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Multi-criteria route planning with risk contour map for smart navigation

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ABSTRACT

Route planning in maritime transportation is the key to safe, efficient, and smart navigation. We propose a multi-criteria route planning technique for operators to objectively determine the routes according to their intentions. In this study, the navigational traffic risk of a route is quantitatively assessed using a model of a ship. Then, a risk contour map is visualized by structuring the data as absolute danger, hazard factors, and influential factors, which is a framework for route planning. Finally, a multi-criteria route could be modeled by considering the safety, efficiency, convenience, and ability of navigation as the main criteria. The technique assesses each criterion by analyzing the cumulative risk per distance, distance, number of waypoints, and risk gradient of derived routes. In addition, the technique proposes routes by utilizing its algorithm and incorporating contour-based projection and reference points. To verify the proposed technique, we carried out numerical simulations and evaluated actual AIS data. The results show that this technique can not only suggest goal-oriented routes but also assess the used routes. Therefore, the proposed technique can improve the route planning method to be more systematic, which contributes both to smart navigation based on the user's purposes and to future autonomous navigation.

1. Introduction

Among various transportation modes, maritime transportation comprises a significant portion, not only in Korea but also worldwide (Equasis, 2016; United Nations, 2017). To operate vessels through maritime navigation, their routes should be appropriate and reasonable based on the requirements of operators. Even if the primary objectives of routes are slightly different from each other, the routes must typically avoid any risky areas to prevent accidents such as groundings, save distances to destinations if possible, and consider the characteristics of vessels, operators, and surrounding situations.

However, route planning, that is, the procedure of designing and creating an appropriate route, is empirically carried out by on-scene experts such as captains and second mates (Swift, 1993; Lee et al., 2018). However, their qualitative, experience-based, and subjective approaches to planning routes can be limited. Indeed, officers in charge of route planning are frequently observed to follow what their predecessors have developed and what the captain asks them to do, or they slightly modify routes without using any detailed, verifiable, and objective method. One of the major problems caused by this conventional approach is that unless any accidents occur, nobody would recognize the risk or the problem. Additionally, despite the numerous available route planning methods, the efficiency-based method receives the most focus (Andersson, 2015; Bijlsma, 2001, 2002, 2004; Guinness et al., 2014; Jeon, 2018; Kang et al., 2015; Kobayashi et al., 2011; Lee, 2005; Lee et al., 2018; Roh, 2013; Vettor and Soares, 2016; Yoo et al., 2015; Yoo and Kim, 2016; Szlapczynski, 2005, 2011), which consider a prerequisite for navigation, i.e., safety, to a lesser extent. More seriously, officers do not appear to have a specific standard to determine the distance at which a ship is considered to safely pass by obstructions, shorelines, and other hazards. Moreover, finding authorized publications or guidelines for route planning is difficult. Therefore, the operators only refer to vague expressions such as substantially far, adequately safe, and in ample time (International Maritime Organization, 1999). Consequently, numerous navigational traffic accidents occur because of inappropriate route planning because the standards for route planning vary considerably depending on individuals (European Maritime Safety Agency, 2017; Mazaheri, 2009; Mazaheri et al., 2015; Pedersen, 2010). In this vein, recent reports have also emphasized that contextual geographic data and information from various sources

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Table 1
Summary of related works.

Category of main focus										Phase of navigation				Related works
Efficiency and economy						Safety				Inland	Harbor	Coastal	Ocean	
Distance	Fuel	Time	Cost	Course change	Weather	Distance	Collision avoidance	Obstacle avoidance	Depth					
	✓	✓			✓								✓	Bijlsma (2001, 2002; 2004)
✓												✓		Lee (2005)
				✓				✓			✓	✓	✓	Szlapczynski (2005)
							✓	✓		✓	✓	✓		Larson et al. (2006)
	✓				✓								✓	Kobayashi et al. (2011)
✓							✓				✓	✓	✓	Szlapczynski (2011)
	✓				✓								✓	Roh (2013)
			✓					✓				✓		Guinness et al. (2014)
	✓	✓			✓								✓	Andersson (2015)
✓	✓	✓							✓			✓		Kang et al. (2015)
	✓				✓								✓	Yoo et al. (2015)
					✓								✓	Yoo and Kim (2016)
	✓	✓											✓	Vettor and Soares (2016)
✓	✓	✓											✓	Lee et al. (2018)
							✓					✓		Jeon (2018)
✓	✓		✓		✓							✓	✓	Eniram (2018)
	✓		✓										✓	LG CNS (2018)
✓	✓	✓	✓		✓							✓	✓	StormGeo (2018)
✓	✓	✓	✓		✓							✓	✓	Weathernews (2018)

should be considered in order to correctly understand the circumstances and make a better decision. In particular, data and information related to meteorological, oceanographic, and user-related datasets have become necessary for calculating and planning alternative routes for vessels (Riveiro et al., 2018).

In this study, we developed a multi-criteria planning technique to plan a route that satisfies the purpose of a navigator and ensures the smart navigation of a vessel in the corresponding circumstances. First, the navigational traffic risk of a vessel's route is assessed using a model of a ship. Then, a risk contour map is visualized by structuring data such as absolute danger, hazard factors, and influential factors, which is used as a framework for the route planning. Finally, the multi-criteria route planning could be modeled by considering the safety, efficiency, convenience, and ability of navigation as the main criteria for route planning. This technique assesses each criterion by analyzing the cumulative risk per distance, distance, number of waypoints, and risk gradient of the derived routes. The technique then proposes multi-criteria routes by utilizing its algorithm and incorporating contour-based route projection and a combination of reference points. To confirm the effectiveness and applicability of the proposed technique, we numerically simulated case studies and evaluated actual automatic identification system (AIS) data for the modeled ship on the west coast of Korea. The results show that the proposed technique can suggest multi-criteria routes in accordance with a user's intentions and quantitatively assess the current routes used by vessels based on various criteria of interest.

Hence, this study presents a novel and significant contribution to the literature as well as a practical application. Specifically, this study can improve a user's cognitive ability to assess risk by visualizing risk using contour lines, thus shifting the risk paradigm from formerly invisible, discrete data to visible, continuous curves. Furthermore, the proposed technique can plan routes and support objective decision making to meet a user's requirements in the corresponding circumstances, in contrast with conventionally qualitative and empirical methods. Thus, the proposed technique can be used by a navigator to plan a fit-for-purpose route.

The rest of this paper is organized as follows: Section 2 systematically reviews related works to gather necessary information and analyzes the focus of existing works to develop the proposed novel approach. Section 3 introduces risk contour mapping as the framework of multi-criteria route planning. The detailed technique and process underlying the multi-criteria route planning are described in Section 4 as the core part of this study. Section 5 discusses the results and applications, and finally, concluding remarks and the directions for future work are presented in Section 6.

2. Related work

2.1. Phase of navigation and route planning

There are four phases of navigation that must be determined. In general, the criteria for determining the phase of navigation comply with standards set by the International Association of Marine Aids to Navigation and Lighthouse Authorities (2018) and the National Imagery and Mapping Agency (2002). First, the inland waterway phase is for piloting through canals, channels, and rivers. Second, the harbor/harbor approach phase is for navigating around harbor entrances and approach channels. Third, the coastal phase is for navigation within approximately 50 miles of a coast or within a depth of 200 m around a shoreline. Lastly, the ocean phase is for navigation outside a coastal area at open sea. Determining the phase is particularly important because the scope and method of route planning depends on the phase of navigation.

Then, the route planning is performed, which is a sequential process to assess, design, plan, execute, and monitor the route for operating the vessel. This process is also categorized into four phases: the appraisal, planning, execution, and monitoring phases (International Maritime Organization, 1999; National Imagery and Mapping Agency, 2002; Swift, 1993). The appraisal phase is one of the most important phases, because it should both include the risk assessment and provide abundant data to a navigator. The planning phase refers to planning, plotting, and designing a ship's route from the start to the destination, helping the ship to prevent accidents by minimizing risk and navigating efficiently by reducing distance and fuel consumption. The execution and monitoring phases are to evaluate and monitor both the ship being operated by the plan and its compliance.

2.2. Ship route planning studies

Several previous works have investigated route planning using diverse methods under different scopes. Here, they were systematically reviewed based on the main focus of the route planning and the applied phase of navigation. Table 1 shows the categorization and specific details of the studies. The main focuses of the studies are divided into two categories, according to the ultimate goal of the proposed methods, namely, efficiency and safety. Furthermore, the route planning methods that focus on efficiency consider the following factors: distance, fuel consumption, time required, expected cost, and weather effects. The route planning methods that focus on safety mainly deal with avoiding other ships or obstacles.

In efficiency-oriented studies, dynamic programming and the Bolza problem were used to minimize fuel consumption in an ocean passage (Bijlsma, 2001, 2002, 2004). A genetic algorithm was used by Lee (2005) for determining the optimal distance in the ocean phase and by Lee et al. (2018) for optimizing fuel consumption and speed. Szlapczynski (2005) focused on avoiding obstacles and encounters with other ships as well as minimizing course changes (Szlapczynski, 2011). A route for autonomous navigation including the collision avoidance or obstacle avoidance of unmanned surface vehicles was proposed by Larson et al. (2006). The relationship between fuel consumption and weather routing was examined in the ocean phase by Kobayashi et al. (2011) and Roh (2013). A route through icy conditions in the Baltic Sea was optimized using the associated cost function while avoiding floating ice (Guinness et al., 2014). A grid search approach was adopted to design routes that separately minimize time, wave height, and fuel consumption (Andersson, 2015). Kang et al. (2015) found a route by considering depth triangulation, fuel consumption, and time in a coastal area. Yoo et al. (2015) provided comparative results through weather routing simulations using a great-circle route. Ocean currents were mainly considered to optimize paths based on machine learning (Yoo and Kim, 2016). Vettor and Soares (2016) studied weather routing to save fuel and time. The past transit data of ships were collected and analyzed to determine a route that prevents the risk of collision in the coastal sea (Jeon, 2018).

Analyzing these related works revealed that most route planning methods and algorithms were related to making routes more efficient. In other words, they focused on reducing distance, required time, fuel consumption, and associated costs based on weather routing. The same tendency was also identified in commercially developed programs that used the Energy Efficiency Operational Indicator (Eniram, 2018; LG CNS, 2018; StormGeo, 2018; Weathernews, 2018). However, the suggested routes are not necessarily the best route in terms of the navigator's intentions. In addition, these works were limited in that they considered safety as a subsidiary factor or assumed the establishment of safety before the application of their methods. Moreover, the routes worked only when a ship was confronted with obstacles and did not preemptively set courses during the planning phase. Therefore, they do not propose fit-for-purpose routes that satisfy user requirements depending on the situations.

In this study, using the basic concepts mentioned above, a route planning technique is proposed to determine multi-criteria routes during the appraisal and planning phases. We focus on the coastal phase because the navigational traffic risks fluctuate widely there due to topographical and sea conditions. The route planning technique considers four criteria, which are defined as the safety, efficiency, convenience, and ability of navigation to satisfy diverse user requirements.

3. Risk contour mapping framework

3.1. Scope of study

3.1.1. Study area (Janganseo)

A specific area should be selected to assess navigational traffic risk and to apply and evaluate the effectiveness of the proposed route planning technique. The selected area is 'Janganseo' (as shown in Fig. 1), which is one of the busiest regions near large Korean ports such as Daesan, Pyeongtaek, Dangjin, Incheon, and Taean ports (Kim et al., 2013; Korea Hydrographic and Oceanographic Administration, 2018). In particular, this study concentrated on the area close to the Janganseo pilot station to effectively perform experiments and validate results. Another reason for selecting this region is that it has no specific traffic lane or scheme; thus, it is appropriate for testing the route planning technique without any predetermined direction of a route.

3.1.2. Model of the ship

A liquefied natural gas (LNG) ship is selected as a representative model of a ship for this study because LNG ships are one of the largest, most frequently observed ships. In addition, LNG ships require the highest safety considerations. The specific ship modeled here is a 135 K LNG carrier, which currently occupies the largest portion of the LNG fleet managed and operated by the Korea Gas Corporation (Javanmardi et al., 2006). Table 2 lists its specifications.

3.1.3. Navigational traffic risk

This study defines navigational traffic risk as the probabilistic risk associated with navigational accidents such as grounding, contact, capsizing, and sinking, resulting from stationary obstacles (Jeong et al., 2017; Kristiansen, 2005; Ulusçu et al., 2009). Thus, other ships or moving objects are not considered because the route planning technique developed in this study focuses on the phases of appraisal and planning. In addition, as the objective of risk assessment is to ensure a ship's safety by not entering a risky area to prevent accidents, the consequential factor of risk is assigned as a constant (Zhen et al., 2017).

3.2. Formulation of risk assessment

3.2.1. Design variables in the assessment area

The variables to be assessed for navigational traffic risk should be identified and analyzed based on previous studies, past accident records, and expert opinions (International Association of Marine Aids to Navigation and Lighthouse Authorities, 2009; International Maritime Organization, 2002; Jebsen and Papakonstantinous, 1997; Kim and Lee, 2012; Korea Maritime Safety Tribunal, 2018; Lee and Kim, 2013; Lin, 1998; PIANC, 2014; Swift, 1993). The variables in the target area can be structured by analyzing and evaluating the data using an electronic navigational chart (ENC), as shown in Fig. 2. A unit assessment area was designated by the definition of the position fixing interval, which is the standard that a ship does not run into a danger during the interval between fixes (Oil Companies International Marine Forum, 2016). Therefore, the shape of the unit area is circular, as shown in the navigational risk assessment stage in Fig. 2. In this study, the applied position fixing interval was 6 min based on the speed and topographical conditions of the area.

In the risk data structure shown in Fig. 2, the absolute danger is the non-navigable area according to a ship's maximum draft including squat and its margin. The hazard factor (in the navigable area), which is related to the hazardous depth and the obstacles, refers to a stationary hazard. The hazardous depth is the minimum water depth within the navigable area of the unit area. Artificial obstacles are typically man-made objects and structures, whereas natural obstacles are naturally created. Finally, the influential factor stands for the sea conditions that indirectly affect an accident (Jeong et al., 2018).

3.2.2. Navigational traffic risk

The assessment of navigational traffic risk for route planning can be described by Eq. (1),

$$NTR_i = f(area_i) = [H_{i,water} \quad H_{i,obstacle}] \begin{bmatrix} A_{i,water} \\ A_{i,obstacle} \end{bmatrix} \cdot \omega_{i,sea\ condi} \tag{1}$$

where NTR_i is the navigational traffic risk in an area i, the subscript i is the area identification number, $H_{i,water}$ is the hazard index derived from the water depth and draft, $H_{i,obstacle}$ is the hazard index derived from the obstacle, $A_{i,water}$ is the geometric weight coefficient for the non-navigable area, $A_{i,obstacle}$ is the geometric weight coefficient for the domain of the obstacle, and $\omega_{i,sea\ condi}$ is the weight coefficient of the influential

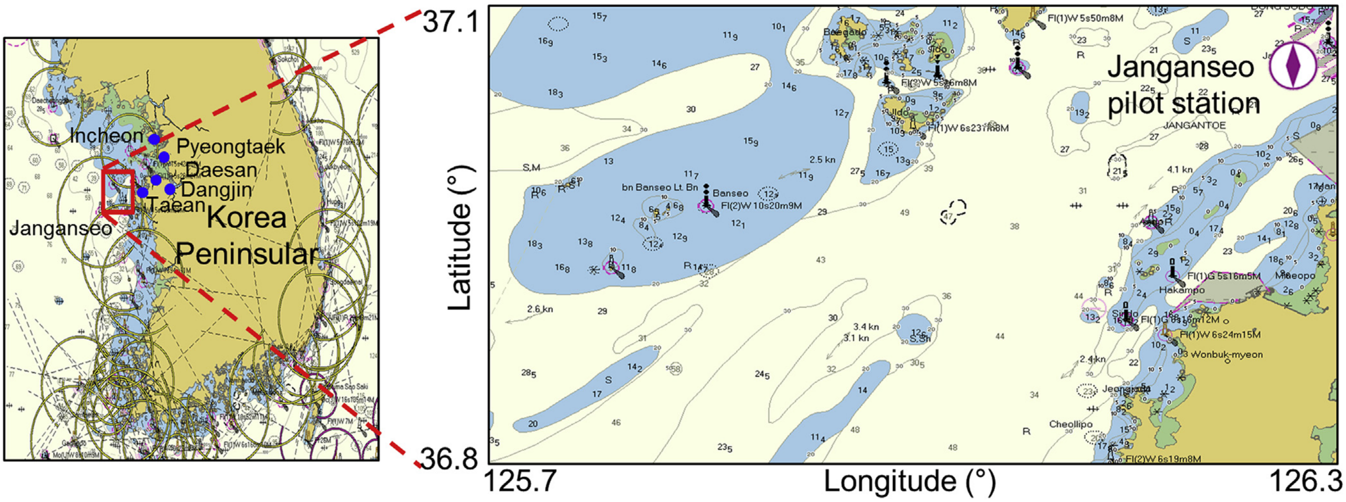

Fig. 1. Model of the study area in Janganseo for assessing navigational traffic risk and applying route planning technique. The location is on the west coast of Korea and near major ports such as Daesan, Pyeongtaek, Dangjin, Incheon, and Taean.

Table 2
Specifications of the modeled ship.

Item	Specification
Type	135 K Class LNG
Length overall(L.O.A) [m]	288.77
Breadth [m]	48.2
Gross Tonnage	113,998
Draft [m]	11 Even Keel
Block Coefficient	0.68
Proceeding Speed [knots]	15

factor.

Each variable is evaluated using a matrix of hazard and influential factors (as shown in Table 3), where h is the minimum depth [m], D is the maximum draft of a ship [m], c is the speed of current [knots], and V is the speed of a ship [knots]. Thus, the default value of the NTR index without $\omega_{i,sea\ condi}$ ranges from 1 to 20. After including influential factors, NTR is fully quantified in consideration of all factors.

3.2.3. Assessment of hazard factor

In Table 3, the hazardous depth is determined by comparing the ratio of the ship's draft to the minimum depth from the ENC. However, the obstacle cohesion should be calculated through a geometric analysis, which includes the number of obstacles and shows the cohesion characteristics in the unit area, as described in Eq. (2),

$$cohesion_i = \frac{1}{n}\sum_{P(x,y)\in area_i} proximity(P,\ C) = \frac{1}{n}\sum_{P(x,y)\in area_i}\sqrt{(x - x_{i,c})^2 + (y - y_{i,c})^2} \quad (2)$$

where $cohesion_i$ is the obstacle cohesion in $area_i$, n is the number of obstacles in the area, P is the position of an obstacle in the area expressed as (x,y), and C is the position of the centroid in the area expressed as $(x_{i,c},y_{i,c})$. Note that the unit of obstacle cohesion is [%F], where F is the position-fixing interval defined as the radius of the unit area (which is a circle). The obstacle cohesion represents the characteristics of the inter-obstacle distance.

In Eq. (1), $A_{i,water}$ can be calculated by the ratio of the non-navigable area to the unit area, which is expressed as the incremental percentage weight. $A_{i,obstacle}$ can be calculated in the same manner if obstacles are polygonal. However, it can be calculated by the ratio of the domain to the unit area, if obstacles are points, such as buoys and wrecks. The domain of the obstacle is defined using the concept of the safe distance, which represents the marginal distance area inside which a ship should not be present. This is determined by the overall length of the ship through the review of studies and a survey of experts (Inoue, 2013; PIANC, 2014; Pietrzykowski and Uriasz, 2009).

3.2.4. Assessment of influential factors

Influential factors are computed by determining the effects of sea conditions on navigational traffic accidents based on an analysis of past data from 2011 to 2017 (Korea Maritime Safety Tribunal, 2018). Therefore, three principal parameters, namely, wind, current, and visibility, were found to affect the occurrence of accidents. Among 786 cases, 631 cases were not related to the sea conditions, whereas 155 cases were influenced by the sea conditions (as shown in Table 4). Accordingly, these three influential factors are reflected by the calculation of $\omega_{i,sea\ condi}$ using Eqs. (3) and (4) from previous studies that calculated the effect of sea conditions (Bialystocki and Konovessis, 2016; Jeong et al., 2018),

$$\omega_{sea\ condi}^{max} = 1 + \frac{num_{total} - num_{net}}{num_{net}} = 1 + \frac{num_{diff}}{num_{net}} \quad (3)$$

where $\omega_{sea\ condi}^{max}$ is the nominal maximum weight coefficient of an influential factor, num_{total} is the total number of navigational traffic accidents during the period, num_{net} is the net number of the navigational traffic accidents not affected by sea conditions, and num_{diff} is the difference between the total number and net number of navigational traffic accidents.

$$\omega_{i,sea\ condi} = 1 + \frac{1}{100}\cdot[\rho_{wind}\ \ \rho_{current}\ \ \rho_{visibility}]\begin{bmatrix} S_{i,wind} \\ S_{i,current} \\ S_{i,visibility}\end{bmatrix} \quad (4)$$

where ρ_{wind}, $\rho_{current}$, and $\rho_{visibility}$ are the portions of wind, current, and visibility among influential factors, and $S_{i,wind}$, $S_{i,current}$, and $S_{i,visibility}$ are the index of wind, current, and visibility among influential factors, respectively, as shown in Table 3.

After analyzing 786 cases from the abovementioned historical data from 2011 to 2017 (Korea Maritime Safety Tribunal, 2018), the portion indexes provided in Table 4 were calculated by multiplying each ratio by a constant of 4.91 to match $\omega_{sea\ condi}^{max}$ according to Eq. (3), wherein $S_{i,wind}$, $S_{i,current}$, and $S_{i,visibility}$ are 5, the highest possible value.

3.3. Risk contour mapping model

3.3.1. Risk contour

Contour lines are widely used in diverse areas such as topographic

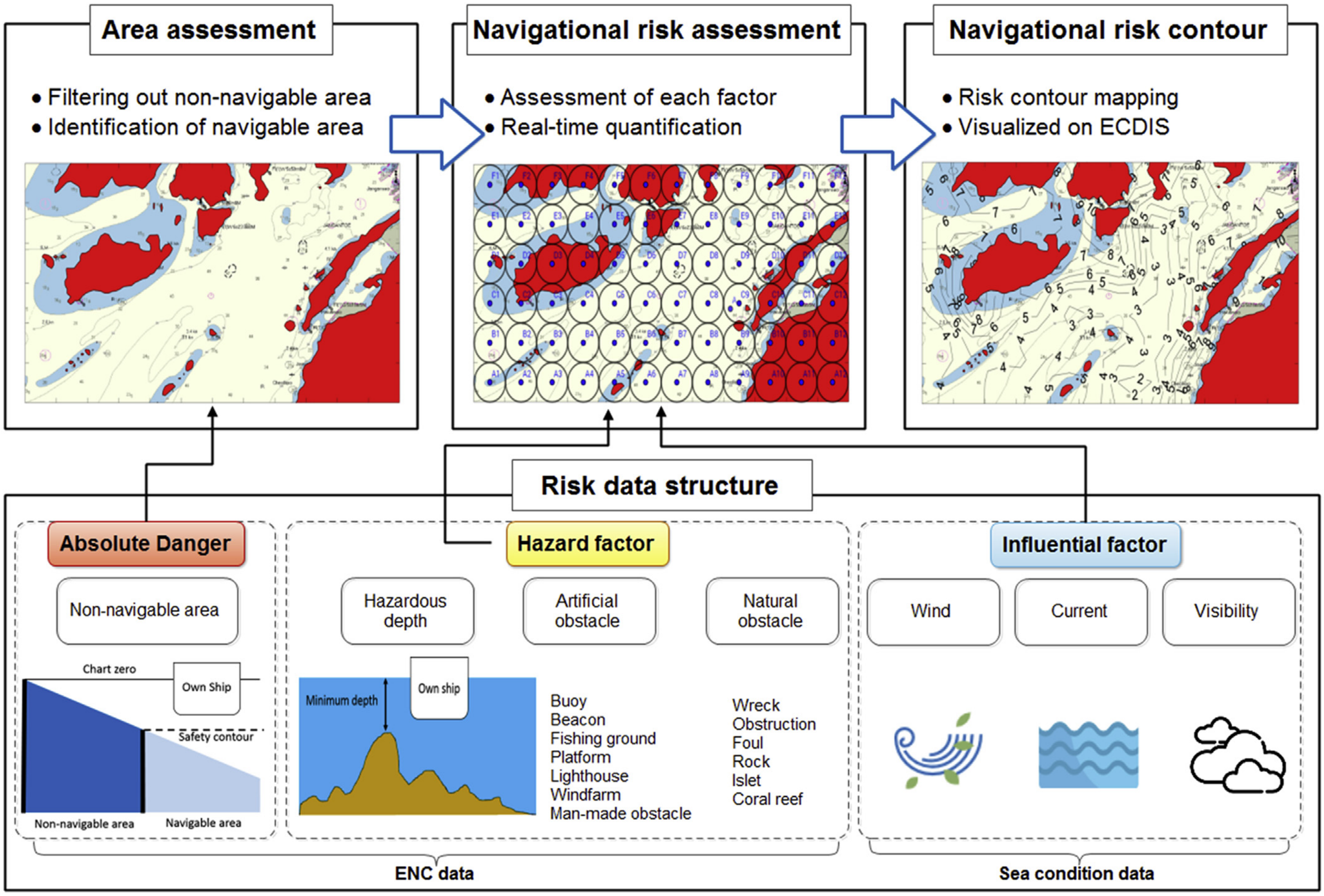

Fig. 2. Risk data structure through ENC and sea conditions and a flowchart of the navigational risk contour mapping. The risk data as variables are composed of absolute danger, hazard factors, and influential factors. During the area assessment, non-navigable areas are filtered out. During the navigational risk assessment, each factor is reflected to quantify the risk index. The levels of navigational risk are visualized as contours on a contour map.

maps, barometric pressure, magnetic field, and oceanographic bathymetry (Casola and Wallace, 2007; Chen et al., 2004; Cronin, 1995; Li and Liu, 2010). Similarly, we developed novel risk contour mapping technique to enable a ship operator not only to identify the distribution of navigational traffic risk in a transit area but also to conduct the smart navigation of a vessel by utilizing risk contours (Jeong et al., 2017, 2018). After the risk assessment, a risk contour is visualized as a two-dimensional equal curve that connects areas with the same risk through interpolation.

3.3.2. Procedure of mapping model

Risk contour mapping is a sequential process consisting of geometric and spatial analysis, risk assessment, and the visualization on the ENC based on essential risk data structures, as shown in Fig. 2. The process consists of the following steps: First, data are received via the ENC in connection with equipment, and they are identified and structured according to their category. Second, the non-navigable area is identified and filtered out by assessing the transit area. Then, the navigational traffic risk in each unit area is assessed. Finally, risk contours are mapped and visualized on the ENC.

Table 4
Analysis of navigational traffic accidents from 2011 to 2017.

Traffic accident data	num_{total}	num_{net}	num_{diff}
Number of accidents	786	631	155
$\omega_{sea\ condi}^{max}$	1.2456		
Category of influential factor	Wind	Current	Visibility
Number of accidents due to weather	99	37	19
Ratio	0.6387	0.2387	0.1226
Portion index (ρ_{wind}, $\rho_{current}$, $\rho_{visibility}$)	3.1373	1.1725	0.6021

3.3.3. Expected value of model

An example of a visualized risk contour map is shown in the last

Table 3
Matrix of hazard factors and influential factors.

Parameter		Type	Rating 1	2	3	4	5
$H_{i,water}$		Hazardous depth (h/D)	≥3.0	< 3.0	< 2.0	< 1.5	< 1.2
$H_{i,obstacle}$		Obstacle cohesion	≥80 %F	< 80 %F	< 60 %F	< 40 %F	< 20 %F
$\omega_{i,sea\ condi}$	$S_{i,wind}$	Wind	< 3.3 m/s	< 8 m/s	< 14 m/s	< 21 m/s	≥21 m/s
	$S_{i,current}$	Current (c/V)	< 0.1	< 0.2	< 0.3	< 0.4	≥0.4
	$S_{i,visibility}$	Visibility	≥5.5 NM	< 5.5 NM	< 1.0 NM	< 0.486 NM	< 0.099 NM

stage in Fig. 2. The risk contours have a significant role and applicability. First, they represent distributed and dispersed data as continuous and connected information. In addition, risk contour mapping enables quantifying and visualizing important data that were previously invisible and intangible. Next, it can be applied to a navigator's decision making, such as route planning in accordance with the navigator's intentions, and the analyses of subsequent data obtained from the contour can broaden the applicability of the risk contours. The multi-criteria route planning technique, which is the core of this study, was developed by utilizing the abovementioned advantage of the model, as described in Section 4.

4. Multi-criteria route planning model

4.1. Design criteria of route planning

Based on an extensive literature review including technical references and previous studies, the main goals of route planning can be categorized into four main criteria, even if the specific requirements might vary depending on the respective studies. These four main criteria are the safety, efficiency, convenience, and ability of navigation, as shown in Fig. 3. They significantly influence planning routes among various options and for various purposes. In addition, we defined and developed particular standards to assess each criterion based on the risk contour map for quantitative analysis.

First, safety is the standard for how safe a route is to prevent navigational traffic accidents. Furthermore, efficiency refers to how efficiently a ship can be operated along a route without significant consumption of fuel. Next, convenience indicates the ease in maneuvering a ship without frequently altering course. Last, the ability of navigation refers to whether a ship and its navigator can perform a voyage along a route, and it is correlated to the risk gradient. The gradient of a mountain is an apt metaphor for the risk gradient. Selecting a route with a steep or gradual gradient when climbing a mountain depends on the ability and professionalism of a climber. Similarly, the ability of navigation differs between high and low gradients. A higher gradient is found to require a higher ability of navigation, e.g., it requires the assistance of additional operators including a master and a pilot, auxiliary equipment, and the experience and expertise of operators.

4.2. Assessment of criteria

In this study, we divided the criteria into a relative five-scale rating from very low to very high, as shown in Fig. 3. Using this concept, we can objectively compare routes and plan a multi-criteria route that

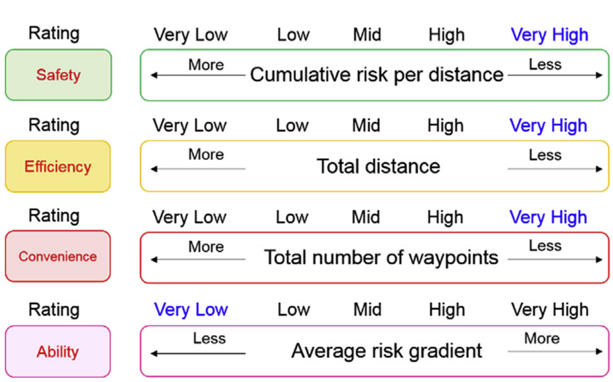

Fig. 3. Four main criteria, each assessed on a five-tier scale in the route planning technique using the measurement standards. Each criterion shows its ideal goal (blue), demonstrating that safety, efficiency, and convenience ratings are inversely proportional to the assessed value, while the ability rating is directly proportional. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

satisfies the purposes of navigators in the corresponding circumstances.

Safety is measured by the cumulative risk per distance along the suggested route on the risk contour plane, as described in Eq. (5),

$$Crd = \frac{\int_{P_{dep}}^{P_{arr}} NTR}{dist} \quad (5)$$

where *Crd* is the cumulative risk per distance, P_{dep} is the position of the departure point, P_{arr} is the position of the arrival point, and *dist* is the distance of the leg from P_{dep} to P_{arr}. As cumulative risk is inversely proportional to safety, a small value of cumulative risk implies a high safety rating.

Furthermore, efficiency is defined by the sum of the distance over an entire route. The distance is also inversely proportional to efficiency, and the rating method is the same as that for safety. Next, convenience is determined by the number of waypoints. The proportional relationship and rating method are the same as those for safety and efficiency. Last, the ability of navigation is determined by the average risk gradient along a route on the contour map, as described in Eq. (6),

$$Agr = \frac{\Delta NTR(P_{dep}, P_{arr})}{dist} \quad (6)$$

where *Agr* is the average risk gradient along a route and $\Delta NTR(P_{dep}, P_{arr})$ is the difference between the navigational traffic risk at P_{dep} and P_{arr}. As the gradient is directly proportional to ability, a small value of the average risk gradient implies a low rating of ability.

In summary, each criterion is measured on a five-tier scale by relative comparison between the minimum and maximum values among all proposed routes obtained by the route planning method. The safety, efficiency, and convenience ratings are inversely proportional to their assessed values, while the ability rating is directly proportional to its value. The ideal goal of each criterion is illustrated in blue in Fig. 3.

4.3. Contour-based route planning

The multi-criteria route planning technique was applied using algorithm codes developed in MATLAB, and it was run on a computer with a 3.30 GHz Intel Core i3 processor and 8 GB DDR4 RAM. Fig. 4 illustrates the flowchart of how route planning is based on multiple criteria depending on different situations, inputs, purposes, and other elements of navigators. The subsequent sections describe each component of the methodological model.

4.3.1. Defining navigational direction

After the risk contour map is visualized, the essential data for route planning should be initially inputted. A navigator defines the departure point, arrival point, acceptable risk, and principal data of a ship. According to the inputted data, the navigational direction used for determining the proposed route is defined. The pseudo-code for defining the navigational direction is expressed as Algorithm 1.

```
Algorithm 1: Define direction
Read   : Risk contour map on electronic navigational chart
Input  : P_dep, P_arr
Output : Quadrant of route direction to be proposed
  Define θ as direction of bearing from P_dep, P_arr
  Quadrant ← 0
  for n = 1 to 4 do
      if 90 * (n− 1) <= θ < 90 *n then
          mark Quadrant as n
      end
  end
  return Quadrant
```

The algorithm defines and returns the quadrant that contains the direction between P_{dep} and P_{arr}. Then, it is assumed that the direction of the proposed route should lie within this quadrant. Otherwise, there can be an infinite number of solutions to reach the destination, e.g.,

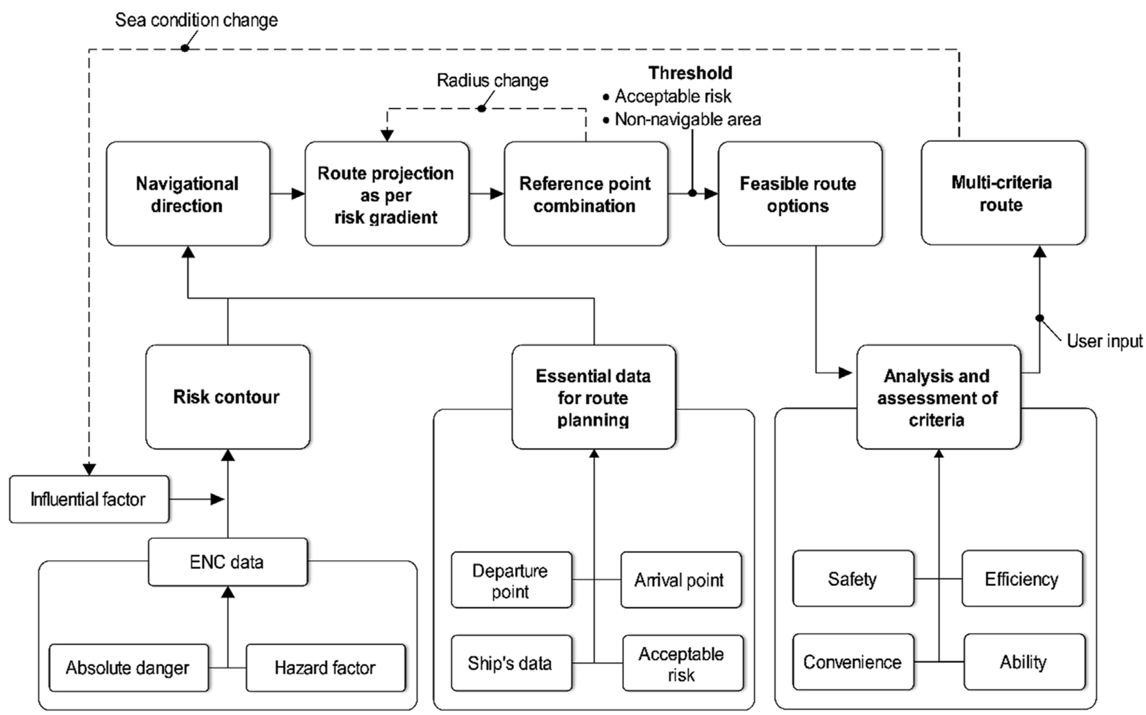

Fig. 4. Flowchart of the multi-criteria route planning process. The process is based on visualizing risk contours on a map as a framework for route planning, and essential data are input according to the circumstances. The procedure is followed by defining the navigational direction, projecting the ship's route according to the gradient, analyzing a combination of reference points, deriving feasible route options, analyzing and assessing the criteria, and finally suggesting a route.

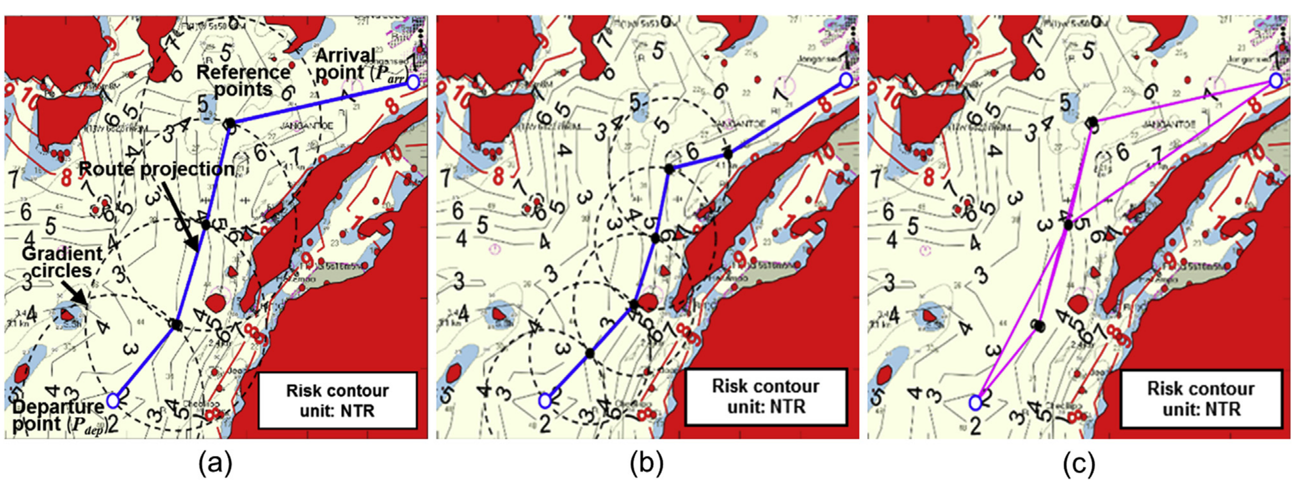

Fig. 5. Routes projected using an algorithm on the risk contour map of the study area: (a) radius of 4.5 NM as a risk gradient (b) radius of 3 NM as a risk gradient (c) combination case ($_3C_2$) among a total of three reference points in the case of a 4.5 NM radius as a risk gradient. NTR: navigational traffic risk.

courses from backward to forward and zig-zag courses. Such solutions are not reasonable when actually planning a route. For instance, Fig. 5(a) represents the navigating area for entering Pyeongtaek port expressed on the risk contour map, which visualizes P_{dep}, P_{arr}, the non-navigable area at a depth of 15 m (red polygons), and an unacceptable risk of 8 NTR (red contours). The values were calculated using the maximum draft including squats and default thresholds for the minimum margin. In addition, it was assumed that the route planning technique was performed with no influences from the tide or weather to propose and verify the method under the default conditions. P_{dep} was randomly selected as the position where ships enter, and P_{arr} was the pilot station of Janganseo. In this case, as the bearing from P_{dep} to P_{arr} lies in the first quadrant, the direction of the proposed routes and their subordinate segments should be within that quadrant. Therefore, the algorithm enables validating the technique regardless of the conditions or the location of P_{dep} and P_{arr}.

4.3.2. Ship's route projection

In this study, the route projection method was developed in accordance with how topographic engineers typically design a road or route in reality (Gu et al., 2015; Rogers, 2005). Engineers find intersections with the height contours of a mountain using a designated gradient up to a destination, and they find the possible routes that are appropriate for cases such as constructing roads and installing a network of lines between stations. However, in contrast with most studies, which used the contours of geographic information, this study adopted the novel risk contour visualization for creating a ship's route projection at sea.

A ship's preliminary routes were projected by the available risk gradients. In other words, upon calculating the displacement of risk

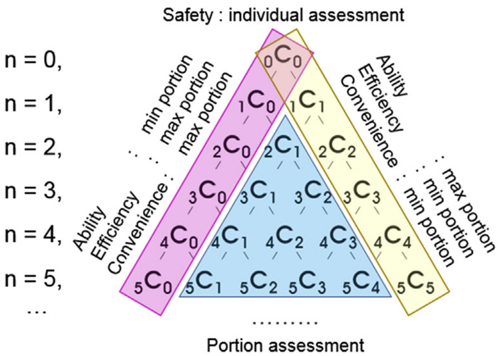

Fig. 6. Mathematical model of criteria in route planning using Pascal's triangle. For each row, indicating the number of reference points (n), the region is based on the desired portions of ability, efficiency, convenience and safety.

from P_{dep} to P_{arr}, the gradients were tested to confirm technical applicability, and thus, numerous values of *Radius* were simulated. The values of *Radius* were applied in consideration of the risk contour's interval, the distance between adjacent lines and the vessel's size and maneuvering characteristics. In addition, to derive each route segment on the preliminary route across the risk contour, the concept of the gradient circle was utilized, as described in Eq. (7) (Gu et al., 2015; Rogers, 2005),

$$Radius = {deltaRisk}/{Gradient} \tag{7}$$

where *Radius* is the distance between two adjacent risk contour lines as the radius of a circle, *deltaRisk* is the displacement of *NTR* between two adjacent lines, and *Gradient* is the intended risk gradient of the route.

As *deltaRisk* was fixed as a constant after the visualization of the risk contour, *Radius* depended only on *Gradient*. In addition, it was assumed that the changes in the risk value across the contours are continuous. As a result, the technique modeled the entire process of the route planning technique via numerical programming. The process of projecting the ship's route can be structured as follows:

1. From the departure point, draw a circle with *Radius* and find any intersection with the next adjacent risk contour.
2. If an intersection exists, mark it as a reference point, connect a segment line from the previous point and repeat Step 1 starting from the reference point. If no intersection exists, draw a line directly to the arrival point.
3. Finish the procedure until the last route segment ends at the arrival point and check the availability of the preliminary route.

Fig. 5(a) demonstrates the ship's route projection as a preliminary route based on the proposed process. In case of multiple intersections on the adjacent contour line, all options are considered by splitting the direction of the segments according to the intersections. Additionally, when there is no intersection in the middle of the process, the route segment directly reaches the arrival point. The extreme cases of *Radius*, such as too small or too large to have an intersection from the departure point, were excluded because the technical applicability was already tested at the beginning.

If another risk gradient is applied, the results would be different owing to different route projection. Fig. 5(b) shows the results obtained for a steeper gradient using circles with smaller *Radius*. The pseudo-code for the entire route projection process is expressed in Algorithm 2.

Algorithm 2: Make the ship's route projection

```
Read   : Risk contour map on electronic navigational chart
Input  : Gradient, Radius
Output : Route projection for corresponding Radius
Define i as label of each contour level from P_dep to P_arr
for Radius = minimum(Radius) to maximum(Radius) do
    draw circle with Radius from P_dep
    mark refPoint as intersection between circle and adjacent risk contour
    add refPoint to Set(refPoint)
    for i = minimum(i) to maximum(i) do
        if circle from refPoint intersect with contour(i+1) then
            mark intersection as refPoint
            add refPoint to Set(refPoint)
        else
            draw direct line from refPoint and P_arr
    end
    connect route from P_dep via Set(refPoint) to P_arr
end
```

4.3.3. Feasible route options and assessment

Based on the projected preliminary route, a mathematical model was developed to analyze and select the feasible route options by combining reference points. In other words, the feasible route options were proposed by the combination of the reference points on the initial preliminary route. If there are n reference points from P_{dep} to P_{arr} on the preliminary route, the option of selecting r reference points can be expressed as Eq. (8),

$$choose_r = nCr \tag{8}$$

where $choose_r$ is the possible number of options of selecting r among n reference points, and ${}_nC_r$ is the combination of r points among n points.

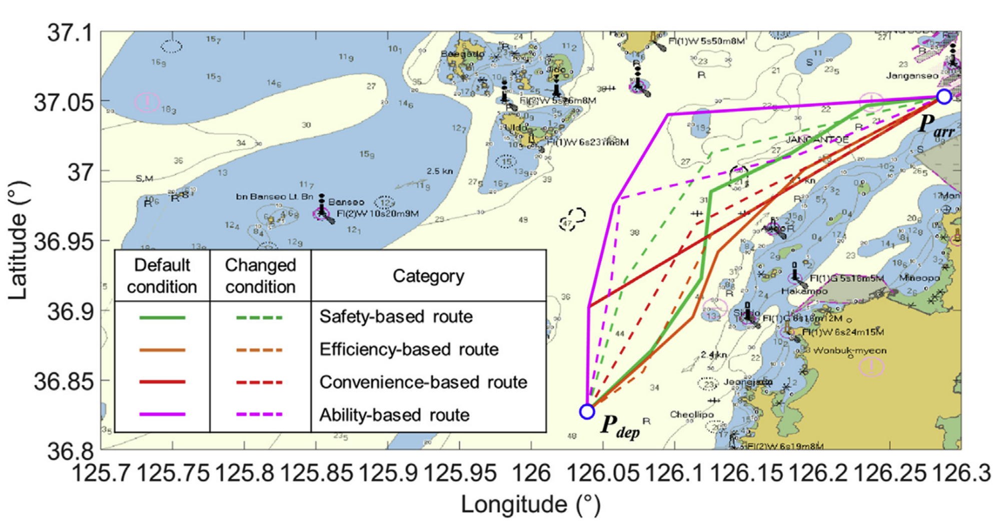

Fig. 7. Simulation results of multi-criteria route planning considering the maximum portion of each criterion under default conditions (without the influence of weather or tide) and changed conditions (with the influence of weather and tide).

Table 5
Results of the multi-criteria routes under default conditions.

Category	Cumulative risk per distance [NTR[1]]	Average risk gradient [NTR/NM]	Distance [NM]	Number of waypoints [EA]	Portion of safety [%]	Portion of efficiency [%]	Portion of convenience [%]	Portion of ability [%]
Safety-based route	4.6435	0.2829	22.04	5	42.58	38.12	Default	19.30
Efficiency-based route	5.4465	0.3009	20.73	4	3.70	76.09	16.05	4.14
Convenience-based route	5.2071	0.2843	21.93	1	12.35	33.46	38.96	15.23
Ability-based route	4.6609	0.2483	25.12	3	34.17	Default	18.81	47.03

[1]NTR: navigational traffic risk.

Furthermore, the total possible number of options can be expressed using the binomial theorem in Eq. (9),

$$ttl_n = nC0 + nC1 + \cdots + nCn - 1 + nCn = \sum_{r=0}^{n} nCr = 2^n \tag{9}$$

where ttl_n is the total possible number of options in the case of n reference points.

For example, if two reference points are selected in Fig. 5(a), the total options are three cases owing to ${}_3C_2$, and the results are shown in magenta in Fig. 5(c). During this stage, any route option that enters the non-navigable area should be excluded, and the remaining options are finally considered feasible.

To generalize the method, it is considered that a principle exists regarding the portion of each criterion reflected in the route planning. This is mathematically meaningful with the use of Pascal's triangle, as shown in Fig. 6. In the figure, if there are three reference points ($n = 3$), the total options are ${}_3C_0 + {}_3C_1 + {}_3C_2 + {}_3C_3$ (8 cases). The pink region, which contains the routes that select none of the reference points, is the region with the maximum portions of efficiency and convenience in route planning but the minimum portion of ability owing to the straight line from P_{dep} to P_{arr}. In contrast, the yellow region, which contains the routes that select all reference points, is the region with the maximum portion of ability but the minimum portions of efficiency and convenience. These low portions are due to the route being longest, because the path is most evasive as it follows the designated gradient on the risk contour. Furthermore, in the blue region, the portions of the criteria can range between the pink and yellow regions. However, as the safety criterion cannot be generalized in this principle because of irregular distribution of hazard factors across the risk contour, it is individually assessed and calculated for each route.

4.3.4. *Multi-criteria route*

After the assessment of criteria among the feasible routes using the proposed method, multi-criteria routes are found by comparison with the portions of the criteria selected by a user. Therefore, in this study, smart navigation is not the one route normally obtained by certain optimizing algorithms in other studies but flexible routes based on the requirement of situations and the purposes and intentions of users. As the non-navigable area is initially filtered out as a default safety criterion, users only have to adjust the portions of safety, efficiency, convenience, and ability without being concerned about any navigational traffic accidents. This is the multi-criteria route planning technique that best fits the requirements of users and makes routes applicable to actual situations through smart navigation.

5. Results and discussion

5.1. *Numerical simulation of application*

5.1.1. *Design of simulation*

To check the applicability and usefulness of the proposed route planning technique, numerical simulation was performed by utilizing the modeled ship in the region. The simulation was conducted under the default conditions, i.e., without the influence of either weather or tide, and under changed conditions with the influence of weather and tide.

P_{dep} and P_{arr} were identified after the visualization of the risk contour map. As the ship approached P_{arr}, the risk contour level showed the tendency to increase because the position became closer to the pilot station of Pyeongtaek port. Based on this navigational environment, the route planning model was applied to mathematically test and verify the results.

As the technique uses *Radius*, which is related to *Gradient*, during the route projection stage to derive a preliminary route, the feasible route options depend on the value of *Radius*. Despite the importance of

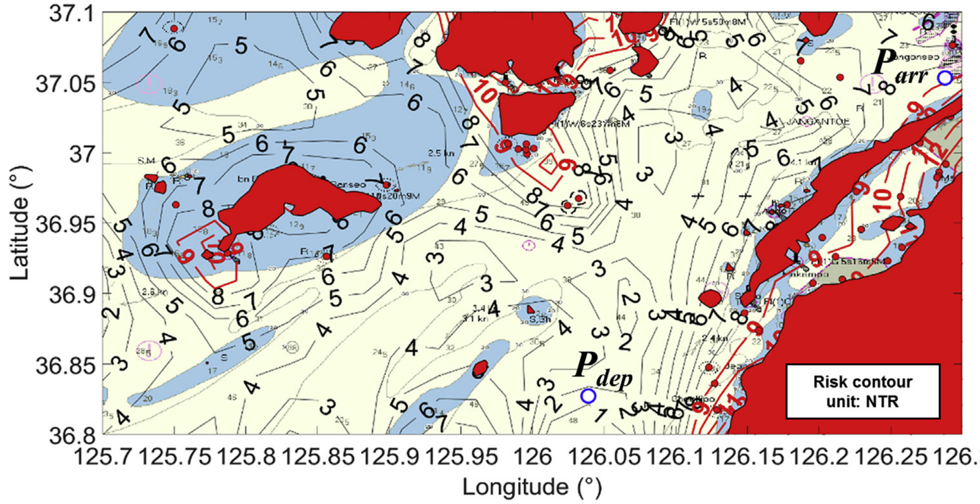

Fig. 8. Newly assessed navigational traffic risk and visualized risk contour map under changed conditions (tidal height of 2.15 m, wind speed of 5.6 m/s, current of 0.46 knots, and visibility of 10 NM at an assessment resolution of 3 min).

Radius to the results, if there is no standard for it, there might be infinite cases of *Radius* that can be applied as a variable. Therefore, to resolve this problem, the sensitivity analysis of *Radius* was performed at regular intervals and applied in consideration of the risk contour's interval, the distance between adjacent lines, and the vessel's size and maneuvering characteristics, as per Section 4.3.2. As a result, 153 cases were derived through the simulations of Radius to find multi-criteria routes.

5.1.2. Results of multi-criteria routes

All feasible routes proposed by the route planning technique were analyzed, and the four criteria were assessed. Based on the relative comparison among all suggested routes, the portions of criteria were normalized so that a user can compare and select them on a common scale.

Fig. 7 shows the results of the multi-criteria route planning under the default conditions as solid lines. The simulation found the routes with the maximum portion of one criterion compared to the others. The details of the multi-criteria routes are given in Table 5. First, the safety-based route almost follows the valley of the risk contour to enable the maximum consideration of the cumulative risk per distance compared to the other criteria. Second, the efficiency-based route is relatively close to the non-navigable area owing to reduction in distance. Next, the convenience-based route consists of only one waypoint while minimizing course alteration. Last, the ability-based route is quite long. However, it does not require considerable support for navigation compared to other routes. To minimize the average risk gradient, the route circumvents a risky area through frequent evasive alterations.

For further verification, the route planning technique was applied to the conditions with actual sea conditions and tidal data under a different resolution of the risk contour map. The sea conditions and tidal data were obtained from the Taean tidal station and Taean ocean data buoy, which are located close to the study area. A different position fixing interval of 3 min was applied for the resolution. The data for a randomly selected date and time were a tidal height of 2.15 m, a wind speed of 5.6 m/s, a current of 0.46 knots, and a visibility of 10 NM. As a result, the risk contour including the non-navigable area in the same ENC was newly assessed and visualized, as shown in Fig. 8. Then, the route planning model was applied in the same manner to check its applicability and effectiveness. The dashed lines (as shown in Fig. 7) show the results of the changes to the proposed routes. The details of the multi-criteria routes in these conditions are given in Table 6. These results confirm that the proposed route planning technique can be applied in real time at sea under various conditions.

To summarize, although the examples were cases based on the maximum portion for each criterion, the proposed technique ensures that routes are based on the options selected by a user adjusting portions of the criteria. This technique is novel because it enables selecting user-based options among several options. This study is different from other studies in which only one optimized route is obtained based on the efficiency.

5.2. Model application to AIS data

5.2.1. AIS data preprocess

The AIS consists of three types of structured data, i.e., static data, dynamic data, and voyage-related data (International Maritime Organization, 2006; Liu and Chen, 2014; Zhang et al., 2017). The past AIS data from Korea Ministry of Oceans and Fisheries were procured to demonstrate the effectiveness of the proposed route planning model. The AIS data of 3717 ships for three months from September 27 to December 27, 2017 were analyzed, as shown by the blue lines in Fig. 9. The data that were not related to this study, including noise, were filtered out owing to their broadness. Therefore, the extracted data consisted of the ship's specifications (static data), the ships underway (dynamic data), and the ships entering the LNG terminal in Pyeongtaek (voyage-related data). Initially, the sea conditions and tidal influence were not considered to compare and analyze the track data on a common scale under the default conditions. However, the extreme sea states during the period, such as typhoons or storm warnings, were excluded to prevent unexpected discrepancy in the data. Through this pretreatment, 36 statistical samples of the past tracks that had the same direction from the West Sea of Korea to the Janganseo pilot station were sorted and visualized, as shown by the red lines in Fig. 9.

5.2.2. Results of AIS data evaluation

The route planning technique proposed in this study was applied to statistically analyze current routes based on actual AIS data as a case study. However, owing to the continuous movements of ships in reality, AIS data were not shown as straight lines or conspicuous waypoints, which is how route plans normally appear. For this reason, the polygonal boundary that connects the outermost parts of past AIS data was identified and plotted, as shown in Fig. 10. Within this boundary area, the routes suggested by the technique were analyzed to evaluate their trends and the portions of the criteria considered by the actual routes.

Regarding the trends of criteria in accordance with the five-tier scale shown in Fig. 3, it was meaningful to find how criteria were distributed using the route planning model, as shown in Fig. 11. The results show that the safety of routes is distributed mainly in the low

Table 6
Results of the multi-criteria routes under changes in weather and tide.

Category	Cumulative risk per distance [NTR[1]]	Average risk gradient [NTR/NM]	Distance [NM]	Number of waypoints [EA]	Portion of safety [%]	Portion of efficiency [%]	Portion of convenience [%]	Portion of ability [%]
Safety-based route	4.7196	0.3262	22.49	3	44.89	25.22	26.64	3.24
Efficiency-based route	5.9140	0.3511	20.89	2	3.92	57.95	38.13	Default
Convenience-based route	5.4099	0.3487	21.03	1	21.58	37.31	41.11	Default
Ability-based route	4.9790	0.3111	23.58	3	15.98	18.12	21.87	44.03

[1]NTR: navigational traffic risk.

and medium scales, as the cumulative risk per distance is fairly high. In addition, the efficiency criterion is distributed between the high and very high scales owing to short-distance routes. Next, the convenience criterion is distributed from the medium to very high scale because most routes consisted of one to three waypoints. Lastly, the ability criterion is distributed mainly in the high or very high scales; this implies that these routes require considerable ability of navigation.

In addition to the scaled analysis of the routes obtained by AIS data, we evaluated the relative portions of the criteria that were considered by actual tracks, as shown in Fig. 12. Efficiency is the most significantly considered criterion, followed by convenience, safety, and ability. This indicates that most currently used routes attempt to reduce their distance and course alteration by focusing on efficient, easy, and convenient navigation. However, the ability criterion lies between the default and a maximum of 18%. This illustrates that ships are relatively vulnerable to handling an abrupt change in navigational traffic risks, which can be recognized by the risk gradient on the risk contour map.

Moreover, route suggestions become available by selecting the portions of the criteria, which were based on evaluated AIS data. For instance, in the event that a navigator wants to design a route conforming to the median value of the statistically assessed results, the route indicated by the blue line in Fig. 10 can be proposed. The suggested routes adopt each criterion at almost the median value of past AIS tracks. It comprises 20% safety, 41% efficiency, 31% convenience, and 8% ability. In addition, the navigator can adjust the portions as freely as possible according to the requirements.

In conclusion, the proposed route planning technique was verified to be effective and sufficiently applicable not only for quantitatively analyzing current routes using AIS data but also for suggesting the route that achieves the desired portions of the criteria.

6. Discussion

In this study, we proposed a route planning technique using four criteria, i.e., the safety, efficiency, convenience, and ability of navigation. Unlike other studies, which optimize only one route by concentrating mainly on efficiency, this study provides several route options as smart navigation according to the preference of users. Providing users with options to select from is useful because the weight of each criterion can vary depending on a user's experience, capability, and situations. Therefore, in addition to the proposed technique, smart navigation must be further developed to realize the automated adjustment of the portions of the criteria.

The four criteria were also evaluated based on respective factors in the process of route planning. However, there are other factors, such as fuel consumption, cost, and weather, which should be considered in more sophisticated route planning. In addition, the ability criterion is determined by whether or not a vessel and operators can conduct navigation based on a ship's specification, cargo specification, other auxiliary systems, and operators' eligibility. Therefore, this technique requires a more detailed, objective, and quantified method for evaluating ability to connect it with the risk gradient.

Furthermore, this study considers the navigational traffic risk posed by stationary obstacles when visualizing the risk contour map as a framework during the appraisal and planning phases of route planning. Therefore, in addition to the current categorization of absolute danger, hazard factors, and influential factors, other mobile and dynamic factors should be further considered, such as moving ships, real-time traffic volume, more accurate data on sea conditions, and their correlations with navigational traffic risks. These considerations can improve the route planning technique and make it more sophisticated in the execution and monitoring phases.

The proposed technique was applied to a coastal area in Korea using the modeled ship. A limitation of this technique is that it cannot be applied to an atypical shape of the risk contour or in an extreme case such as an area within traffic separation schemes. Therefore, to extend

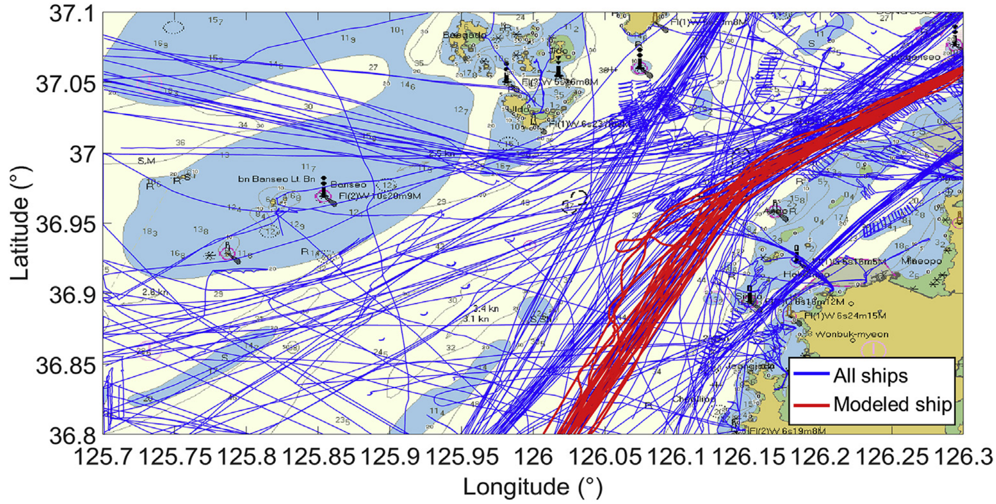

Fig. 9. Statistical AIS data analysis for filtering tracks of the modeled ship among all ships in the study area from September 27 to December 27, 2017.

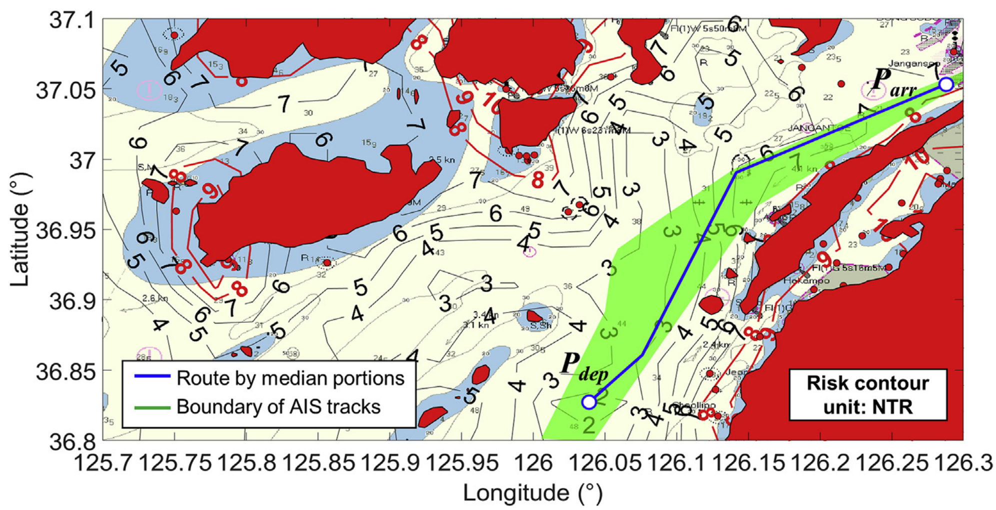

Fig. 10. Polygonal boundary of past AIS tracks using the modeled ship and an example of a route selected from the statistically assessed routes using the median portion for each criterion.

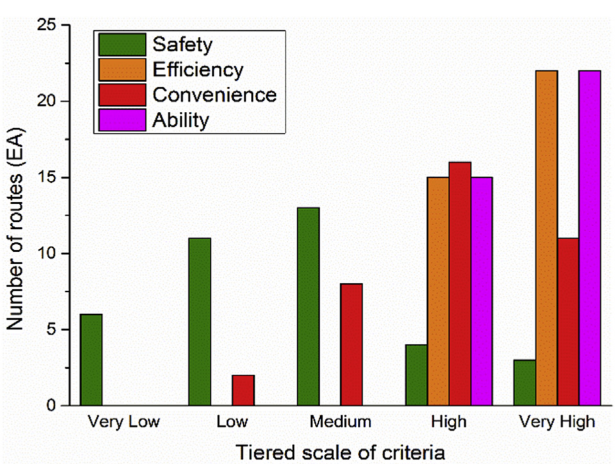

Fig. 11. Evaluation of statistical AIS tracks using the modeled ship for trends of criteria (safety, efficiency, convenience, and ability) on a five-tier scale (from very low to very high).

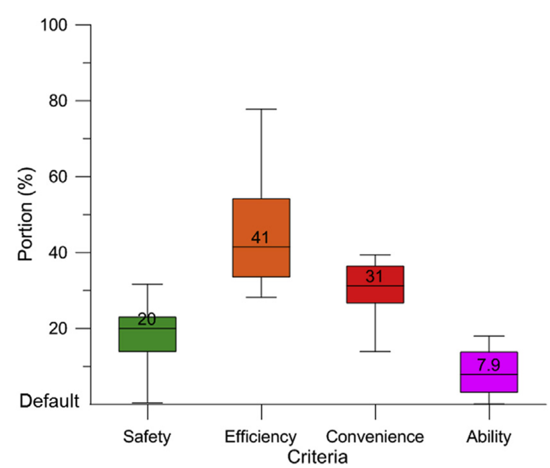

Fig. 12. Evaluation of statistical AIS tracks using the modeled ship for portions of the considered criteria (safety, efficiency, convenience, and ability). The efficiency is the most heavily considered criterion, followed by convenience, safety, and ability.

the validation of this study, other regions with various conditions should be considered with more statistical AIS data for the modeled ship. However, using the risk contour is verified and validated to be useful and advantageous in normal sea areas, regardless of the types and sizes of vessels. This technique will provide the advantage of fully smart navigation if it is expanded to the entire voyage from a departure port to an arrival port.

Despite the abovementioned challenges, which will be strengthened in the future, this study is valuable because it can provide a user with multi-criteria route options from an infinite number of possible routes. As demonstrated by the results of the applications, this route planning technique is expected to be utilized in diverse areas. We can apply the technique not only to smart navigation but also to broader areas such as the quantitative analysis of traffic accidents arising from inappropriate routes and decision-making for the navigation of autonomous vessels.

7. Conclusions and future work

In this study, a multi-criteria route planning technique was developed to enable navigators to quantitatively and objectively determine their routes in compliance with their goals and preferences. First, risk contour mapping, which uses absolute danger, hazard factors, and influential factors, was applied as a framework of the route planning technique to assess and visualize navigational traffic risk of a navigation area as equal curves. Then, as the core part of this study, the multi-criteria route planning technique was modeled by designing four main criteria, i.e., the safety, efficiency, convenience, and ability of navigation. Parameters such as the cumulative risk per distance, distance, number of waypoints, and risk gradient were considered to assess the four criteria. The suggested algorithm analyzed feasible route options derived by utilizing contour-based preliminary route projections and a combination of reference points. To illustrate the effectiveness and applicability of the proposed technique, we numerically simulated case studies and evaluated actual AIS data within the west coast of Korea. The results showed that this novel technique is effective for objectively planning routes that fit the intentions of users in real time. In addition, it can be applied to quantitatively evaluate the routes currently used by maritime transportation. Therefore, the proposed technique practically supports on-scene decision making by overcoming the empirical and subjective method, which has been conventionally used thus far. In summary, the proposed technique is novel not only because was the new risk contour developed to continuously express previously discrete data but also because multi-criteria route planning enables the navigator to plan a fit-for-purpose route using quantitative and objective methods, which can significantly beneficial to the operator's decision making.

Even though the technique proposes multi-criteria routes, more factors such as dynamic objects or traffic volumes should be considered to improve the route planning technique. In addition, this study can be more broadly applied not only to the appraisal and planning phases in route planning but also to the execution and monitoring phases. The study is expected to provide more advantages once the method can be more universally applied in other terrestrial areas. Finally, in the future, we will examine the automated adjustments of criteria portions combined with this technique to contribute to the analysis of traffic accidents related to route decisions as well as decision-making for autonomous ships.

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References

Andersson, A., 2015. Multi-objective Optimisation of Ship Routes. Master’s Thesis. Chalmers University of Technology.

Bialystocki, N., Konovessis, D., 2016. On the estimation of ship's fuel consumption and speed curve: a statistical approach. J. Ocean Eng. Sci. 1, 157–166. https://doi.org/10.1016/j.joes.2016.02.001.

Bijlsma, S.J., 2001. A computational method for the solution of optimal control problems in ship routing. Navig. J. Inst. Navig. 48, 144–154. https://doi.org/10.1002/j.2161-4296.2001.tb00238.x.

Bijlsma, S.J., 2002. On the applications of optimal control theory and dynamic programming in ship routing. Navig. J. Inst. Navig. 49, 71–80. https://doi.org/10.1002/j.2161-4296.2002.tb00256.x.

Bijlsma, S.J., 2004. On the applications of the principle of optimal evolution in ship routing. Navig. J. Inst. Navig. 51, 93–100. https://doi.org/10.1002/j.2161-4296.2004.tb00343.x.

Casola, J.H., Wallace, J.M., 2007. Identifying weather regimes in the wintertime 500-hPa geopotential height field for the Pacific-North American sector using a limited-contour clustering technique. J. Appl. Meteorol. Climatol. 46, 1619–1630. https://doi.org/10.1175/JAM2564.1.

Chen, J., Qiao, C., Zhao, R., 2004. A Voronoi interior adjacency-based approach for generating a contour tree. Comput. Geosci. 30, 355–367. https://doi.org/10.1016/j.cageo.2003.06.001.

Cronin, T., 1995. Automated reasoning with contour maps. Comput. Geosci. 21, 609–618. https://doi.org/10.1016/0098-3004(94)00100-9.

Eniram, 2018. Eniram ROUTE. https://www.eniram.fi/services/route/, Accessed date: 22 February 2018.

Equasis, 2016. The World Merchant Fleet in 2016 Statistics from Equasis 1–64. Available at: http://www.equasis.org/EquasisWeb/public/PublicStatistic?fs=HomePage.

European Maritime Safety Agency, 2017. Annual Overview of Marine Casualties and Incidents 2017. Available at: http://www.emsa.europa.eu/publications/technical-reports-studies-and-plans/item/3156-annual-overview-of-marine-casualties-and-incidents-2017.html>.

Gu, H., Wang, J., Lin, Q., Gong, Q., 2015. Automatic contour-based road network design for optimized wind farm micrositing. IEEE Trans. Sustain. Energy 6, 281–289. https://doi.org/10.1109/TSTE.2014.2369432.

Guinness, R.E., Saarimäki, J., Ruotsalainen, L., Kuusniemi, H., Goerlandt, F., Montewka, J., Berglund, R., Kotovirta, V., 2014. A method for ice-aware maritime route optimization. In: Rec. - IEEE PLANS, Position Locat. Navig. Symp, pp. 1371–1378. https://doi.org/10.1109/PLANS.2014.6851512.

National Imagery, Mapping Agency, 2002. The American Practical Navigator Originally by Bowditch N. LL. D. Bicentennial Edition Pub No.9.

Inoue, K., 2013. Theory and Practice of Ship Handling. Sanghakdang, Seoul.

International Association of Marine Aids to Navigation and Lighthouse Authorities, 2009. IALA Risk Management Tool for Ports and Restricted Waterways. Recommendation O-134.

International Association of Marine Aids to Navigation and Lighthouse Authorities, 2018. Navguide 2018, eight ed. Saint Germain en Laye. Available at: http://www.iala-aism.org/product/iala-navguide-2018-digital-copy/.

International Maritime Organization, 1999. Annex 25 Guidelines for Voyage Planning-resolution A.893(21). SOLAS (Chapter 5). Safety of Navigation.

International Maritime Organization, 2002. Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-making Process.

International Maritime Organization, 2006. Model Course 1.34 Automatic Identification Systems.

Javanmardi, J., Nasrifar, K., Najibi, S.H., Moshfeghian, M., 2006. Feasibility of transporting LNG from South-Pars gas field to potential markets. Appl. Therm. Eng. 26, 1812–1819. https://doi.org/10.1016/j.applthermaleng.2006.02.003.

Jebsen, J.J., Papakonstantinous, V.C., 1997. Evaluation of the Physical Risk of Ship Grounding. Master’s Thesis. Massachusetts Institute of Technology.

Jeon, H., 2018. Development and Application of Collision Risk Assessment System for Establishing Optimum Safe Route. Master’s Thesis. Korea Maritime and Ocean University.

Jeong, M.-G., Lee, M.-J., Lee, E.-B., 2017. A study on the visualization of hns hazard levels to prevent accidents at sea in real-time. J. Korean Soc. Mar. Environ. Saf. 23, 242–249. https://doi.org/10.7837/kosomes.2017.23.3.242.

Jeong, M.-G., Lee, M.-J., Lee, E.-B., 2018. A study on intuitive technique of risk assessment for route of ships transporting hazardous and noxious substances. J. Navig. Port Res. 42, 97–106. https://doi.org/10.5394/KINPR.2018.42.2.97.

Kang, D., Oh, S., Kim, S., Jung, J., 2015. Automatic route checking method using post-processing for the measured water depth. 2015. In: International Association of Institutes of Navigation World Congress (IAIN) 20–23, . https://doi.org/10.1109/IAIN.2015.7352240.

Kim, C., Lee, H., 2012. A basic study on assessment criterion of the risk factor for the marine traffic environment. J. Korean Soc. Mar. Environ. Saf. 18, 431–438. https://doi.org/10.7837/kosomes.2012.18.5.431.

Kim, S.-W., Park, Y.-S., Lee, Y.-S., 2013. A study on the evaluation for the safety of passing vessel in the vicinity of the seasands gathering area by marine traffic safety diagnostic scheme. J. Fish. Mar. Sci. Educ. 25, 677–689. https://doi.org/10.13000/JFMSE.2013.25.3.677.

Kobayashi, E., Asajima, T., Sueyoshi, N., 2011. Advanced navigation route optimization for an oceangoing vessel. TransNav, Int. J. Mar. Navig. Saf. Sea Transp. 5, 377–383.

Korea Hydrographic and Oceanographic Administration, 2018. West Coast of Korea Pilot. (2018 Edition).

Korea Maritime Safety Tribunal, 2018. Accident Position Information Based on Electronic

Chart. http://www.kmst.go.kr/WebVMS_KMST/WebVMS.jsp, Accessed date: 16 February 2018.
Kristiansen, S., 2005. Maritime Transportation-safety Management and Risk Analysis, first ed. Elsevier, Oxford.
Larson, J., Bruch, M., Ebken, J., 2006. Autonomous navigation and obstacle avoidance for unmanned surface vehicles. In: . Proc. SPIE 6230: Unmanned systems technology VIII, pp. 17–20. https://doi.org/10.1117/12.663798.
Lee, B., 2005. An Optimal Route Decision and LOS Guidance System for Automatic Navigation of Ships. PhD Thesis. Korea Maritime University.
Lee, H.H., Kim, C.S., 2013. An analysis on the relative importance of the risk factors for the marine traffic environment using analytic hierarchy process. J. Korean Soc. Mar. Environ. Saf. 19, 257–263.
Lee, S.M., Roh, M. Il, Kim, K.S., Jung, H., Park, J.J., 2018. Method for a simultaneous determination of the path and the speed for ship route planning problems. Ocean Eng. 157, 301–312. https://doi.org/10.1016/j.oceaneng.2018.03.068.
LG CNS, 2018. iSEMS. http://isems.lgcns.com/LGCNS.ISE.Main/EN/iSEMS/Overview.aspx, Accessed date: 4 May 2018.
Li, M., Liu, Y., 2010. Iso-Map: Energy-efficient contour mapping in wireless sensor networks. IEEE Trans. Knowl. Data Eng. 22, 699–710. https://doi.org/10.1109/TKDE.2009.157.
Lin, S., 1998. Physical Risk Analysis of Ship Grounding. Master's Thesis. Massachusetts Institute of Technology.
Liu, C., Chen, X., 2014. Vessel track recovery with incomplete AIS data using tensor CANDECOM/PARAFAC decomposition. J. Navig. 67, 83–99. https://doi.org/10.1017/S0373463313000398.
Mazaheri, A., 2009. Probabilistic Modeling of Ship Grounding. A Review of the Literature. Helsinki University of Technology.
Mazaheri, A., Montewka, J., Kotilainen, P., Sormunen, O.V.E., Kujala, P., 2015. Assessing grounding frequency using ship traffic and waterway complexity. J. Navig. 68, 89–106. https://doi.org/10.1017/S0373463314000502.
Oil Companies International Marine Forum, 2016. Vessel inspection questionnaires for oil tankers, combination carriers, shuttle tankers. In: Chemical Tankers and Gas Tankers (VIQ 6), vol. 2014.
Pedersen, P.T., 2010. Review and application of ship collision and grounding analysis procedures. Mar. Struct. 23, 241–262. https://doi.org/10.1016/j.marstruc.2010.05.001.
PIANC, 2014. Harbour Approach Channels Design Guidelines. Report No.121. .
Pietrzykowski, Z., Uriasz, J., 2009. The ship domain - a criterion of navigational safety assessment in an open sea area. J. Navig. 62, 93–108. https://doi.org/10.1017/S0373463308005018.
Riveiro, M., Pallotta, G., Vespe, M., 2018. Maritime anomaly detection: a review. In: WIREs Data Min. Knowl. Discov. 8. pp. 1–19. https://doi.org/10.1002/widm.1266.
Rogers, L.W., 2005. Automating Contour-based Route Projection for Preliminary Forest Road Designs Using GIS. Master's Thesis. University of Washington.
Roh, M.I., 2013. Determination of an economical shipping route considering the effects of sea state for lower fuel consumption. Int. J. Nav. Archit. Ocean Eng. 5, 246–262. https://doi.org/10.3744/JNAOE.2013.5.2.246.
StormGeo, 2018. Ship Routing Services. http://www.stormgeo.com/solutions/shipping/ship-routing/, Accessed date: 1 June 2018.
Swift, A., 1993. Bridge Team Management. The Nautical Institute, London.
Szlapczynski, R., 2005. A new method of ship routing on raster grids, with turn penalties and collision avoidance. J. Navig. 59, 27–42. https://doi.org/10.1017/S0373463305003528.
Szlapczynski, R., 2011. Evolutionary sets of safe ship trajectories: a new approach to collision avoidance. J. Navig. 64, 169–181. https://doi.org/10.1017/S0373463310000238.
Ulusçu, Ö.S., Özbaş, B., Altıok, T., Or, İ., 2009. Vessel traffic in the strait of istanbul. Simulation-based case stud. Logist. Educ. Appl. Res. 29, 189–207. https://doi.org/10.1007/978-1-84882-187-3_11.
United Nations, 2017. Review of Maritime Transport 2017, New York and Geneva.
Vettor, R., Soares, C.G., 2016. Development of a ship weather routing system. Ocean Eng. 123, 1–14. https://doi.org/10.1016/j.oceaneng.2016.06.035.
Weathernews, 2018. WNI Optimum Ship Routing. https://global.weathernews.com/your-industry/shipping/, Accessed date: 10 March 2018.
Yoo, B., Kim, J., 2016. Path optimization for marine vehicles in ocean currents using reinforcement learning. J. Mar. Sci. Technol. 21, 334–343. https://doi.org/10.1007/s00773-015-0355-9.
Yoo, Y., Choi, H.-R., Lee, J.-Y., 2015. Comparative results of weather routing simulation. J. Soc. Nav. Archit. Korea 52, 110–118.
Zhang, D., Li, J., Wu, Q., Liu, X., Chu, X., He, W., 2017. Enhance the AIS data availability by screening and interpolation. In: 4th Int. Conf. Transp. Inf. Safety, ICTIS 2017 - Proc. 981–986, . https://doi.org/10.1109/ICTIS.2017.8047888.
Zhen, R., Riveiro, M., Jin, Y., 2017. A novel analytic framework of real-time multi-vessel collision risk assessment for maritime traffic surveillance. Ocean Eng. 145, 492–501. https://doi.org/10.1016/j.oceaneng.2017.09.015.