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A Study on the Method of Simultaneous Determination of Path and Speed for Ship Route Planning

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Contents

Abstract **1**

1. Introduction **3**

1.1. Ship-route-planning problem of real world 3

1.2. Motivation for work 5

1.3. Related works 6

2. Ship-route-planning problem **10**

2.1. Framework of ship-route-planning problem 10

2.2. Overview of this study 13

2.3. Input and output information 14

3. Optimization model **16**

3.1. Theoretical background 17

3.1.1. Cell-based algorithm 18

3.1.2. Cell-free algorithm 22

3.1.3. Comparison 26

3.2. Formulation of the ship-route-planning problem as the optimization problem 28

3.2.1. Design variables 28

3.2.2. Objective functions 29

3.2.3. Constraints 30

3.3. Route construction from elements of formulation 31

3.3.1. Route definition 32

3.3.2. Route generation 33

3.3.3. Route evaluation 38

4. Performance-evaluation model 39

4.1. FOC estimation 41

4.1.1. Theoretical background 43

4.1.2. FOC estimation of this study 44

4.2. Space calculation 48

4.2.1. Theoretical background 49

4.2.2. Distance calcuation of this study 51

4.3. Seakeeping evaluation 51

4.3.1. Seakeeping evaluation of this study 53

4.4. Avoidance of obstacles 54

5. Route-finding model 56

5.1. Theoretical background 56

5.1.1. Metaheuristic algorithm 58

5.1.2. Genetic algorithm (GA) 58

5.1.3. Evolutionary strategy (ES) 60

5.1.4. Particle swarm method (PSO) 61

5.2. Seed genetic algorithm for optimal solution 63

6. Development of the program 67

6.1. Multilayer architecture as data structure 68

6.1.1. Map projection 69

6.1.2. Weather 71

6.2. Functions 72

7. Verifictaions 72

7.1. Verification of optimization model 74

7.1.1. Case 1 74

7.1.2. Case 2 79
7.2. Verification of performance-evaluation model 82
7.2.1. Case 3 82
7.2.2. Case 4 85
7.3. Verification of route-finding model 88
7.3.1. Case 5 88
7.3.2. Case 6 89

8. Applications 91
8.1. Application 1 92
8.2. Application 2 94
8.3. Application 3 95

9. Conclusion and future works 96

References 99

국문 초록 105

Figures

Figure 1 Conceptual diagram for ship-route-planning problem of real world.....3
Figure 2 Configuration of key models in this study.....13
Figure 3 Comparison between the cell-based algorithm and the cell-free algorithm.....18
Figure 4 Configuration of formation shape of cell into geographical map 19
Figure 5 Flow chart of Dijkstra algorithm.....20
Figure 6 Flow chart of A-star algorithm.....22
Figure 7 Concept image of Isochrone method.....24
Figure 8 Concept of the 3D dynamic programming 26
Figure 9 Configuration of concept of each path-finding algorithm 28
Figure 10 Configuration of route definition 33
Figure 11 Configuration for the determination of the next route.....34
Figure 12 Application of design variables for obtaining route in this study 35
Figure 13 Difference between two ways for reaching the arrival point 37
Figure 14 Configuration for the evaluation of the segment.....38
Figure 15 Concept of ISO15016:2015 44
Figure 16 Comparison between ISO15016:2015 and proposed way of FOC calculation.46
Figure 17 Comparison between Haversine's formula and Vincenty's formula 50
Figure 18 Method for avoidance of the land using the geographic map 56
Figure 19 Procedure of genetic algorithm.....59
Figure 20 Procedure of evolutionary strategy 61
Figure 21 Procedure of particle swarm optimization.....62
Figure 22 Procedure of seed genetic algorithm 64
Figure 23 Management of seed using seed pool based on the ports and time 66
Figure 24 GUI of the developed program 67
Figure 25 Concept of data structure for multilayer architecture.....69
Figure 26 Concept of the Mercator projection 70
Figure 27 Expansion of world map for solving discontinuous problem 71
Figure 28 Configuration of paths from each optimization model in March.....75

Figure 29 Comparison between the results of the commercial program and the proposed optimization model in March 78

Figure 30 Configuration of paths from each optimization model in June 80

Figure 31 Comparison between the results of the commercial program and the proposed optimization model in June 82

Figure 32 Configuration of paths from each performance-evaluation model in June 83

Figure 33 Comparison FOC estimation of the proposed method with FOC estimation of commercial program using graphs of longitude-FOC and longitude-added resistance in June 84

Figure 34 Configuration of paths from each performance-evaluation model in March 86

Figure 35 Comparison FOC estimation of the proposed method with FOC estimation of commercial program using graphs of longitude-FOC and longitude-added resistance in March 87

Figure 36 Configuration of paths from each monthly seed of route-finding model 90

Figure 37 Visualization of routes for application 1 93

Figure 38 Visualization of routes for application 2 94

Figure 39 Visualization of routes for application 3 95

Tables

Table 1 Summary of related studies and its optimization model 7
Table 2 Input information for ship-route-planning 14
Table 3 Output information for ship-route planning 16
Table 4 Comparison between path-finding algorithms and application for speed optimization 27
Table 5 FOC estimation for ship-route planning 41
Table 6 Main estimations and its solving ways handled in ISO15016:2015 43
Table 7 Seakeeping evaluation for ship-route planning 52
Table 8 Applicable optimization techniques with optimization problems..... 56
Table 9 Verification cases for proposed models 72
Table 10 Condition of verification cases 74
Table 11 Result of routes from each optimization model in March 76
Table 12 Result of routes from each optimization model in June 80
Table 13 Result of routes from each performance-evaluation model in June..... 83
Table 14 Result of routes from each performance-evaluation model in March..... 86
Table 15 Result of routes from each optimization technique of route-finding model..... 89
Table 16 Result of routes from each monthly seed of route-finding model 90
Table 17 Input information of application for the proposed method 91
Table 18 Result of routes for application 1 93
Table 19 Result of routes for application 2 95
Table 20 Result of routes for application 3 96

Abstract

A Study on the Method of Simultaneous Determination of Path and Speed for Ship Route Planning

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Ship-route planning is a good solution to some problems facing recent issues such as the problem of financial difficulty of shipping companies, the strengthening of international regulations of pollutants and the safety of operating ship etc. However, the current ship-route planning is determined by non-quantitative methods such as chief mate's experience and simple manuals. In addition, algorithms used for ship-route planning are also mostly conducted only for path planning, and the method of simultaneously optimizing to include the speed planning was not sufficiently studied.

In this study, a framework for studying ship-route planning is proposed, and based on this framework, a ship-route-planning method that simultaneously optimizes path and speed is also proposed. First, the optimization model is proposed to formulate the ship-route-planning problem as the optimization problem and to construct a route with this

formulated element. For this, the route is defined as a set of path (heading angle) and speed (engine rpm), thereby maximally describing the actual appearance of ship. Second, in order to evaluate this route, targeting fuel oil consumption, distance, seakeeping and land avoidance, the performance-evaluation model is proposed using theory and regulations. Third, a seed genetic algorithm is proposed to provide and manage initial solution as the route-finding model to optimize route. A program that implements multilayer structure is developed based on three previously proposed models, the excellence and applicability of three models is confirmed through six verifications and three applications.

The proposed ship-route-planning method provides better routes than the existing ship-route-planning method and commercial program. Moreover, the utility of the proposed optimization model, performance-evaluation model, route-finding model and program are confirmed.

Keywords: Ship route planning, Simultaneous optimization, Ship performance, Seed genetic algorithm

Student number: 2015-22687

1. Introduction

1.1. Ship-route-planning problem of real world

The ship-route-planning problem of real world is described as Figure 1.

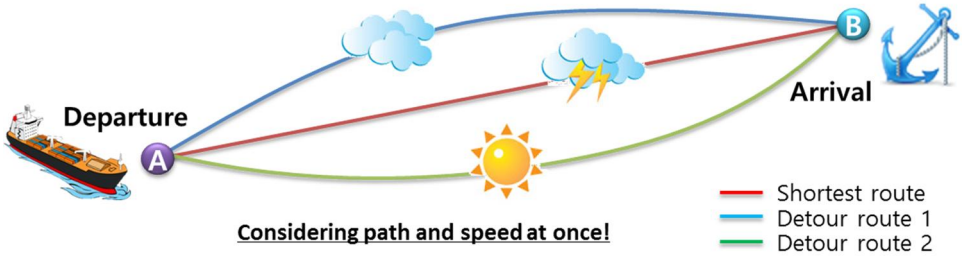

Figure 1 Conceptual diagram for ship-route-planning problem of real world

The ship-route-planning problem is a problem for finding a best route that departs from port A and allows safe arrival at port B within the required time. The performance of the ship is influenced by a lot of conditions such as terrain and weather etc. Recently, various considerations have been reflected on the ship-route-planning. Especially, as interest in the economic operations becomes bigger, the ship has been operated not on the shortest path, but on the route that minimizes fuel oil consumption. Assuming that the speed is same on the whole route, the shortest path and the route with the lowest fuel oil consumption are same. However, considering facts that the speed is changed according to the weather condition and the speed can also be planned, there is a route that travel a little more distance than the shortest path, but the whose fuel oil consumption is the smallest.

Therefore, the ship-route planning should include not only path planning, but also speed planning. In the past, the route of the ship was simply regarded as path only. However, for this reason, the studies involving speed planning on the route appears and the meaning of route is being changed.

Meanwhile, this ship-route planning is generally the responsibility of the captain and the chief mate. Especially, in the past when the computer system was not developed, the ship-route planning has been determined by the experience of the captain and the chief mate based on several established route. This method based on experience of them does not incur a problematic result but it is susceptible to improvement. Meanwhile, the present theoretical methods and the present commercial programs have been developed, and these are used. However, as far as the development of computer systems, they still have decided the route depending on their vocational experience or manual from shipping company because the majority of the methods have been insufficient for the satisfaction of the user expectations. Although the ship-route-planning programs and algorithms are existed, it is difficult to accept a digitized system because the captain and chief mate trust the traditional operating method and experience (Choi, 2007). These are often used in auxiliary operation program to help to decide as providing various solutions regarding ship operations in present. Of course, there are many advances for the interest and development of recent ship-route-planning method, and the scope of application is gradually expanding only for programs that have been verified at a certain level accordingly.

1.2. Motivation for work

Recently, the number of problems are scattered in ship operation. Firstly, competition of operating cost has been increasing day by day due to economic depression. The current charter fare declined because the growth rate of China, a self-appointed world's factory, has stagnated and ship was oversupplied at that time. In order to cope with lower charter fare, shipping companies basically are striving to reduce the operating cost. A fuel cost is a large part of the operating cost. The fuel cost takes more than 40% of the operating cost (Journee and Meijers, 1980). Therefore, the importance of the economical operation is highlighted. Next, human health issues and environmental problems have come to the fore recently, whereby the international-standard regulations have been strengthened regarding gas emissions. IMO adopted the MARPOL as requirements addressing pollution from chemicals, other harmful substances, garbage, sewage. Under an Annex VI of MARPOL, in particular, the reduction of pollutant emissions is mandatorily imposed at all ships including new ships (IMO 2008, Third IMO GHG Study 2014). Lastly, the ship casualty of 'Sewol' has occurred as one of the biggest accidents. The dangerous route is assumed as one reason of the accident. The need for prevent accidents and minimizing risk during operation is emphasized. The necessities of a ship-route-planning method for which the path and the speed are simultaneously considered have been recently raised from previous problems because an improvement of the ship-route-planning method can bring the low fuel cost by providing more effective route, decrease pollutant emission and make more safe route. On the other hand, the established ship-route-planning method which are used in ship operation programs has original limitations for each algorithm. Each algorithm has different original limitations, but one of the biggest original limitations is that each algorithm does not perform speed planning but finds path only.

Since only path has been considered so far, it was possible to plan effectively in ship-route planning even by established ship-route-planning method. However, as mentioned earlier, because the speed planning has also been included as part of the ship-route planning recently, the ship-route-planning method which can perform the speed planning must be developed. Additionally, at the viewpoint of expanding business area of shipbuilding, the ship-route planning is good area to access. Interest of the shipbuilding and demand for ship-route-planning are rising. Therefore, in this study, ship-route-planning method is proposed and developed as program for proving solutions to these various problems and for overcoming limitations of the established algorithms at the same time.

1.3. Related works

The ship-route-planning study is a comprehensive study including many types of study. Therefore, the study can be conducted on the overall ship-route planning, or only in a part of the ship-route planning. In generally, topics of ship-route-planning study are as follows.

- Study of optimization model for formulating ship-route-planning problem as optimization problem
- Study of performance-evaluation model for estimation of ship performance under given condition.

- Study of route-finding model using optimization technique to find the best route
- Study of data structure for provision of continuous or discretized maps

All topics associated with the ship-route planning are handled in this study. There are also a lot of established studies involved in the ship-route planning. All related studies are handled in this related works section, but it can cause a confusion and a difficulty because there are too many studies. Therefore, related works involved in main contents are only described in this section. Others are handled in the theoretical background of related section for being referred to in more detail. Meanwhile, one of the most important topics performed in this study are the optimization model and the route-finding model, so studies related with these model are shown in Table 1.

Table 1 Summary of related studies and its optimization model

Related studies	Optimization model			
	Simultaneous optimization	Path optimization	Speed optimization	Limitation of algorithm
Choi et al. (2015)	X	A-star algorithm	-	Fixed speed, non smooth path
Joo et al. (2012)	X	A-star and Dijkstra algorithm	Evolutionary strategy	
Bang et al. (2014)	X	A-star and evolutionary strategy	Evolutionary strategy	
Park et al. (2015)	X	A-star algorithm	Geometric programming	
Wei and Zhou (2013)	X	3D dynamic programming	-	Non smooth path
Chen (2013)	X	3D dynamic programming	-	
Roh (2013)	X	Improved Isochrone method	-	Fixed speed
EN-Saver (2015)	X	Improved Isochrone method	Genetic algorithm	
ENIRAM (2016)	X	Empirical method	Empirical method	Local optimum

Vettor et al. (2016)	O	SPEA2 and Dijkstra algorithm	Non smooth path, Imperfect simultaneous optimization
This study	**O**	**Seed genetic algorithm**	**-**

Studies in Table 1 are papers and programs in terms of the path planning and speed planning of ship and Table 1 is a table that summarizes the optimization models used in each study. The path optimization means an execution of the path planning, and the speed optimization means an execution of the speed planning. The simultaneous optimization means that the path optimization and the speed optimization are executed at the same time. If the path optimization and the speed optimization are executed independently, it is not the simultaneous optimization, but just two-stage optimization.

Choi et al. (2015) targeted the ship-route planning for the Arctic sea. Since the floating ice, one of the important weather condition on the Arctic sea, moves from moment to moment, they developed an ice model in consideration of ice-behavior uncertainties. They proposed a method for the determination of the optimal path under a time-varying weather condition with the use of the A-star algorithm. However, they did not perform a speed optimization on the path. Joo et al. (2012) found the optimal path in a fixed-speed state by using the A-star algorithm, and they modified the path in consideration of the weather condition by using the Dijkstra algorithm. Afterward, the speed on the path was optimized. Similarly, Bang et al. (2014) found the optimal path in a fixed-speed state by using the A-star algorithm, but they modified the found path in consideration of the weather condition by using the evolutionary strategy. Afterward, they adjusted the speed on the path. Park et al. (2015) found the optimal path in a fixed-speed state by using the A-star algorithm, and then they optimized the speed on the path by using geometric

programming. Wei and Zhou (2013) used three-dimension dynamic programming (3DDP) to propose a method for ship-route planning. Similarly, Chen (2013) developed a software using 3DDP. Roh (2013) proposed an improved Isochrone method for ship-route planning, whereby obstacles such as land were considered. Developed by Samsung Heavy Industries, EN-Saver (2015) was a commercial program for ship-route planning that found the path by using the improved Isochrone method, and then it performed the speed optimization using the genetic algorithm. ENIRAM (2016) was a commercial program that used empirical data based on the actual ship route. The studies of Joo et al. (2012), Bang et al. (2014), Park et al. (2015), EN-Saver (2015) conducted the path optimization and the speed optimization independently. Though different optimization methods were used for each study, for all three studies, the shortest path was identified in the first stage, followed by the optimization of the speed on the path in the second stage. In general, a solution of several-stage optimization is one of local optimums of one-stage optimization (simultaneous optimization). That is, one-stage optimization will provide better solutions than two-stage optimization. This point will be examined in verification section. In this reason, a trend of the recent ship-route-planning studies is changed from the two-stage optimization to the simultaneous optimization. Meanwhile, ENIRAM (2016) use not optimization, but statistic method. Of course, the route can be planned without optimization, however, in this case, its result is not the optimum, but just a feasible solution.

Vettor et al. (2016) formulated a ship-route-planning problem in terms of a multi-objective optimization problem for which the positions and speeds are design variables. They mainly used SPEA2, one type of the genetic algorithm, for the formulation of a route that comprises several nodes, and specifically, Dijkstra algorithm was used to calculate the objective functions between the neighbor nodes. This method was, therefore,

named the “SPEA2-Dijkstra Method” due to its similarity regarding the Dijkstra algorithm, whereby the speed can be changed at each segment between the nodes. Vettor et al. also designed a weather-condition model for ship-route-planning problems. These studies proposed the simultaneous optimization, but algorithms used in studies have limitations like Table 1. Its limitations in Table 1 are original weakness of each algorithm, so it is hard to overcome the limitations. Therefore, a new algorithm is necessary to overcome the limitations. In this study, a new ship-route-planning method for which the path and the speed are considered simultaneously is proposed. The proposed method used Seed genetic algorithm also proposed in this study. This proposed method will provide better solution than previous methods and overcome the limitation of other methods.

2. Ship-route-planning problem

2.1. Framework of ship-route-planning problem

The ship-route-planning problem is almost solved by using the optimization technique. that is because the characteristics of the ship-route-planning problem that need to provide on optimal route is corresponded to the characteristics of the optimization technique well. However, the optimization technique is not unique way to solve. Statistic method can also apply to ship-route-planning problem such as ENIRAM (2016) in related works section, but it is not used a lot because its result is not the optimum, but just a feasible solution.

Meanwhile, as mentioned in related works section, topics of study in the ship-route planning are as follows.

- Study of optimization model for formulating ship-route-planning problem as optimization problem
- Study of performance-evaluation model for estimation of ship performance under given condition.
- Study of route-finding model using optimization technique to find the best route
- Study of data structure for provision of continuous or discretized maps

First, the optimization model is one of important part of ship-route planning. It defines the element of optimization. The form of formulation depends on which one is optimized (design variable), what is optimizing object (objective function) and what should be satisfied (constraint). Except for several studies, objective functions and constraints were almost same. However, the design variable was different each other. Moreover, if the concept of design variable is changed, a way of route construction will also be changed in contrast with the objective function or the constraint. Therefore, ways of route construction are also different each other. Second, there is a study on a performance evaluation model for quantitatively evaluating routes. The ship performance described in the ship-route planning is a FOC (fuel oil consumption), a seakeeping etc. and it is necessary to finally calculated these based on the input information. Study on this is a performance-evaluation model. Third, there are route-finding model using optimization

technique. This part is related with optimization model. The optimization technique is selected by considering formulated elements of optimization. Last, it is possible to become a field of study about acquisition of data and management of information for ship-route planning. The important information used for ship-route planning is composed of geographical information and weather condition. Generally, in order to target the whole world, the amount of information must be very large and the type of information must be diverse. However, depending on whether ship-route planning is calculated to some extent in detail, the amount of information can vary with a wide range. In other words, the amount of information depends on the detailed calculation level required from the ship-route-planning method. For example, in the case of weather information, the information should be provided in time and space according to the type of information used in the ship-route planning. However, all the detailed information of the continuous time and space is difficult to obtain practically, in the case of normal weather condition, measure at twelve-hour interval in time and measure at one degree in space. Also, one of important problems on ship-route planning is a prediction of weather condition. The application on the actual ship-route planning is based on the predicted weather condition. Since the predicted weather condition can be wrong, the planned route can also be mistaken.

Usually, the first and the third topics of study are called an optimization algorithm for ship-route-planning. Most of studies does not distinguish the optimization model and the route-finding model. Therefore, the established optimization algorithm for ship-route planning has low flexibility about applying other several optimization technique or formulation. Dividing the topics of ship-route planning, it is possible to clearly classify and to freely apply other ways. Meanwhile, each topic of study can be proposed as independent single topic of study. Of course, there are studies containing more than one,

and all topics are developed and incorporated for development of ship-route-planning program.

2.2. Overview of this study

In this study, all topics are handled. The overview of study is as shown in Figure 2.

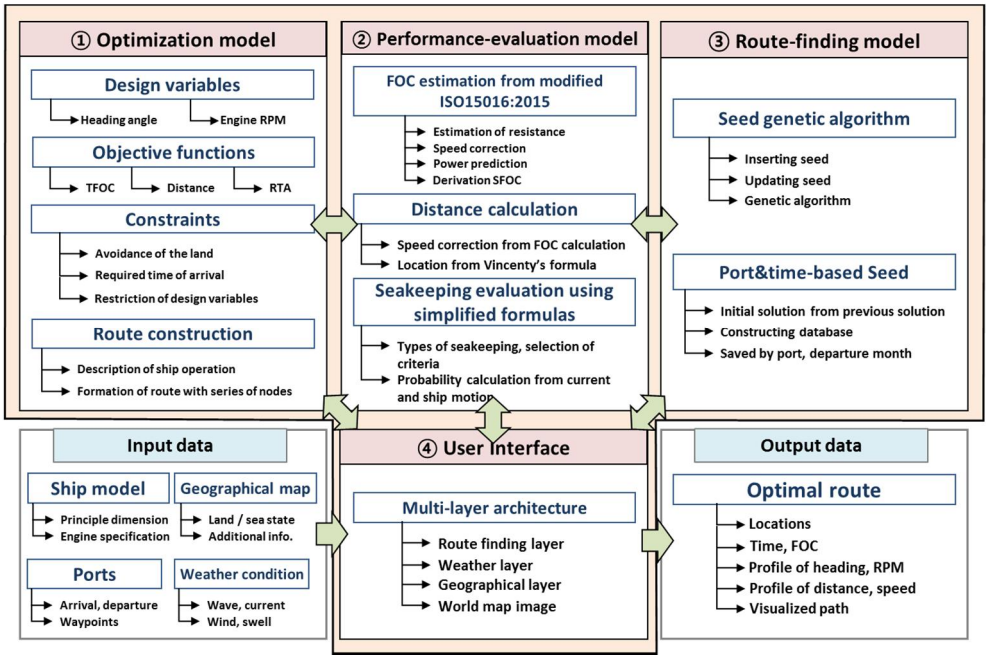

Figure 2 Configuration of key models in this study

In this study, first, optimization model is proposed to formulate the ship-route-planning problem as an optimization problem. The optimization model defines each element necessary for optimization and includes a way of route construction. Second, performance-evaluation model which evaluates the constructed route is proposed. The objects of performance evaluation are FOC estimation, distance calculation and seakeeping evaluation. These objects are based on various theories and studies. Next, the route-finding model is proposed to obtain an optimal solution from the optimization problem. Finally, program containing whole models is developed and applied to a number of examples. Details will be explained one by one from the next section.

2.3. Input and output information

Before describing the ship-route-planning method, input and output information is organized for solving the ship-route-planning problem. Table 2 shows input information.

Table 2 Input information for ship-route-planning

Category	Items [unit]
Ship information	Main dimension, coefficients, engine specification etc.
Ports and waypoints	Latitude [degree], Longitude [degree]
Time	Departure time, RTA (Required time to arrival) [day]
Geographic information	State; Binary value of each cell [1: Land, 0: Sea]
Weather condition	Wind direction [degree], Wind speed [knot], Current direction [degree], Current speed [knot], Wave direction [degree], Wave height [meter], Wave period [second], Swell direction [degree], Swell height [meter], Swell period [second]

To solve the ship-route-planning problem, ship information, ports and waypoints, time, geographic information and weather condition are basically necessary. First, information on the target ship is required. The types of detailed ship information depend on the performance-evaluation model of the ship-route-planning method. There must be information necessary to estimate the performance of the ship. Generally, the more accurate and the more complex performance-evaluation model is used, the more ship information is necessary. Approximately, ship's main dimension, various coefficients and engine specification etc. are required. The ship information used in this study is arranged in appendix A. Second, the ports and waypoints are necessary. A position, a set of longitude and latitude, of port and name are needed. Usually, a departure port and an arrival port are enough to form the ship-route-planning problem, but several positions are necessary in case of passing though several waypoints and ports. Third, the time information is also necessary. The types of time are a departure time and RTA (Required time of arrival). Fourth, the weather condition is needed. The weather condition must have a value depending on a type, a time and a position. In the same case of the ship information, the types of weather condition required for the ship-route-planning utilizes in the performance-evaluation model is required. These types of weather condition are a wind, a current, a wave and a swell. In more detail, there are wind direction, wind speed, current direction, current speed, wave direction, wave height, wave period, swell direction, swell height and swell period by time and position. The weather condition can be obtained from government agencies or weather companies. Last, geographic information is necessary. In order to solve only the ship-route-planning problem, only geographical information that informs the state whether the place is land or ocean is necessary. However, the information used in the basic map as well as state information is

necessary for the user. For example, additional information such as international border information and city name information is also necessary. The map including auxiliary information can also be obtained from government agencies or map companies. Basically the above information is necessary for ship-route-planning. If there are other necessary information in the performance-evaluation model, that information is also needed. Meanwhile, output information for ship-route planning is shown in Table 3.

Table 3 Output information for ship-route planning

Category	Items [unit]
Route	Profile of position: Longitude [degree], Latitude [degree] Profile of speed[knot]
Performance	Profile of FOC[ton], profile of distance[NM], profile of seakeeping
Time	Arrival time

The output information of ship-route-planning is a route, performances on the route and time. As explained later, a route is defined as a set of paths and speeds. Values of performances on the route are calculated by segment. Therefore, the ship-route-planning problem finally provides in the form of profiles of a route and performances on the route.

3. Optimization model

In general, the ship-route-planning problem is solved with the optimization problem

because the objective of problem is clear and the result is demanded with an optimum. Before applying the optimization technique, the element of optimization must clearly be defined. The optimization model is composed of a mathematical model for finding optimal route and route construction from the mathematical model. In the theoretical background, the established path finding algorithms are explained and its original limitations are described. And then, in the formulation, the mathematical model is formed for overcoming limitations of the established algorithm. Design variables, objective function and constraints are described. Finally, in the route construction, a route is defined and it assigns the meaning of route to mathematical model.

3.1. Theoretical background

The established ship-route-planning algorithms are conducted with the speed planning, but their originality is based on the path-finding algorithm. Therefore, the path-finding algorithm is also handled in this section. There are several ways to classify the path-finding algorithm. Among these ways, the use of cell is important classification criterion. The use of cell means a map is divided by cell. According to criterion, the use of cell, the path-find algorithm are divided into a cell-based algorithm and a cell-free algorithm. It seems that there is not much difference between the cell-based algorithm and the cell-free algorithm. However, there is a difference in the approach to the problem. First, the cell-based algorithm is based on the discretized space. In many cases, its discretized space is expressed with points. With connecting points, the route is completed. Usually, the distance from point to point and weights applied on point are given. These types of problem are representatively a travelling salesman problem (TSP) and a Eulerian graph

problem. Meanwhile, the cell-free algorithm is based on the continuous space. There is no limitation for direction, so it could make more smooth path than the cell-based algorithm. Also, the route cannot help consisting of points, just curved line. This algorithm should have ways to calculate distance or weights from the space because these information is not given usually. These types of problem are a great circle problem. Figure 3 shows the difference between the cell-based algorithm and the cell-free algorithm.

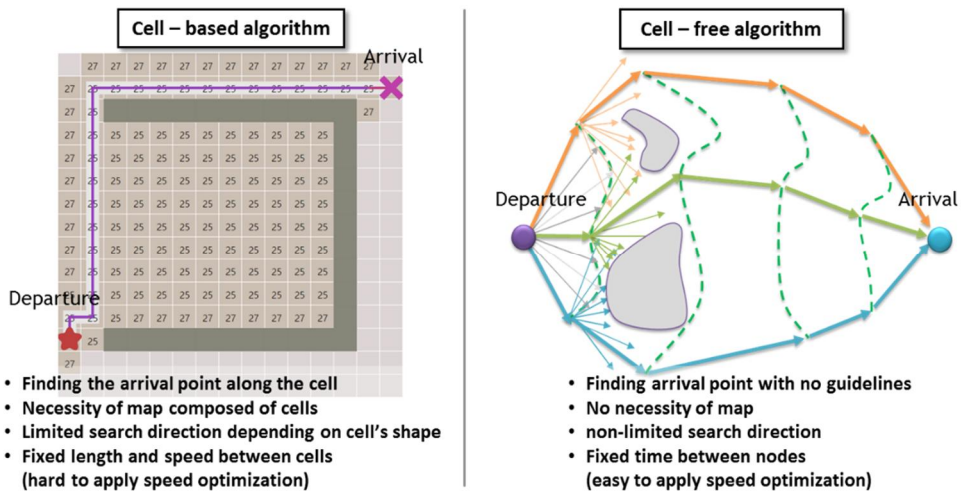

Figure 3 Comparison between the cell-based algorithm and the cell-free algorithm

3.1.1. Cell-based algorithm

In case of cell-based algorithm, cells are defined on the matched region of map and all of information are stored into cells. Therefore, all of information are described by cell. Figure 4 shows the formation of shape of cell into geographical map.

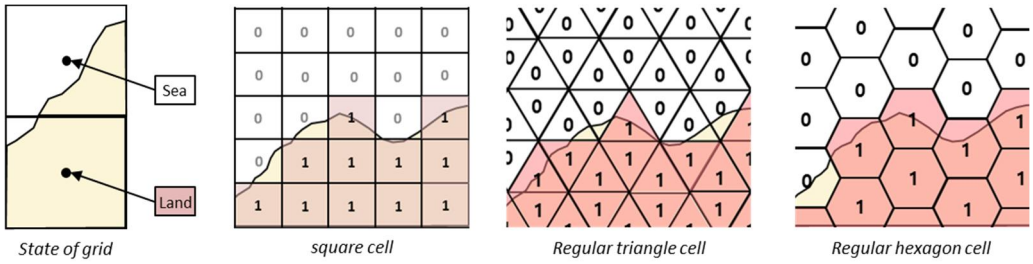

Figure 4 Configuration of formation shape of cell into geographical map

For example, the movement of ship can be switched to the movement from the cell including the starting point of ship to the cell including the ending point of ship. Therefore, even though there are cases having the different starting point and the different ending point, each case will get the same length of each movement case if the starting point and ending point of each case belong to the same cell. Like this example, the shape of cell and the size of cell are important because information is stored on the basis of the cell. Generally, the cell is a square shape in algorithms for finding the optimal path. Dijkstra algorithm and A-star algorithm belong to the cell-based algorithm. Dijkstra and A-star algorithms are the well-known path-finding algorithm for which the speed optimization was not performed. Most of the ship-route-planning studies are concerned with the cell-based method, and the path optimization and the speed optimization are accordingly separated.

- Dijkstra algorithm

Dijstra algorithm (Dijkstra, 1959) is an optimization algorithm to generate the global optimum with searching the all of range on the basis of cost. In here, this algorithm will find the shortest path if the cost is referred to as the cumulative moving distance. Its computation time is relatively long, because this algorithm searches for the path in all of range. Figure 5 shows the flow chart of Dijkstra algorithm.

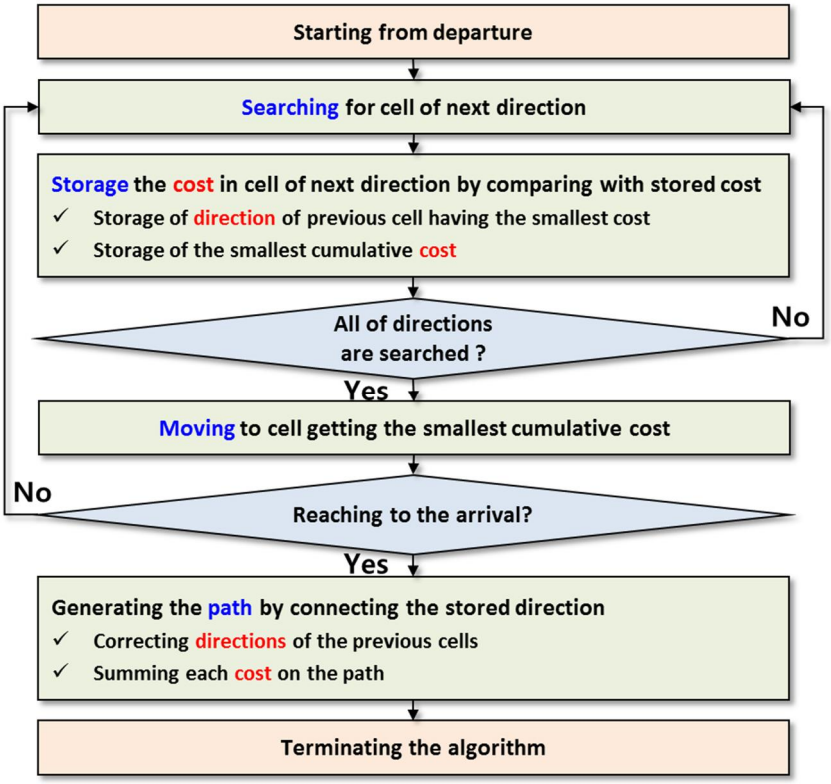

Figure 5 Flow chart of Dijkstra algorithm

As shown in Figure 5, Dijkstra algorithm is progressed with this procedure. The speed can be only described after assuming the speed during moving from one cell to another

cell. Then, the time is obtained by multiplying the moving distance and assumed speed. The route cannot consider ship performance about the total route such as RTA (Required time to arrival) because the ship performance is determined when moving from cell to another cell, not about total route. For example, the optimal way moving from cell to another is determined as the lowest speed is applied. The procedure is iterated with the same way. Then, the route will not satisfy RTA because the lowest speed is always applied. Therefore, to apply the speed planning, this algorithm requires an addictive procedure or the speed planning is performed after the algorithm is completed.

- A-star algorithm

A-star algorithm (Hart et al., 1968) is made of mixing Dijkstra algorithm and Greedy best-first search. This algorithm is almost similar with Dijkstra algorithm in view of procedure. Greedy best-first search is inserted into the Dijkstra algorithm and it is served as a directivity. This directivity is reflected into the calculation of the cost and it adds into the cost as a term named heuristic. From here, if the cost is considered as the cumulative moving distance and the heuristic is switched to the predicted distance from locating cell to arrival cell, the optimal path will be found. Although its path is not a global optimum, its computation time is much faster than Dijkstra algorithm and its path is nearly similar with that of Dijkstra algorithm. Figure 6 shows the flow chart of A-star algorithm. The same with Dijkstra algorithm, the speed can be only described after assuming the speed during moving from one cell to another cell. Then, the time is obtained by multiplying the moving distance and assumed speed. Therefore, to apply the speed planning, this algorithm requires an addictive procedure or the speed planning is performed after the algorithm is completed. Main differences between A-star algorithm and Dijkstra

algorithm is caused by heuristic term inspired from Greedy best-first search. The heuristic term leads direction where the arrival is located. It leads a reduction of the searching range although it leads a local optimum, not a global optimum.

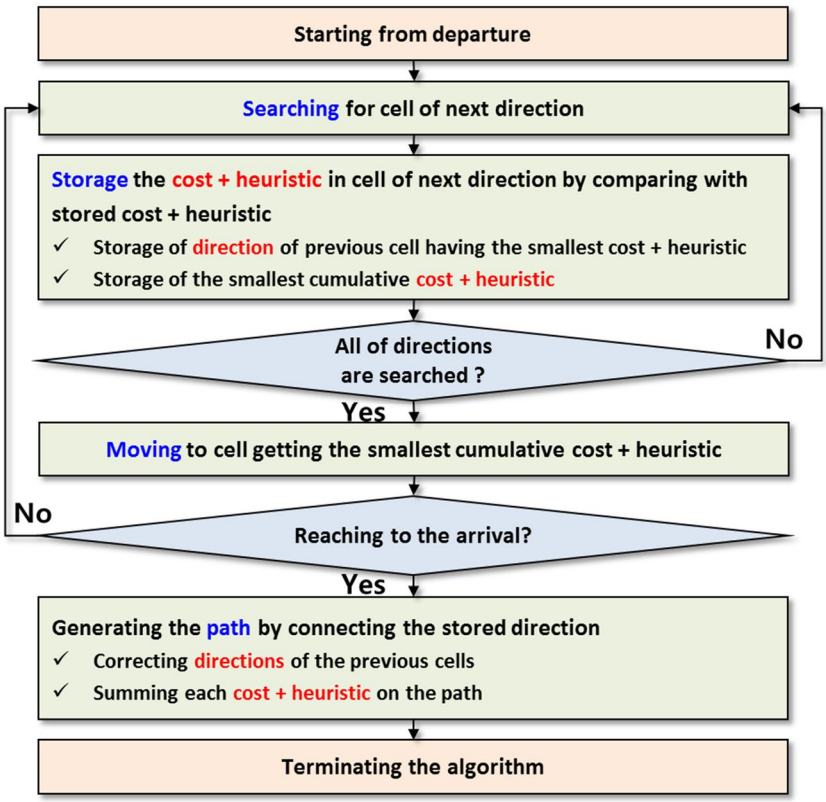

Figure 6 Flow chart of A-star algorithm

3.1.2. Cell-free algorithm

The route of cell-free algorithm cannot help consisting of points, just curved line. In view of this, a problem can be analytically defined such as Equation 1 and Equation 2.

Here, we set the objective of problem is a total fuel oil consumption.

$$\text{Minimize } \int TFOC(v, w, m)\, ds \qquad \text{Equation 1}$$

$$v(s,t) = 0 \;,\; w(s,t) = 0 \qquad \text{Equation 2}$$

TFOC is a function of total fuel oil consumption, v is a function of ship speed, w is a function of weather condition, m is a function of ship model, s is a path, and t is a time. Given the function of weather condition and function of ship model, the TFOC can be renewed like Equation 3 and Equation 4.

$$\text{minimize } \int TFOC(v)\, ds \qquad \text{Equation 3}$$

$$v(s,t) = 0 \qquad \text{Equation 4}$$

To solve Equation 3 and Equation 4, equations should be derivative on path and time. However, these equations cannot be solved with analytical method because total fuel oil consumption and speed are coupled. Also, it cannot be expressed in forms of explicit function and mostly, total fuel consumption is a function based on the empirical equation. Therefore, for solving them, another method is applied like numerical method or heuristic method. To cope with this situation, several researchers have proposed another way to

consider the speed in ship route planning. In case of cell-free algorithm, exact values can be accessed regardless how shape of cell or size of cell is defined. The representative algorithm is Isochrone method and 3DDP.

- Isochrone method

Isochrone means the line made up connecting the points which can be reached from starting point during constant time. Isochrone method (James, 1957) finds the shortest path by iterating to draw isochrones. Figure 7 shows a concept image of Isochrone method.

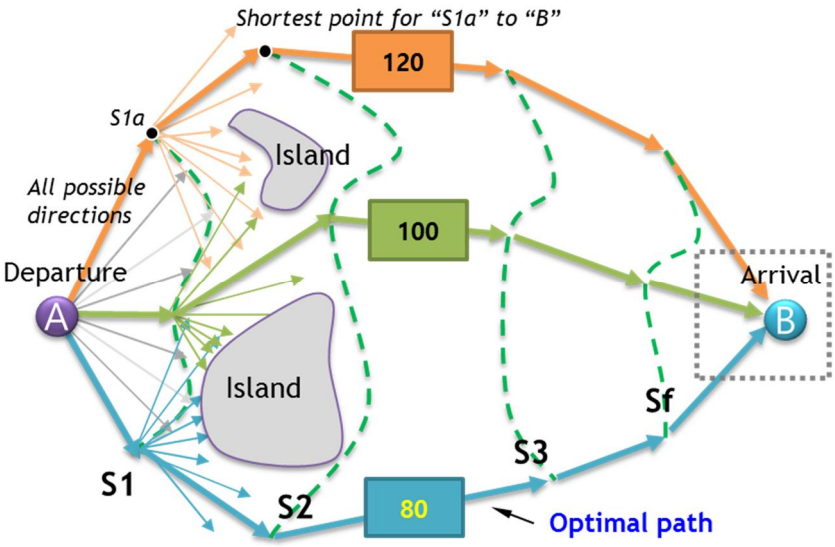

Figure 7 Concept image of Isochrone method

To use Isochrone method, its procedure is as follows. First, set the information used in Isochrone method, including constant time and constant speed. The constant time and the constant speed are applied in the interval between isochrones. This time and the speed are constant throughout progressing the whole procedure. Second, search for the locations to be able to arrive from departure. And then, search for the locations obtained by regarding the locations as starting point again. At this moment, there are lots of isochrones because lots of locations at the first isochrone are set and draw the next isochrones from each location. Among them, the farthest locations are selected. And iterating the same process until the arrival exists in the isochrone. There is a significant point in setting the constant speed and the constant time. Although the speed is constant in Isochrones method, it is open to change each interval between isochrones.

- 3D dynamic programming

The 3DDP (Wei and Zhou, 2013) is a method of finding the great circle line and finding the route on the basis of the point on the perpendicular line (stage) where the great circle line is equally divided at regular intervals.

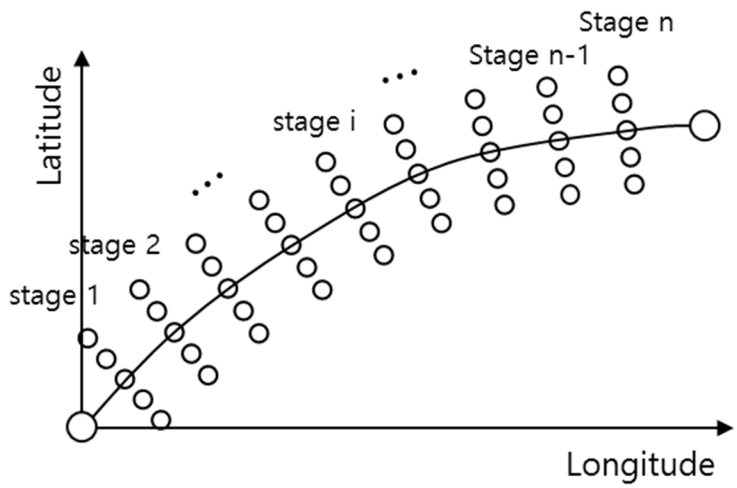

Figure 8 Concept of the 3D dynamic programming

On stage, the 3DDP select the point of next stage. Between stages, the time interval is existed. Therefore, the 3DDP is similar with Isochrone method. In Isochrone method, isochrones were drawn with constant time and constant speed between one isochrone and next isochrone. However, 3DDP drew lines with constant time and constant distance, not constant speed. That was, speed depended on constant time, constant distance and weather condition. If the land is on all point of stage, it cannot pass though that route. But this algorithm can consider added constraints such as seakeeping.

3.1.3. Comparison

As explained above section, there are two types of algorithm, the cell-based algorithm and the cell-free algorithm. The representative algorithm on the cell-based algorithm is Dijkstra algorithm and A-star algorithm. Also, the representative algorithm on the cell-

free algorithm is Isochrone method and 3DDP. These four algorithms are compared in Table 4 in view of probability of speed optimization.

Table 4 Comparison between path-finding algorithms and application for speed optimization

Algorithm		Use of cell	Fixed value	Smoothing path	Computation time	Speed optimization	Correction for speed optimization
Cell-based	Dijkstra	O	Direction, speed	X	Long	Relatively hard to apply	Evolutionary strategy, Genetic algorithm
	A-star			X	Short		
Cell-free	Isochrone	X	Time, speed	O	Normal	Relatively easy to apply	
	3DDP			Δ	Normal		

The algorithm using the cell, Dijkstra algorithm and A-star algorithm, cannot help limiting the searching direction inevitably because the shape of cells is fixed. Therefore, these algorithms assume that the direction and the speed from cell to another is fixed. Its path gets a rough and angled shape so post-treatments are needed for making the smooth path. Furthermore, as previously mentioned, the concept of time is not contained in the cell-based algorithm so the speed optimization should be operated separately.

However, the algorithm un-using the cell, Ishochrone method and 3DDP, is not limited on searching direction, so its gets smooth path. Also, the concept of time is contained in the cell-free algorithm so these are relatively easy to be applied into the algorithm. However, the speed optimization is still limited, so these algorithms also perform the speed optimization independently. Figure 9 shows the concept of each path-finding algorithm.

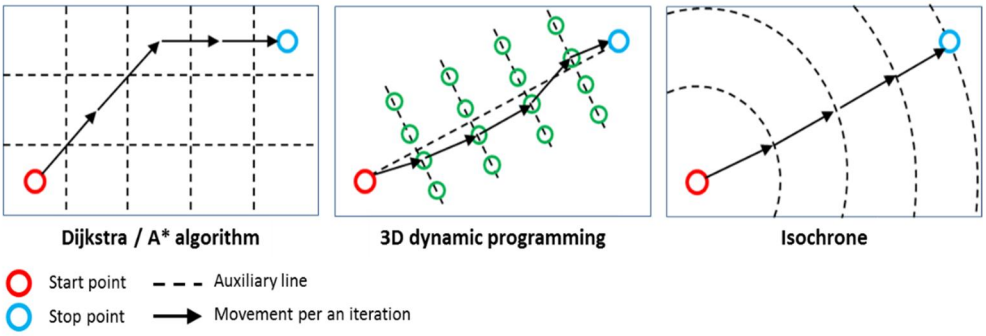

Figure 9 Configuration of concept of each path-finding algorithm

3.2. Formulation of the ship-route-planning problem as the optimization problem

To determine a route, the optimal route problem is formulated as a mathematical model; that is, an optimization problem. The optimization problem consists of design variables, objective functions, and constraints. Each component of the problem is described in the subsequent sub-sections.

3.2.1. Design variables

The design variable is an object to find in the optimization problem. In this study, the route is the object and the route is expressed with the path and speed. The heading angle is related to the path and the engine RPM is related to the speed of the ship. Therefore, the path is expressed with heading angles (θ) of ship and the speed is expressed with engine RPMs (rpm) of ship. Equation 5 and Equation 6 show the design variables in this

study.

$$\boldsymbol{\theta} = \{\theta_0, \theta_1, \cdots, \theta_i, \cdots, \theta_{n-1}\} \qquad \text{Equation 5}$$

$$\mathbf{rpm} = \{rpm_0, rpm_1, \cdots, rpm_i, \cdots, rpm_n\} \qquad \text{Equation 6}$$

The bold θ is a set of heading angles and the bold rpm is a set of rpms. Subscripts mean the order of nodes and n is the number of nodes. It should be noted that θ_0 means the azimuth of ship and the others are related heading angle of ship. The reason for setting heading angles like that is expressed in view of user. The captain and the chief mate control the direction in the ship so related angles are used. One more thing to note is that the heading angle does not have the (n)-th heading angle (θ_n). As explained later, the route is completed by connecting the last waypoint and the arrival port. Therefore, the last heading angle on the last waypoint is not unknown, the determined value so the heading angle does not have the (n)-th heading angle. The total number of design variables in this problem is therefore 2n + 1.

3.2.2. Objective functions

An objective function in the optimization problem is used as a criterion for the selection of the best one from a number of alternatives. In this study, the TFOC is used as an objective function. Of course, others can become an objective function. For example,

the distance of route or the arrival time can be set as an objective function and it is introduced in application. However, the TFOC is basically set as an objective function in this study. The TFOC is a function of design variables, heading angle and engine RPM. That is, the TFOC depends on the route including the weather condition. The TFOC estimation is described as shown in Eq. (3). The exact way to obtain TFOC is explained at performance-evaluation model.

$$\text{Minimize } TFOC(\boldsymbol{\theta}, \mathbf{rpm}) \qquad \text{Equation 7}$$

3.2.3. Constraints

A constraint in the optimization problem is used as a limitation for filtering the solutions from a number of candidates. Five constraints are used in this study. First, the route for the ship should not pass through obstacles such as land. This constraint is checked with identifying the state of points. Second, the ship should not arrive at the arrival port beyond the latest time of arrival (RTA), which is given by the designer. The arrival time is calculated with ETA. Therefore, this constraint is obtained as subtracting RTA from ETA. Third, the ship should operate on the safe route. The criterion of safety is obtained from calculating seakeeping. Fourth, the route for ship should be smooth path and the ship cannot make a rapid direction change. Therefore, one of the design variable, heading angle, should have a restriction. Last, the engine of ship has a range of operation. Therefore, engine RPM also has a restriction. The five constraints are expressed as Equation 8-12.

$$\|P_i(\boldsymbol{\theta}, \boldsymbol{rpm}) - P_{land}\| \leq 0 \qquad \text{Equation 8}$$

$$ETA(\boldsymbol{\theta}, \boldsymbol{rpm}) - RTA \leq 0 \qquad \text{Equation 9}$$

$$Seakeeping_i \leq criteria \qquad \text{Equation 10}$$

$$\theta_{min} \leq \theta_i \leq \theta_{max} \qquad \text{Equation 11}$$

$$rpm_{min} \leq rpm_i \leq rpm_{max} \qquad \text{Equation 12}$$

All constraints are expressed simply in Equation 8-12. The exact expressions and ways for obtaining constraints are explained in performance-evaluation model. it should be noted that the first heading angle (θ_0) is an azimuth angle and the others are related angles in the fourth constraint, the restriction of heading angle.

This optimization problem is therefore a kind of constrained optimization problem that comprises 2n + 1 design variables, one objective function, and five forms of the inequality constraints.

3.3. Route construction from elements of formulation

The ship-route-planning problem cannot always be solved directly after the formulation has been executed. The formulation is nothing more than the classification and description for solving the optimization problem. Therefore, the process that gives

meaning to formulated variables and expressions is necessary. Without this process, the formulated variables and expressions are meaningless as if these were simply unknowns and equations. Also, this process helps in interpreting the results after the route was planned. The generation of route gives meaning to formulated variables and expressions via each element of formulation totally. In this section, the route definition, the way of constructing route with the formulated variables and expressions and the way for evaluating route are described.

3.3.1. Route definition

In the many previous ship-route-planning studies, they defined a route as path only and they only provide the result as waypoints. In this study, a speed as well as a path is included to ship-route planning. Therefore, the definition of the route is defined as a path profile and a speed profile composed of nodes and speeds. Nodes are the intermediate points between the departure and arrival ports. That is, node means a path of route. The route can be described as Equation 13.

$$\boldsymbol{Route} = \left\{ \begin{bmatrix} \boldsymbol{P_0} \\ \boldsymbol{v_0} \end{bmatrix}, \begin{bmatrix} \boldsymbol{P_1} \\ \boldsymbol{v_1} \end{bmatrix}, \cdots, \begin{bmatrix} \boldsymbol{P_i} \\ \boldsymbol{v_i} \end{bmatrix} \cdots, \begin{bmatrix} \boldsymbol{P_{n-1}} \\ \boldsymbol{v_{n-1}} \end{bmatrix}, \begin{bmatrix} \boldsymbol{P_n} \\ \boldsymbol{v_n} \end{bmatrix} \right\}, \qquad \text{Equation 13}$$

P is a position and v is a speed. Subscripts mean the order of nodes and n is the number of nodes. The number of nodes(n) is set though the basis of time duration. While, P can be expressed as longitude and latitude such as Equation 14.

$$\boldsymbol{Route} = \left\{ \begin{bmatrix} \boldsymbol{Lon_0} \\ \boldsymbol{Lat_0} \\ \boldsymbol{v_0} \end{bmatrix}, \begin{bmatrix} \boldsymbol{Lon_1} \\ \boldsymbol{Lat_1} \\ \boldsymbol{v_1} \end{bmatrix}, \cdots, \begin{bmatrix} \boldsymbol{Lon_i} \\ \boldsymbol{Lat_i} \\ \boldsymbol{v_i} \end{bmatrix} \cdots, \begin{bmatrix} \boldsymbol{Lon_{n-1}} \\ \boldsymbol{Lat_{n-1}} \\ \boldsymbol{v_{n-1}} \end{bmatrix}, \begin{bmatrix} \boldsymbol{Lon_n} \\ \boldsymbol{Lat_n} \\ \boldsymbol{0} \end{bmatrix} \right\} \qquad \text{Equation 14}$$

Lon is a longitude and Lat is a latitude. The route is composed of coordinates of longitude and latitude and speeds. As explained above, values of route cannot be obtained directly from the formulated variables and expressions. Meanwhile, there is one caution that the speed of the last node is zero. This can be understood by examining the meaning of coordinates and speed like Figure 10.

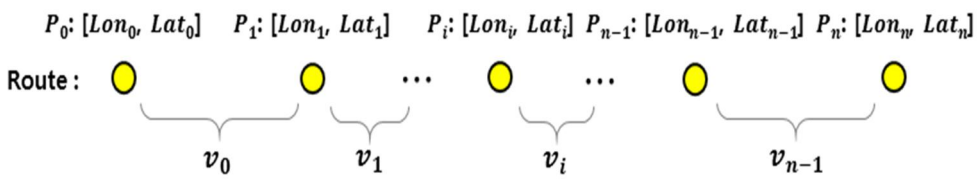

Figure 10 Configuration of route definition

The coordinate means the position of node, but speed is a fixed value between nodes. Therefore, the number of speeds is one less than the number of coordinates and the last speed of node is zero.

3.3.2. Route generation

To obtain node position (P_i), the formulated variables and expressions are used. The design variables of the optimization problem are the direction (or heading angle, θ), in Eq. (1), and the engine RPM (rpm), in Eq. (2). Figure 11 shows the configuration for the determination of the next route.

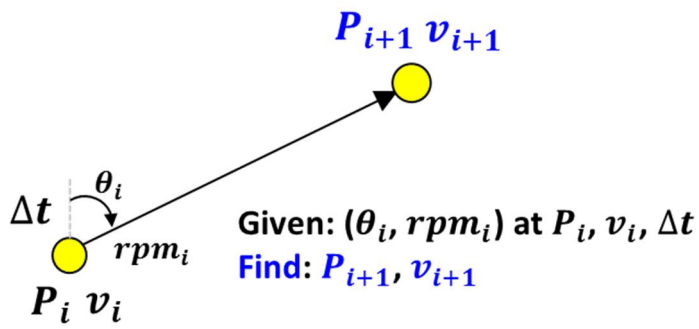

Figure 11 Configuration for the determination of the next route

To obtaining the next node (P_{i+1}) from the present node (P_i), the (i)-th heading angle (θ_i) and the present speed (v_i) are necessary. In addition, it is assumed that the time duration (Δt) between two adjacent nodes is a constant value (e.g., 12 hours) as shown in Figure 11. By calculating the heading angle, the present speed and the time duration with the polar coordinate, the next node could be obtained from the present node. This can be expressed like Equation 15.

$$P_{i+1} = \left(P_{i,x} + \sin(V_i \cdot \Delta t), P_{i,y} + \cos(V_i \cdot \Delta t)\right) \qquad \text{Equation 15}$$

Meanwhile, the next speed of route (v_{i+1}) can also be obtained by calculating performance-evaluation model using engine RPM (rpm_{i+1}) and weather condition at the next node (P_{i+1}). With the same way of this, the whole route (P_i, v_i) can be obtained. Figure 12 shows the application of design variables for obtaining route in this study.

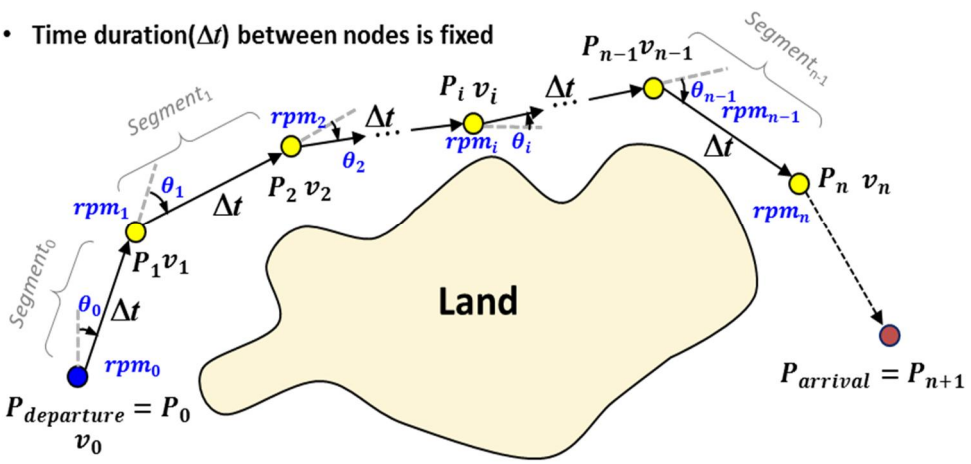

Figure 12 Application of design variables for obtaining route in this study

First, the first node (P_0) of route is the departure port ($P_{departure}$). Second, the speed (v_0) of route is obtained with performance-evaluation model using the first engine RPM (rpm_0) of design variables. Then, the first value of route can be determined with P_0 and v_0. Third, in order to obtain the second node (P_1) of route, the first heading angle (θ_0) and time duration (Δt) are used. Fourth, in order to obtain the second speed (v_1) of route, the second engine RPM (rpm_1) and weather condition at the second node (P_1) are used.

To obtain all of route, the procedure of the third and the fourth iterates until all of the design variables are used. Then, the (n)-th node (P_n) and the (n)-th speed (v_n) of route can be obtained. Lastly, the last node (P_{n+1}) of route is the arrival port ($P_{arrival}$). Also, the last speed (v_{n+1}) of route is zero as explained previous section. Then, the route is finally determined. Meanwhile, the last time duration from the front of the last node (P_n) to the last node (P_{n+1}) is not the same with other time duration. Because, the last node is not calculated from the (n)-th heading angle (θ_n), the front of the last node (P_n) and the time duration (Δt) unlike previous procedure. Therefore, time duration is obtained with the front of the last speed (v_n) and the distance between the front of the last node and the last node. That is, time duration is obtained from performance-evaluation model. Additionally, the (n)-th heading angle (θ_n) is also obtained.

The above procedure has three advantages as follows. First, this procedure can be possible to do simultaneous optimization. This procedure fits to two formulated design variables, heading angle and engine RPM. In point of setting the design variables as the path and the speed, design variables can be performed a completely simultaneous optimization. Second, this procedure describes the actual ship operation. During the sailing, crew including a captain can control the heading angle and engine RPM only. Last, this procedure is easy to use in the actual operation. The design variables, heading angle and engine RPM, is more familiar to crew than others. And time duration is fixed so this procedure is able to give the regular operating time to crew. For example, if the time duration is set with 12 hours, then crew will just maneuver the heading angle and the engine RPM at the fixed time.

Another noteworthy point is that the way for reaching the arrival. There are two ways for reaching the arrival. One is a connection between the last waypoint and the arrival

point like above, the other is a deletion of waypoints which are later than reached waypoint within the range of the arrival point. Figure 13 shows the difference between two ways for reaching the arrival point.

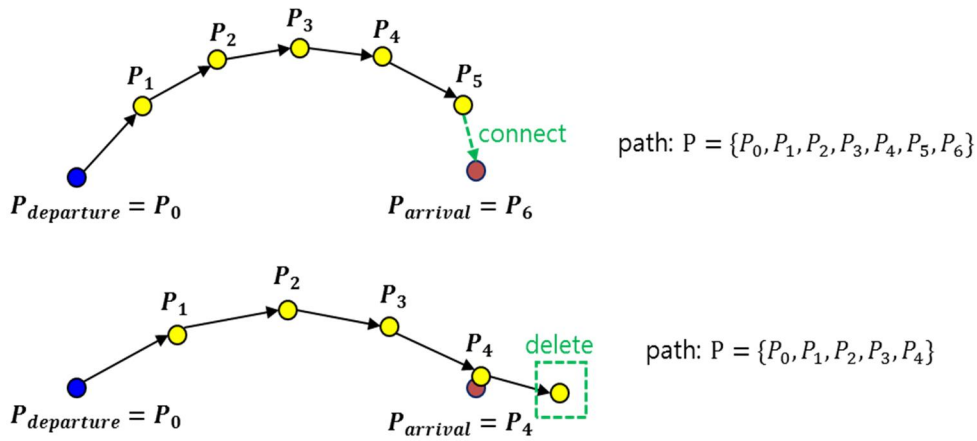

Figure 13 Difference between two ways for reaching the arrival point

Each way has advantage and weakness respectively. The connection always makes a ship to reach the arrival point because the arrival point is absolutely connected with the last node. However, if the number of nodes are larger, the route can become a winding path. On the contrary to the connection, the deletion can prevent a winding path. However, it cannot reach the arrival point if there is no node to satisfy the range of the arrival point. In this study, the connection is selected because the ship must reach the arrival point and the weakness of it can be overcame by providing proper number of nodes.

3.3.3. Route evaluation

The generation of the route is performed though the introduced procedure at the previous section. Meanwhile, the way for evaluating route is also necessary. An important assumptions in the way for evaluating route is that all of values are constant during the time duration (Δt). That is, variations between nodes are ignored during moving from one node to other node. Figure 14 shows the configuration for the evaluation of the segment.

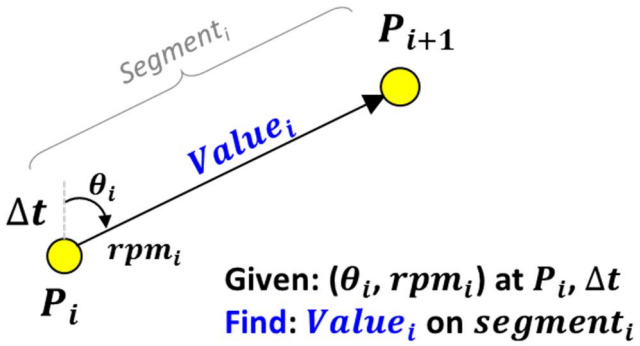

Figure 14 Configuration for the evaluation of the segment

In the actual operating ship, whatever values associated with position and time are changed during passing this segment. However, the assumption is not quite violated compared with the actual operating ship. The variation of position and time means the weather condition is changed. However, in terms of time, time duration is not usually too long compared with inputting time of weather data because the time interval of the given weather data from weather casting company is usually 12 hours. Therefore, weather data

does not change during time duration so the difference from the time variation can be ignored. Meanwhile, in terms of position, the distance of ship during time duration looks like too long. However, this distance is short in view of the earth and the difference of weather data caused by distance is slight. According to these reasons, the assumption that variations between nodes are ignored during moving from one node to other node is valid.

As shown in Equation 16 and Figure 12, the value of total route is calculated by adding all the value on the segment.

$$\boldsymbol{Value} = \sum_{\boldsymbol{i=0}}^{\boldsymbol{n}} \boldsymbol{Value}_{\boldsymbol{i}} \qquad \text{Equation 16}$$

Meanwhile, value means all things obtained from route in this section. Because there are many types of value and these values are evaluated with the same way. The types of value and the methods of calculation are described in performance-evaluation model. The types of value are mainly FOC, distance, seakeeping etc.

4. Performance-evaluation model

The performance-evaluation model is ways for evaluating the performance of ship. Its targets are all performance which has to be calculated for solving ship-route-planning problem. The FOC, the distance, the seakeeping and the avoidance of land are main target

of performance-evaluation model as the objective function and the constraints in optimization model. Each target has different ways to evaluate. There is no definite way for evaluating performance of ship. Therefore, many studies developed their own way. This study also develops and proposes new ways to evaluate based on various theories and comments. The proposed ways of this study is mainly based on method from the international organizations such as ISO and IMO. Therefore, proposed ways are more easy to apply and more reliable than other studies.

Meanwhile, performances of the ship change from moment to moment while operating. The external effect caused by wave and wind induces various performances of ship like ship motion, maneuvering, stability and seakeeping. However, the microscopic changes of performance are not considered in the ship-route-planning, but the macroscopic parts are only handled. There are several reasons for handling macroscopic parts only. First, the ship-route planning is for targeting what is calculated on the global scale on the distance and it takes days to arrival on the time. Second, the type and size of the information provided is limited. Basically, terrain information and weather condition are given, but more detailed information and other information are not given in most cases. Because there is not much provided information, information for calculating performance is lacking. For example, most of information is given in degrees, weather information is provided with one information in 12 hours. Because of the characteristic of the ship-route-planning, it is necessary to calculate the result within a limited time. therefore, the short calculating time is more important than the long calculating time of the exact performance even if the accuracy drops.

4.1. FOC estimation

FOC means all fuel oil quantities used in ship, and this means not only the fuel necessary for the operation, but also all the fuel oil consumption required for operation, such as fuel oil consumed by generators that produce the necessary electricity. Since consumed fuel oil in the engine occupies a large part of the amount of used fuel oil for normal operation, it can be seen as FOC for this operation. There are many number method for obtaining the FOC as shown in Table 5.

Table 5 FOC estimation for ship-route planning

<table>
<tr><th>Paper</th><th>Resistance in still water</th><th colspan="2">Added resistance</th><th>Speed loss</th><th>Change of advance ratio</th><th>MEFOC</th></tr>
<tr><td>EN-Saver (2015)</td><td colspan="6">Regression analysis</td></tr>
<tr><td rowspan="4">ISO15016:2015 (2015)</td><td rowspan="4">Model test</td><td>Wind tunnel test</td><td>STAWAVE-1</td><td rowspan="2">Iterative method</td><td rowspan="4">Direct power method (load factor)</td><td rowspan="4"></td></tr>
<tr><td>STA-JIP coefficients</td><td>STAWAVE-2</td></tr>
<tr><td>Regression formula (Fujiwara)</td><td>Theoretical method (Maruo's theorem)</td><td rowspan="2">Mean of means method</td></tr>
<tr><td>Effect of temperature & density</td><td>Seakeeping model test</td></tr>
<tr><td>Vettor et al. (2016)</td><td>Holtrop-Mennen method</td><td colspan="2">Faltinsen method</td><td>Empirical approach</td><td>B-series model test</td><td>Engine specifications</td></tr>
<tr><td>Park et al. (2004)</td><td>Experiment data</td><td colspan="2">Panel method</td><td colspan="2">Iterative method</td><td>Engine specifications</td></tr>
<tr><td>Park et al. (2015)</td><td colspan="3">-</td><td>Equation of speed loss using BN</td><td colspan="2">Regression analysis</td></tr>
<tr><td>This study</td><td>Holtrop-</td><td>STA-JIP</td><td>STAWA</td><td>Effect of</td><td>Effect of</td><td>Direct power</td><td>Engine</td></tr>
</table>

	Mennen method	coefficients	VE-2	temperature & density	current	method (load factor)	specifications

The FOC is obtained in roughly two ways. First, there is a regression analysis between measured ship performance and measured FOC. In this case, since it is calculated based on the actual operation data, accurate values can be calculated. However, since it is effective only for this ship, there are severe weaknesses to apply to other ships. Second, there is a theoretical way of estimation from ship information and engine specification. In this case, it is not the value obtained by the actual data, so its precision is reduced. However, it is relatively versatile and can be applied selectively since there are various theoretical methods. This case go through the procedure as shown in legend of Table 5. First, the ship resistance is estimated. Second, the added resistance caused by external condition is estimated. Next, the speed loss is estimated and change of the advance ratio is estimated. Last, MEFOC which means consumed fuel oil per unit time is estimated from engine specification. From these procedure, FOC is estimated by multiply the MEFOC by operating time. Each stage of the procedure, used theories can be selected. Every theory has the strengths and weaknesses, so the selection of estimating theories on each stage is examined thoroughly.

In this study, the theoretical way of estimation from ship information and engine specification is used, and the theories on each stage are modified from ISO15016:2015. That is, the way of FOC calculation used in this study is proposed based on ISO15016:2015. The ISO15016:2015 is a conversion way of ship performance proposed from ISO. Therefore, the ISO15016:2015 has the similar procedure of the theoretical way. The theories used in each stage are guaranteed because it is verified from ISO.

4.1.1. Theoretical background

The purpose of ISO15016:2015 is for estimation of ship performance after construction of a ship. The ship performance is measured from a trial test. The trial test is performed in condition of good weather like a calm wave and a calm wind. However, although the trial test is performed in good condition, a difference between still water and actual sea state occurs from the external effects. Therefore, the ship performance will be described based on the state of still water. ISO15016:2015 is a proposed international standard that eliminates the influence of external effects from the performance measured in trial test and converts it into the performance within the state of still water. Therefore, in order to apply ISO15016:2015, the weather information and measured performance in trial test are necessary, and from this, the corrected performance in the state of still water is consequently estimated. The main contents are measurement methods of weather in trial test, measurement method of performance, and various ways that can be converted into the state of still water. Several ways can be selectively applied for user's convenience rather than one way. Reasons and references are made in theory and empirical formula adopted in ISO, so study and implementation are easy. ISO15016:2015 mainly handles estimation of the added resistance, correction of speed and correction of power (change of advance ratio). Table 6 shows the main estimation and its solving ways handled in ISO15016:2015.

Table 6 Main estimations and its solving ways handled in ISO15016:2015

Classification	Calculation of the added resistance	Correction of speed	Correction of power

	wind	wave	Temperature & density	Current	Shallow water	Power
Possible to apply ways	Wind tunnel test	STAWAVE-1	Effect of temperature & density	Iterative method	Effect of shallow water	Direct power method
	STA-JIP coefficients	STAWAVE-2		Mean of means method		
	Regression formula (Fujiwara)	Theoretical method (Maruo's theorem)				
		Seakeeping model test				

4.1.2. FOC estimation of this study

From the previous section, the ISO is explained briefly. That is, ISO is a method of converting the weather and performance in trial test into weather and performance in the state of still water. It can be thought of as a type of function as Figure 15.

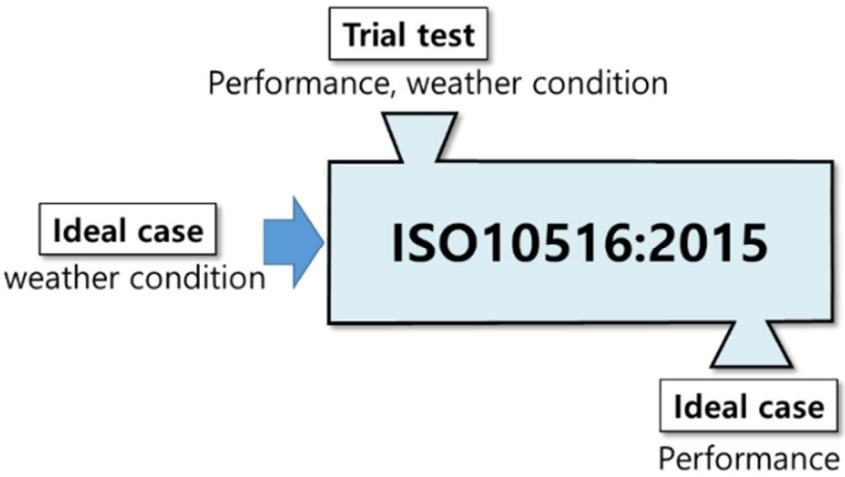

Figure 15 Concept of ISO15016:2015

Meanwhile, with such a conversion described as Figure 15, the state of operation (exactly trial test) can be obtained with weather and performance in state of still water. Here, the state of still water means the ideal state, and the theoretically obtained values in the ship-route-planning method corresponds to this. Also, although the state of operation means a condition in a relatively calm weather like the trial test, the performance in operation will be obtained from weather condition if the given weather condition is inputted as measured weather condition. However, considering that this conversion method is applied in a calm weather condition as trial test, it is impossible to guarantees the result of a poor weather condition. More details are explained in verification section. Meanwhile, it does not mean that ISO should be applied in reverse. The concept of ISO is a conversion, so the procedure of modified ISO is maintained and just input information should be changed with the weather condition and performance in state of still water. Figure 16 shows the comparison ISO and modified ISO (proposed way of FOC calculation). One of important points is a load factor. Based on the load factor, ship performance is converted.

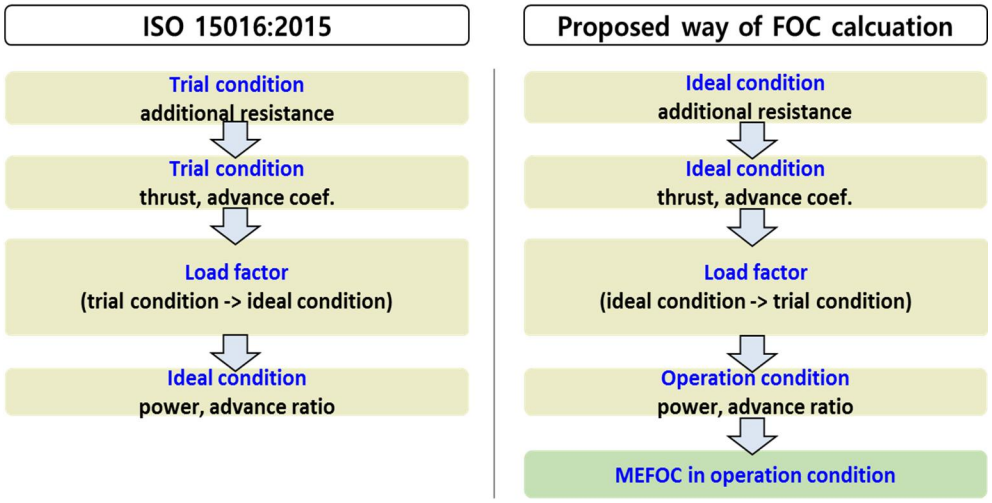

Figure 16 Comparison between ISO15016:2015 and proposed way of FOC calculation

In this study, the proposed way of FOC calculation goes through a procedure: resistance in still water, added resistance, speed loss, change of advanced ratio and calculation of MEFOC. The last line of Table 5 shows the detailed ways used in this study, but its procedure is slightly different with the order of Table 5. Exactly, the ship performance is obtained from the direct power method and the engine specification only. However other processes such as resistance in still water, added resistance and speed loss are needed for values used in the direct power method. Therefore, the order of procedure is not fixed, but used flexibly. In this study, the procedure is conducted as follows. First, the resistance in still water is estimated with Holtrop-mennen method (Holtrop et al., 1982). Main dimension of ship and other information of ship are used in Holtrop-mennen method. Second, the added resistance of wind is obtained using STA-JIP coefficients. Third, the added resistance of wave is obtained using STAWAVE-2. Fourth, the added resistance of temperature and density is obtained with effect of temperature & density. However, it is assumed that the value of temperature and density is constant because

these are not quite different and its magnitude is also small. Fifth, the direct power method is used for considering load factor. To estimate the efficiencies of propeller and the advance ratio, the resistance in still water is used. To obtain thrust and torque coefficient, the approximation formula by Wageningen B-series (Van et al., 1969) is used. And then, the load factor is obtained and used like Equation 17.

$$\boldsymbol{\tau_{P_{id}}} = \frac{\boldsymbol{K_{T0}}}{\boldsymbol{J_0^2}} \qquad \text{Equation 17}$$

$\boldsymbol{\tau_{P_{id}}}$ is the load factor of ideal condition, $\boldsymbol{K_{T0}}$ is the thrust coefficient and $\boldsymbol{J_0}$ is the advance ratio. Meanwhile, the association of the load factor and resistance is shown in Equation 18.

$$\boldsymbol{R_{id}} = \boldsymbol{\tau_{P_{id}}}(\boldsymbol{1} - \boldsymbol{t})(\boldsymbol{1} - \boldsymbol{w})^{\boldsymbol{2}}\boldsymbol{\rho_{id}}\boldsymbol{V_{id}^2}\boldsymbol{D_p^2} \qquad \text{Equation 18}$$

$\boldsymbol{R_{id}}$ is the resistance of ideal condition, t is the trust deduction fraction, w is the wake fraction, $\boldsymbol{\rho_{id}}$ is the density of water of ideal condition, $\boldsymbol{V_{id}}$ is the speed of ideal condition and $\boldsymbol{D_p}$ is propeller diameter. From this association, the association between the load factor of ideal condition and the load factor of operation condition is shown in Equation 19-20.

$$\boldsymbol{R_{op} = R_{id} + \Delta R} \qquad \text{Equation 19}$$

$$\boldsymbol{(1-t)(1-w)^2 \rho_S V_S^2 D_p^2 \tau_{P_{op}} = \tau_{P_{id}}(1-t)(1-w)^2 \rho_S V_S^2 D_p^2 + \Delta R} \qquad \text{Equation 20}$$

$\boldsymbol{R_{op}}$ is the resistance of operation condition, $\boldsymbol{\rho_S}$ is the density of water of operation condition, $\boldsymbol{V_S}$ is the speed of operation condition and $\boldsymbol{\Delta R}$ is the total added resistance obtained from previous procedure. Using the $\boldsymbol{R_{op}}$, the efficiencies of propeller and the advance ratio in operation condition can be estimated. Next, the speed is obtained from the advance ratio and corrected with current effect. Meanwhile, the specific fuel oil consumption (SFOC) is calculated with the engine specification. And finally, the MEFOC is obtained from SFOC and the obtained speed.

4.2. Space calculation

The contents on space dealt with here includes the calculation of distance and the calculation of geodetic coordinate system. The calculation of space is very important because it is a part that affects all elements of the ship-route planning. Meanwhile, as it seems to be familiar, the earth is not simply a sphere but an ellipsoid containing roughness of the terrain. Therefore, the calculation of the distance on the macroscopic region should be calculated based on the shape of the earth such as the curvature, not by a simple straight line. There are two types of calculation on the space in the ship-route

planning. One is the calculation of the coordinates utilized on the map and the other is the calculation of the distance calculated on the performance of the ship. First, there are many theories about the calculation of the geodesic coordinate system. What is widely used are the Vincenty's formula (Vincenty, 1975) and the Haversine's formula (Robusto, 1957). Second, the calculation of the distance is calculated by the performance of the ship, and this part is proposed in this study.

4.2.1. Theoretical background

Explained above, the calculation of the geodesic coordinate system has been well developed in many studies. The ways to introduce are the Haversine's formula and the Vincenty's formula. Figure 17 shows the concept of two formulas.

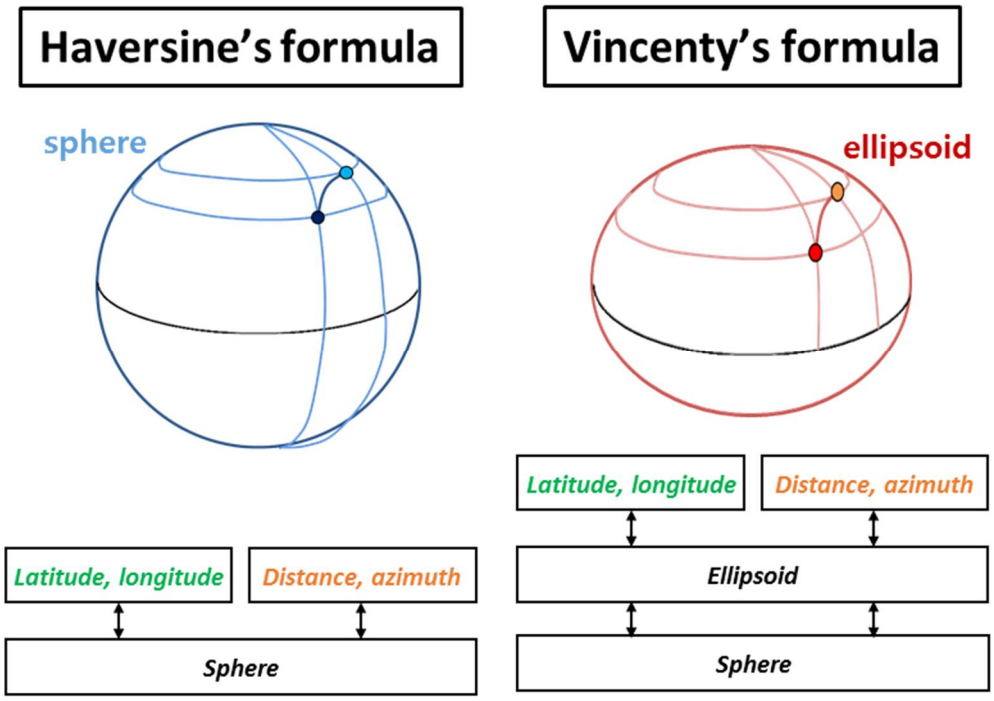

Figure 17 Comparison between Haversine's formula and Vincenty's formula

Two formulas resemble each other. The difference between two formulas is the assumption. The Haversine's formula assumes that the earth is a sphere, but the Vincenty's formula assumes that the earth is an ellipsoid. Therefore, Vincenty's formula is more accurate and more complex. Meanwhile, each formula has two types of solution. One is a direct solution which converts longitude and latitude into distance and azimuth. The other is an inverse solution which converts distance and azimuth into longitude and latitude. Since the Haversine's formula assumed the earth as a sphere, the solution directly is obtained. However, in case of the Vincenty's formula, the solution needs another one more process of converting the ellipsoid to the sphere. For detailed proofs and explanations of each way, refer to appendix and papers.

4.2.2. Distance calcuation of this study

For calculating the distance from the performance of ship, the corrected speed explained in FOC estimation is used. This corrected speed means an estimated ship speed reflecting the effect of the weather condition. Therefore, the distance is easy to be obtained from multiplying the correct speed by time. For example, the distance of a segment of route is obtained from multiplying the correct speed by time duration because of assumption which values are constant on a segment. Additionally, this distance using the above way is used on the calculating the changes of position of ship.

4.3. Seakeeping evaluation

In general, the seakeeping refers to the ability to maintain the performance of ship on external condition. The external condition which leads to consideration in ship-route planning is the weather condition. Moreover, the weather condition affects only a part of the seakeeping. The ship motion is caused by weather, and the evaluation of seakeeping is possible from the calculation of the ship motion. Therefore, it is necessary to select the evaluation object and the evaluation criteria of seakeeping, and the evaluation object and the evaluation criteria of seakeeping is selected through the paper study. The evaluation object and the evaluation is shown Table 7.

Table 7 Seakeeping evaluation for ship-route planning

Study	Ship type (reference ship type)	Phenomenon	Criterion	Reference
Lloyd, A. R. J. M. (1989)	All (Warship, Merchant ship)	Slamming	Prob. 1~4 %	Various papers
		Deck wetness	Prob. 2~7 %	
		Propeller emergence	Prob. 10~25 %	
		Vertical acceleration	SM = 12~15	
Vettor et al. (2016)	Container ship (Merchant ship)	Slamming	Prob. 3 %	Various papers
		Green water (=deck wetness)	Prob. 5 %	
		Vertical acceleration	RMS 0.4 g	
		Roll motion	RMS 4°	
		Risk(normalization of seakeeping)	-	
Park et al. (2004)	Container ship (All)	Slamming	Prob. 1 %	The Society of Naval Architects of Japan
		Deck Wetness	Prob. 1 %	
		Screw Racing	Prob. 1 %	
		Vertical Acceleration	RMS 0.215 g	
		Lateral Acceleration	$\overline{A_{1/3}}$ 0.2 g	
		Roll	RMS 6°	
		Pitch	$\overline{A_{1/3}}$ 3°	
		Heave	RMS 3m	
		Dynamic Bending Moment	$\overline{A_{1/3}}$ 0.417 Mwx	
Park et al. (2015)	Container ship (All)	Sur-riding and broaching-to	Y/N	IMO (2007)
		Parametric-rolling	Y/N	

As can be seen from the Table 7, similar phenomena and criteria are proposed for seakeeping in many studies. The evaluation object of seakeeping mainly evaluates a phenomena caused by the ship motion, and its criteria are mainly calculated with probability. Though these paper studies, the slamming, the deck wetness, the propeller emergence are selected as the evaluation object of this study because these phenomena are typically used in many studies. Additionally, the sur-riding and broaching-to and the parametric-rolling used in IMO (IMO, 2007) are selected as the evaluation object of this study. Also, the evaluation criteria are roughly selected by setting to large values among the proposed values. These values cannot be determined simply by the input information of ship-route planning, but it is necessary to estimate the ship motion and to calculate the probability of phenomena. In this study, a series of process for evaluating seakeeping

have been proposed though referring to various papers.

4.3.1. Seakeeping evaluation of this study

Sur-riding and broaching-to and parametric-rolling is obtained from IMO. Meanwhile, the probabilities of phenomena are obtained as follows: ship motion, probability of phenomenon and criterion. To express the ship motion, RAO (Response Amplitude Operator) is usually used. Acquisition of the analytical solution of RAO is very difficult to obtain. Most of ship's RAO is from model test. However, in this study, the RAO is obtained with simplified formula proposed by ABS (ABS, 2014). ABS described the relative vertical motion for analysis of vessel motion. In detail, for the vertical wave-induced motions of a homogeneously loaded box-shaped vessel derived analytically by the linear strip theory, the frequency response functions for heave and pitch (Gerrutsna et al., 1964) is proposed. Using this way, the RAO on vertical motion is obtained. From RAO, a forward draft (used in slamming evaluation), the height of freeboard (used in deck wetness evaluation) and an after draft (used in propeller emergence evaluation) is obtained. Next, the probabilities of phenomena should be estimated. The probability density function of wave is obtained with assumption that the wave satisfies the Rayleigh distribution. Then, the probability density function of wave is expressed as Equation 21.

$$\boldsymbol{PDF(A) = 1 - e^{-\frac{A^2}{2m_0}}} \qquad \text{Equation 21}$$

A is the height according to phenomena and $\boldsymbol{m_0}$ is the zeroth moment in wave spectrum. Changing this density function into cumulative probability function and probability of exceedance, the expression is shown in Equation 22.

$$\boldsymbol{Q(A) = e^{-\frac{A^2}{2m_0}} = e^{-\frac{A^2}{0.131072H_{1/3}^2}}} \qquad \text{Equation 22}$$

$\boldsymbol{H_{1/3}}$ is the significant wave height and it is provided from weather condition. To obtain the probability of slamming, the forward draft is substituted for A. To obtain the probability of deck wetness, the height of freeboard is substituted for A, and to obtain the probability of propeller emergence, the after draft is substituted for A. Using this procedure, the probabilities of phenomena can be obtained. Meanwhile, the criterion of each phenomenon is selected with referring other studies. In this study, the criteria are set as follows: slamming (prob. 4%), deck wetness (prob. 7%), propeller emergence (prob. 25%)

4.4. Avoidance of obstacles

When generating the route, the segment between two nodes can interfere with obstacles such as land; therefore, a suitable method is required to check whether the segment interferes with any land masses. In this study, a geographic map that has been generated from the geographic information on the route is used. Since the geographic

information includes the information on the land and the sea, it is possible to check whether a certain point on the route is on the land or at sea. First, a world map is divided into a number of cells through the insertion of evenly distributed horizontal and vertical lines into the world map (e.g., longitude and latitude of 1 degree); accordingly, the map is called “geographic map” in this study. For each cell, the geographic information is used to check whether the centroid of the cell is on land or at sea; if it is on land, the value of the cell is 1, and if it is not on land, the cell value is 0. Each route segment is then divided into several portions (e.g., 1 degree), and then several checking points are made, as shown in Figure 18. For each checking point, the cell is found in the geographic map, and if the value of the cell is 1, the checking point is on land. Due to the possibility that the segment including the checking point could interfere with land, the route that comprises the segment cannot be selected as an optimal route. At this time, the accuracy of the method depends on the level of detail of the geographic map; that is, as the cell sizes are decreased, the accuracy of the method is increased, and the computation time of the method is lengthened.

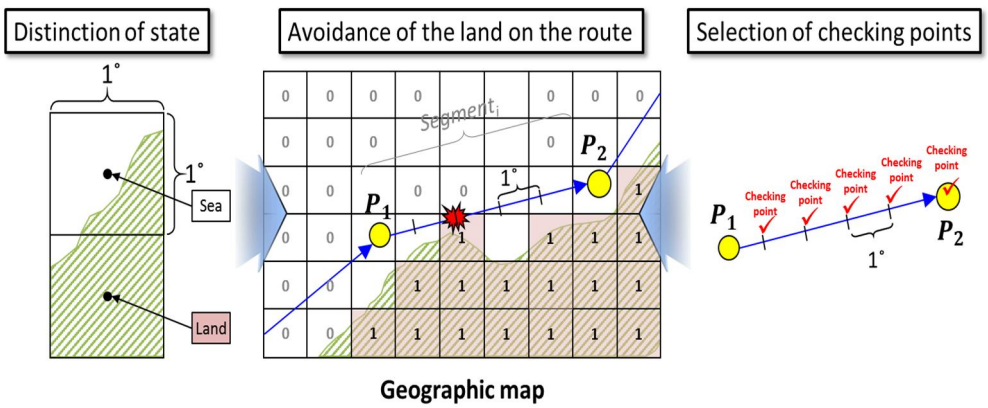

Figure 18 Method for avoidance of the land using the geographic map

5. Route-finding model

The route-finding model is a methodology for obtaining the optimal route based on optimization model and performance-evaluation model, that is an optimization technique. There are many optimization techniques for applying the optimization problem, the optimal solution can be obtained through selecting the appropriate optimization technique which is suitable to types and characteristics of problem.

5.1. Theoretical background

The optimization techniques were steadily studied in many studies. Various techniques were proposed until now and by doing this, it is possible to obtain an optimal solution that matches the situation of problem. Table 8 is a table describing applicable optimization techniques with optimization problems.

Table 8 Applicable optimization techniques with optimization problems

	Unconstrained optimization problem		Constrained optimization problem	
	Linear	Nonlinear	Linear	Nonlinear
Continuous	① Gradient method		Linear	Penalty function method

<table>
<tr><td rowspan="3">value</td><td rowspan="3">- Steepest descent method
- Conjugate gradient method
- Newton method
- Davidon-Fletcher-Powell (DFP)
- Broyden-Fletcher-Goldfarb Shanno (BFGS) method

② Enumerative method
- Hooke & Jeeves method
- Nelder & Mead method
- Golden section search method</td><td>Programming (LP)</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Simplex Method</td><td rowspan="2">Quadratic programming (QP)</td><td>Sequential Linear Programming (SLP)</td></tr>
<tr><td>Sequential Quadratic Programming (SQP)</td></tr>
<tr><td>Discrete value</td><td colspan="4">Integer programming: Cut algorithm, Enumeration algorithm, Constructive algorithm</td></tr>
<tr><td>Metaheuristic optimization</td><td colspan="4">Genetic algorithm (GA), Evolutionary strategy (ES), Particle swarm optimization (PSO), Ant algorithm, Simulated annealing, etc.</td></tr>
</table>

In case of relatively simple optimization problem, that is unconstrained problem and variables of continuous value, this optimization problem can be analytically solved by differentiation. The gradient method is a method using first derivative of variable or Jacobian matrix. Additionally, second derivative or Hessian matrix are also used for fast convergence speed and discrimination about state of optimum. When derivative cannot be used for non-differentiable function, a use of enumerative method can be also considerable. In case of constrained problem, linear programming is usually used in many cases. The simplex method is an optimization technique emphasizing the procedure for optimization. Besides, penalty function method, sequential linear programming and sequential quadratic programming are also applied to nonlinear problem. Interest in optimization problems which is about nonlinear function and variable of discontinuous value are increased recently. However, there is no general analytical solution yet so the methods using procedure are used. Among them, Monte Carlo method fully depends on random value. Meanwhile, metaheuristic algorithm is an algorithm using guided random

search inspired by natural phenomena.

5.1.1. Metaheuristic algorithm

Mentioned above, metaheuristic algorithm is an algorithm using guided random search inspired by natural phenomena. The originality of metaheuristic algorithm is based on the random basis, so there are disadvantages that it demands a number of iterations for obtaining a global optimum and if the solution falls into a local optimum, the it is difficult to break out at the local optimum. Therefore, when applying this in practice, it is hard to input the number of iterations and conditions in order to obtain the global optimum. As a result, a local optimum is calculated, and in this case, since it is possible to calculate different values for each execution, it is hard to have reliability on the metaheuristic algorithm. However, the metaheuristic algorithm is almost the only way that solve the nonlinear and discontinuous problem. Therefore, the metaheuristic algorithm is used in many optimization study, and the technique for reinforcing the above-mentioned weaknesses is complemented and studied. Meanwhile, a number of natural phenomena are used into metaheuristic algorithms and there are so many types of metaheuristic algorithm. Among them, genetic algorithm, evolutionary strategy and particle swarm method are well known.

5.1.2. Genetic algorithm (GA)

GA is one of widely used optimization technique. GA is inspired by the process of natural selection. It can find the global optimum. The population size of generation is

fixed and this population undergoes are commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover and selection. To overcome the existing limitation, the NSGA-II (Deb et al., 2002) and SPEA2 (Zitzler et al., 2001) global and multi-objective optimization algorithm, which are well-known and proven GAs, was selected for this study to solve the ship-route-planning optimization problem that was formulated in each step. Its procedure is shown in Figure 19.

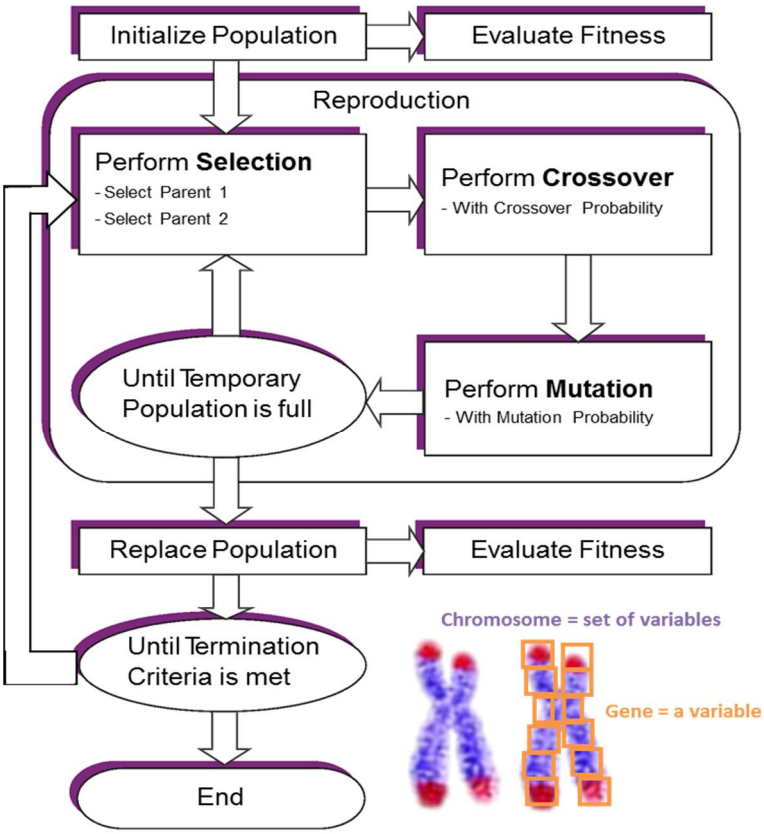

Figure 19 Procedure of genetic algorithm

First, the initial individuals are generated based on random. These initial individuals become a population and the first generation. Like the natural selection, the fitness of each individual is evaluated. And then, individuals matched as parents through several ways. The children are generated through crossover and mutation between parents' gene. Next, the selection is performed based on the fitness among children and parents because the elitism is used during the selection generally. These selected individuals form a new population and it will be the second generation. The fitness of population is performed again and the termination criteria is evaluated. If not satisfied, the next generation is formed with the same ways of previous procedure.

5.1.3. Evolutionary strategy (ES)

ES theoretically based on evolution it is done in the similar way as GA. The difference with GA is that GA creates many children with many individuals as a population and children through this, the spectrum is widely formed, thereby predicting the number of different cases, Find the overall optimal solution. On the other hand, in the case of ES, there is a difference showing the fast rapid change through the following parent (usually one set of parents). Therefore, ES or GA can be selected and used depending on the problem to be applied. Its procedure is shown in Figure 20. The procedure of ES is almost same with GA. The small number of population is used, so ES is sensitive at the mutation and selection.

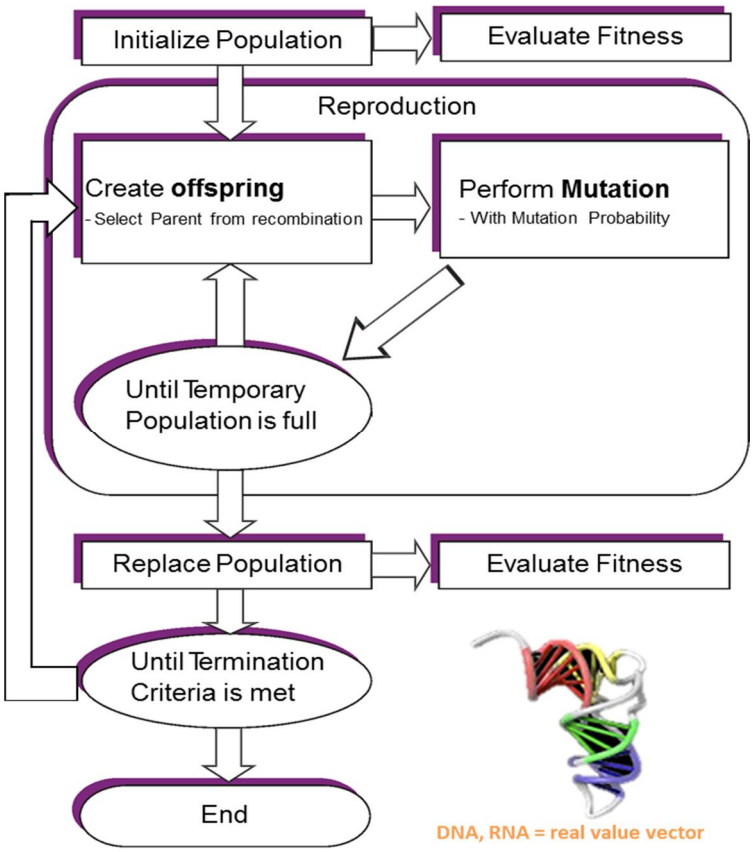

Figure 20 Procedure of evolutionary strategy

5.1.4. Particle swarm method (PSO)

PSO is also one of widely used optimization technique. PSO is inspired by the process of swarm intelligence such as a behavior of flock of birds. This algorithm portrays that a swarm moves the optimal position based on the current position, past position and leader's position. To overcome the existing limitation, the SMPSO (Nebro et al., 2009) global and multi-objective optimization algorithm, which is a well-known and proven

PSO. Its procedure is shown in Figure 21.

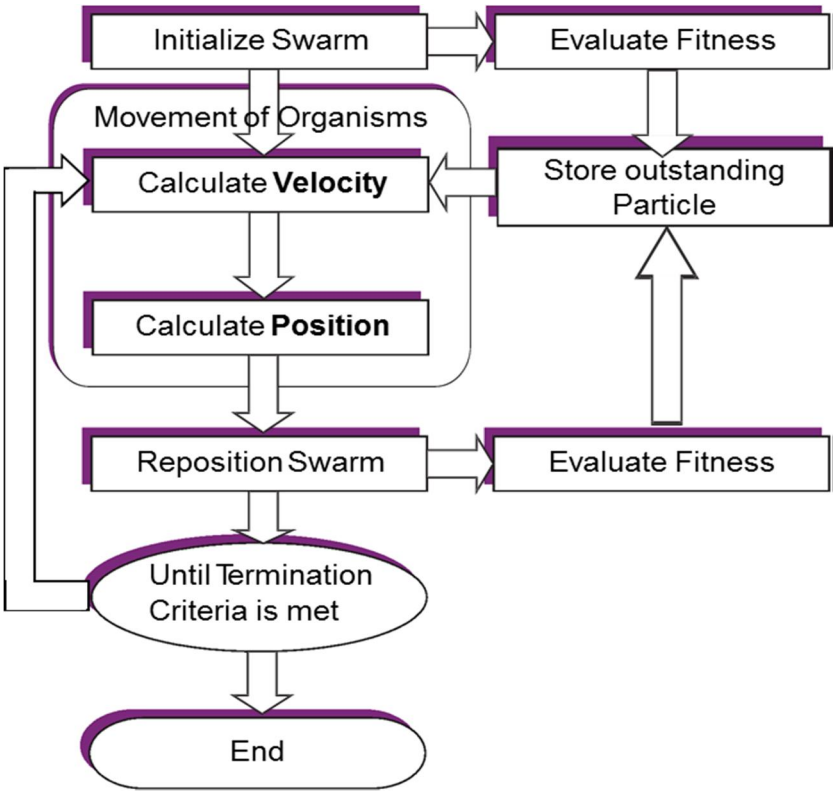

Figure 21 Procedure of particle swarm optimization

First, the initial particles are generated based on random. These particles move around the N-dimension space (usually N is the number of design variables). Each particle has a position and velocity respectively. Second, the first set of particles is evaluated its fitness and positions of the outstanding particles are stored, and a best particle is elected as a leader. And Next, the new position of particle is calculated with the velocity based on the current position, the best position of the past outstanding particle and the current leader's

position. The fitness of particles is performed again and the termination criteria is evaluated. If not satisfied, particles will move with the same ways of previous procedure.

5.2. Seed genetic algorithm for optimal solution

The seed genetic algorithm is proposed in this study. The seed genetic algorithm is an algorithm based on genetic algorithm for providing initial solution, seed, as an individual among the initial population. There are two reasons behind the proposal of the seed genetic algorithm. First, the genetic algorithm has original limitations, exactly original limitations of metaheuristic algorithm. As mentioned above, the genetic algorithm belongs to the metaheuristic algorithm based on random search. Although the algorithm makes up for the weak points with the procedure inspired from naturally optimal phenomena, the improvement of solution depends on coincidence. Therefore, a number of iterations are necessary to provide the global optimum. Furthermore, if the solution of metaheuristic algorithm falls into local optimum, it cannot guarantee a detection of the global optimum. However, there is not much time given to ship-route planning. Other ship-route-planning algorithms roughly take from three minutes to five minutes (Samsung heavy industry, 2015; Eniram, 2016). Therefore, if the required time for optimization is adjusted to five minutes, metaheuristic algorithm will provide the local optimum. Additionally, this local optimum may be provided different results all the time, that is, the consistency of results can be lacked. This can act as a fatal weak point in the application of ship-route-planning method. Second, there are several characteristics on ship-route planning. Usually, a ship which transport cargo or container operates fixed ports. Additionally, paths of route are similar in case of the same between the departure port and

the arrival port. In other words, there is not much difference between the global optimum and the local optimum, that is, there will be the global optimum nearby the local optimum.

From the two reasons, the original limitations of metaheuristic algorithm and characteristics of ship-route planning, the provision of an initial solution, seed, has a meaning. By providing the initial solution the genetic algorithm can be possible to take fast convergence speed and finding a good solution even if only few iterations are calculated. The initial solution plays a role as the local optimum, and this algorithm can find the global optimum effectively. Absolutely, seed genetic algorithm will provide better solution than the initial solution, the local optimum. Because of these kinds of reasons and effects, seed genetic algorithm is proposed in this study. The procedure of seed genetic algorithm is shown in Figure 22.

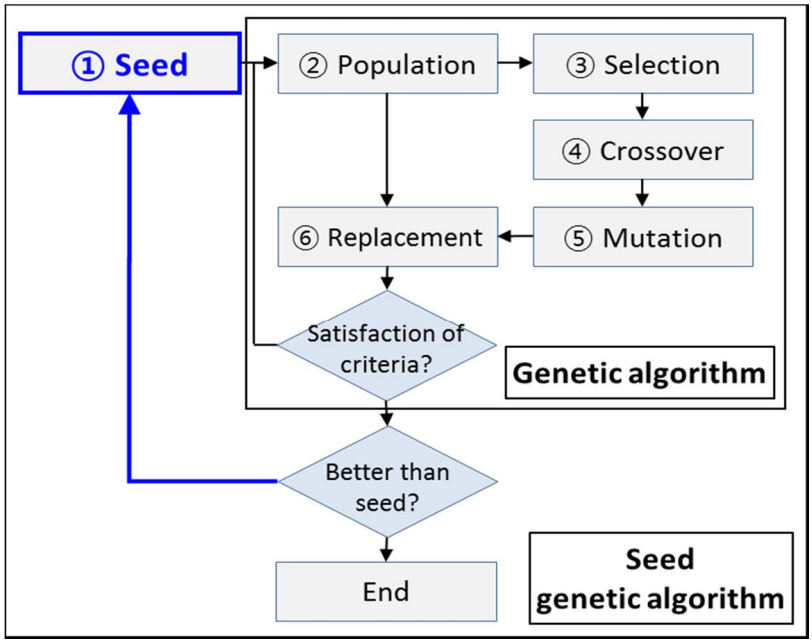

Figure 22 Procedure of seed genetic algorithm

Looking at the procedure of the seed genetic algorithm in detail, it is as follows. First, Seed is an obtained solution from the previous ship-route planning or inputted manual solution. Seed, an initial solution, is provided into the population of the genetic algorithm. The iterated procedure from the second to the sixth is the same with the genetic algorithm. It is composed of population, selection, crossover, mutation, replacement and decision. At the second, Population, the seed is applied into first generation as partial individuals. And then, the fitness of each individual in the population is evaluated. At the third, Selection, two individuals of good fitness are selected as parents. At the fourth, Crossover, two children are generated from the parents. At the fifth, Mutation, children are changed by introducing the property which the parents don't have. At the sixth, Replacement, the individuals of bad fitness are replaced with children of good fitness. The series of processes as described above is iterated. At last part of genetic algorithm, an optimal solution is obtained. Next, the obtained solution is compared with the seed, the initial solution. And then, better solution is saved in seed. Finally, the optimal solution, the better solution, is provided to user.

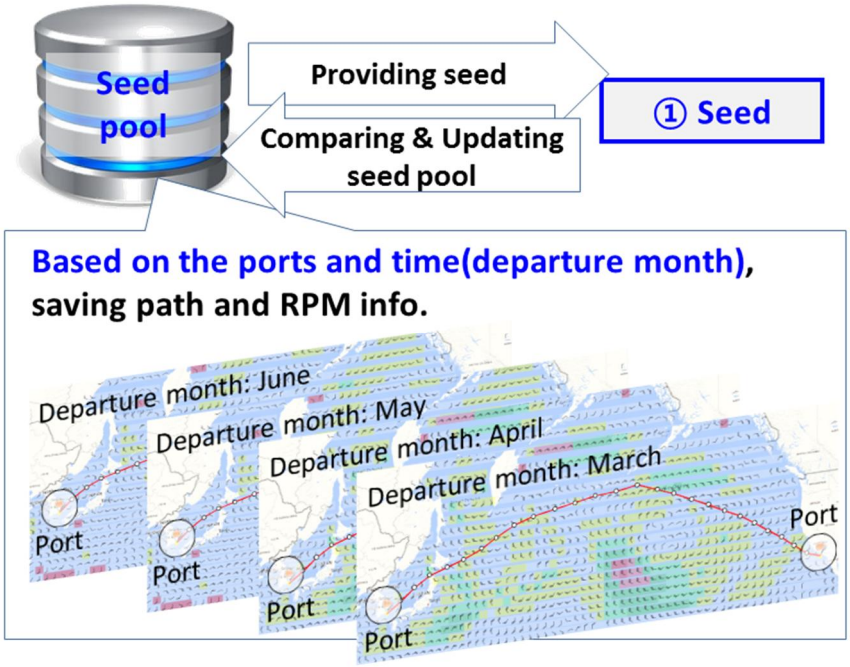

Figure 23 Management of seed using seed pool based on the ports and time

Figure 23 shows the introduction of seed pool for management of seed. The seed is not a strictly fixed value. The management of seed is necessary because there are a number of seeds. They are stored and managed in the seed pool. The seed pool is one of database of seed. Seeds are managed based on the ports and time. Ports mean the departure port and the arrival port. However, time mentioned above does not mean the exact sailing time. Time indicates the approximate departure time. In general, weather condition repeats on a similar aspect every year. The route also has the similar aspect every year because the route depends on the weather condition. Therefore, it is not necessary to manage the seed based on the exact time but seeds are managed based on the approximate departure time. In this study, the approximate departure time is divided by month. Meanwhile, a seed does not have all information about route. If only design variables are completely given,

the route can be fully implemented. A seed just has design variables and several route information like port and time for distinction of route.

6. Development of the program

A prototype program that is based on the proposed method, for which the C# language is used in the environment of Microsoft Visual Studio 2017, was developed for this study. Figure 24 shows the GUI (Graphical user interface) of prototype program, wherein the program consists of a ribbon menu, planning view, and map view.

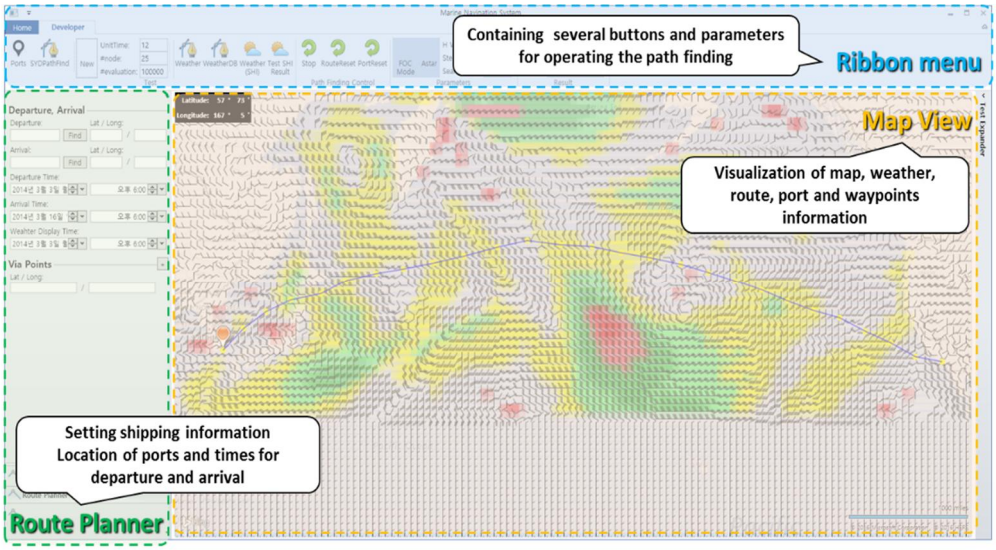

Figure 24 GUI of the developed program

Especially, the prototype program was developed based on three models. For the development of the ship-route-planning program, it is necessary to implement not only three models, but also a lot of parts such as visualized graphical map, weather map and convenient functions etc. This prototype program was developed at the same level as the commercial program.

6.1. Multilayer architecture as data structure

In the prototype program, multilayered maps are used to find the optimal route, as shown in Figure 25. The multilayered maps consist of three different maps. First, as mentioned previously, the geographic map includes the geographic information regarding the route, and each cell in the map has a binary value that represents the land and the sea. For this study, the geographic information was obtained from NOAA (National Oceanic and Atmospheric Administration). The route-based TFOC of the ship depends on the weather condition. The weather map includes the on-route weather condition, and a specific weather condition is relevant for each cell at a certain time. For this study, the weather condition was obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts). The last map is the world-image map, which includes the shape of the world including the land and the sea, that is used to visualize the result of the ship-route-planning. For this study, Microsoft Bing Maps was used for the world-image map. With these multilayered maps, the geographic information, weather-condition information, and pixel information can all be obtained for a certain ship position; moreover, the level of detail of each map can be different.

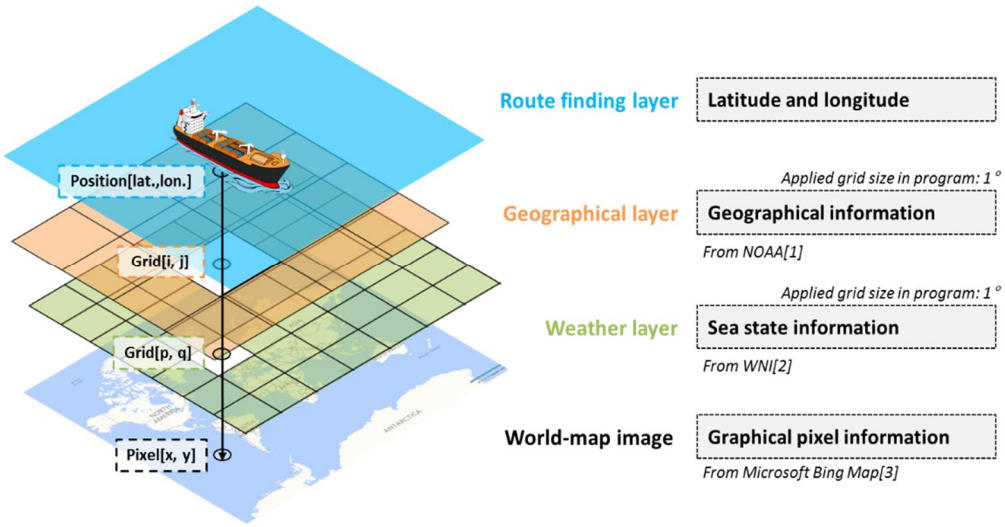

Figure 25 Concept of data structure for multilayer architecture

The most important thing to develop a multilayer structure is the medium that connects each layer. In this study, various maps were connected by using the position, that is, longitude and latitude as a medium.

6.1.1. Map projection

The earth is a three-dimensional ellipsoid, but the place you have to express is a two-dimensional plane. Therefore, there is no method of perfect conversion, and multiple map projections for drawing a map to the target have been developed. The most popular map projection is the Mercator projection. Figure 26 shows the concept of the Mercator projection.

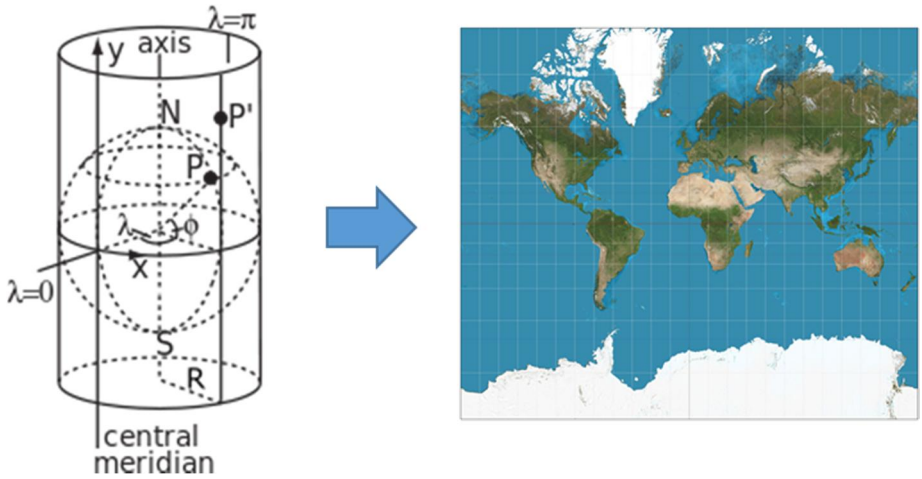

Figure 26 Concept of the Mercator projection

The Mercator projection is a map projection projected from the center of the earth onto a cylinder around the equator as shown in Figure 26. It is easy to understand since the longitude and latitude are positioned vertically and horizontally. However, the problem with the Mercator projection is that errors in the higher latitude, and theoretically it cannot express polar regions. Therefore, the latitude is expressed from -82° up to 82°, in which case the latitude and longitude become a square. The reason for using the Mercator projection in this study is not only to set the main target of study as route from Asian to Europe or from Asian to America but also to provide the familiar map to user. Meanwhile, one of noteworthy points for using longitude is a period of longitude. There are several ways to express longitude and latitude, but in general, it is used periodicity based on $[-180: 180) \times [-82: 82)$. In this case, the discontinuous problem occurs when the longitude of created route is from 180° to -180° or from -180° to 180°. That is the

route of the Pacific Ocean. In order to solve this problem, the $[-180:360) \times [-82:82)$ map is used in this study. Figure 27 shows the discontinuous problem and its solution by expanding the map.

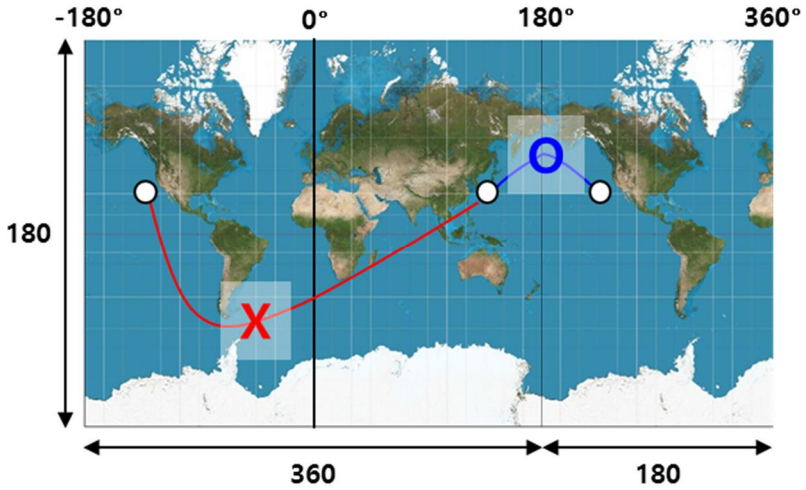

Figure 27 Expansion of world map for solving discontinuous problem

6.1.2. Weather

The weather condition used in this study utilizes four types and fourteen items of weather condition. The weather condition is provided by WNI. The program has reduced the burden of allocating large memory of the weather condition through calling the weather condition based on the limited time and space of where is looking for.

6.2. Functions

Even if there is a ship-route-planning method, the actual ship-route-planning program is not completed. The actual ship-route-planning program must have many useful functions for the user. Various functions for user were implemented in this program.

7. Verifictaions

The verification examined the validity and effectiveness of each model through six verification cases in total for the previous three proposed models. The verification cases are shown in Table 9.

Table 9 Verification cases for proposed models

Verification	Case	Comparison	Condition
Optimization model	Case 1	Proposed optimization algorithm / Other route find algorithm (Commercial, A-star, Dijkstra)	Within the same FOC calculation
	Case 2		
Performance-evaluation model	Case 3	Proposed FOC calculation / FOC calculation of commercial program (estimating equation using non-linear multiple regression from the actual FOC data)	On the same route
	Case 4		
Route-finding model	Case 5	Proposed optimization algorithm / other heuristic algorithms (NSGAII, SMPSO, SPEA2)	Within acceptable computing time
	Case 6	Performance of monthly seed (seed for March, seed for June)	Within acceptable computing time

First, the verification of the optimization model is examined with case 1 and case 2. As explained related study section, there are many number of ship-route-planning method. Among them, representative algorithms for ship-route planning are selected with Isochrone method, A-star algorithm and Dijkstra algorithm. Verifying the superiority of the proposed method through comparison with representative algorithms. The verification is conducted under the same FOC calculation model (proposed theoretical method in this study) as well as the same input information. Therefore, the pure performance of optimization model is emerged. Second, the verification of the performance-evaluation model, exactly FOC calculation, is examined with case 3 and case 4. The validation of theoretical method is evaluated by comparing with FOC which is utilized in commercial program. The FOC estimation of the commercial program uses nonlinear regression analysis from the actual measured ship performance and FOC data. As explained in performance-evaluation model section, the commercial program shows the very accurate FOC in this ship. Therefore, the comparison it with the commercial program is the same with comparison with the actual FOC of the ship. Third, the verification of the route-finding model, exactly seed genetic algorithm, is examined with case 5. Through comparison with other metaheuristic algorithms, the superiority and reliability of the optimal solution calculated by seed genetic algorithm are evaluated. Last, the verification on the route-finding model, exactly use of monthly seed, is examined with case 6. Through an example applying another seed, it is shown that the proper use of monthly seed provides better solution. All six verification cases were applied as shown in Table 10.

Table 10 Condition of verification cases

Verification	Case	Departure port	Arrival port	RTA	Departure time
Optimization model	Case 1	Busan Korea (35.08N, 129.112E)	Long Beach, USA (33.694N, 118.251W)	13 days	3/3 18:00 (bad weather)
	Case 2				6/1 00:00 (good weather)
Performance-evaluation model	Case 3				6/1 00:00 (good weather)
	Case 4				3/3 18:00 (bad weather)
Route-finding model	Case 5				3/3 18:00 (bad weather)
	Case 6				3/3 18:00 (bad weather)
Ship information	SN1973 HANJIN 4,600 TEU container ship (Lbp: 241m / Breadth: 37.5m / Depth: 19.5m)				
Node information	Δt (time duration) = 12 hours No. node = 25 EA (except departure port & arrival port)				

All verification routes were set from Busan, Republic of Korea, to Long Beach, U.S.A. the ship is selected with a forty-six hundreds TEU container ship and the departure time is selected the March or the June. It is to indicate the difference due to the weather condition because a bad weather condition is in March and a good weather condition is in June.

7.1. Verification of optimization model

7.1.1. Case 1

First, in the verification of optimization model, it is a comparison between the proposed optimization model and another established optimization model. Figure 28

shows the paths obtained from each optimization models. As mentioned in related works section, this case shows that the one-stage optimization will provide better solutions than two-stage optimization.

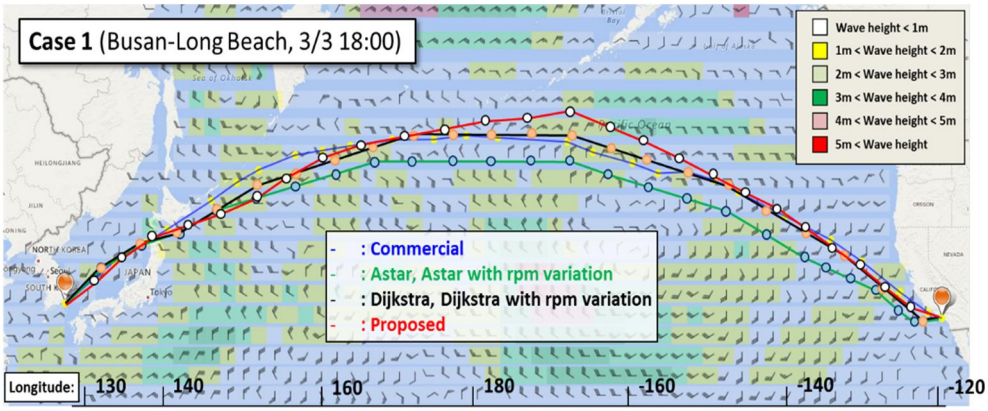

Figure 28 Configuration of paths from each optimization model in March

As shown in Figure 28, blue path is from a commercial program. The commercial program is based on the improved Isochrone method (path optimization). Green path is from an A-star algorithm (path optimization) and an A-star algorithm with rpm variation (two stage optimization). Black path is from a Dijkstra algorithm (path optimization), and a Dijkstra algorithm with rpm variation (two stage optimization). Lastly, red path is from the proposed optimization model. The algorithms which perform rpm variation have the same path with the original algorithm. That is because the algorithms which perform rpm variation are two stage optimization. Therefore, in the path optimization stage, the original algorithms and the algorithms which perform rpm variation are exactly same. Table 11 shows the detailed result of routes from each optimization model.

Table 11 Result of routes from each optimization model in March

Methods	TFOC [ton]		Total distance [NM]		Arrival time (March 16, 18:00)	Avoidance of the land	Engine RPM [rpm]	Computing time [second]
Commercial (path only)	684.8	100.0 %	5,248	100.0 %	March 16, 06:25 (O)	O	77	300
Dijkstra (path only)	692.3	101.1 %	5,239	99.8 %	March 16, 07:34 (O)	O	77	695
A-star (path only)	697.7	101.8 %	5,257	100.2 %	March 16, 09:55 (O)	O	77	46
Dijkstra with rpm variation (two stage)	654.5	95.4 %	5,239	99.8 %	March 16, 18:00 (O)	O	Varied	821
A-star with rpm variation (two stage)	660.2	96.3 %	5,256	100.2 %	March 16, 18:00 (O)	O	Varied	280
Proposed (one stage)	629.4	91.2 %	5,223	99.5 %	March 16, 18:00 (O)	O	Varied	138

As shown in Table 11, all of the algorithms and model yielded routes that satisfy the RTA requirement (arrival time) and the avoidance of land. That is, constraints are completed in all of algorithms and model. While, in the objective function (TFOC), TFOC is low in the order of the path only optimization (Isochrone method, Dijkstra algorithm, A-star algorithm), the two stage optimization (Dijkstra algorithm with rpm variation, A-star with rpm variation), the one stage optimization (proposed optimization model). The proposed method yielded the route with the least TFOC and it can be confirmed that TFOC is reduced by 8.8 % compared with the commercial program. In terms of the total distance, the proposed optimization model is also the shortest distance. From this comparison with the other methods, the capacity of the proposed method

enables the provision of the most-economical route in terms of the minimum TFOC.

It is for three reasons that the proposed optimization model shows a good result. First, it is from maximizing arrival time. Algorithms that optimize only routes, methods with fixed rpm, have no way to control time. While, the proposed method can control time, so the proposed method maximizes the arrival time and bring the benefits of FOC. Second, in case of Dijkstra algorithm and A-star algorithm, these algorithms belong to the cell-based algorithm that dividing the map by cell. The limitation of the cell-based algorithm is that a non-smooth path will come out. The proposed method has no direction restriction and can calculate a smooth path, which makes it possible to reduce distance and FOC. Last, the proposed method can do speed planning. Figure 29 shows the comparison between the results of the commercial program and the proposed optimization model in March.

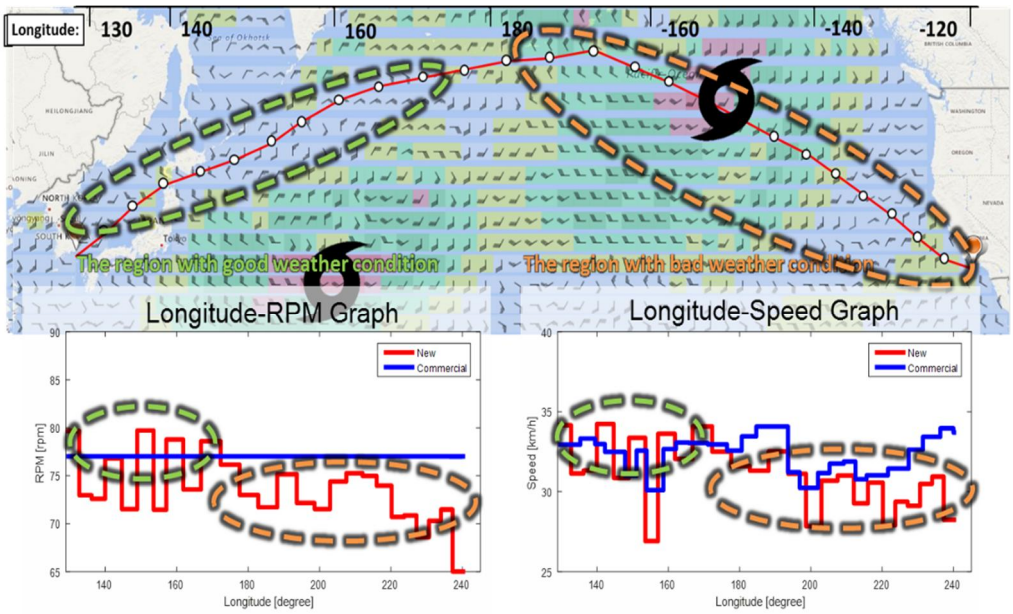

Figure 29 Comparison between the results of the commercial program and the proposed optimization model in March

As shown in Figure 29, the green circles represent the calm weather-condition regions, whereas the orange circles represent the problematic weather-condition regions. A typhoon occurs in the latter half of the route. Two graphs are shown the variation of rpm and the speed along the longitude. The proposed method moves quickly on early, fine days, in bad weather, slowly move to get the benefits of FOC it will be considered. In these graphs, the blue line is the result of the commercial program (Isochrone method), and the red line is the result of the proposed method. In the engine-RPM graph (left in Figure 29), the engine RPM is variable for the proposed method, whereas it is fixed for the Isochrone method. In particular, for the proposed method, the engine RPM in the favorable weather-condition regions increased, whereas the engine RPM in the problematic weather-condition regions decreased. In the graph of the ship speed (right in

Figure 29), for the proposed method, the ship speed in the favorable weather-condition regions increased, whereas it decreased in the problematic weather-condition regions; here, the increase of the ship speed in the favorable weather-condition regions compensates for the loss of the ship speed in the problematic weather-condition regions to satisfy the ETA requirement. Since the engine RPM of the Isochrone method is maintained even in the problematic weather-condition regions, the FOC increased suddenly in these regions. From the results of this case, the impact of the speed optimization on the minimization of the TFOC is major. In summary, in the latter half of the route, when a typhoon occurs, the proposed method moves quickly on early, fine days, in bad weather, slowly move to get the benefits of FOC it will be considered.

7.1.2. Case 2

In case 2, it is a comparison between the proposed optimization model and another established optimization model in June. The weather condition in June is even more calm than the weather condition in March, case 1. Figure 30 shows the paths obtained from each optimization models.

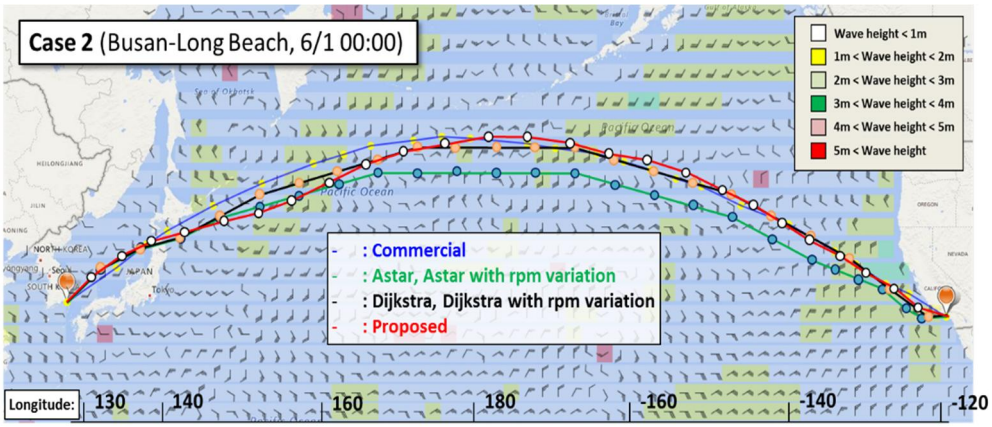

Figure 30 Configuration of paths from each optimization model in June

For Case 2, it is the same departure, when you depart your departure time from the arrival port in June. As shown in Figure 30, blue path is from a commercial program. The commercial program is based on the improved Isochrone method (path optimization). Green path is from an A-star algorithm (path optimization) and an A-star algorithm with rpm variation (two stage optimization). Black path is from a Dijkstra algorithm (path optimization), and a Dijkstra algorithm with rpm variation (two stage optimization). Lastly, red path is from the proposed optimization model. The algorithms which perform rpm variation have the same path with the original algorithm. Table 12 shows the detailed result of routes from each optimization model.

Table 12 Result of routes from each optimization model in June

Methods	TFOC [ton]	Total distance [NM]	Arrival time (June 14, 00:00)	Avoidance of the land	Engine RPM [rpm]	Computing time [second]

Commercial (path only)	671.7	100.0 %	5,236	100.0 %	June 13, 04:35 (O)	O	77	300
Dijkstra (path only)	670.7	99.9 %	5,239	100.1 %	June 13, 04:08 (O)	O	77	623
A-star (path only)	675.3	100.5 %	5,356	102.2 %	June 13, 06:08 (O)	O	77	32
Dijkstra with rpm variation (two stage)	600.1	88.1 %	5,239	100.1 %	June 14, 00:00 (O)	O	Varied	860
A-star with rpm variation (two stage)	608.1	89.5 %	5,256	102.2 %	June 14, 00:00 (O)	O	Varied	264
Proposed (one stage)	591.7	86.4 %	5,231	99.9 %	June 14, 00:00 (O)	O	Varied	143

In same with case 1, the one-stage optimization provides better solutions than two-stage optimization. Actually, the TFOC of the proposed method is less than that of the Isochrone method by approximately 13.6 %, although the total distance is shorter than that of the Isochrone method by approximately 0.1 %, as shown in Figure 31. The reason for FOC reduction can be thought of as the cause of maximizing arrival time, generating smooth path, and conducting speed planning as in the same with case 1.

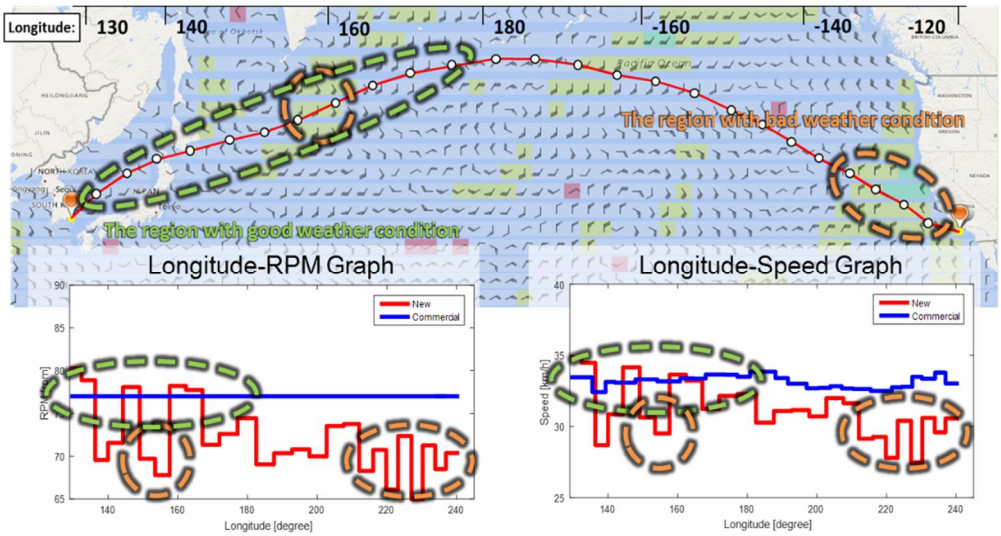

Figure 31 Comparison between the results of the commercial program and the proposed optimization model in June

Figure 31 shows a comparison between the results of the Isochrone method and the proposed method, including the change of the engine RPM and ship speed along the longitude. Akin to the results for case 1, the proposed method yielded a more-economical route compared with the Isochrone method through the speed optimization, that is, the change of the engine RPM.

7.2. Verification of performance-evaluation model

7.2.1. Case 3

In case 3, this case shows the verification of performance-evaluation model. It is a comparison between the proposed FOC estimation of the proposed method and that of

commercial program. FOCs of each method are estimated on the same route under the same input information. That is, all condition and input information are completely same except for way of FOC estimation. Figure 32 shows the configuration of paths from each performance-evaluation model in June. In June, the weather condition is calm over all region of route. As mentioned above, the commercial program uses nonlinear regression analysis from the actual measured ship performance and FOC data. Therefore, values from commercial program is same with values of actual ship performance. The TFOC and the total distance are obtained as shown in Table 13.

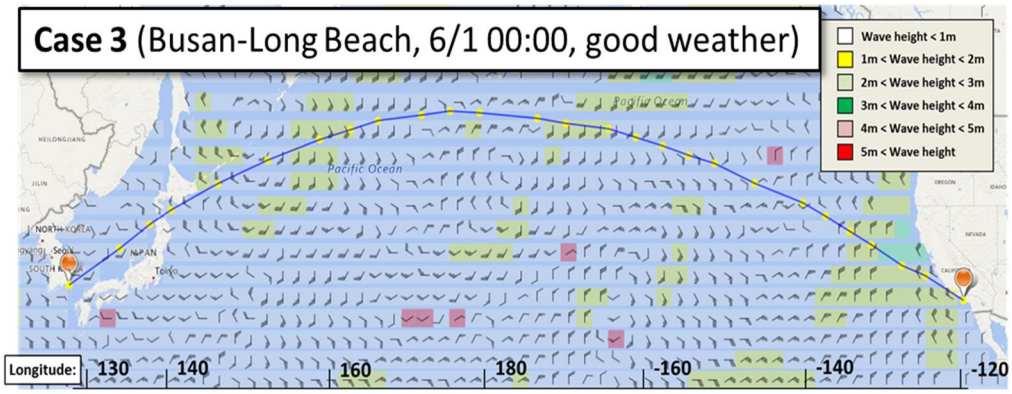

Figure 32 Configuration of paths from each performance-evaluation model in June

Table 13 Result of routes from each performance-evaluation model in June

Methods	TFOC [ton, %]		Total distance [NM]	Arrival Time	Engine RPM
Commercial	672.2	100.0 %	5,236	June 13, 04:01	77
ISO 15016:2015	671.7	99.9 %		June 13, 04:35	77

In case 3, the TFOC are almost same in each method. The minute difference of TFOC is caused from that of speeds and this difference of speed also causes the difference of arrival time between methods because the time is calculated from distance between nodes and speed between nodes. Figure 33 shows the detailed result of each route as graph form.

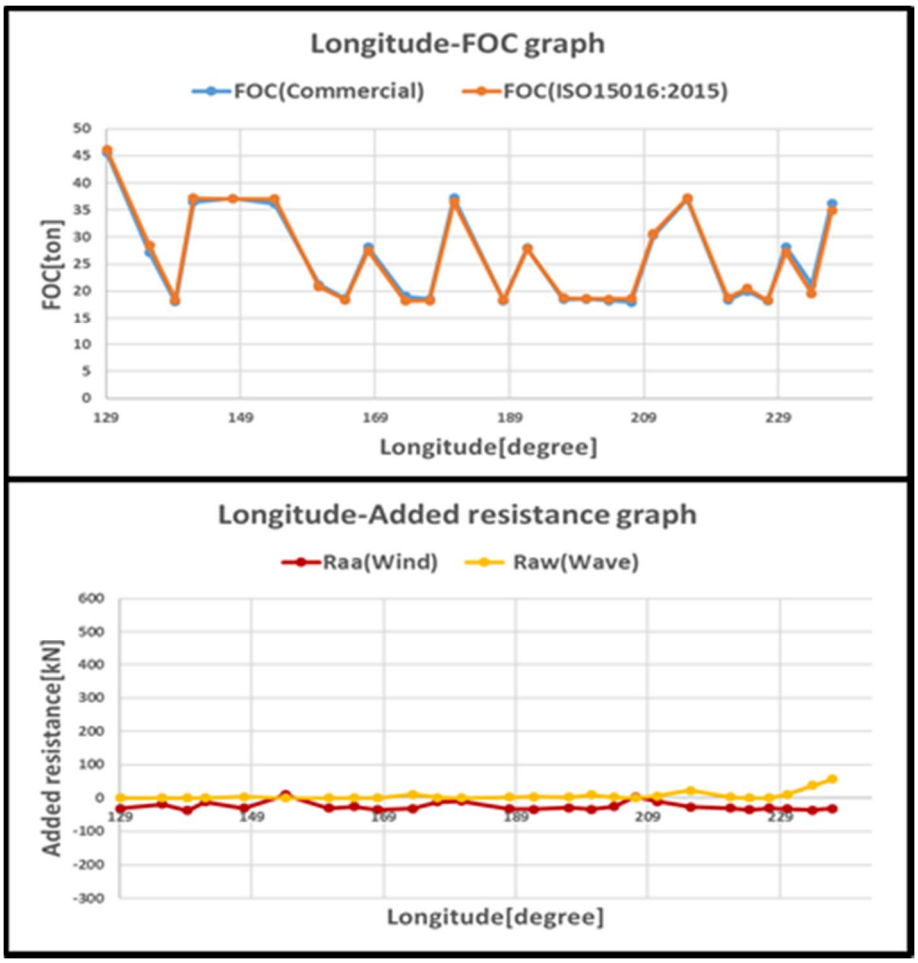

Figure 33 Comparison FOC estimation of the proposed method with FOC estimation of commercial program using graphs of longitude-FOC and longitude-added resistance in June

The upper graph of Figure 33 shows the FOC along to longitude of each method. The blue line means the result of FOC estimation of commercial program and the orange line means the result of FOC estimation of proposed method. The lower graph of Figure 33 shows the added resistance of proposed FOC estimation method. The red line means the result of the added resistance caused by wind (Raa) and the yellow line means the result of the added resistance caused by wave (Raw). The FOC estimation of each method is almost same and the added resistances caused by wind and wave are small in comparison to scale of ship. From this result, the FOC estimation of the proposed method is valid to apply to actual performance of ship in calm weather condition.

7.2.2. Case 4

In case 4, this case also shows the verification of performance-evaluation model. all conditions are the same with case 3 except for departure time or weather condition. Figure 34 shows the configuration of paths from each performance-evaluation model in March. In March, the weather condition is bad over all region of route on the contrary to case 3. The TFOC and the total distance are obtained as shown in Table 14. In case 4, the TFOC are slightly different in each method. The TFOC of the proposed FOC estimation is less than that of the commercial program by approximately 5.3 %.

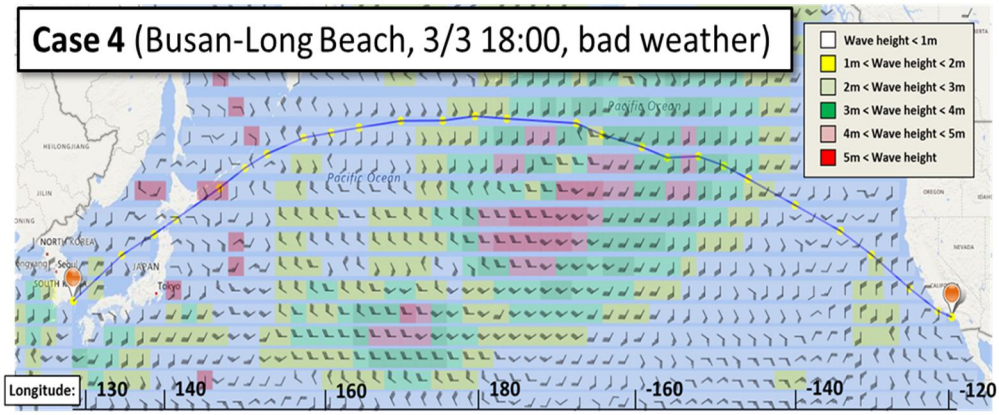

Figure 34 Configuration of paths from each performance-evaluation model in March

Table 14 Result of routes from each performance-evaluation model in March

Methods	TFOC [ton, %]		Total distance [NM]	Arrival Time	Engine RPM
Commercial	721.4	100.0 %	5,248	March 16, 06:25	77
ISO 15016:2015	684.8	94.7 %		March 16, 06:30	77

The difference of FOC is confirmed like the upper graph of Figure 35. The interval of different FOC is observed on red boxes in Figure 35. In the red interval of the lower graph of Figure 35, the added resistance caused by wind (Raa) has large minus values. The minus value of the added resistance of wind means the wind blowing from behind pushes the ship to forward. Therefore, the reason for difference of FOC on the red interval having large minus values of the added resistance of wind is analyzed as follows. The proposed method overestimates the added resistance of wind. This means faster ship speed is calculated than actual ship speed. Moreover, the faster ship speed causes the lower moving time and the lower moving time caused the lower FOC because other

information is same.

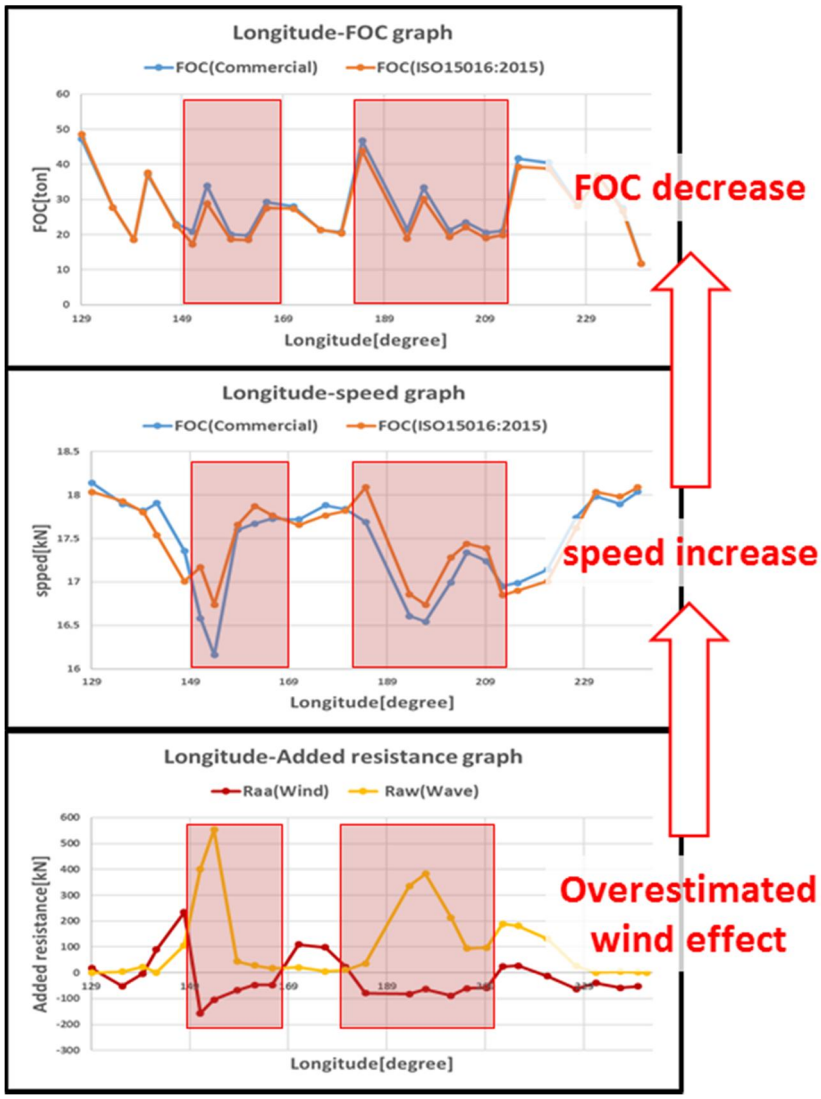

Figure 35 Comparison FOC estimation of the proposed method with FOC estimation of commercial program using graphs of longitude-FOC and longitude-added resistance in March

From case 3 and case 4, FOC estimation of the proposed method is almost same with actual FOC in calm weather condition. Although the proposed method is slightly different with actual FOC in bad weather condition, an error is judged to be acceptable level.

7.3. Verification of route-finding model

7.3.1. Case 5

Case 5 is a verification of optimization techniques of route-finding model by comparing between the proposed route-finding model, exactly Seed genetic algorithm, and another metaheuristic algorithm. There are five metaheuristic algorithm, SPEA2, SMPSO (PSO), NSGAII (GA), Seed-SPEA2, Seed-PSO (Seed particle swarm optimization) and Seed-GA (Seed genetic algorithm). The algorithms which does not have a word 'Seed' are original optimization algorithms used in many studies, and the algorithm having a word 'Seed' are applied with concept of seed. Except for the optimization technique, the case 5 is conducted in the same conditions and input information. All metaheuristic algorithm may find the global optimum if it is performed for a long time. However, the ship-route-planning method should finish the whole procedure within five minutes usually. Therefore, case 5 is conducted around five minutes, exactly adjusted the number of iterations of each algorithm to be the same. Table 15 shows the five results each algorithm respectively.

Table 15 Result of routes from each optimization technique of route-finding model

Algorithms		1	2	3	4	5	Average [ton, %]		Standard deviation [ton, %]	
Global optimum		629.4								
TFOC [ton]	SPEA2	685	683	676	695	670	681.8	108 %	9.5	1.4 %
	SMPSO (PSO)	693	683	678	697	739	698	110 %	24.1	3.5 %
	NSGA-II (GA)	689	692	686	695	665	685.4	108 %	11.9	1.7 %
	Seed-SPEA2	707	697	696	696	696	698.4	110 %	4.8	0.7 %
	Seed-PSO	732	692	692	692	692	700	110 %	17.9	2.6 %
	Seed-GA	**689**	**670**	**667**	**663**	**656**	**669**	**106 %**	**12.3**	**1.8 %**

The global optimum of this problem is 628.4 tons in TFOC. Seed-GA shows the lowest TFOC compared with others. In addition, results of the original metaheuristic algorithms (SEPA2, SMPSO, NSGAII) are relatively bad and results does not have reliability, that is unstable. Even if the seed is applied in other metaheuristic algorithm (Seed-SPEA2, Seed-PSO), their results are not improved compared to initial seed (first result of each algorithm). On the other hand, Seed genetic algorithm is improved more and more. Also, algorithms applied to concept of seed can shorten the time if the time should be more short.

7.3.2. Case 6

Case 6 is a verification of monthly seeds of route-finding model by comparing between a correct monthly seed and another monthly seed. Figure 36 shows the configuration of paths from each monthly seed of route-finding model. The departure time is in March. The blue line is a path from March seed and the red line is a path from June seed. Table 16 shows the detailed result of both routes.

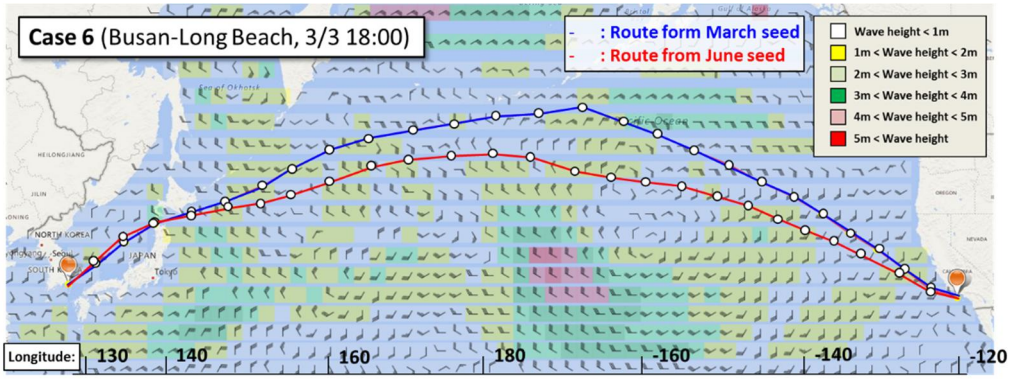

Figure 36 Configuration of paths from each monthly seed of route-finding model

Table 16 Result of routes from each monthly seed of route-finding model

Methods	TFOC [ton]		Total distance [NM]		Arrival time (March 16, 18:00)	Avoidance of the land	Engine RPM [rpm]	Computing time [second]
Route from March seed	629.4	100.0 %	5,223	100.0 %	March 16, 18:00 (O)	O	Varied	138
Route from June seed	662.0	104.9 %	5,243	100.4 %	March 16, 16:48 (O)	O	Varied	173

TFOC of the route from March seed is smaller than TFOC of the route from June seed. Both cases will find the global optimum if it is performed for a long time. However, like

case 5, case 6 is adjusted the number of iterations of each algorithm to be the same. Therefore, the route from June seed look like finding a local optimum.

8. Applications

To check the efficiency and the applicability of the proposed method, applications are performed. Several cases are selected for demonstrating the excellence of the proposed method and the developed program in this study. The proposed method and the prototype program were also applied to various examples, and the results are described and discussed in this section. For the examples, Table 17 shows three routes were selected.

Table 17 Input information of application for the proposed method

<table>
<tr><th>Meaning</th><th>Cases</th><th>Departure port</th><th>Arrival port</th><th>RTA</th><th>Departure time</th></tr>
<tr><td rowspan="8">Complex route</td><td rowspan="8">Application 1</td><td colspan="2">Shanghai, China (31.13N, 122.3E)</td><td rowspan="8">28 days</td><td rowspan="10">3/3
18:00</td></tr>
<tr><td colspan="2">Ningbo, China (29.53N, 122.33E)</td></tr>
<tr><td colspan="2">Xiamen, China (24.35N, 118.25E)</td></tr>
<tr><td colspan="2">Yantian, China (22.45N, 114.45E)</td></tr>
<tr><td colspan="2">Singapore, Singapore (1.3N, 104.4E)</td></tr>
<tr><td colspan="2">Felixstowe, UK (51.95N, 1.37E)</td></tr>
<tr><td colspan="2">Rotterdam, Netherlands (52.0N, 4.05E)</td></tr>
<tr><td colspan="2">Gdansk, Poland(54.6N, 19.25E)</td></tr>
<tr><td>Change of objective function</td><td>Application 2</td><td rowspan="2">Yokohama, Japan (34.95N, 139.61E)</td><td rowspan="2">Vancouver, Canada (48.54N, 124.87W)</td><td rowspan="2">10 days</td></tr>
<tr><td>Considering seakeeping constraint</td><td>Application 3</td></tr>
</table>

Ship information	SN1973 HANJIN 4,600 TEU container ship (Lbp: 241m / Breadth: 37.5m / Depth: 19.5m)
Node information	Δt (time duration) = 12 hours

Application 1 is a complex route that moves several ports. The departure port is Shanghai in China and the arrival port is Gdansk in Poland. Also, this route should pass though several straits, canal and waypoints (Ningbo in China, Xiamen in China, Yantian in China, Singapore in Singapore, Felxstowe in UK, Rotterdam in Netherlands). In this case, the land impact is relatively bigger, but the impact of the weather condition rarely appears (no wave and no wind). This application shows the applicability of the proposed method about complex route. Application 2 is an example that the objective function of the proposed method is changed with other objective functions in the same condition. The objective function is changed with minimizing TFOC, minimizing distance and minimizing ETA. This application shows the various applicability of the proposed method. Application 3 is an example changed seakeeping constraint in the same condition. The route is considered with including seakeeping and excluding seakeeping. In application 2 and application 3, the land impact is relatively smaller, except near the departure and arrival ports, but the impact of the weather condition appears prominently.

8.1. Application 1

The first example is an intricate route that departs from Shanghai and passes through multiple ports and straits, canals as shown in Figure 37.

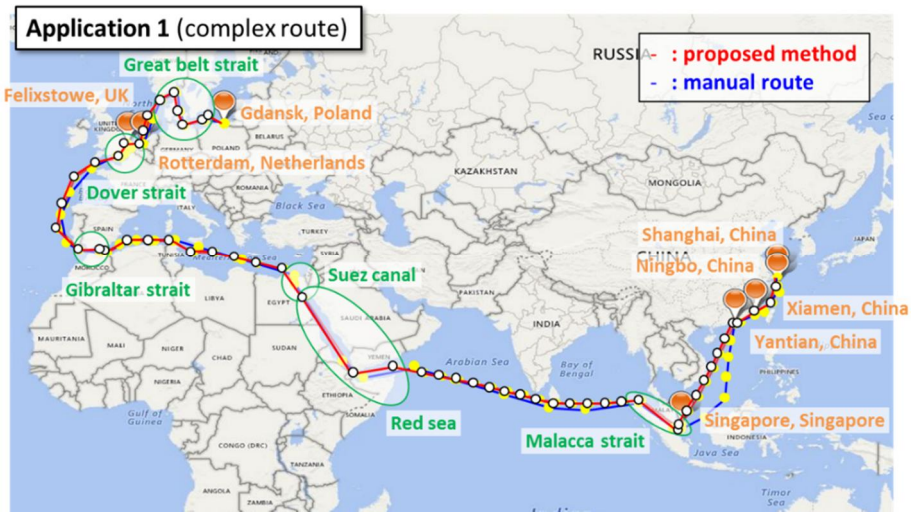

Figure 37 Visualization of routes for application 1

The red route shows a route using the proposed method and the blue route shows a route from AIS (Automatic Identification System) of IMO. As shown in Figure 37, the results for this application are for a complicated route and a calm sea condition with no wave or wind. The details of routes are show in Table 18. Each method yielded routes without any land or island interferences, and the route shapes for all of the methods are almost the same. It can be confirmed that the proposed method can apply to complex route with good TFOC and total distance.

Table 18 Result of routes for application 1

Methods	TFOC [ton]	Total distance [NM]	Arrival time (March 31, 18:00)	Avoidance of the land	Engine RPM [rpm]	Computing time [second]
Manual	1502.0	11,771	March 31, 12:15 (O)	O	77	-

(AIS from IMO)						
Proposed	1,381.5	11,735	March 31, 18:00 (O)	O	Varied	187

8.2. Application 2

In application 2, the route is found by changing the objective function as shown in Figure 38.

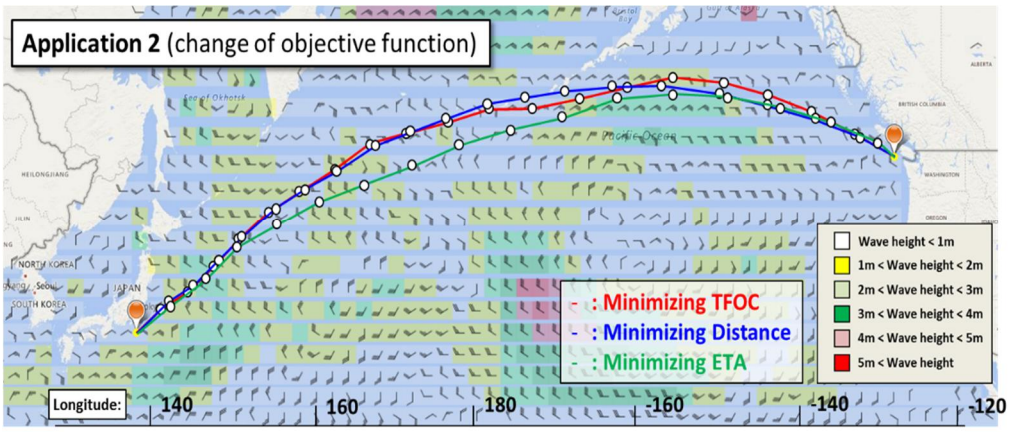

Figure 38 Visualization of routes for application 2

The red route is a route set with minimizing TFOC as the objective function, the blue route is a route set with minimizing distance as the objective function and the green route is a route set with minimizing arrival time, that is ETA. The details of routes are show in Table 19. It was confirmed that each result was found according to intention of each objective function, and it can be confirmed that the proposed method can be used for

various purposes.

Table 19 Result of routes for application 2

Methods	TFOC [ton]	Total distance [NM]	Arrival time (March 13, 18:00)	Avoidance of the land	Engine RPM [rpm]	Computing time [second]
Minimize TFOC	498.3	4,113	March 13, 18:00 (O)	O	Varied	155
Minimize distance	526.4	4,094	March 13, 16:33 (O)	O	Varied	149
Minimize ETA	692.5	4,114	March 11, 23:00 (O)	O	Varied	169

8.3. Application 3

Application 3 shows the difference between the case with seakeeping constraint and the case without seakeeping constraint.

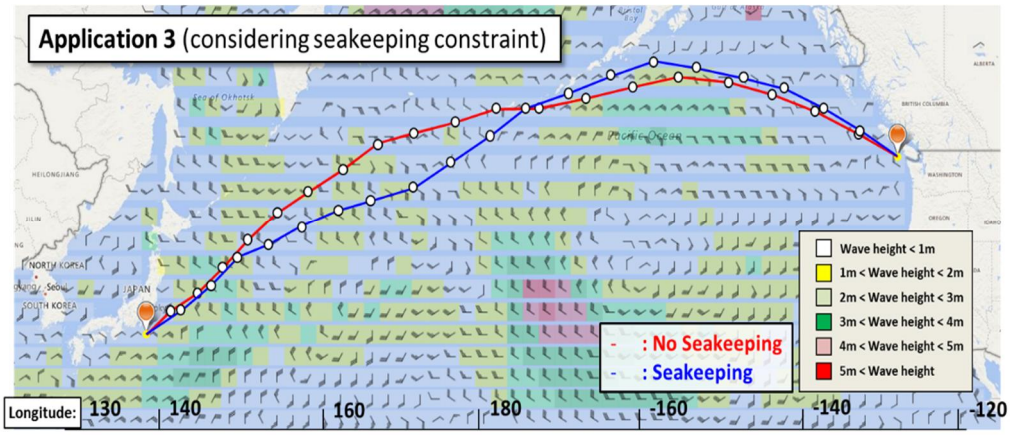

Figure 39 Visualization of routes for application 3

The red route is a route which does not consider the seakeeping performance and the blue route is the route considering the seakeeping performance. As shown in Figure 39, typhoons come from the early part of the routes and from the latter part of routes. The red route pass through the typhoon, but the blue route moving away from the typhoon. The details of routes are show in Table 20. Although TFOC of the blue route (seakeeping) is bigger than that of the red route (no seakeeping) and the total distance of the blue route is bigger than that of the red route, the blue route can be confirmed that the seakeeping performance is satisfied. It was confirmed that the proposed method can be consider the seakeeping constraint effectively.

Table 20 Result of routes for application 3

Methods	TFOC [ton]		Total distance [NM]		Arrival time (March 13, 18:00)	Avoidance of the land	Seakeeping	Engine RPM [rpm]	Computing time [second]
No seakeeping	498.3	100.0 %	4,113	100.0 %	March 13, 18:00 (O)	O	X	Varied	155
Seakeeping	513.5	103.0 %	4,165	101.2 %	March 13, 18:00 (O)	O	O	Varied	217

9. Conclusion and future works

In this study, an efficient ship-route-planning method was proposed through the mathematical formulation of a ship-route-planning problem as an optimization problem,

whereby a simultaneous optimization of the path and the speed of the ship was enabled. To estimate ship performance, the FOC, the distance, the seakeeping and the avoidance of land is evaluated with proposed methods in this study. The problem was finally solved through the use of Seed genetic algorithm, initial solution was used and updating by managing into the seed pool. In addition, a prototype program that is based on the proposed method was developed with multilayer structure. The validation of the proposed method was evaluated alongside those of the other methods according to verification cases. The verification is conducted in all proposed models, optimization model, performance-evaluation model and route-finding model. All verification cases show the superiority and validation of proposed models and method. Finally, to check the applicability of the proposed method, it was applied to three cases. These cases show the strength of proposed method which is possible to apply complex route, to change the objective function and to change the constraints.

In the future, recently, interest in the Arctic routes has increased. The proposed method can be applied with change of object from the Pacific Ocean to the Arctic sea. Of course, there are several difficulties to apply in the Arctic sea. Basically, the map in this study is expressed with Mercator projection, but it is unstable for the Arctic sea because Mercator projection does not include the Arctic sea and its visualization is uncomfortable. Also, the information about the arctic area is hard to come to hand. The information on glaciers and floating ice as well as the existing information are unusual. Therefore, if the map projection and information are obtained, the proposed method can also be applied in the Arctic sea. Furthermore, more realistic consideration need for actual ship-route planning. the proposed method already considers a lot of points with the objective function and constraints. Like the pirate problem, we believe that more actual ship-route planning is possible if the consideration in selecting the route of the captain is reflected in

this proposed method.

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국문 초록

선박 항로 계획을 위한 최적 경로 및 속도 결정 방법에 관한 연구

선박 항로 계획은 해운회사의 경영 악화 문제, 오염 물질에 대한 국제 규정의 강화 그리고 운항 중의 항로의 안전성 문제 등의 최근의 직면한 여러 문제들에 대해 좋은 해결책이 될 수 있다. 하지만 현재 선박 항로 계획은 항해사의 경험 또는 단순한 매뉴얼 등의 비정량적 방법으로 결정된다. 또한 항로 계획에 사용되는 알고리즘 역시 대부분 경로만을 계획하는 방법들이 많으며 속도를 항로에 포함하여 동시에 계획하는 방법은 충분히 연구되지 않았다.

본 연구에서는 선박 항로 계획을 연구하기 위한 프레임워크를 제안하고, 이를 바탕으로 항로와 속도를 동시에 최적화하는 선박 항로 계획 방법을 제안하였다. 먼저 선박 항로 계획 문제를 최적화 문제로 풀이하기 위한 정식화 과정을 제안하고, 이 정식화된 식들로 항로를 구성하는 모델을 제안하였다. 이를 위해 항로를 선박의 경로 (선수각)와 속도 (엔진 rpm)의 집합이라고 정의하여 실제

선박의 운항 모습을 최대한 모사하였다. 해당 항로를 평가하기 위하여 크게 연료 소모량, 이동거리, 내항성능 그리고 육지 회피를 대상으로, 이를 평가 할 수 있는 모델을 이론과 규정 등을 활용하여 제안하였다. 또한 항로를 최적화하는 모델으로써 초기해를 제공하고 관리하는 초기해 유전자 알고리즘 (Seed genetic algorithm)을 제안하였다. 앞선 3 가지 모델을 바탕으로 다층구조를 구현한 프로그램을 개발하였으며, 6 가지의 검증예제와 3 가지의 적용예제를 통해 제안한 3 가지 모델과 구현된 프로그램의 우수성과 적용가능성을 확인하였다.

제안된 선박 항로 계획 방법은 기존의 항로계획 방법과 상용 프로그램보다 우수한 항로를 산출하였다. 또한 제안된 최적화 모델, 성능평가 모델, 항로탐색 모델 그리고 프로그램의 효용성 역시 확인 할 수 있었다.

Keywords: 선박 항로 계획, 동시 최적화, 선박 성능 평가, 초기해 유전자 알고리즘

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