type 1 and from type 3 to type 4. The details of the stiffener types are listed in Table 5. By changing the stiffeners attached to the top plate from type 6 to type 1, the mass reduction of the stiffeners is quite significant, and the sectional area of each stiffener decreases from 2736 mm² to 1187 mm². Meanwhile, the stiffeners attached to the bottom plate change their types from Type 3 to Type 4 so that each sectional area increases from 1650 mm² to 1900 mm². These stiffener-type changes are due to a low stress distribution on the top plate and a high stress distribution on the bottom plates. The maximum von Mises stresses on the top and bottom plates at the initial design are 156.7 MPa and 193.9 MPa, respectively. The thickness of the top plate and the size of the stiffener attached to the top plate decrease through the first and second stages, whereas both the thickness of the bottom plate and the size of the stiffener attached to the bottom plate increased.

The second stage is the determination of plate thickness, which is a process that is integrated with the first stage. After size optimization, some plates have a reduction in thickness whereas others experience increases, as detailed in Table 7 and Figure 8.b. The increase in thickness in some plates is due to a change in the type of plate material from HT32 to MS, which has lower strength, thereby requiring a larger thickness. The results of the hybrid GA optimization in the first and second stages resulted in a 23% reduction in material costs, as shown in Figure 8a. Meanwhile, the mass reduction is 6.5%, which does not have to be so effective since the target of this optimization is cost minimization.

Table 7. Optimization result

Plate / stiffener number	Initial design		1 st stage	2 nd stage	3 rd stage	
	Mat type, thickness (mm)	Plate layout (Top & Bottom plate)	Mat type	thickness (mm)	thickness (mm)	Plate layout (Top & Bottom plate)
0	HT32 9.00		MS	7.80	8.08	
1	HT32 11.00		MS	9.08	9.36	
2	HT32 9.00		MS	6.44	6.00	
3	HT32 11.00		MS	8.42	8.09	
4	HT32 10.00		MS	11.86	12.02	
5	HT32 9.00		MS	9.79	9.51	
6	HT32 10.00		HT32	12.05	12.37	
7	HT32 10.00		HT36	7.22	7.08	
8	MS 8.00		MS	6.00	6.00	
9	HT32 11.00		HT36	12.50	12.74	
10	MS 8.00		MS	6.00	6.00	
11	MS 8.00		MS	6.00	6.00	
12	MS 8.00		MS	6.00	6.00	

13	HT32	9.00		MS	9.27	9.31	
14	HT32	10.00		MS	10.20	10.27	
15	HT32	9.00		MS	11.11	9.48	
16	HT32	10.00		MS	12.57	13.03	
17	6			1			
18	6			1			
19	3			4			
20	3			4			
Welding line (x ₁ , x ₂ , y ₁ , y ₂)	Top plate			Top plate		Top plate	
	3708.25; 3708.25; 8140.6; 8140.6			3708.25; 3708.25; 8140.6; 8140.6		2472.17; 2472.17; 8140.6; 7546.32	
	Bottom plate			Bottom plate		Bottom plate	
	3708.25; 3708.25; 8140.6; 8140.6			3708.25; 3708.25; 8140.6; 8140.6		5562.38; 5562.38; 8140.6; 7546.32	
Mass (kg)	22,585.86			21,129.67		20,471.25	
Material cost (in million) (¥)	1.782			1.376		1.338	
CPU time (h)				7.7		0.1	

The third stage is a layout optimization that determines the arrangement of the plates by shifting the welding lines with the aid of thickness modification. In the layout optimization of the top plate, the plates 0 and 1 increase their thickness as well as decrease their areas, while the plates 2 and 3 decrease their thickness as well as increase their areas as depicted in Table 8. Thus, the layout optimization successfully reduces the material cost of the top plate by 3.8%. The most significant change in the thicknesses of plates 13, 14, 15, and 16 is observed in plate 15, where the thickness is reduced by 1.63 mm. This is achieved by passing the high-stress region in plate 15 to plate 16, whose thickness increases by 0.46 mm. Enlarging the area of plate 14 as well as shrinking the area of plate 16 also contributes to a reduction in the material cost of the top plate because the amount of increase in the thickness of plate 14 is smaller than that of plate 16, thereby resulting in a 6.2% reduction. This layout optimization process requires a short computational time but can result in a reduction in material cost of 3% from the end of the second stage, as shown in Figure 8a. Overall, the proposed 3-stage optimization method succeeded in reducing the material cost by 25%.

Table 8. Summary of the layout optimization

Top Plate								
Plate	before 3 rd stage			after 3 rd stage			after - before	
	A (mm ²)	t (mm)	Volume (mm ³)	A (mm ²)	t (mm)	Volume (mm ³)	ΔA (mm ²)	Δt (mm)
0	30187380	7.80	235461564	20124955	8.08	162609638	-10062425	0.28
1	15426320	9.07	139916722	10284231	9.36	96260406	-5142089	0.29
2	30187380	6.44	194406727	37311479	6.00	223868874	7124099	-0.44
3	15426320	8.42	129889614	23506734	8.09	190169481	8080414	-0.33

Total	91227400		699674627	91227400		672908399	Volume (mm ³) -26766229 (-3.8%)	
Bottom Plate								
Plate	before 3 rd stage			after 3 rd stage			after - before	
	<i>A</i> (mm ²)	<i>t</i> (mm)	Volume (mm ³)	<i>A</i> (mm ²)	<i>t</i> (mm)	Volume (mm ³)	ΔA (mm ²)	Δt (mm)
13	30187380	9.27	279837012	45281070	9.31	421566761	15093690	0.04
14	15426320	10.20	157348464	23139480	10.27	237642460	7713160	0.07
15	30187380	11.11	335381791	13991817	9.48	132642424	-16195563	-1.63
16	15426320	12.57	193908842	8815033	13.03	114859881	-6611287	0.46
Total	91227400		966476110	91227400		906711526	Volume (mm ³) -59764584 (-6.2%)	

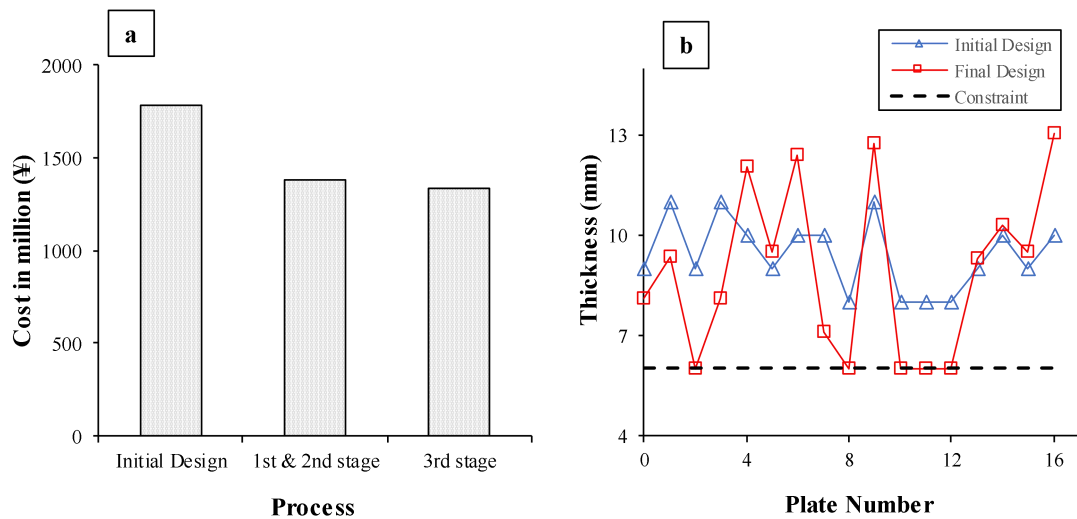


Figure 8. (a) Material cost reduction each stage and (b) plate thickness distribution

Table 9 details the results of the optimization process performed based on the limits issued by the IACS Common Structural Rules to facilitate its use by a shipyard. The plate thickness is treated as a continuous variable to meet the constraints more accurately. However, the plate thickness will be adjusted according to the available size on the market later. The results of the analysis indicate that both the maximum stress and shear stress have met the constraints. The decrease in the thickness of several plates stopped at the limit thickness of 6

mm, although their stresses were smaller than the constraint values. Moreover, the section modulus and shear area of the stiffener are still within the specified constraints.

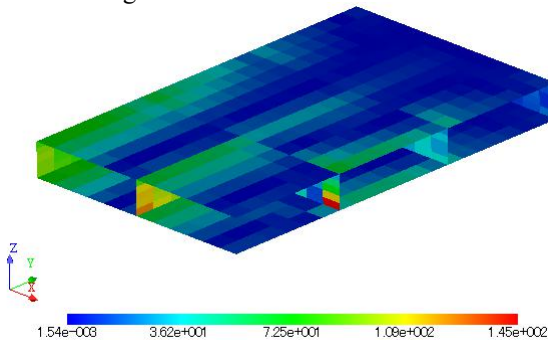
Table 9. Output data comparison for initial design and final design

Item	Unit	Limitation	Initial design	f = material cost
Maximum stress (MS Plate)	N/mm ²	188.0	76.6	188.0
Maximum stress (HT32 Plate)	N/mm ²	252.0	233.2	217.6
Maximum stress (HT36 Plate)	N/mm ²	284.0	-	204.7
Shear stress (MS Plate)	N/mm ²	108.1	39.9	102.5
Shear stress (HT32 Plate)	N/mm ²	144.9	184.2	69.0
Shear stress (HT36 Plate)	N/mm ²	163.3	-	162.8
Maximum Deflection	mm	159.5	136.1	133.8
Minimum Thickness	mm	6	6	6
Minimum Section Modulus of Stiffener (Top; Bottom)	cm ³	46.7	230; 97.2	72.5; 97.2
Minimum shear Area (Top; Bottom)	cm ²	2.25	27.36; 11.87	11.87; 19.00
Plate number (MS; HT32; HT36)	-	-	4; 13; N/A	14; 1; 2
Mass	kg	-	22,585.86	20,471.25
Material cost (in million)	¥		1.782	1.337
Mass reduction	%			9%
Material cost reduction	%			25%

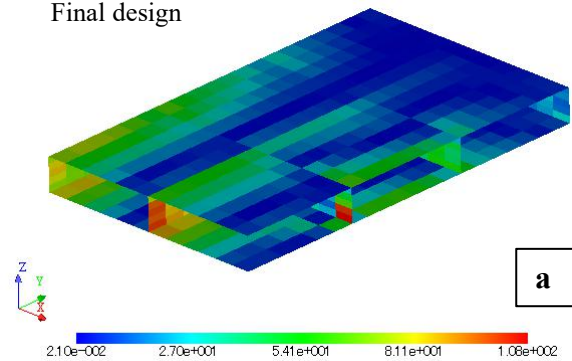
Figure 9 (a) illustrates the shear stress distribution in which the maximum shear stress is observed on the transversal girder. This is due to the large shear force at the junction of the transverse and longitudinal girder plates. However, the shear stress on the top and bottom plates is not excessively high, as displayed in Table 9. The maximum stress is illustrated in Figure 9 (b), where the maximum stress of the final design on the hatch cover occurs on the bottom plate of the hatch cover because the bottom plate is thinner than the top plate. Meanwhile, the largest deflection occurred in the top plate or surface of the hatch cover that directly faces the given load, as depicted in Figure 9 (c). These results validate the success of this method in reducing material costs and complying with constraints.

In addition to reducing material costs, the proposed optimization method can also be used to reduce the mass of ship structures by altering the objective function. As illustrated in Table 10, the objective function is changed to the minimization of mass and the HT32/HT36 material types are selected at the first stage. HT32/HT36 is preferred over MS because it has greater strength, thereby requiring a thinner plate. The proposed optimization method results exhibit a 20% reduction in mass.

Initial design

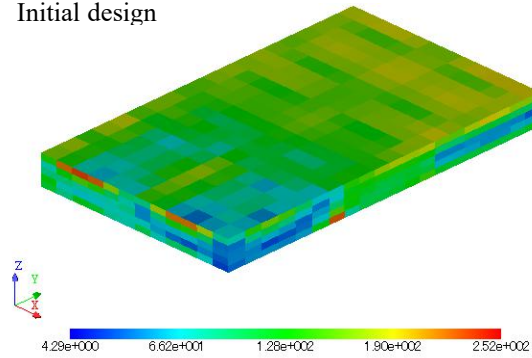


Final design

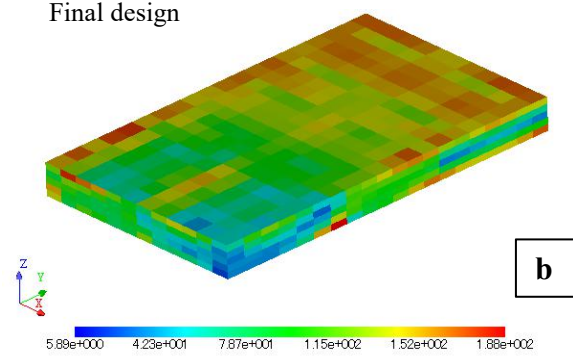


a

Initial design

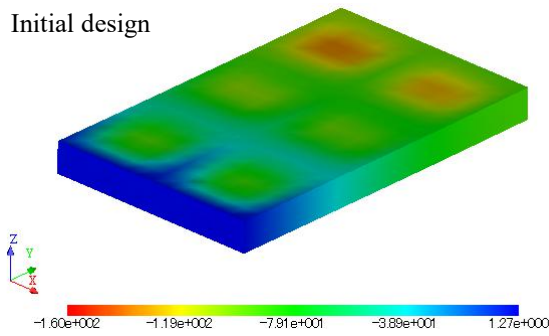


Final design

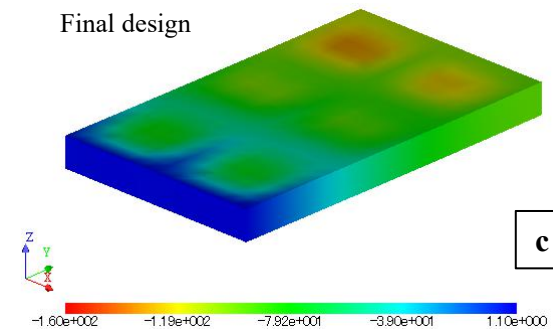


b

Initial design



Final design



c

Figure 9. (a) shear stress, (b) maximum stress, and (c) displacement

Table 10. Optimization result

Plate / stiffener number	Initial design		1 st stage	2 nd stage	3 rd stage	
	Mat type, thickness (mm)	Plate layout (Top & Bottom plate)	Mat type	thickness (mm)	thickness (mm)	Plate layout (Top & Bottom plate)
0	HT32 9.00		HT32	6.00	6.00	
1	HT32 11.00		HT32	6.00	6.00	
2	HT32 9.00		HT32	6.00	6.00	
3	HT32 11.00		HT32	6.00	6.00	
4	HT32 10.00		HT36	9.10	8.95	
5	HT32 9.00		HT36	8.23	8.29	
6	HT32 10.00		HT36	12.58	12.53	
7	HT32 10.00		HT36	9.15	7.37	
8	MS 8.00		MS	6.00	6.00	
9	HT32 11.00		HT36	14.48	14.40	
10	MS 8.00		HT32	6.00	6.00	
11	MS 8.00		HT32	6.00	6.00	
12	MS 8.00		MS	6.00	6.00	
13	HT32 9.00		HT32	7.87	7.16	
14	HT32 10.00		HT32	8.59	9.03	

15	HT32	9.00		HT32	9.18	9.64	
16	HT32	10.00		HT32	10.14	10.92	
17	6			1			
18	6			1			
19	3			4			
20	3			4			
Welding line (x_1 , x_2 , y_1 , y_2)	Top plate			Top plate		Top plate	
	3708.25; 3708.25; 8140.6; 8140.6			3708.25; 3708.25; 8140.6; 8140.6		5562.38; 5562.38; 8140.6; 7546.32	
	Bottom plate			Bottom plate		Bottom plate	
	3708.25; 3708.25; 8140.6; 8140.6			3708.25; 3708.25; 8140.6; 8140.6		3708.25; 3708.25; 8140.6; 8140.6	
Mass (kg)	22,585.86			18,461.98		18,069.29	
CPU time (h)				7.7		0.1	

5 Conclusion

This study proposes a three-stage optimization method to minimize the cost of materials used in the construction of a hatch cover. The first and second stages are termed hybrid GAs, namely a combination of the GA optimization method for selecting plate material and the stiffener types with size optimization to determine the optimal plate thicknesses. The third stage is called layout optimization, which adjusts the welding line position to obtain an optimal plate arrangement. The results of this optimization demonstrate a significant reduction in material costs for manufacturing the hatch cover, namely 25%. Thus, this study can be successfully applied in the shipbuilding industry to minimize material costs.

The proposed optimization method can also be used to minimize the mass of ship structures simply by changing the objective function from the material cost to the mass. In addition, it can accomplish a more significant reduction in material costs for other parts of the ship structure in future research on shipbuilding. However, there is still room for development because the GA optimization method exhibits a high computation time. Thus, a shorter yet accurate method is required to replace the GA optimization method.

Acknowledgements

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