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A Spatial Layout Optimization Program considering the Survivability of a Naval Vessel in the Early Design Stage

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As mission capability and scope of naval vessels are increasing, there has been an emphasis on the importance of survivability of naval vessels. Elements of survivability include susceptibility, vulnerability, and recoverability among which vulnerability is directly associated with the interior spatial layout of a naval vessel. However, various other elements also must be simultaneously considered in the design phase of a naval vessel. Accordingly, this study proposes a method that considers survivability an assessment factor by quantifying vulnerability in attacks, which is directly associated with the effect of spatial layout of a naval vessel. Furthermore, to automatically create spatial layout alternatives of naval vessels and efficiently deduce optimum spatial layout results, this study developed an optimization program for the spatial layout of naval vessels. The differential evolution algorithm was used for the optimization, and its effectiveness was validated by applying it to various examples.

Keywords: combinatorial optimization; differential evolution algorithm; naval vessel; spatial layout; survivability; vulnerability

1. Introduction

The spatial layout problem, arranging equipment and facilities that perform various functions in a limited space, requires various layout alternatives to reflect the intention of the designer. The problem of arranging equipment and compartments in a vessel can also be regarded as spatial layout problem. In particular, spatial layout of a naval vessel must consider the characteristics of the naval vessel, which performs multiple tasks such as battle, habitation, maintenance, and communication to establish systematic spatial layout strategies.

Many studies have been conducted regarding ways to perform spatial layout in light of various elements from the initial design phase of naval vessels. The intelligent ship arrangement (ISA) algorithm has been proposed by the University of Michigan research team in the United States (Parsons et al. 2008). The University College London (UCL) research team in the UK also proposed a ship design method using the design building block concept (Andrews 1998), and then extended their research to apply the simulation-based design concept (Andrews 2006). In the Netherlands, the TU Delft research team suggested a method of applying the packing approach to the initial design stage of the vessel (van Oers & Hopman 2010; van Oers 2011). Especially, the UCL research team developed the naval vessel design module SURFCON, which is applicable to the PARAMARINE ship design software. In Korea, regulations and the system for designing naval vessels and spatial layout are defined, but there are no processes or specific methodologies to apply them to the actual naval vessel design process. Therefore, spatial layout of naval vessels is being carried out based on the experience and subjective judgment of experts.

Recently, as weapon systems embedded on a single naval vessel are becoming more advanced and the survivability of the naval vessel itself has gained importance, there has been an increasing interest in naval vessel design considering survivability. However, there is no clear method to quantitatively assess survivability in the spatial layout phase. And it is highly difficult to design the spatial

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layout considering the correlation between various equipment and compartments at the initial phase of the ship design process because there is not enough information to determine spatial layout. Shin (2013), Hwang et al. (2014), and Kim et al. (2014a) began research on methods to perform spatial layout considering survivability, but insufficient research has been conducted on specific cases or optimization programs. Accordingly, this study suggests a method to design spatial layout using basic information at the initial phase of the ship design process and simultaneously considers survivability as an assessment factor of spatial layout. Based on this method, an optimization program was developed that deduces optimum spatial layout plans.

Most studies on the spatial layout of a naval vessel are based on research of the general arrangement process of naval vessels by Carlson and Fireman (1987). This research proposed a method to perform spatial layout using the method of dividing the interior space of the naval vessel into bulkheads and decks, and allocating functions to those divided spaces. Han (2001) simplified this spatial layout method and formulated the compartment arrangement problem on a single deck. Then, he presented an algorithm to deduce the optimum spatial layout for the single deck by applying the genetic algorithm and applied it to an actual naval vessel (FF-21). Lee et al. (2005) improved the study by Han (2001) and presented an improved genetic algorithm that can resolve the problem of compartment arrangement for multiple decks.

The aforementioned study by Parsons et al. (2008) proposed the ISA algorithm. This is an algorithm for spatial layout of naval vessels developed by the University of Michigan, which systemized the spatial layout process of a naval vessel into two phases: phase 1 is allocation and phase 2 is arrangement. Each phase considered various elements such as compartment relationships, location preferences of compartments, and geometry of compartments and presented methods to deduce the optimum spatial layout alternative by using the genetic algorithm.

Basic methods and procedures for analyzing survivability of a naval vessel were established by Ball and Calvano (1994). This study expressed survivability elements of a naval vessel in terms of probabilities and presented a procedure for calculating these factors quantitatively. In addition, studies on how to quantify the survivability of a naval vessel based on vulnerability were conducted by Lim (2006) and Kim and Lee (2012). In particular, Kim et al. (2014) studied ways to assess the susceptibility of a naval vessel using a probability density function (PDF). Methods to assess survivability of a naval vessel have been established to a certain extent through such studies, but they are limited in that they fail to consider spatial layout and survivability in association with each other in the initial design phase.

Studies that applied the concept of survivability to the problem of naval vessel spatial layout include the aforementioned studies by Hwang et al. (2014) and Kim et al. (2014). Hwang et al. (2014) applied systematic layout planning to the process of performing naval vessel spatial layout, and proposed a general arrangement process and spatial layout methodology that assesses survivability based on vulnerability. However, their research focuses on the process of assessing the created alternatives rather than generating various spatial layout alternatives and deducing the optimum alternative among them. Therefore, there are limitations in that the deduced outcome may not be the optimal spatial layout. Kim et al. (2014) presented an optimization algorithm for two-dimensional naval vessel spatial layout based on the research findings of Hwang et al. (2014). Here, the differential evolution algorithm was used for the optimization algorithm. Their study simplified the two-dimensional naval vessel spatial layout problem into a one-dimensional allocation problem using a space-filling curve. It also performed optimization by formulating objective functions that simultaneously considered the assessment factors of compartment relationships and survivability. However, there are limitations in that the results of naval vessel spatial layout are too dependent on the shape of the space-filling curve, and alternatives with a greater deviation from the actual layout may be created. Although not related to spatial placement algorithms, research has been conducted on tools and methods for evaluating survivability at the initial design stage. Heywood and Lear (2006) developed a vulnerability assessment program, PREVENT, for the early design stage of naval vessels. Piperakis (2013) analyzed various definition methods and evaluation methods of survivability, and proposed a naval vessel survivability evaluation method considering the recoverability.

In this study, an optimization program based on the ISA algorithm is developed for spatial layout of a naval vessel considering vulnerability in attacks, which overcomes the limitations of the previous studies. Previous research had also tried to perform spatial layout considering various factors in the initial design stage, but did not consider survivability which is an important factor in naval vessel operation. In this study, the survivability assessment factor was added to the spatial layout evaluation factor to overcome this point. Here, the algorithm of naval vessel spatial layout consists of two phases (allocation and arrangement) similar to the ISA algorithm. In the allocation phase, compartment relationships, compartment location preferences, the area utilization ratio, and survivability were used as assessment factors. In the arrangement phase, the geometry of compartments, relationships among compartments, and survivability were used as assessment factors.

The initial design phase lacks detailed information. Therefore, this study proposed a method to quantitatively evaluate the survivability with limited information that can be applied in the initial design stage. In the previous research, there was a problem that the spatial layout result considering the survivability was dependent on the space-filling curve. In this study, stochastic growth algorithm (SGA), which is used in the ISA algorithm, is used to define the shape and location of the compartment so that realistic and various spatial layout alternatives can be derived. Furthermore, this study defined a simple way to express various layouts for the optimization algorithm. And we use a differential evolution algorithm as an optimization algorithm.

2. Naval vessel spatial layout using the ISA algorithm

The ISA algorithm, proposed by Parsons et al. (2008), is a typical method to systematically perform naval vessel spatial layout. The ISA algorithm divides the naval vessel spatial layout into allocation and arrangement as shown in Fig. 1. In the allocation phase, compartments are allocated to zone-decks that are divided into bulkheads and decks. The arrangement phase is when the relative location and geometry of compartments assigned from the allocation phase are determined. To conduct the arrangement process, the results of the allocation phase and detailed information about the zone-deck such as passages, geometry, and fixed compartments must be defined in advance. The arrangement phase is then divided

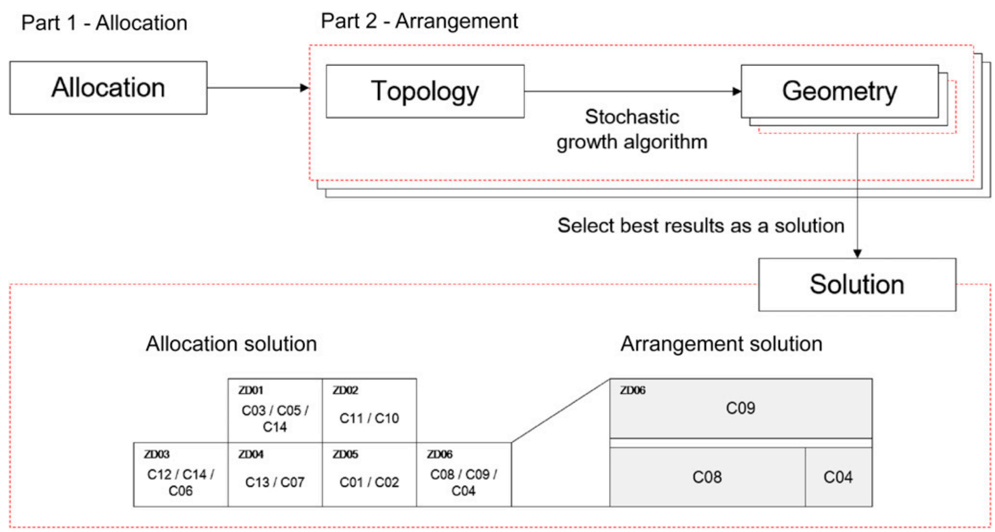


Fig. 1 Basic process and result of spatial layout design using the ISA algorithm

into topology and geometry determination phases. The topology determination phase determines the relative locations of compartments within the zone-deck, and defines the central point of each compartment as the starting point of an SGA used in the geometry determination phase. Then, the geometry determination phase generates the specific geometry of compartments using SGA based on the centers of the compartments. SGA is a method that enlarges compartments to achieve the required area for each compartment. Because compartments are grown using probability, the method has the advantage of being able to deduce various arrangement alternatives.

The ISA algorithm groups the compartments considering the use and characteristics of compartments for a naval vessel and defines the location preferences of each compartment group and relationship satisfaction among compartment groups. The arrangement phase assesses and determines the geometry of compartments. In this phase, various elements related to the geometry of the compartment and relationship satisfaction among compartments are used as assessment factors. Fuzzy functions are used here to quantify subjective assessment factors, and optimization is carried out using the genetic algorithm.

3. Assessment and optimization of naval vessel spatial layout

3.1. Assessment of naval vessel spatial layout considering vulnerability in attacks

In this section, a method that assesses a naval vessel spatial layout that considers vulnerability in attacks is suggested. The vessel layout algorithm is based on the ISA algorithm, but a survivability assessment factor has been added both in the allocation and arrangement steps to consider the vulnerability during attacks. In the allocation step, the vulnerability of a compartment is calculated based on the importance according to the kill types of the equipment stationed in a compartment. Then, the survivability is quantified using the status of whether the compartment is shot or not. All the other assessment factors except the survivability factor were used likewise as in the ISA algorithm. The allocation step only determines what compartments are assigned to which zone-deck. Next, in the arrangement step, the vulnerability of compartments is calculated in the same way as in the allocation step. However, when calculating the susceptibility, a detailed level of calculation is carried out by defining the probability of being shot according to the position of the compartment. Other assessment factors are the same as in the ISA algorithm. Through the arrangement step, the position of each compartment is determined. More details are given in the following text.

Survivability of a naval vessel can be classified into susceptibility, vulnerability, and recoverability. Ball and Calvano (1994) defined killability of a naval vessel as the susceptibility probability of a naval vessel multiplied by the vulnerability probability in attacks. Survivability (P_{S}) can be represented by using killability (P_{K}) as shown in equation (1), and killability is the susceptibility probability (P_{H}) multiplied by the vulnerability probability in attacks ($P_{\mathrm{K/H}}$) as shown in equation (2).

$$P_{\mathrm{S}} = 1 - P_{\mathrm{K}} \tag{1}$$

$$P_{\mathrm{K}} = P_{\mathrm{H}} \cdot P_{\mathrm{K/H}} \tag{2}$$

This study considered survivability when performing naval vessel spatial layout based on the aforementioned method (equations [1] and [2]). Moreover, the basic spatial layout methodology follows the ISA algorithm, and the latter parts of this study will define the space that is divided into decks and bulkheads as a zone-deck (ZD), assigning multiple compartments (C) to each zone-deck. Compartments are outfitted with equipment (E) that performs different functions, which will be referred to in this study as shown in equation (3).

$$i \in \mathrm{ZD}, j \in C, k \in E \tag{3}$$

Binary variables were defined as follows to represent compartments arranged in a zone-deck, equipment installed in compartments, and zone-decks included in the scope of attack. First, binary variable α_{ij} was defined as shown in Equation 4 to represent compartments arranged in a specific zone-deck. This variable has the value of 1 when zone-deck i includes compartment j, and 0 if not. In the same way, binary variable β_{jk} was defined as shown in equation (5) to represent equipment installed in specific compartments. Finally, variable b_i was defined as shown in equation (6) to represent whether a zone-deck is included in the scope of attack, and takes a value of r_i if zone-deck i is included in the scope of attack, and 0 if not. Here, r_i represents the rate of impact on equipment installed in the compartment i when the compartment is exploded. The range of this value is between .0 and 1.0.

$$\alpha_{ij} = \begin{cases} 1 & \text{if } \mathrm{ZD}_i \text{ contains } C_j \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\beta_{jk} = \begin{cases} 1 & \text{if } C_j \text{ contains } E_k \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$b_i = \begin{cases} r_i & \text{if } \mathrm{ZD}_i \text{ is exploded} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

Multiple studies have been conducted on how to assess or quantify survivability of a naval vessel, but specific methods to connect the spatial layout of a naval vessel to survivability have been defined by Shin (2013). To quantify vulnerability when a naval vessel is attacked by using the theory of Ball (2003), this study applied failure mode and effective analysis (FMEA) and fault tree analysis (FTA) to critical equipment stationed in each compartment based on the method defined by Kim (2011). Kim (2011) defined the kill types, which are criteria for what condition the vessel lies in after being shot and for the effects of being shot on the mission capability. Shin (2013) defined the importance for each kill type. This study defined the importance of equipment based on the precedent works to quantify the vulnerability. According to Kim (2011), a naval vessel can carry out multiple missions, and each mission consists of multiple functions. A function comprises systems and subsystems, and a subsystem may be related to multiple compartments. These relations can be expressed as in Fig. 2. Among the equipment stationed in a compartment, if critical equipment designated by an expert group is destroyed, the functionality of the compartment where that critical equipment is stationed is assumed to be lost. Once the functionality of a compartment is lost, the status of related subsystems, systems, function, and mission becomes failure. Based on this relation, the kill type and importance of equipment can be defined. Figure 2 depicts a situation where equipment 4 in compartment A, equipment 2 in compartment B, and equipment 2 in compartment C are destroyed. In this case, equipment 2 in compartment B is not critical equipment, and hence does not affect the higher levels. However, the rest of the destroyed equipment affect the failure of mission A and B and the failure of mission B, as tagged, respectively. In this way, the effects of destroyed equipment on the mission capability can be identified. Then, using the predefined importance for each kill type, the importance of equipment can be deduced.

This study defined the importance of equipment k deduced through FMEA and FTA as e_k. The value should be derived from repetitive analysis and should have a statistically meaningful repetition count. This study has a limited scope that suggests a method of assessment of spatial layout from a viewpoint of survivability using the equipment importance value. And the maximum importance of equipment arranged in the compartment is defined when multiple equipment systems are arranged in compartment j as vulnerability in attack on compartment j (v_j). This can be represented as equation (7) using the binary variables (β_{jk}) defined in equation (5).

$$\begin{aligned} v_j &= \max\left(\beta_{j1}e_1, \ldots, \beta_{jk}e_k, \ldots, \beta_{jK}e_K\right) \\ K &= \text{number of equipments} \end{aligned} \tag{7}$$

If multiple compartments are arranged in a single zone-deck, the biggest value of vulnerability of compartments is defined as the

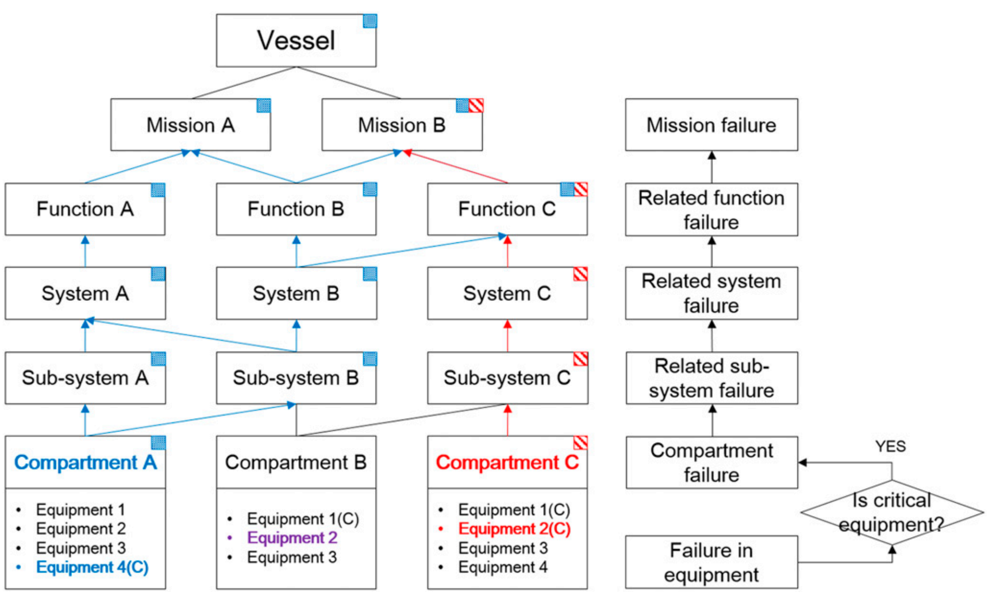


Fig. 2 Vulnerability assessment process for a single vessel

vulnerability of the relevant zone-deck. In the allocation phase, the killability of zone-deck i can be defined as susceptibility probability multiplied by vulnerability in attack as defined in equation (2). In the allocation phase, an attack on the zone-deck defined in equation (6) is used as susceptibility probability to perform a rough calculation. Moreover, using vulnerability in an attack on compartment j defined in equation (7) and the binary variables defined in equation (4), the killability $(P_{K_1,i})$ of zone-deck i can be defined as shown in equation (8).

$$\begin{aligned} P_{K_1,i} &= b_i \cdot \max\left(a_{i1}v_1, \ldots, a_{ij}v_j, \ldots, a_{iJ}v_J\right) \\ J &= \text{number of compartments} \end{aligned} \tag{8}$$

Finally, when survivability is defined using killability as represented in equation (1), the survivability $(P_{S_1,i})$ of zone-deck i in the allocation phase can be represented as equation (9).

$$\begin{aligned} P_{S_1,i} &= 1 - P_{K_1,i} \\ &= f_{4,i} \end{aligned} \tag{9}$$

To assess the spatial layout results in the allocation phase, the ISA algorithm simultaneously considers area utilization ratio $(f_{1,j})$, location preference $(f_{2,j})$, and relationship satisfaction among compartments $(f_{3,i})$ of the zone-deck to formulate the objective function. This study added survivability factor $(f_{4,i})$ defined as shown in equation (9) to the assessment factors used in the ISA algorithm. Each assessment factor takes a value between .0 and 1.0, and the objective functions for each assessment factor are multiplied to obtain the integrated objective function of the zone-deck. Four weights $(w_{f_1}, w_{f_2}, w_{f_3}, w_{f_4})$ are defined as equation (10) to give a difference in the importance of each evaluation factor. The integrated objective function of the allocation phase is defined as the smallest value among the objective functions of each zone-deck, which can be represented as equation (10).

$$\begin{aligned} f_0 = \min\Bigg(&\frac{f_{1,1}}{w_{f_1}} \cdot \frac{f_{2,1}}{w_{f_2}} \cdot \frac{f_{3,1}}{w_{f_3}} \cdot \frac{f_{4,1}}{w_{f_4}}, \ldots, \frac{f_{1,i}}{w_{f_1}} \cdot \frac{f_{2,i}}{w_{f_2}} \cdot \frac{f_{3,i}}{w_{f_3}} \cdot \frac{f_{4,i}}{w_{f_4}}, \ldots, \\ &\frac{f_{1,I}}{w_{f_1}} \cdot \frac{f_{1,I}}{w_{f_1}} \cdot \frac{f_{1,I}}{w_{f_1}} \cdot \frac{f_{1,I}}{w_{f_1}}\Bigg) \\ I = \text{number of zone-decks}& \end{aligned} \tag{10}$$

When applying the optimization algorithm, the allocation problem was driven in a direction that maximized the integrated objective function of each zone-deck as shown in equation (11) so that generally excellent allocation results can be deduced for all zone-decks.

$$\text{Step 1} \quad \text{Allocation : Maximize}\left(f_0\right) \tag{11}$$

To assess the arrangement results, the ISA algorithm used compartment geometries and relationships as assessment factors. This study used the assessment factors and methods of arrangement used in the ISA algorithm, and additionally assessed survivability by considering vulnerability in an attack inside the compartment arranged in the two-dimensional grid.

The value v_j defined in equation (7) is used as the vulnerability in an attack on each compartment in the arrangement phase. However, compartments are arranged on a two-dimensional plane represented as a unit grid in the arrangement phase. Moreover, the probability of susceptibility is defined according to the location, and this study performed a more detailed assessment than the probability of susceptibility in the allocation phase, represented as binary variables by defining the PDF of the susceptibility according to the location.

Figure 3 shows how to define the value of susceptibility probability according to the location in the arrangement phase. With the length of the naval vessel as the x-axis and the width from the center as the y-axis, the probabilities of longitudinal and transverse susceptibility are defined respectively as $P_{\mathrm{H,l}}(x)$ and $P_{\mathrm{H,t}}(y)$ as shown in Fig. 3. Furthermore, the probability of susceptibility of a place on the grid with the location of x' in the x direction and y' in the y direction is defined as the probability of longitudinal susceptibility multiplied by that of transverse susceptibility in the relevant location as shown in equation (12).

$$P_{\mathrm{H}}(x', y') = P_{\mathrm{H,l}}(x') \cdot P_{\mathrm{H,t}}(y') \tag{12}$$

If a compartment takes up some area, the probability of susceptibility of the compartment is obtained by integrating the PDF of susceptibility corresponding to the area included in the compartment. Moreover, the vulnerability in an attack of each compartment uses the value equivalent to the one used in the allocation phase as mentioned previously. Through this method, the killability $(P_{K_2,j})$ of compartment j in the arrangement phase can be represented as equation (13). Here, C_j indicates the area taken up by compartment j.

$$P_{K_2,j} = v_j \iint_{C_j} P_{\mathrm{H}}(x, y)\,\mathrm{d}x\mathrm{d}y \tag{13}$$

The killability of a zone-deck that includes multiple compartments in the arrangement phase is defined as killability of the compartment with the largest killability value. By using this method and the binary variables defined in equation (4), the survivability $(P_{S_2,i})$ of zone-deck i in the arrangement phase can be represented as shown in equation (14).

$$\begin{aligned} P_{S_2,i} &= 1 - \left(\max\left(\alpha_{i1}P_{K_2,1}, \ldots, \alpha_{ij}P_{K_2,j}, \ldots, \alpha_{iJ}P_{K_2,J}\right)\right) \\ J &= \text{number of compartments} \\ &= g_{3,i} \end{aligned} \tag{14}$$

The arrangement phase carried out based on the result of allocating compartments to the zone-decks separately calculates objective functions and optimizes each zone-deck. The integrated objective function of each zone-deck i $(g_{0,i})$ in the arrangement phase consists of not only the geometry assessment factors $(g_{1,i})$ and the adjacency/separation assessment factors $(g_{2,i})$ used in the ISA algorithm, but also the survivability assessment factors $(g_{3,i})$ proposed by this study. As in the allocation phase, each assessment factor takes a value between .0 and 1.0, and integrated objective functions per zone-deck are obtained by multiplying the objective function values and weights $(w_{g_1}, w_{g_2}, w_{g_3})$ of each assessment factor. This can be represented as equation (15).

$$g_{0,i} = \left(w_{g_1}g_{1,i}\right) \cdot \left(w_{g_2}g_{2,i}\right) \cdot \left(w_{g_3}g_{3,i}\right) \tag{15}$$

Finally, when applying the optimization algorithm to the arrangement phase of compartments in zone-deck i, the arrangement

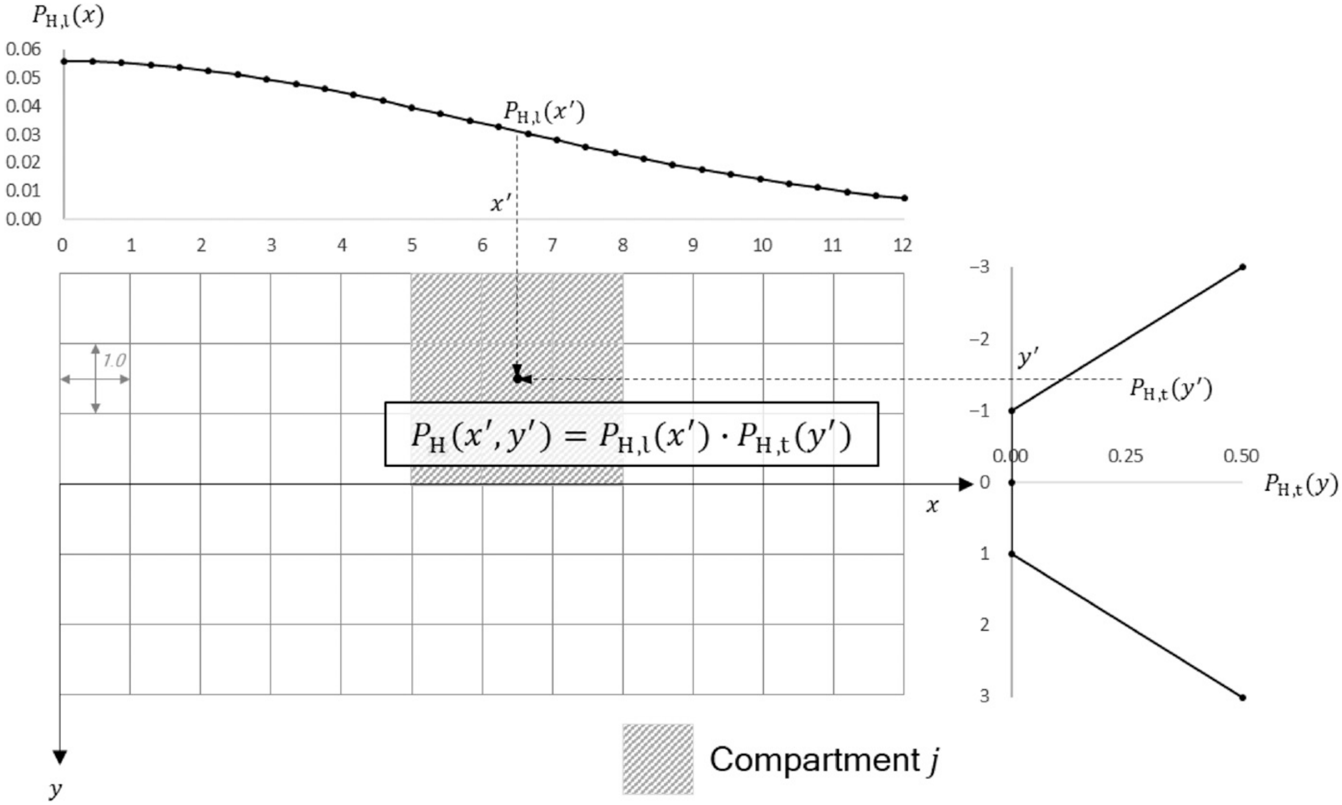


Fig. 3 Longitudinal and transverse PDFs and susceptibility probability of the individual compartment

problem was driven in a direction that maximized the integrated objective function as shown in equation (16).

$$\text{Step 2 Arrangement}\left(\mathrm{ZD}_i\right) : \text{Maximize}\left(g_{0,i}\right) \tag{16}$$

3.2. Optimization of naval vessel spatial layout using the differential evolution algorithm

This study applied the optimization algorithm to compare and assess multiple alternatives in performing naval vessel spatial layout based on the ISA algorithm and to deduce the optimum alternative. The differential evolution algorithm proposed by Storn and Price (1997) was used as the optimization algorithm. This algorithm was suggested as a method to resolve the optimization problem defined in sequential space, and various methods to apply this to combinatorial optimization problems defined in a discrete space were also developed by Onwubolu and Devendra (2009). In particular, because the method to express and implement the values is simple, it is used in various industries to resolve optimization problems. In the shipbuilding industry, it is also used to solve the problem of surface plate layout according to a study by Shin et al. (2008).

Similar to the well-known genetic algorithm, the differential evolution algorithm adopts an evolutionary approach. The basic process of the differential evolution algorithm consists of the following four phases, where the algorithm constantly repeats mutation, crossover, and selection to improve the quality of the solution set.

1) Initialization: generate a set of solutions expressed as real-number vectors.
2) Mutation: select a random pair of vectors, calculate their difference, and account for weighted value to mutate the existing vectors.
3) Crossover: generate a set of temporary solutions for the offspring generation, accounting for the crossover rate.
4) Selection: check whether the objective function of the temporary solutions has been improved, and when improved, apply it to the set of solutions for the offspring generation.

The differential evolution algorithm is a method to optimize solutions that can be expressed as vectors of real numbers. In this study, ranking of each vector component represents the allocation results of each compartment. When arranging J compartments into I zone-decks, the constant vector that represents the zone-deck with allocated compartments in the differential evolution algorithm has J components, and each component shows the serial number of the zone-deck. This can be represented as equation (17).

$$\begin{aligned} \vec{x} &= (x_0, x_1, \ldots, x_i, \ldots, x_{J-2}, x_{J-1}) \\ x_i &\in \{0, 1, \ldots, I-1\} \end{aligned} \tag{17}$$

When arranging six compartments into four zone-decks using the expression defined in equation (17), the result can be represented as $\vec{x} = (2, 3, 1, 0, 0, 3)$. Here, $x_0 = 2$, thus indicating that the zeroth compartment is arranged in the second zone-deck. Allocation solutions were expressed in the same way in the differential evolution

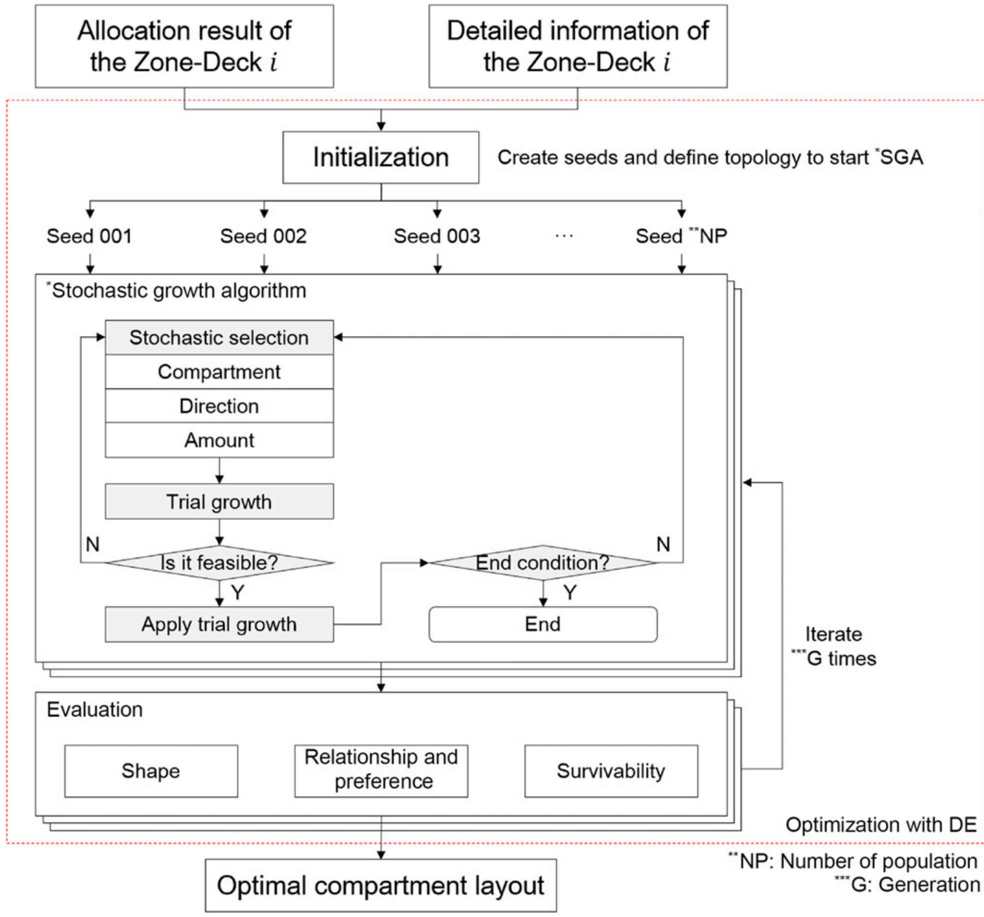
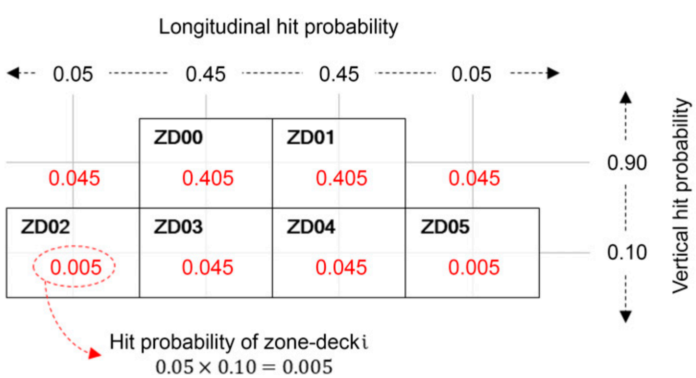


Fig. 4 Optimization process of the compartment arrangement using SGA and Differential Evolution (DE)

algorithm. The ISA algorithm applied a probability-based growth algorithm to create an arrangement layout. To create multiple alternatives in this algorithm, an initial starting point considering the topology relationship among the compartments was created, after which the relevant compartments for growth, growth direction, and growth amount were selected considering the probability. This study found the optimal arrangement layout considering topology relationships, geometry, and survivability of compartments arranged in the zone-deck using SGA and the differential evolution algorithm.

To perform compartment arrangement, there is a need for detailed information on the zone-deck such as the results of allocating compartments to zone-decks and the geometry of zone-decks. Based on this information, the growth seed of the compartments allocated to the zone-decks is defined. As many seeds are created as the number of populations forming one generation



Zone-deck	b_i
ZD00	1.0
ZD01	1.0
ZD02	0.0
ZD03	0.0
ZD04	0.0
ZD05	0.0

Fig. 5 b_i value calculation method for example #1

Table 1 Input data for example #1

Items	Compartment	Input value or condition
Vulnerability	C00–C07	.10
	C08–C14	.90
Preference	C00–C04	ZD00, ZD01 (upper deck)
	C05–C09	ZD02, ZD03 (stern)
	C10–C14	ZD04, ZD05 (bow)
Relationship	If C00–C03 are adjacent to each other	.90
	If C04–C07 are adjacent to each other	.90
	If C08–C11 are adjacent to each other	.90
	If C12–C14 are adjacent to each other	.90
	Otherwise	.10
Weights $(w_{f_1}, w_{f_2}, w_{f_3}, w_{f_4})$		1.0

of the differential evolution algorithm, and each population draws up an improved compartment arrangement alternative as generations go through the differential evolution algorithm. Details of the optimization process of the compartment arrangement are as shown in Fig. 4.

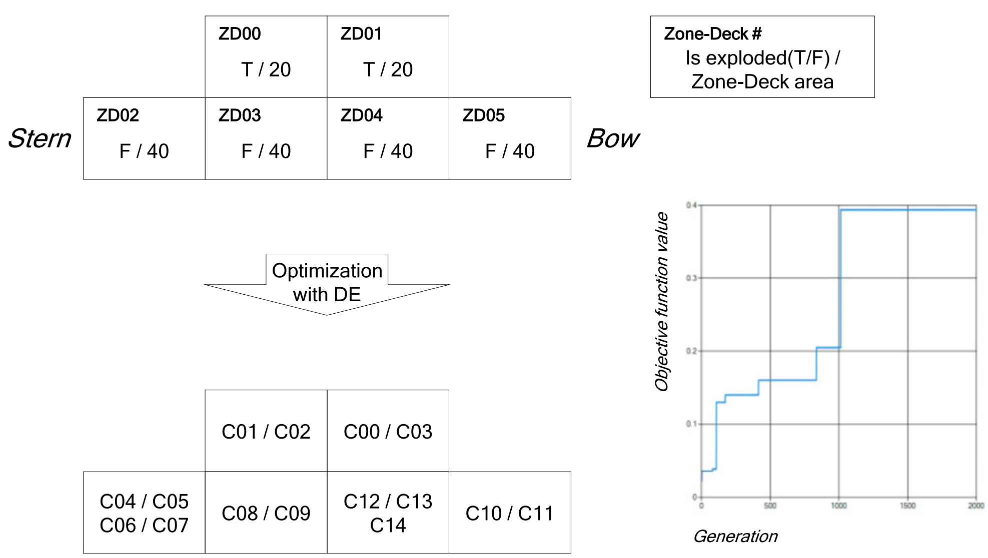
4. Application and verification

4.1. Application and verification in the allocation stage

The problem of allocating compartments to a zone-deck is that the number of combinations that can be created increases exponentially as the number of zone-decks and compartments increases. Therefore, to come up with the optimal alternative that meets the intention of the designer among various allocation alternatives, there is a need for an automation program that quickly creates and assesses values. This section introduces programs that apply the previously defined allocation optimization algorithm and assessment method, and verifies the developed programs based on virtual naval vessel data.

To perform optimization of the allocation phase, an input file is needed that can express the geometry and compartment information of the naval vessel. The input file contains the geometry, compartment, and compartment relationship information of the naval vessel. Here, the geometry information of the naval vessel indicates rough geometry information of the naval vessel for allocation, and the compartment information indicates basic information of the compartments (name, vulnerability under attack, area, and deck on which they are included) and location preference information. The compartment relationship information represents the values of quantified relationships among all compartments expressed in the input file in the form of a matrix. By performing optimization of allocation based on this information, it is possible to verify the results of allocating compartments to the zone-deck and the values of the objective function.

A virtual naval vessel with six zone-decks and 15 compartments is defined to verify the allocation optimization program ($I = 6$, $J = 15$). In an actual situation, it is necessary to determine whether the zone-deck will explode considering various threat situations. However, in this example, a longitudinal hit probability and a



Allocation example #1 result *Objective function plot*

Fig. 6 Optimization result of example #1 vertical hit probability for a specific threat are defined and used for simplification. The hit probability of zone-deck i is calculated by multiplying these values. The result is shown on the left side of Fig. 5. In this example, if the hit probability of the zone-deck value exceeds the predefined threshold value, the zone-deck is assumed to explode. The threshold value was set to .30. As a result, b_i values were determined assuming that ZD00 and ZD01 were fully exploded as shown on the right side of Fig. 5 ($b_0 = 1.0, b_1 = 1.0$). And the area (expressed in terms of unit area) of the upper zone-decks (ZD00, ZD01) is 20, and that of the lower zone-decks (ZD02–ZD05) is 40. The required area of all compartments in the virtual naval vessel was unified as 10, and the vulnerabilities, preferences, relationships, and weighted values are defined as shown in Table 1.

Allocation optimization was performed using the program developed in this study with the aforementioned input file. The maximum number of repeats in the differential evolution algorithm is limited to 2000 times. Because it is a simple problem with a small number of zone-decks and compartments, the objective function was found to converge quickly, as shown in the graph located on the lower right corner of Fig. 6. An analysis of the results verifies that the compartments with high vulnerability in an attack are arranged in the lower zone-decks that are not attacked. As intended in the input file, compartments with small numbers prefer the stern and upper zone-decks, whereas compartments with large numbers prefer the bow and lower zone-decks. Figure 6 shows detailed allocation results and changes in the objective function according to generation. Thus, the utility of the allocation optimization program was verified by a simple example.

The second example defines a virtual naval vessel with 10 zone-decks and 20 compartments ($I = 10$, $J = 20$), and performed optimization under different assessment factor weights to check the influence of allocation results for different assessment factor weights. The combinations of assessment factor weights are as follows, and the allocation optimization results are shown in Fig. 7.

Case 1: considering only the survivability factor $(w_{f_1}, w_{f_2}, w_{f_3} = 0.0,\ \ w_{f_4} = 1.0)$

Case 2: considering only the location preference factor $(w_{f_1}, w_{f_3}, w_{f_4} = 0.0,\ \ w_{f_2} = 1.0)$

Case 3: considering all assessment factors simultaneously $(w_{f_1}, w_{f_2}, w_{f_3}, w_{f_4} = 1.0)$

This example assumed that zone-decks located at the stern (ZD02, ZD03, ZD06, and ZD07) are the ones attacked. As a result, it was found that when considering only the survivability factor, compartments with low vulnerability values in the input data were allocated to those zone-decks (Fig. 7, Case 2-1). On the other hand, when considering only the location preference factor, all compartments were allocated to the preferred zone-decks defined in the input data (Fig. 7, Case 2-2). Finally, when considering all assessment factors simultaneously, the area utilization ratio of zone-decks and the compartment relationships, which had not been considered in previous cases, were additionally considered. By contrast with the previous results, in this case, two compartments were allocated to each of the zone-decks (Fig. 7, Case 2-3). This indicates that compartments were evenly allocated, considering the area utilization ratio. This example proves that the allocation

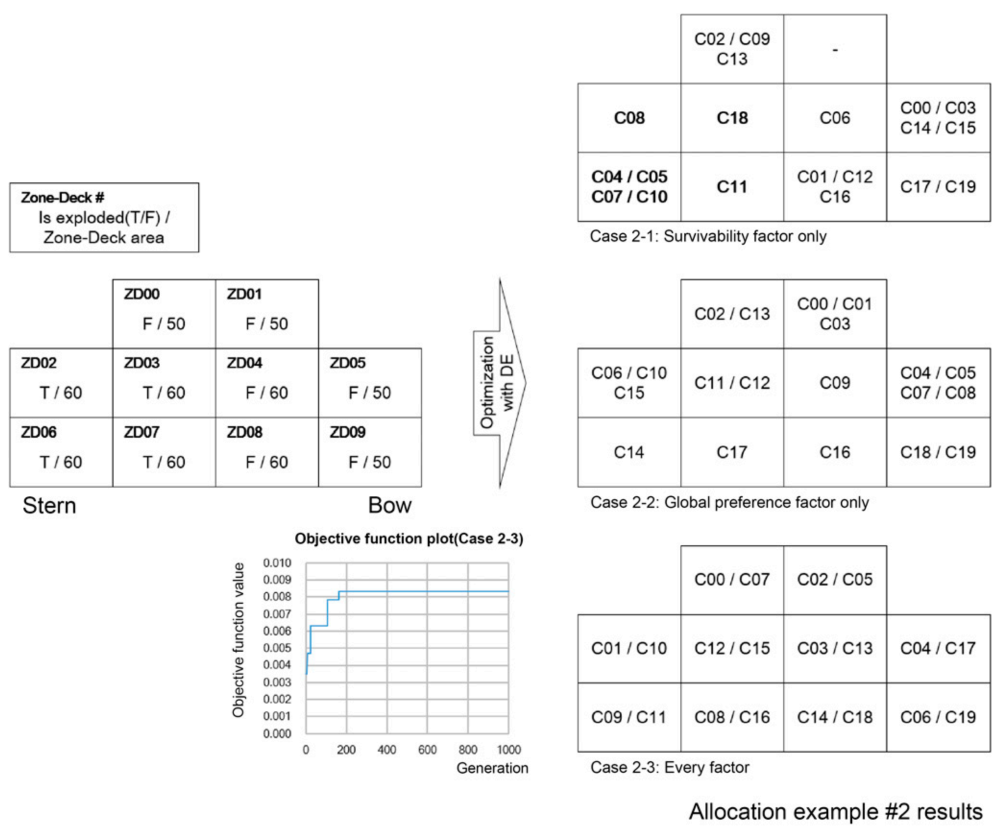


Fig. 7 Optimization result of example #2

Table 2 Input data for the compartment arrangement example

	C01	C02	C03	C04	C05	Vulnerability	Required area
C01	—	1	1	−1	−1	.1	250
C02	1	—	1	1	−1	.1	250
C03	1	1	—	0	0	.1	500
C04	−1	1	0	—	1	.1	750
C05	−1	−1	0	1	—	.9	750

1: adjacency condition; −1: separation condition; 0: none.

optimization program can identify allocation alternatives suitable for the intention of the designer.

4.2. Application and verification of the SGA in the arrangement stage

Arrangement stage was performed by modifying the SGA used in the arrangement stage of the ISA algorithm. Arrangement using an SGA first determines the location of the seed for each compartment and repeats the process of selecting the growth compartment, growth amount, and growth direction considering probability. Then, the desired geometry for the compartments is deduced. Here, the seed of each compartment determines the longitudinal location in proportion to the required area for the compartment. Moreover, the growth compartment, growth amount, and growth direction were assigned probabilities among the alternatives considering the required area achievement and geometry of compartments, and alternatives were selected through a randomization process. The program developed in this study can automatically repeat this process.

Table 2 shows the basic input data to perform the SGA process. Input data includes the relationships among compartments, vulnerability, required area per compartment, and the susceptibility probability distributions along the longitudinal and transverse direction. Vulnerability per compartment uses the same values as were defined in the allocation phase, and the relationships among compartments are divided into adjacency condition (1), separation condition (−1), and none (0). The compartments to which the adjacent conditions are applied include naval artillery and

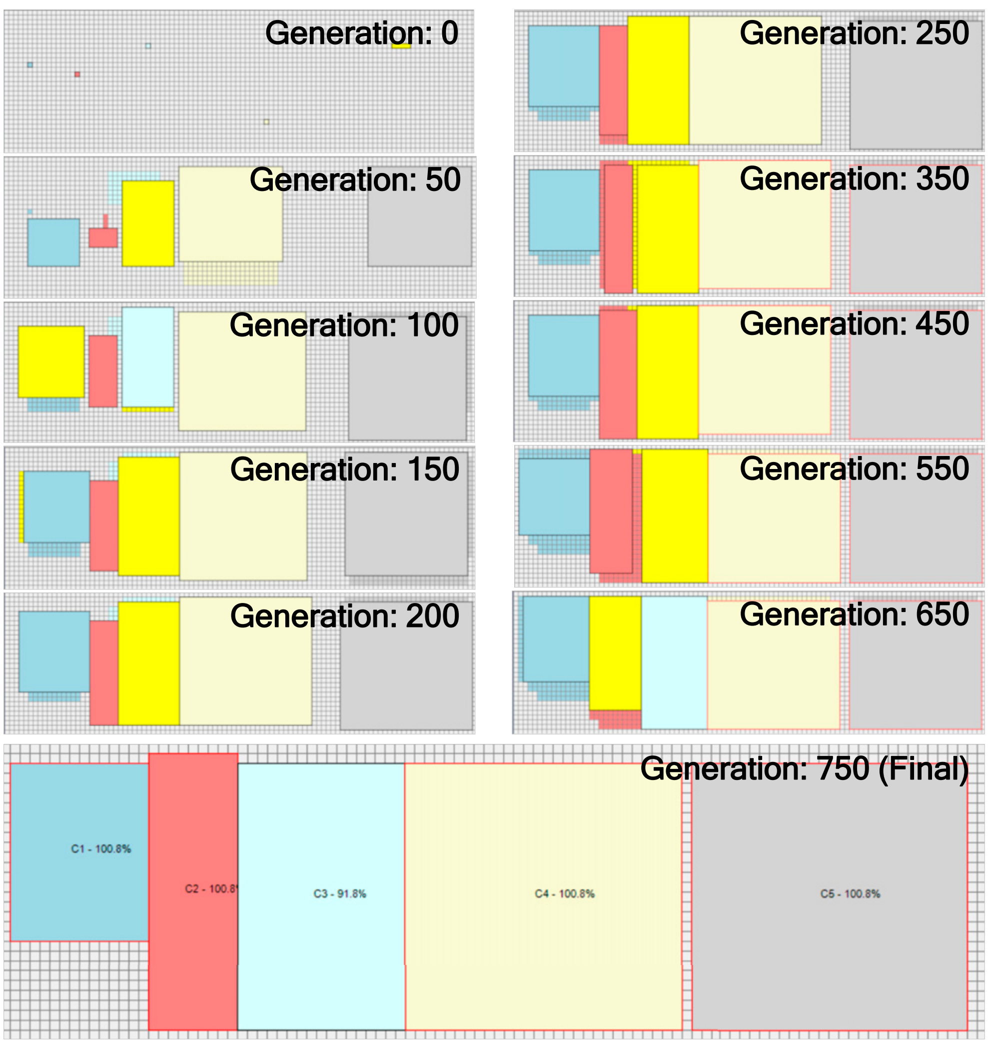


Fig. 8 Compartment shape and positioning results using SGA

ammunition compartments, crew bedrooms and dining rooms, and the compartments to which the separation conditions are applied include crew living spaces and noisy spaces such as the engine room.

Figure 8 shows the SGA implementation process and results when the conditions of Table 2 and the susceptibility probability distribution per location of the target zone-decks are entered as shown in Fig. 9. The susceptibility probability of Fig. 9 is a result of visualizing the value of longitudinal susceptibility probability (part of a normal distribution function) and transverse susceptibility probability (U-shaped function) shown in Fig. 3 by multiplying them as shown in equation (12).

In the result of the zeroth generation marked on the upper left corner of Fig. 8, the seeds of compartments C01–C05 are arranged in order from the left. The location of the seed of each compartment along the length was determined by the ratio of the required area, and the location in the width direction was determined randomly. The program developed in this study marks the compartments selected for growth in each generation in yellow, and if the current area of the compartment is 90–110% of the required area, the outlines are marked in red. When the required areas are attained, the selection probability of the growth direction is changed so that growth is discontinued and compartments only move in parallel. Thus, as generations pass, the locations of compartments change, rather than their geometry. The results located at the bottom of Fig. 8 were obtained by repeating the SGA 750 times, and prove that all compartments achieved their required areas. Eventually, compartment arrangement results are assessed by combining assessment factors considering the relationships factors among compartments, survivability assessment factors, and the geometric assessment factors such as achievement of the required areas.

By inspecting the results in detail, it can be confirmed that compartment C05, whose vulnerability is high, is located near the stern, where the probability of susceptibility is the lowest. Also, according to the adjacency and separation condition defined in Table 2, compartments C01–C02, C01–C03, C02–C03, and C04–C05 get a higher assessment value when they are closer to each other, and compartments C03–C04, C03–C05 get a higher assessment value when they are located far away from each other. Comparing with the final arrangement result, we can confirm that most of the conditions are met, except the C01–C03 adjacency condition and C03–C04 separation condition. All the conditions may not be satisfied, because the adjacency and the separation conditions were used as assessment factors, not as constraints. If there are must-satisfied adjacency conditions and separation conditions, we can resolve the problem by defining them as constraints.

Different arrangement results can be produced even when the arrangement using the SGA starts from the same location of the seed. This study created multiple seeds for a single arrangement problem, and compared and assessed the arrangement results created by applying SGA to each seed. This method was applied to the differential evolution algorithm to identify the optimal arrangement alternative. This section verifies the utility of the proposed method by comparing the results obtained from the same location of the seed.

Figure 10 shows the results of input data per compartment defined in Table 2 and applying the SGA according to the susceptibility probability in Fig. 9. The SGA was applied a total of five times, and each result is the final outcome of performing SGA 750 times. The input order of the seeds was maintained the same: C01–C02–C03–C04–C05. As mentioned previously, different results were produced even though the location of the seeds were the same; in some cases, the algorithm failed to achieve 80% of the required area for the compartments. Table 3 shows the assessment of dividing the results produced by the SGA into geometric factors, relationship factors, and survivability factors. In this table, the total score and subtotal score of each factor are shown in bold, and case 3 with the highest score is shown in gray. The method to assess geometric factors and relationship factors was based on the method of assessing the arrangement of the ISA algorithm, and survivability factors were assessed based on the method proposed in Section 3. Each assessment factor was constructed to produce a value between .0 and 1.0 using fuzzy functions.

Table 3 shows the minimum value per compartment for each assessment factor and the relevant compartment. For example, the required area achievement of case 1 produced a minimum value of .295 in C01 compartment, and the adjacency condition among compartments produced a minimum value of .911 in both the C02 compartment and the C04 compartment. In the results of Table 3 and Fig. 9, the quantitative assessment result of case 1 is the lowest.

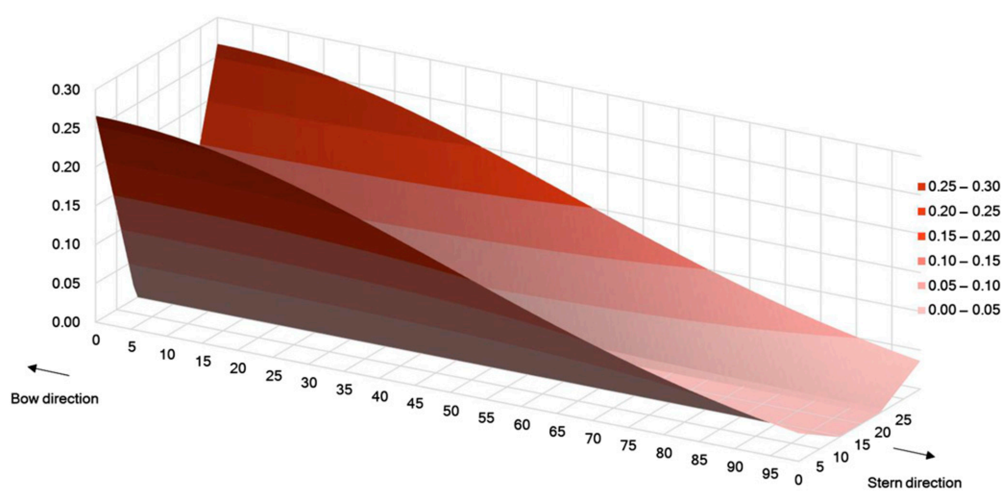


Fig. 9 Susceptibility probability of the target zone-deck

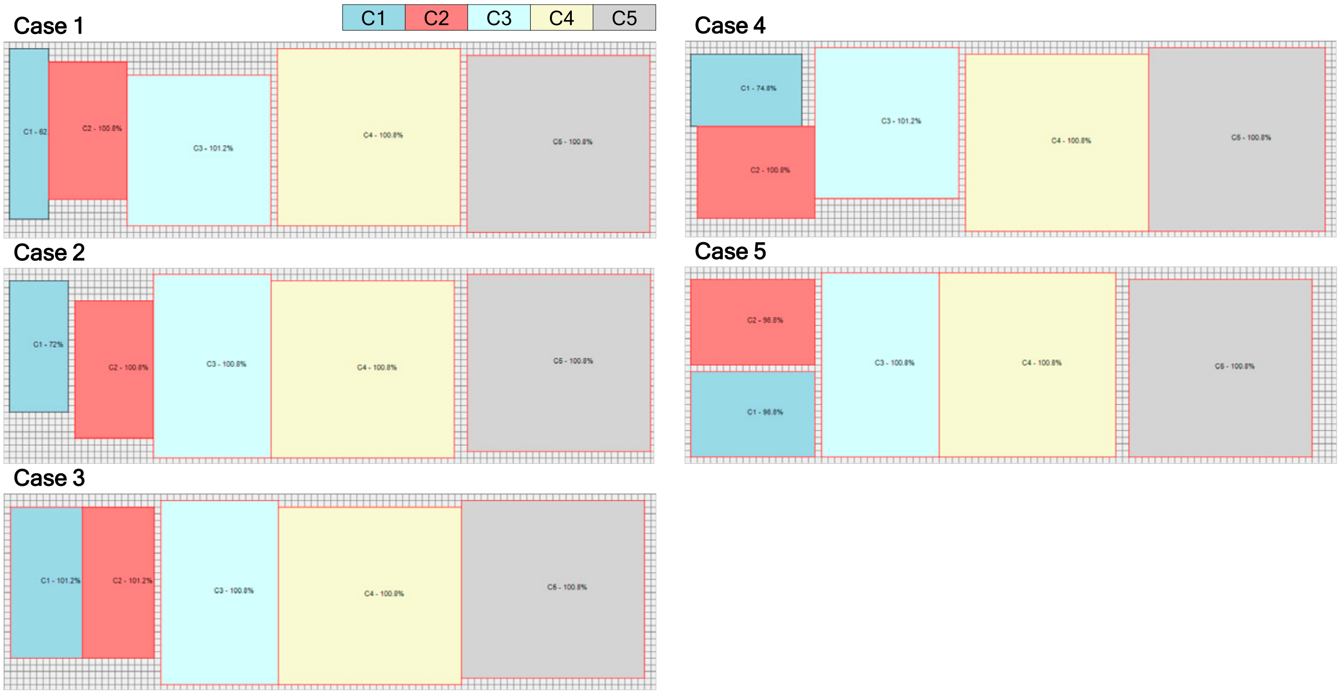


Fig. 10 Arrangement optimization results using SGA (shape and position)

The reason is that the required area achievement of the compartment is too low to get a normal score. And from the viewpoint of the geometry, the aspect ratio of the compartment is larger than normal compartments. Moreover, the survivability assessment results for all cases showed high values in excess of .9, which is because the compartment with high vulnerability is arranged at the stern where the susceptibility probability is relatively low. The overall assessment result was calculated by multiplying the minimum values of the survivability assessment factor, the geometry assessment factor, and the relationship assessment factor. Case 3, which generally has good arrangement results, showed the highest assessment results. When applying the optimization algorithm using the differential evolution algorithm, it was implemented in such a way that the optimal arrangement alternatives are deduced using quantitative assessment of arrangement alternatives.

5. Conclusions

This study developed an optimization program for naval vessel spatial layout considering vulnerability under attacks based on the ISA algorithm. The ISA algorithm performs naval vessel spatial layout by dividing the process into allocation and arrangement phases, and the optimization algorithm proposed in this study follows the same approach. However, this study added survivability assessment factors considering vulnerability to the objective functions, and proposed a mathematical model that can quantitatively assess survivability in the allocation and arrangement phases.

Furthermore, this study proposed an optimization algorithm for a spatial layout problem by applying the differential evolution algorithm that uses an evolutionary approach. In the allocation phase, optimal allocations were obtained by considering location preferences, compartment relationships, and survivability. In the arrangement phase, optimal arrangements were obtained by considering the geometry factors, relationship factors, and survivability factors of the compartments. In particular, the geometry and location of compartments were determined based on an SGA in the arrangement phase, which allowed more various alternatives to be generated.

Finally, to verify the effectiveness of the proposed method, the results were analyzed by defining example allocation and arrangement problems. The analysis demonstrated that allocation alternatives that satisfy the intention of the designer can be obtained, including allocation alternatives that simultaneously consider

Table 3 Arrangement optimization results using SGA

		Geometry				Relationship			
	Survivability	Area satisfaction	Aspect ratio	Minimum overall dimension	Min.	Adjacency	Separation	Min.	Total
Case 1	**.951**	.295 (C01)	.038 (C01)	.038 (C01)	**.038**	.911 (C02–C04)	.953 (C01–C04)	**.911**	**.033**
Case 2	**.951**	.485 (C01)	1.000 (—)	1.000 (—)	**.485**	.934 (C02–C04)	.952 (C01–C04)	**.934**	**.431**
Case 3	**.949**	1.000 (—)	1.000 (—)	1.000 (—)	**1.000**	.931 (C02–C04)	.952 (C01–C04)	**.931**	**.883**
Case 4	**.946**	.541 (C01)	1.000 (—)	1.000 (—)	**.541**	.911 (C02–C04)	.951 (C01–C04)	**.911**	**.466**
Case 5	**.945**	1.000 (—)	1.000 (—)	1.000 (—)	**1.000**	.930 (C02–C04)	.951 (C01–C04)	**.930**	**.880**

multiple factors. Furthermore, applying the SGA in the arrangement phase was found to produce different results for the same seeds. It was also found that arrangement results can be quantitatively assessed by considering geometry factors, relationship factors, and survivability factors.

The optimization program for naval vessel spatial layout considering vulnerability under attacks has significance in that it quickly creates various layout alternatives considering survivability with basic information of naval vessels, which had not been considered in spatial layout in the initial design phase of naval ships, and also it proposes improved layout alternatives. Future research will complement the survivability assessment method and develop programs applying three-dimensional spatial layout optimization algorithms by integrating the allocation and arrangement phases.

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