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Simulation for Designing the Transition to Autonomous Shipping – Japanese Coastal Shipping -

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ABSTRACT

In Japanese coastal shipping, there is a need to introduce automation technology to alleviate the shortage of seafarers, but its introduction has an indirect impact on coastal shipping due to the interaction between transportation demand and freight rates in a market with a variety of stakeholders. Therefore, it is difficult to make decisions about its introduction. This study uses a simulator that mimics the Japanese cargo market to evaluate the impact of the deployment. The results show that the introduction of autonomous vessels, even in the middle of development, may bring benefits, and that remote maneuvering technology with a crew on board may not produce positive impacts.

KEY WORDS
Simulation, Autonomous ship, Technology adoption, Mobility transition, Coastal Shipping

1. INTRODUCTION

Background

On a kilometer basis, more than 90% of Japan's domestic freight transportation is by automobile. However, on a ton-kilometer basis, coastal shipping accounts for about 40%, and coastal shipping plays a large role, especially in long-distance transportation (MLIT, 2022). However, coastal shipping is facing a serious shortage of labor, which is reflected in the fact that in recent years the ratio of effective job offers to applicants has consistently exceeded 2 and is even above 2.5 (MLIT, 2019). The aging of the seafarer population is also a problem, with about half of the seafarers over the age of 50 (MLIT, 2021). The number of seafarers is expected to decrease further soon. Therefore, the introduction of automation technology is expected to reduce the demand for seafarers and secure a stable supply of new seafarers. In addition to reducing the demand for seafarers, the introduction of automation technology is also expected to reduce accidents caused by human error, which is estimated to account for 80% of maritime accidents and reduce carbon dioxide emissions by reducing fuel consumption through optimization of routes and vessel shapes.

For these reasons, various projects are underway in Japan and abroad to develop automation technology. In Japan, a project called MEGURI2040 was launched in 2020 with the goal of commercializing unmanned vessels by 2025 and of having half of all domestic vessels operated by unmanned vessels by 2040 (The Nippon Foundation, 2022). At the same time, the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project is one of the big projects held in 2015-2020 outside of Japan. Project Report (MUNIN, 2015) concluded that autonomous vessels are feasible, although some barriers still remain. The MUNIN project is not only developing the technology but is also investigating the economic evaluation of autonomous vessels and discussing their feasibility. According to Bellingomo et al. (2023), the technology to develop autonomous vessels has been well developed by these projects, and it is technically feasible to introduce autonomous vessels in the near future.

The economics of autonomous vessels were analyzed by MUNIN (2015) and Kretschmann (2017). They compare the operating costs of autonomous vessels with conventional vessels for the bulk vessels envisaged in the MUNIN project. Akbar (2019) analyzes the total costs of introducing autonomous vessels on Norwegian coastal routes, based on actual routes and cargo volumes. These studies show that autonomous vessels are economically profitable, and when operated on actual routes,

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costs can be further reduced through route optimization. Dantas et al. (2023) compare the operating costs of a typical Norwegian short-haul vessel with those of a conventional autonomous vessel (TAS), and a new configuration of autonomous vessels (NGAS) with reduced crew living space and other functions made unnecessary by unmanned autonomous vessels and concluded that the reduction of crew facilities on autonomous vessels helps to reduce costs. As for the impact of automation technology on crewing demand, Kretschmann (2017) proposed a system in which instead of crewing autonomous vessels, autonomous vessels are monitored from a remote operations center (ROC). They estimate that 112 people would be needed for one ROC, including standby operators, watchkeepers, and managers. It also estimates that one ROC can operate 90 vessels. Kooij (2021) also conducted a study on the impact of the introduction of automation technology, analyzing the tasks required to operate a 750 TEU container ship with a crew of 12 and the tasks that could be replaced by the introduction of automation technology. The analysis showed that the number of seafarers required was reduced by only one second officer, but the workload of the seafarers was significantly reduced. Therefore, the study concluded that for shipowners, the economic benefit of reducing automation technology is small because it does not significantly reduce the demand for seafarers, but the reduction in workload improves the working environment and contributes to a reduction in maritime accidents, which account for 80% of all maritime accidents due to seafarer fatigue. Further research on policies that promote automation technology includes Nakashima et al. (2023). This study estimated that a combination of deregulation and appropriate assistance could hasten the introduction of fully autonomous vessels by more than 10 years.

Although the introduction of automation technology in coastal shipping is ongoing due to the background described in the previous part, the introduction of autonomous vessels with no crew on board will not be possible anytime soon. Therefore, until the introduction of autonomous vessels becomes feasible, one measure to maintain the market share of coastal shipping and ensure stable transportation is to eliminate the shortage of seafarers by utilizing the automation technology to be introduced in autonomous vessels and reduce the number of seafarers required. On the contrary, if automated technologies are rapidly introduced, a rapid drop in the demand for seafarers could lead to an oversupply of seafarers, which could worsen the employment environment for seafarers, and an oversupply of seafarers could lead to extra labor costs. Under these circumstances, it is desirable to introduce automated technology to match the shortage of seafarers. However, while there have been studies on the economics of autonomous vessels and the number of seafarers that would change with the introduction of automation technology, few studies have analyzed the impact of the introduction of such technology on seafarer employment and how the early introduction of automation technology used on autonomous vessels would improve shipping capacity by reducing the seafarer shortage in the transitional period.

Purpose of this study

The introduction of automation technology also has a direct impact on seafarer demand and operating costs and an indirect impact on coastal shipping due to the interaction between transportation demand and freight rates in a market with a variety of stakeholders. In the presence of such complex factors, it is difficult for coastal shipping to make decisions to introduce automation technology more quickly while maintaining its transportation capacity as an industry in terms of employment and economics. Therefore, this study aims to support this decision-making process through a simulator that models the costs of coastal shipping and car transport in Japan and designs the transition to autonomous shipping driven by the introduction of automation technology.

2. PROPOSED METHOD

Overview of the proposed method

We propose a method to evaluate the impact of the introduction of automation technology by shipping companies. As shown in Figure 1, the method begins by developing a simulator that models the domestic freight market in Japan, including the estimated parameters. The simulator models how to calculate costs and set freight rates for coastal shipping and automobile transport, and at each step, decisions are made on factors related to the calculation of costs, such as investment in facilities and hiring of employees for each transportation demand. In addition, changes in the determined freight rates change the transportation demand for each means of transport in the next step. These complex interactive demands represent the Japanese freight market. Next, the case study is conducted as shown below using the simulator developed. The inputs to the case study are a combination of a shipping company's decision-making strategy regarding the introduction of automation technology and future trends in total transportation demand. The strategy regarding the introduction of automation technology relates to whether to introduce each of the four stages of technology envisaged as stages in the development of automation technology. The future trend of total primary demand is a set of future trends in total transportation demand from 2010, the starting year of the simulation. Based on these inputs, the simulation is run for a one-time step of 1 week between 2010 and 2070, and output results include the transition of shipping costs. Finally, the result is transformed into three indexes between 2025, when we assume that automation technology can be implemented, and 2070, when the simulation ends, as the NPV considered for the time discount rate, the total lost transportation opportunity ratio, and the cumulative early retirement crew ratio, by total transportation demand. After that, they are plotted on a scatter plot. The scatter plots are plotted on the horizontal axis with the cumulative percentage of early retired seafarers on the right decreasing, and on the vertical axis with the percentage of lost transportation opportunities on the bottom decreasing. The color of the plotted points expresses the NPV of the shipping company's ton-kilometer-based costs and the larger the costs are, and the closer to yellow, the smaller the costs are red. The above methodology is proposed in this study as a method for evaluating the impact of shipping companies on the adoption of automation technology.

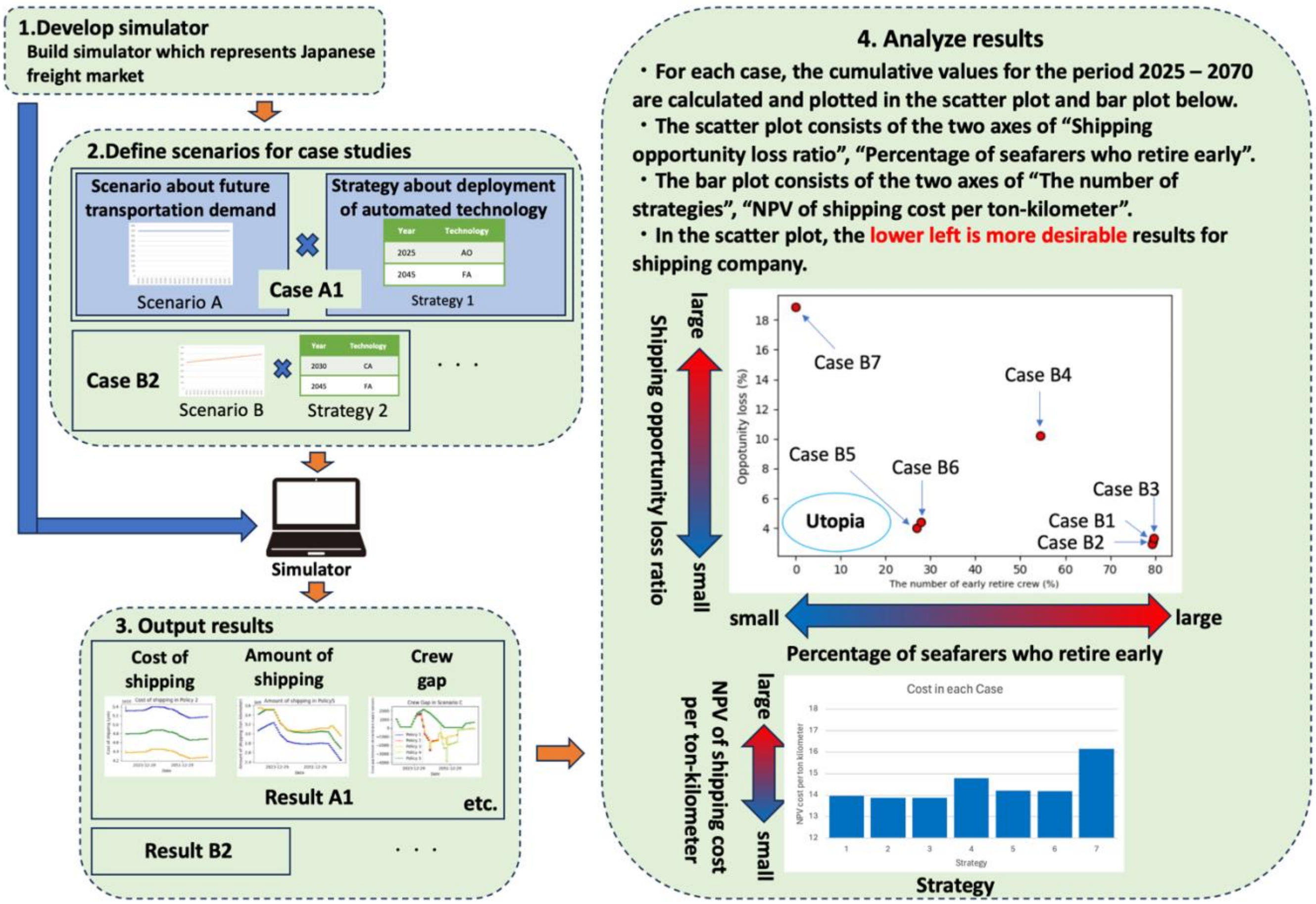

Figure 1: The abstract of proposed method

Simulation calculation flow

In the previous part, we proposed a method to provide decision support to shipping companies regarding the introduction of automation technology. In this section, we describe the specific computational flow of the simulator. Firstly, variables that are considered necessary for the simulator to be developed are selected based on previous studies and will be described later in subsequent parts. At each time step, the variables for the next time step are also calculated. As shown in Figure 2, the simulator was conducted with a time unit of 1 week from 2010 to 2070, the year when autonomous ships and self-driving cars are expected to be widely used. The simulator is divided into two parts: a transportation demand estimation model and a transportation cost estimation model. The transportation demand estimation model calculates transportation demand by transportation agency according to the freight market conditions. Then, based on the transportation demand, the transportation cost estimation model calculates transportation costs for each transportation. The relationships between the variables represented by the arrows in Figure 3 were developed based on previous studies. The sequence of calculations in the transportation cost estimation model is likewise shown in Figure 3.

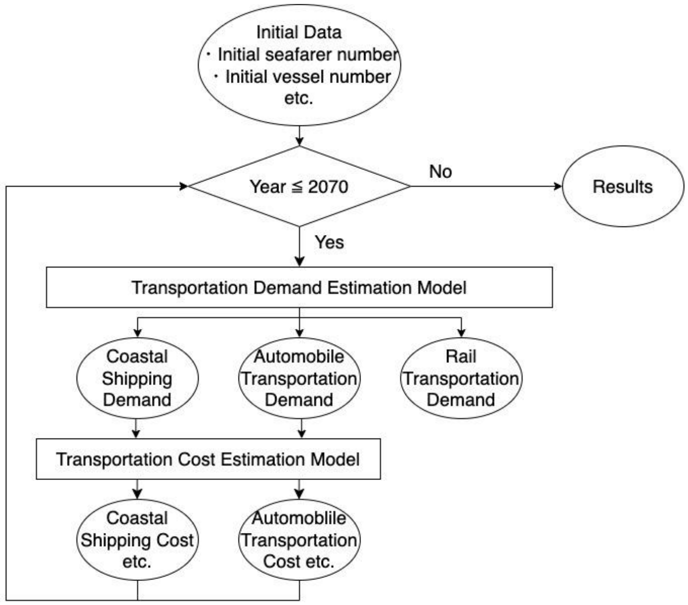

Figure 2: The abstract of simulator

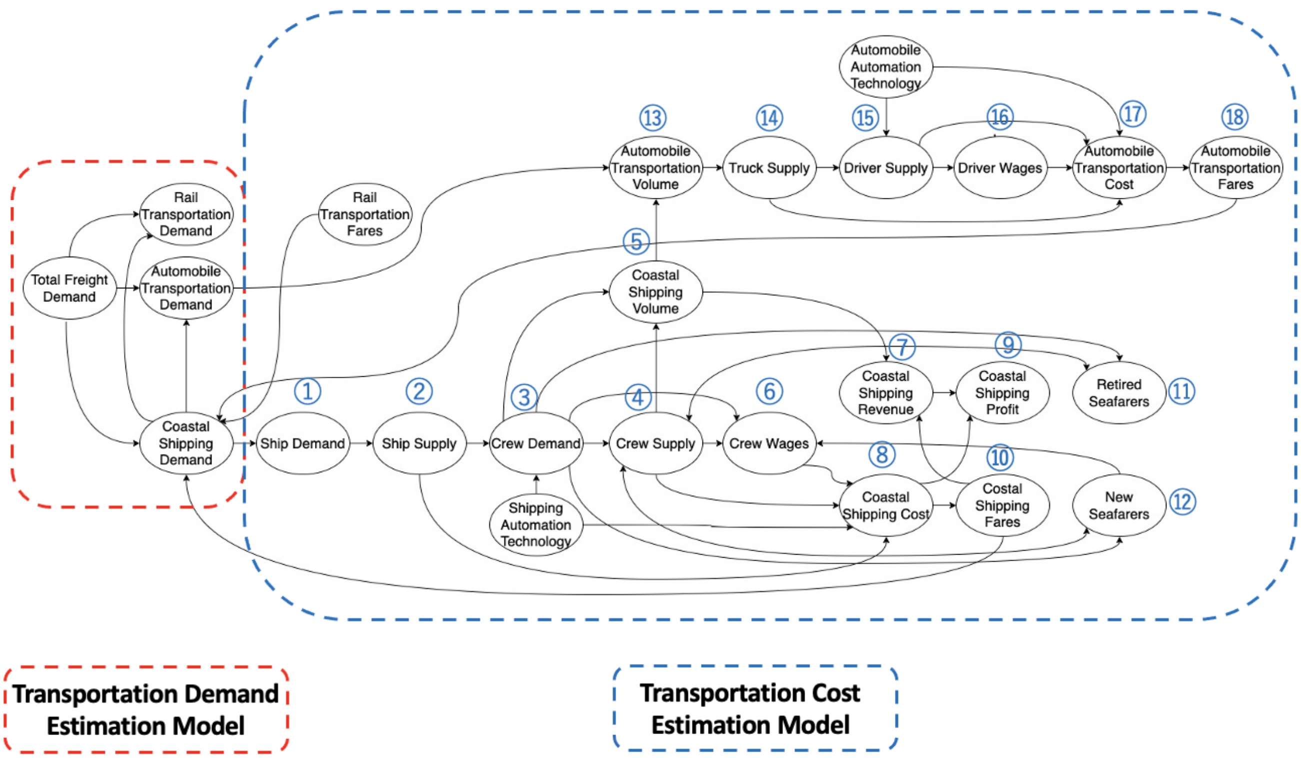

Figure 3: The relationships among variables in one loop. Source: Prepared by the authors from (Shinke, 2007), (Kretschmann, 2017) and (Lee, 2023)

Simulation model variables

Air transportation was not treated in this study because its share of transportation is small (less than 1%). In addition, rail transportation was treated with fixed freight rates because the percentage of transportation has been fixed in recent years, although there is a certain amount of transportation (The Japanese Shipowners' Association, 2021). For the variables used, the variables necessary for transportation demand allocation (Shinke, 2007) and for calculating the costs of coastal shipping (Kretschmann, 2017) (Lee, 2023) and automobile transportation were selected (Table 1) with reference to previous studies.

Table 1: The variables in the simulator

modes of transportation	variable
Coastal shipping	Transportation demand, number of vessels demanded/supplied, crew demand/supply, crew labor costs, transportation expenditures, fare, and transportation revenues
automobile	Transportation demand, truck demand/supply, truck driver demand/supply, truck driver labor costs, transportation expenditures, freight rates, and transportation revenues
railroad	Transportation demand, freight rates

Estimation of transportation demand

In this study, 47 prefectures are treated as nodes, and the links connecting these nodes are treated as a domestic freight transportation network. Transportation demand by each mode of transportation is distributed by a multinomial logit model. The calculation of the probability $P_{m,o,d,t}$ of transportation m from node o to node d at time t is defined in Equation [1], and the transportation demand $X_{m,o,d,t}$ is obtained by the expected value using the total transportation demand $G_{o,d}$ and $P_{m,o,d,t}$ as shown in Equation [5]. The utility calculated by the logit model $V_{m,o,d,t}$ is the freight rate per ton-kilometer $F_{m,t}$ (discussed after) and transport distance $L_{m,o,d}$ (discussed in Appendix) and time $T_{m,o,d}$ (discussed in Appendix) based on previous studies and defined in Equations [2] through [4]. The parameters α used in these equations are described below in Appendix.

$$\boldsymbol{P_{m,o,d,t}} = \frac{\mathbf{exp}(\boldsymbol{V_{m,o,d,t}})}{\sum \mathbf{exp}(\boldsymbol{V_{m,o,d,t}})} \quad [1]$$

$$V_{ship,o,d,t} = \alpha_{time} T_{ship,o,d} + \alpha_{cost} F_{ship,t} L_{ship,o,d} \quad [2]$$

$$V_{rail,o,d,t} = \alpha_{time} T_{rail,o,d} + \alpha_{cost} F_{rail,t} L_{rail,o,d} + \alpha_{rail} \quad [3]$$

$$V_{truck,o,d,t} = \alpha_{time} T_{truck,o,d} + \alpha_{cost} F_{truck,t} L_{truck,o,d} + \alpha_{truck} \quad [4]$$

$$X_{m,o,d,t} = G_{o,d} P_{m,o,d,t} \quad [5]$$

Shipping

Automation progress

Referring to IMO's definition (IMO, 2016) for automation technology and AUTOSHIP's roadmap (Nordahl, 2023), the following stages of automation technology development were established as Table 2.

Table 2: Automation technology development stage (Nordahl, 2023)

Automation phase	Description.
AO (Automatic Operation)	Automated technologies such as automatic ship holding and automatic ship release are beginning to be implemented, but decisions are made by the ship's crew.
RC (Remote Control)	Predictive breakdowns of machinery will be possible, and maintenance of machinery will be performed when the vessel makes port calls. The ship will be constantly monitored from shore, and the conventional control system will remain, but decisions will be made remotely from the RCC.
CA (Constrained Autonomy)	The vessel operates autonomously under general conditions, although its autonomy is limited. The vessel no longer requires a crew to be on board and is only operated remotely from a remote-control center (RCC) under complex conditions, such as bad weather.
FA (Full Autonomy)	Full autonomy is achieved, with no crew on board or in the RCC. However, the operator of the RCC must deal with fallback recovery.

Fleet configuration

The demand for the number of vessels of each size $D_{ship,size,t}$ is calculated based on transport demand and defined in Equation [6]. The weekly transport volume β_{ship} per pair of vessels calculated from the past data to calculate the total tonnage required by the vessel. The ship types described in this study are four typical ship types (MLIT, 2021) is assumed that the ratio of the number of vessels by ship size $A_{ship,size}$ does not change, we calculate the demand for the number of vessels for each ship size.

$$D_{ship,size,t} = \left\lceil \frac{A_{ship,size}}{\beta_{ship}} \sum_{o,d} X_{ship,o,d,t} \, L_{ship,o,d} \right\rceil \quad [6]$$

Number of vessels supply

The shipping company determines the supply of vessels of ship age age, $S_{ship,size,phase,age,t}$ based on the demand $D_{ship,size,t}$. In this study, it is assumed that ships are used for 14 years, which is the statutory service life of a ship in Japan, and that they are not scrapped in the middle of their service life. The number of new vessels is determined by the difference between the demand for vessels and the number of existing vessels in the current time step for each vessel type to meet the demand. The number of vessels in each automation phase is defined by Equations [7] and [8] to be allocated to the number of vessels in each automation phase according to the C_{phase}.

$$S_{ship,size,phase,age+1,t} = S_{ship,size,phase,age,t-1} \; if (0 \le age \le 13) \quad [7]$$

$$S_{ship,size,phase,0,t} = \left(D_{ship,size,t} - \sum_{phase} \sum_{age}^{13} S_{ship,size,phase,age,t-1} \right) C_{phase} \quad [8]$$

Seafarer demand

The demand for seafarers $D_{crew,t}$ is the supply of number of vessels $S_{ship,size,phase,t}$ and the demand for seafarers per vessel $B_{ship,size,phase}$ is calculated using Equation [9]. One of the purposes of introducing automated technology is to solve the shortage of seafarers, and the demand for seafarers is greatly affected by the introduction of automated technology. The factors affecting the demand for seafarers at each stage of automation technology are summarized in Table 3 with reference to AUTOSHIP (Nordahl, 2023). The demand for seafarers for conventional vessels is based on the Ministry of Land, Infrastructure, Transport and Tourism (2021).

Table 3: Factors influencing the demand for seafarers at each stage (Nordahl, 2023).

Automation phase	Seafarer services to be reduced
AO	The demand for seafarers on deck will decrease with the introduction of automated technologies such as sensors on the hull, automatic ship holding and automatic ship release.
RC	Machinery maintenance will be performed by the port's machinery mechanics when they call at the port as machine failures can now be predicted MUNIN Project Report. (2015) According to the MUNIN project report (2015) the maintenance that used to be performed during the 216-day voyage is now performed during the 120-day voyage when the vessel is in port. It was assumed that the number of seafarers in the machinery department would effectively increase by a factor of 120/216 as they would be serviced. At the same time, the demand for seafarers in the deck section would be substantially reduced as remote monitoring facilities would provide around-the-clock monitoring and decision making.
CA	Ships will navigate autonomously under all but the most complex conditions, such as bad weather, reducing the number of seafarers required at remote monitoring facilities MUNIN Project Report. (2015) According to the MUNIN project report (2015), the MUNIN project envisions a single remote monitoring facility to monitor 90 autonomous vessels with a crew of 112.
FA	If no abnormalities occur on the vessel, it will operate autonomously, further reducing the number of crew members required at the remote monitoring facility.

$$D_{crew,t} = \sum_{i,j} S_{ship,size,phase,t} B_{ship,size,phase} \quad [9]$$

Seafarer supply

Seafarers are divided into two categories: staff and departmental staff. Staff members are required to obtain national certification by graduating from a seafarer training school, but they are indispensable to the operation of a ship. Therefore, in this study, it is assumed that new seafarers are hired at the age of 20, when licenses can be issued, and retire at the age of 70 defined by Equation [10]. New Seafarers $S_{crew,20,t}$ is the new potential seafarer $N_{crew,t}$ and is calculated as the minimum of the gap between seafarer supply and demand, defined by Equation [11]. New potential seafarers $N_{crew,t}$ is calculated using Equation [12], assuming that the number of potential new seafarers will decrease by 1% each year from the current number of 900, which is the number of new seafarers in Japan, taking into account the decline in Japan's population. $E(= 0.01)$ is the seafarer retirement rate for each year. In this study, based on the number of seafarers in 2010, the initial values for seafarers are used, separated by age groups by one year of age. Equation [13] and [14] defines the actions of shipping companies with respect to the dismissal of seafarers. In this model, shipping companies are assumed that they lay off seafarers when the number of seafarers exceeds a certain ratio $\kappa(= 1.1)$ of the current demand for seafarers. The model is set up so that when dismissing a seafarer, the older seafarers would be dismissed first.

$$S_{crew,age,t} = (1 - E)S_{crew,age-1,t-1} - I_{crew,age,t} \; if \; (21 \le age \le 70) \quad [10]$$

$$S_{crew,20,t} = \min\{N_{crew,t}, (D_{crew,t} - S_{crew,t})\} \quad [11]$$

$$N_{crew,t} = 900 * \{1 - 0.01 * (t - 2010)\} \quad [12]$$

$$I_{crew,t} = \sum_{age} (S_{crew,age,t}) - \kappa D_{crew,t} \quad [13]$$

$$I_{crew,age,t} = max\left(0, I_{crew,t} - \sum_{i=0}^{70-age} S_{crew,70-i,t}\right) \quad [14]$$

Worker labor costs

The wage of workers is calculated as defined in Equations [15] and [16] from the effective job openings ratio (the gap between supply and demand for seafarers divided by the number of potential new seafarers) with reference to the Bank of Japan's past analysis (2017).

$$Q_t = 1 + 0.5\left(\frac{D_{crew,t} - S_{crew,t}}{N_{crew,t}} - 1\right) \quad [15]$$

$$W_{crew,t} = W_{crew,t-1}\left(1 + \frac{Q_t}{100}\right) \quad [16]$$

Vessel transportation expenditures

The multiple subcontracting structure of the Japanese transportation industry has become a problem because it leads to lower profit margins. In this study, we assume a "time-charter contract" as one of these employment types. In this type of employment, the shipowner pays operating costs such as crew costs and ship repair costs, as well as capital costs such as depreciation, and earns charter fees by leasing the ship to an operator who actually carries the cargo. The operator, on the other hand, rents the people and equipment necessary to operate the ship from the shipowner, and in addition pays voyage expenses such as fuel to actually transport the cargo. The operator's source of income is the freight charges from the shipper.

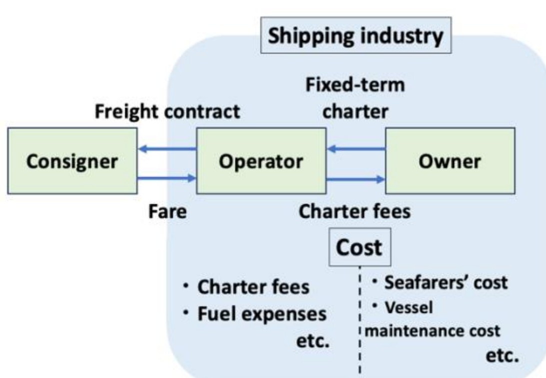

Figure 4: The market structure of Japanese coastal shipping (MLIT, 2020)

In this study, the cost to the owner was calculated with reference to the Maritime Industry Research Institute (2004). The operator's costs were calculated based on a survey by the Ministry of Land, Infrastructure, Transport and Tourism (2010). The following are the costs for each of the conventional sizes. Since only data for 199 GT, 499 GT, and 699 GT were available for the owner's costs, data for 799 GT and 5000 GT were prepared assuming that all costs except crew costs are proportional to the size of the vessel.

Table 5: The change of cost in each phase (MUNIN, 2015), (Dantas, 2023)

	existing ship	admission office	reinforced concrete reactor	CA	FA
capital cost	0	+7.5%	+15%	+10%	
freight costs	0				
fuel expenses	0		-5%		
harbor charges	0		+20%		
remote facility	0		Construction costs are \$2,100 thousand. Maintenance costs are \$874 thousand.		

There are also several possible costs that will increase or decrease with the autonomous vessels. Below is a summary of equipment costs that will vary with the introduction of autonomous vessels. The MUNIN report (2015) analyzes the costs associated with remote monitoring facilities to monitor autonomous vessels. It also points out the increased costs associated with port employees performing berthing tasks that would traditionally be performed by the crew. The cost of vessel construction is also expected to change. Various methods have been proposed in the past to estimate the cost of building a conventional ship (Caprace, 2009). Based on these methods, MUNIN (2015) and Dantas et al (2023) have estimated costs. Based on the above, this study has determined that the cost of transportation by ship is shown in the following Table 5.

Marine transportation revenues

Revenues from shipping $R_{ship,t}$ are calculate by freight rates $F_{ship,o,d,t}$. In this study, freight rates are calculated as in Equation [17] in a way that is consistent with the actual situation.

$$R_{ship,t} = F_{ship,t} \sum_{o,d} F_{ship,o,d,t} X_{ship,o,d,t} L_{ship,o,d} \quad [17]$$

Maritime transportation profit

Profit from shipping $H_{ship,t}$ is calculated as in Equation [18] from the difference between income $R_{ship,t}$ and expenditure $C_{ship,t}$.

$$H_{ship,t} = R_{ship,t} - C_{ship,t} \quad [18]$$

Shipping freight rates

In this study, shipping companies try to keep profit margins. In other words, freight rates fluctuate according to the shipping companies' costs. Using historical data (Maritime Industry Research Institute, 2004), the shipping company was set to maintain a 2% profit margin. Overall freight rates and standard overall freight rates calculated from J_{ship} and standard freight rates for each link $E_{m,o,d}$ (discussed below in Appendix), as shown in Equation [19].

$$F_{ship,o,d,t+1} = \frac{C_{ship,t} E_{m,o,d}}{J_{ship} \sum_{o,d} X_{ship,o,d,t} L_{ship,o,d}} \quad [19]$$

Automobile transport

Automation progress

Automation is being promoted not only in coastal shipping, but also in the automobile industry. Already in 2023, there have been demonstrations of Level 4 automated trucks on highways (unmanned operation under certain conditions) (LNEWS, 2023). In addition, the Japanese government's roadmap sets the goal of social implementation of Level 4 automated trucks at 2026 (MLIT, 2023a). Automated driving outside of expressways will be available after 2026, but in terms of modal shift to and from marine transportation, the modal shift in automobile transportation is mainly for long-distance transportation, and many of them use expressways. Therefore, we assumed that the demand for transportation will change with shipping due to automation on highways, and that the introduction rate of automated trucks will increase linearly between 2026 and 2060.

Number of trucks

Truck demand at time t $D_{truck,t}$ is calculated from the ton-kilometer-based transportation demand calculated and weekly transport volume per vehicle β_{truck} (All Japan Trucking Association, 2010) as defined in Equation [20].

$$D_{truck,t} = \left\lceil \frac{\sum_{o,d} X_{truck,o,d,t}\, d_{truck,o,d}}{\beta_{truck}} \right\rceil \quad [20]$$

In addition, the supply of trucks $S_{truck,t}$ The supply of trucks is assumed to be equal to the demand as shown in Equation [21] because the number of trucks produced is large and the lead time of production is small, so the supply can be changed flexibly in response to fluctuations in demand.

$$S_{truck,t} = D_{truck,t} \quad [21]$$

Number of truck drivers

In this study, we assumed that the proportion of trucks $S_{truck,t}$ and the number of drivers is not likely to change. In addition, the results of a comparison of the number of trucks and drivers using historical data (All Japan Trucking Association, 2022) are shown that the number of drivers per vehicle has not changed significantly over the last eight years. Therefore, as shown in Equation [22], B_{driver} drivers are needed per vehicle ($B_{driver} = 0.60$).

$$D_{driver,t} = S_{truck,t} B_{driver} \quad [22]$$

In addition, there are fewer barriers for people to obtain a license to drive trucks. Although a license is certainly required to transport medium-sized or larger trucks, the demand for small truck drivers is also high, so we assumed that supply and demand would almost balance, as in the case of the number of trucks, as in Equation [23], and that demand and supply $S_{driver,t}$, as in the case of the number of trucks.

$$S_{driver,t} = D_{driver,t} \quad [23]$$

Trucking expenditures

Trucking expenditures are calculated from the number of trucks and the number of drivers. In this study, per-vehicle costs were calculated based on data from the All Japan Trucking Association (2022), and costs were divided into four major categories: labor, fuel, insurance, and other vehicle-related costs. In addition, the variation in transportation costs when automated technology is implemented. Lee et al. (2023) conducted a cost analysis of the implementation of automation technology in 1-ton trucks. With reference to those analyses, this study established the costs of automobile transportation as shown in Table 6.

Table 6: The change of cost of trucking

	Conventional (thousand yen)	Autonomous (thousand yen)
personnel expenses	1.25 Wages	0.125 Wages
fuel expenses	246	196.8
insurance premium	41	36.9
Other expenses related to the vehicle	775	775

Trucking fare

Trucking freight rates $F_{truck,o,d,t}$ is the cost to maintain a profit margin similar to that of shipping companies. In this study, the formula was set up as shown in Equation [24], assuming that the profit margin is kept at 2% with reference to past data (All Japan Trucking Association, 2022).

$$F_{truck,o,d,t+1} = \frac{C_{truck,t} E_{truck,o,d}}{J_{truck} \sum_{o,d} X_{truck,o,d,t} L_{truck,o,d}} \quad [24]$$

3. CASE STUDY

Case study subject

The purpose of this study is to analyze how coastal shipping can introduce automation technology that is desirable from the perspective of employment and economics while maintaining shipping capacity in a market that includes complex interactions between freight rates, transportation demand, and other factors. Therefore, the case study will focus on which stage of automation to choose when building a ship.

Case study settings

With regard to the strategy for introducing automation technology, the roadmap created by AUTOSHIP, as mentioned earlier in Section 2, aims to develop automation technology in four phases. In this study, assuming that the development of automation technology will proceed according to the roadmap, whether or not shipping companies will start introducing automation technology when vessels in each phase are ready for introduction is defined in Figure 5 divided into Strategy 1 to 16. as follows. Furthermore, these strategies are divided into Group 1 through Group 4 based on the introduction of CA and FA.

	Group 1 (With CA and FA)				Group 2 (With CA and no FA)			
	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5	Strategy 6	Strategy 7	Strategy 8
AO	✓	✓			✓	✓		
RC	✓		✓		✓		✓	
CA	✓	✓	✓	✓	✓	✓	✓	✓
FA	✓	✓	✓	✓				

	Group 3 (With FA and no CA)				Group 4 (Without CA and FA)			
	Strategy 9	Strategy 10	Strategy 11	Strategy 12	Strategy 13	Strategy 14	Strategy 15	Strategy 16
AO	✓	✓			✓	✓		
RC	✓		✓		✓		✓	
CA								
FA	✓	✓	✓	✓				

Figure 5: The strategy of deploying automated technology

In addition, three scenarios of future demand for freight transportation were considered: "demand will increase," "demand will remain unchanged," and "demand will decrease”. The three scenarios were developed as shown in Table 7.

Table 7: Total transportation demand assumptions for each scenario

scenario	Description.
Scenario A	Total transport demand increases by 0.5% per year
Scenario B	Aggregate demand for transportation does not change
Scenario C	Total transport demand decreases by 0.5% per year

Results and Discussions

The results of the case study described in the previous part are presented below. The scatter plot shows the cumulative percentage of seafarers who retired early due to the oversupply of seafarers [%] on the horizontal axis, the percentage of lost transportation opportunities [%] due to the shortage of seafarers on the vertical axis. The lower right of the graph is the preferred result because the cumulative percentage of seafarers who retire early is smaller, and the cumulative transportation opportunity loss percentage is also smaller. Also, the bar plot shows the cumulative cost [yen/ton-kilometer] on a ton-kilometer basis for shipping companies calculated using a discount rate of 3% in the marker color for simulation results for 2025 to 2070 when automated technologies can be introduced.

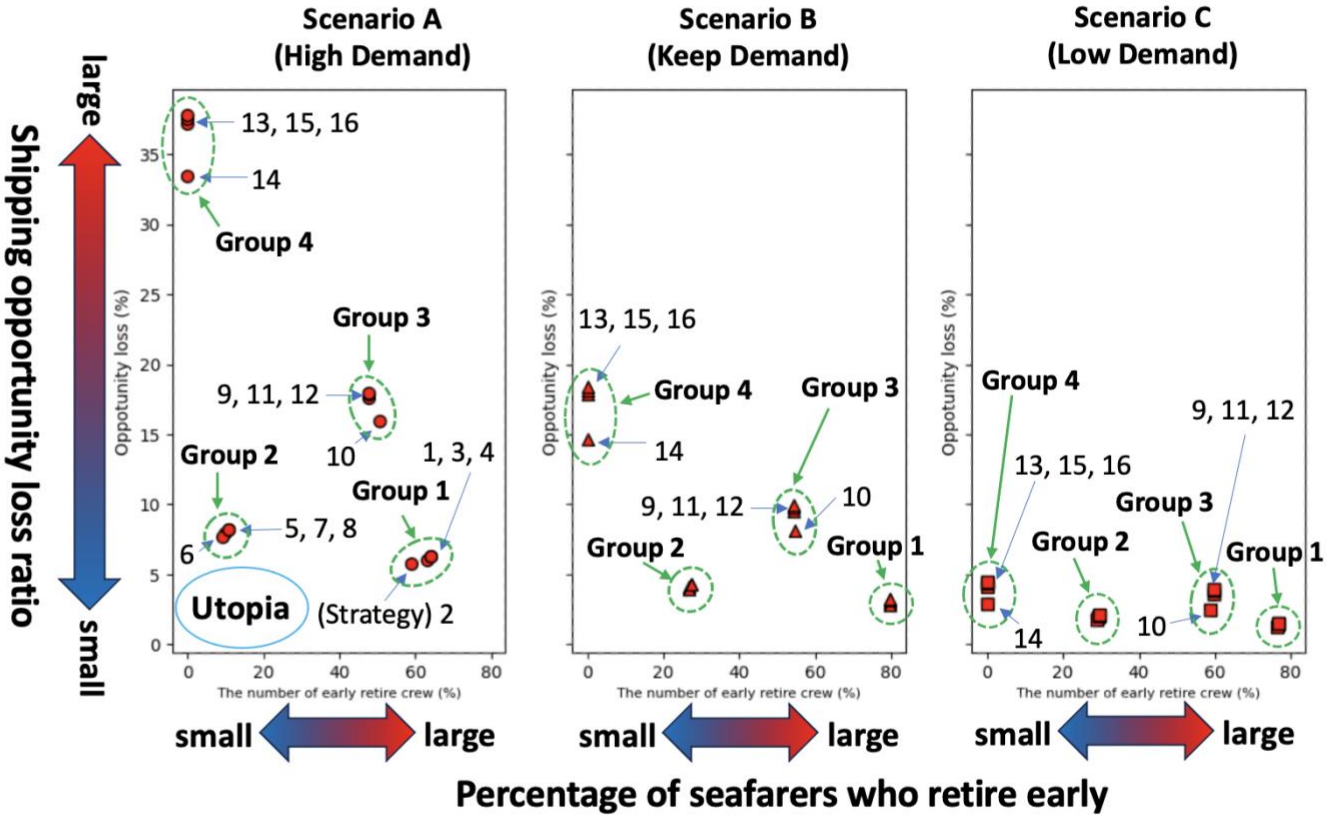

Figure 6: The results by case in Model A

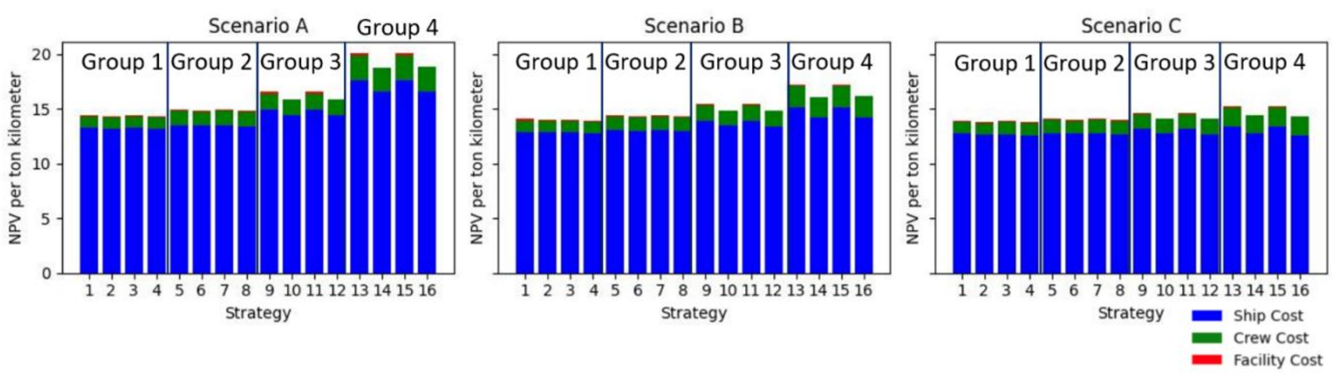

Figure 7: The results by case in Model A

Table 8: The influence of each technology

	Retirement of seafarers	Opportunity loss	Shipping cost
AO	+ (in most cases)	+	+
RC	almost zero	almost zero	—
CA	— —	++	++
FA	—— (when used with CA, —)	++ (when used with CA, +)	++ (when used with CA, +)

・"+" means positive influence and "—" means negative influence.
・The number of icons represents the size of influence.

From the assumptions of this research, these results can be divided into four Groups, and it can be read that the impact of the introduction of CA and FA is significant. A comparison of each of these groups shows that Group 3 is completely inferior to

Group 2, while Group 1, 2, and 4, are in a trade-off relationship, with no strategy superior to the other strategies in all indicators, indicating that the decision to introduce automation technology is difficult. The overall result of the three indicators shows that as the total demand for transportation increases, the strategy that does not introduce autonomous ships significantly increases “Shipping opportunity loss ratio” and “NPV cost per ton kilometer”, indicating the superiority of Group 2 that only introduces CA in these scenarios, while in the scenario where the total demand for transportation decreases, the strategy that only introduces autonomous ships is superior to Group 2. In the scenario where the total demand for transportation decreases, Group 4, which does not introduce autonomous vessels, shows a smaller difference in the two indicators, indicating that the demand for introducing autonomous vessels in this scenario is small.

In the following parts, we will discuss in detail the impact of the introduction of automation on each of these indicators.

Retirement of seafarers

1) The impact of deploying CA and FA is larger than that of deploying AO and RC, and these results are divided into four groups.
2) The ratio of early retired seafarers increases with the introduction of CA and FA regardless of the scenario of the transport demand, while the introduction of AO has reduced the percentage of early retired seafarers in most cases.
3) The number of early retired seafarers fluctuates with changes in total transportation demand, but not monotonically.

In discussing these results, we use Figure 8, a graph on the supply-demand gap for seafarers, with positive values on the y-axis indicating a shortage of seafarers and negative values indicating a surplus of seafarers. At the same time, the x-axis represents the year. In Figure 8, Strategy 1 is used to represent Group 1, Strategies 6, 7 and 8 to represent Group 2, Strategy 12 to represent Group 3, and Strategy 16 to represent Group 4. And to evaluate the impact of the introduction of AO, and Strategy 7 to evaluate the impact of the introduction of RC by comparing Strategy 7 and Strategy 8. It is clear from these comparisons that the introduction of CA and FA has significantly changed the supply and demand for seafarers, indicating the magnitude of the impact of the introduction of CA and FA as described in 1).

Regarding 2), the introduction of CA and FA has caused an excess of seafarers. Figure 8 shows that the introduction of FA without CA has caused a temporary large overcrowding of seafarers due to the rapid alleviation of the seafarer shortage. Comparing Strategy 6 and Strategy 8 for the introduction of AO, the number of seafarer shortages during the period when a seafarer shortage is occurring is mitigated by a decrease in the demand for seafarers per vessel. At the same time, the reduction in the number of seafarers employed in the cases where AO was introduced due to the reduction in the seafarer shortage also alleviated the seafarer surplus during the period after the seafarer shortage was resolved.

With regard to 3), the percentage of early retired seafarers is expected to decrease as the demand for transport increases because the demand for seafarers also increases, but no significant change was observed between Scenario B, where the demand for transport is maintained, and Scenario C, where the demand for transport decreases (Figure 6). The simulation results indicate that when transport demand declines, shipping companies hire fewer new seafarers, which reduces the supply of seafarers, and as a result, the number of seafarers who retire early also declines. However, there is a slight difference in the trend between policies, suggesting that changes in transport demand affect the environment of seafarers’ employment.

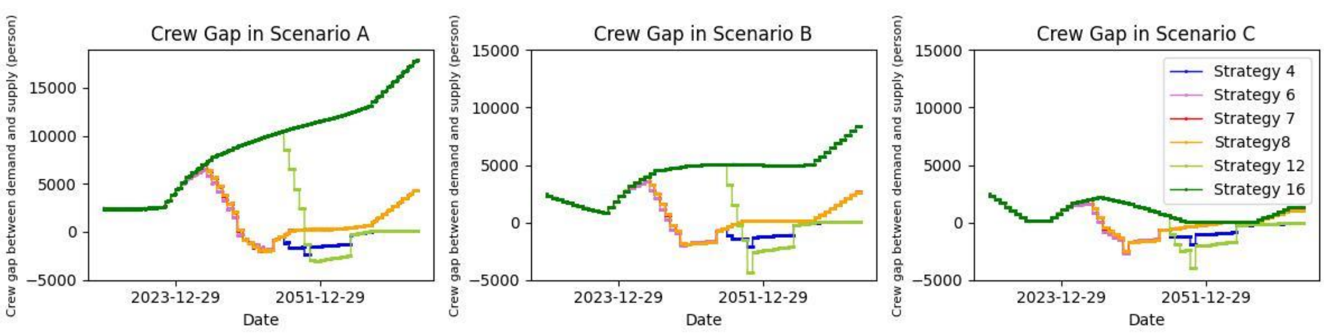

Figure 8: The difference between the supply and demand of seafarers in each case

Opportunity loss

1) Under different total transportation demand scenarios, the opportunity loss rate increases with an increase in total transportation demand.
2) Groups 1, 2, and 3 with autonomous technology successfully reduce the impact of the increasing total transportation demand compared to Group 4 without autonomous technology.

3) With respect to the introduction of AO and RC, both reduced “Opportunity loss”, but the impact was less than that of CA and FA. The reduction in Opportunity loss due to AO implementation can be read from the Figure 6 in most cases, while the reduction due to RC implementation was very small.

Figures 9 and 10 are used to discuss these results. In both graphs, the horizontal axis represents years and shows the results for each scenario in Strategy 1. The left graph in Figure 9 shows the volume transported by coastal shipping, while the middle graph shows the difference between supply and demand for seafarers, as discussed in Figure 8. Finally, Figure 10 shows the number of seafarers in each age group.

As can be read from the middle graph in Figure 8, before the introduction of autonomous vessels such as CA and FA, the shortage of seafarers accelerated as total transport demand increased. This is due to the aging of seafarers in Japan's coastal shipping industry, which is resulting in the retirement of currently elderly seafarers on a large scale (Figure 9). This shortage of seafarers is causing the drop in coastal shipping volumes seen through the second half of 2020, as seen in the left graph in Figure 8, and leads to the result in 1), "As total transportation demand increases, the proportion of lost transportation opportunities due to the shortage of seafarers increases.

In addition, as described in 1), the shortage of seafarers accelerates in line with the increase in total transportation demand before the introduction of CA and FA autonomous vessels, while the supply-demand balance for seafarers after the introduction of CA and FA does not differ significantly between scenarios (Figure 8), indicating the benefits of introducing autonomous vessels, especially in a scenario where total transportation demand increases, as described in 2).

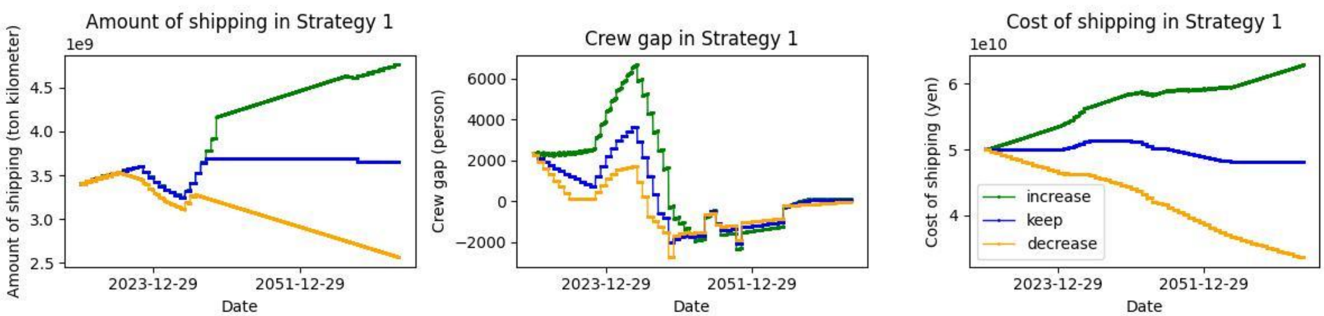

Figure 9: Shipping volume, crew gap, and shipping costs of Strategy 1 under each scenario.

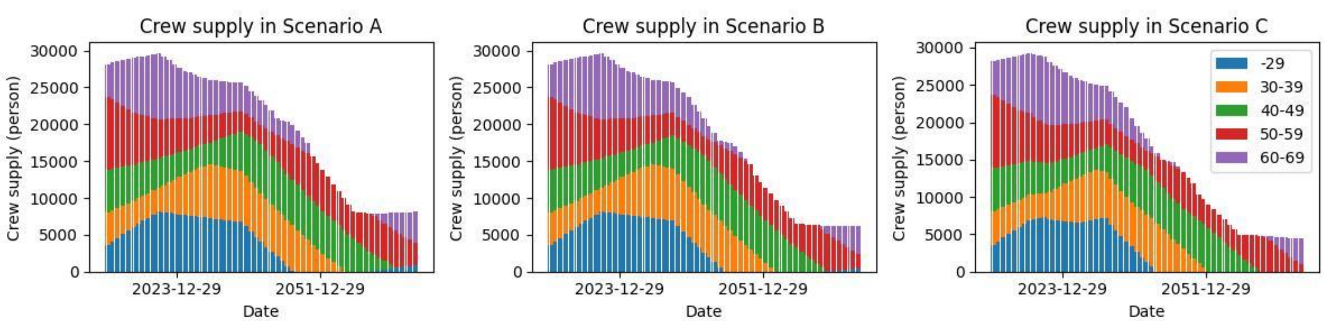

Figure 10: Change in the number of seafarers in Strategy 1 under each scenario.

Shipping cost

1) Except AO and RC, the deployment of autonomous technology helps shipping companies to reduce their shipping cost.
2) Under different total transportation demand scenarios, the transportation cost increase with an increase in total transportation demand.
3) As opportunity loss, Groups 1, 2, and 3 with autonomous technology successfully mitigate the impact of the increase compared to Group 4 without autonomous technology.

Firstly, 1): the impact of each strategy on costs is discussed. Figure 11 shows the costs for each of all transportation demand scenarios. The results show that for all transport demand scenarios, the impact of automation technologies other than FA on pure costs was not significant. However, the introduction of AO and RC increases costs, while the introduction of CA slightly decreases costs, and the introduction of FA significantly decreases costs. However, the difference between Strategies when comparing costs based on the volume of transportation activity is due to the increase in the volume of transportation due to the introduction of automation technology, which will alleviate the labor shortage. This effect for AO results in the cost increase due to the introduction of AO almost offsetting the increase in transport volume, while for CA and FA, the increase in transport volume results in a significant decrease in cost per transport volume on a ton-kilometer basis.

As for 2), as can be read from Figure 8, the greater the scenario of aggregate demand for transport, the more the shortage of seafarers accelerates, resulting in higher wages for seafarers. Figure 6 shows that this effect raises the labor cost of seafarer wages, resulting in higher costs. However, even in scenarios where demand increases, the introduction of autonomously operated vessels has succeeded in mitigating the adverse effects, as mentioned in 3) and like “Opportunity loss” 2).

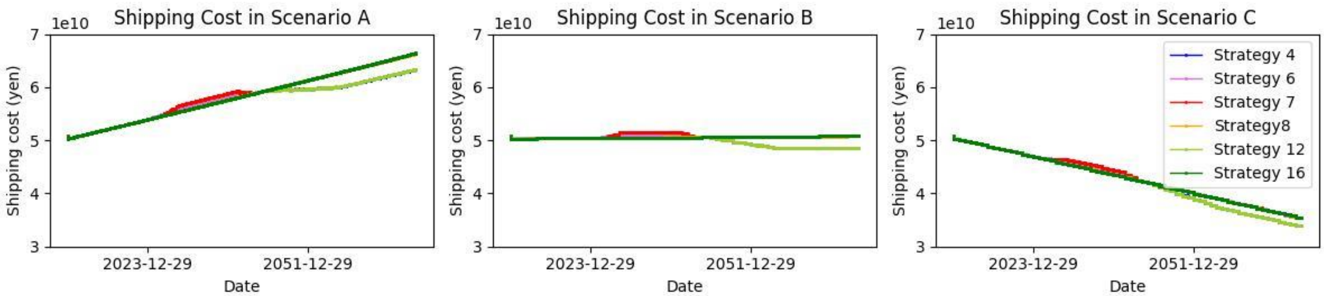

Figure 11: Transportation costs in each case.

4. SUMMARY

The following findings were obtained from Section 3 in the assumption of this research.

・While the introduction of autonomous vessels reduced transportation costs and lost transportation opportunities, the number of early retired seafarers increased significantly with their introduction. At the same time, the introduction of automation technology to support navigation has had a positive impact in many cases, and there are advantages to early deployment even in this model, which does not consider the experimental introduction of new technology to promote technology maturity.

・In the case where automation technology was introduced, a case with RC (Remote Control) was inferior to strategy without RC in all three indicators and in the transportation demand scenario. However, the other policies had a trade-off relationship with each other on one of the indicators, so it was not possible to conclude which strategy was better.

・The current Japanese domestic logistics transportation mode choice has low sensitivity to freight rates, and the decrease in transportation demand due to higher freight rates is smaller than the increase in freight rates, making higher freight rates one effective means for shipping companies to pursue profits.

5. CONCLUSION

In this study, we developed a simulator based on a Japanese cargo transport model and proposed a method to evaluate the impact of introducing automation technology. The results of the simulation showed changes in the impact of several policies on the economics and employment of seafarers and provided decision-making support for shipping companies on the introduction of desirable automation technology.

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AUTHOR CONTRIBUTION

Author 1: Conceptualization; methodology; writing – review & editing.
Author 2: Conceptualization; data curation; investigation; methodology; software; writing – original draft.
Author 3: Writing – review & editing.

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A. Appendix

Transportation choice model

Various models of transportation mode choice have been studied. Typical examples include the logit model and the sacrifice quantity model. In this study, the logit model was employed to express the interaction between each transportation mode and the equilibrium that results from the interaction. In addition, many studies on modal shifts take a wide area as the target region or limit the routes to be covered, however, we wanted to create a model that covered the entire country. Therefore, this study calculates utility based on time and cost with reference to the study by Shinke et al (2007). In this study, 47 prefectures are considered as nodes, and the links connecting these nodes are treated as a transportation network.

Transportation distance for each transportation agency

Regarding transport distances, the transport distances for coastal shipping are listed in the domestic shipping distance table published by the Nippon Kaiun Syukaijyo (2013). The distance between representative ports in each prefecture was used as a shipping distance. For automobiles and railroads, Google Map was used, and distances between prefectural offices were used. Transportation distances within the same prefecture were calculated from transportation time and average speed using the average speed described below. For links for which transport time data was not available, the average transport distance within the same prefecture was used. Also, National Freight Forwarding Survey (MLIT, 2022) and the distances collected in the above method were used to calculate transport volume on a ton-kilometer basis, and the transport volume calculated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2023b). A discrepancy was observed when two statistics were compared. Therefore, we adjusted the transport distances for each transportation mode by multiplying them by a constant in order to match the latter transport volume. The following are the transport distances for each transport mode. Inland shipping links with no ports are indicated by 0.

Transportation time for each transportation agency

Comparing transport times in 2005, 2010, and 2015 collected from the Logistics Census (MLIT, 2022) with the transport distances, there is a proportional relationship between transport distance and transport time for coastal shipping and rail transport, while transport time for automobile transport increases slowly as the distance increases. Therefore, in this study, the transport m from node o to node d, $T_{m,o,d}$ is calculated using the following Equations [A1] ~ [A3]. They are calculated using $L_{m,o,d}$ and average transport speed v_m for ocean and rail transport, and the square root of transport distance and parameters γ_{truck} and δ_{truck} for automobile transport. For auto transport, we used the minimum transport time in the 2005, 2010, and 2015 data because in some cases the transport distances were small, and the time was negative.

$$T_{ship,o,d} = \frac{L_{ship,o,d}}{v_{ship}} \quad [A1]$$

$$T_{rail,o,d} = \frac{L_{rail,o,d}}{v_{rail}} \quad [A2]$$

$$T_{truck,o,d} = \gamma_{truck}\sqrt{L_{truck,o,d}} + \delta_{truck} \quad [A3]$$

Fares for each mode of transportation

Comparing freight rates per ton-kilometer for 2005, 2010, and 2015 obtained from the Logistics Census (MLIT, 2022) and the transport distance, it can be said that freight rates per unit ton-kilometer decrease with increasing transport distance for all transport modes. Therefore, as well as the transport time, the fare of transport m from node o to node d, $E_{sm,o,d}$ is calculated by the following Equations [A4] ~ [A6], respectively $L_{m,o,d}$ and the parameters ε_m, θ_m. Note that when calculating freight rates, negative values may be obtained due to long transport distances, in which case the lowest freight rates from the 2005, 2010, and 2015 data were used.

$$E_{ship,o,d} = \varepsilon_{ship}\sqrt{L_{ship,o,d}} + \theta_{ship} \quad [A4]$$

$$E_{rail,o,d} = \varepsilon_{rail}\sqrt{L_{rail,o,d}} + \theta_{rail} \quad [A5]$$

$$E_{truck,o,d} = \varepsilon_{truck}\sqrt{L_{truck,o,d}} + \theta_{truck} \quad [A6]$$

Parameter optimization of logit model

When optimizing the parameters, in the National Net Freight Flow Survey (MLIT, 2023b), there were some routes that did not have any transportation performance. Since this study focuses on the variation in transportation demand among transportation agencies, the parameters are divided among the cases of "routes with a track record of transportation by coastal shipping and a track record of transportation by rail or trucks", "coastal shipping & automobiles & rail". In this case, the amount of transportation may be biased toward one mode of transportation on a particular route, and modal shift is unlikely to occur on that route due to the large dominance of that particular transportation agency. Therefore, the case classification of routes is defined as follows.

・Coastal & Automobile & Rail": Ratio of coastal shipping, automobile, and rail transportation to all transportation is 0.1 or more.
・Coastal & Automobile": Ratio of coastal shipping and automobile transportation is more than 0.1 and that of rail transportation is less than 0.1.
・Coastal & Automobile": Ratio of coastal shipping and automobile transportation is more than 0.1 and that of rail transportation is less than 0.1.
・"Coastal & Rail": characteristics of each link based on the definition of a transport ratio of more than 0.1 between coastal and rail transport and less than 0.1 between car transport.

Freight and Passenger Regional Flow Surveys (MLIT, 2023b) in 2005, 2010 and 2015 were used to determine the characteristics of each link. For parameter optimization, the 2005, 2010, and 2015 national freight net flow surveys (MLIT, 2022). freight hours, fare per ton-kilometer were used. The results are shown in Table A-1 below.

Table A-1 Parameters of the logit model in each case

＼parameter case	α_{time}	α_{cost}	α_{rail}	α_{truck}
Coastal & Automobile & Railroad	$-1.02 * 10^{-2}$	$-1.24 * 10^{-5}$	$-6.87 * 10^{-1}$	$-7.34 * 10^{-1}$
Coastal & automobile	$3.27 * 10^{-3}$	$-2.00 * 10^{-6}$	$-5.12 * 10^{-1}$	0
Coastal Shipping & Railroad	$4.95 * 10^{-3}$	$-2.20 * 10^{-6}$	0	$1.27 * 10^{-2}$

Using the parameters obtained, the 2010 Freight and Passenger Regional Flow Survey (MLIT, 2023b) to predict the data. The obtained ton-kilometer-based transport volumes are shown in Table A-2 shows that 15~30% of the total transport volume is subject to modal shift.

Table A-2 Comparison of predicted and measured values on a ton-kilometer basis

		coastal shipping	automobile	railroad
Measured value		179,898	20,398	246,175
Predicted value	whole	162,122	22,750	271,231
	fixed content	114,504	15,617	231,417

Model with greater impact by transportation cost (Model B)

The previous part discussed the impact of automation technology on shipping companies. However, in the freight transportation demand estimation model within the simulator, the impact of the cost term was small, and transportation demand did not change much in response to changes in freight transportation costs and associated changes in freight rates. This may be due to a lack of explanatory variables, the limited impact of freight rates on the Japanese freight market, or other factors. The model reflects the impact of freight rate changes on transportation demand by setting the parameters in the cost term to the same order as the parameters in the constant term. This new model is called Model B and the previous one is called Model A thereafter.

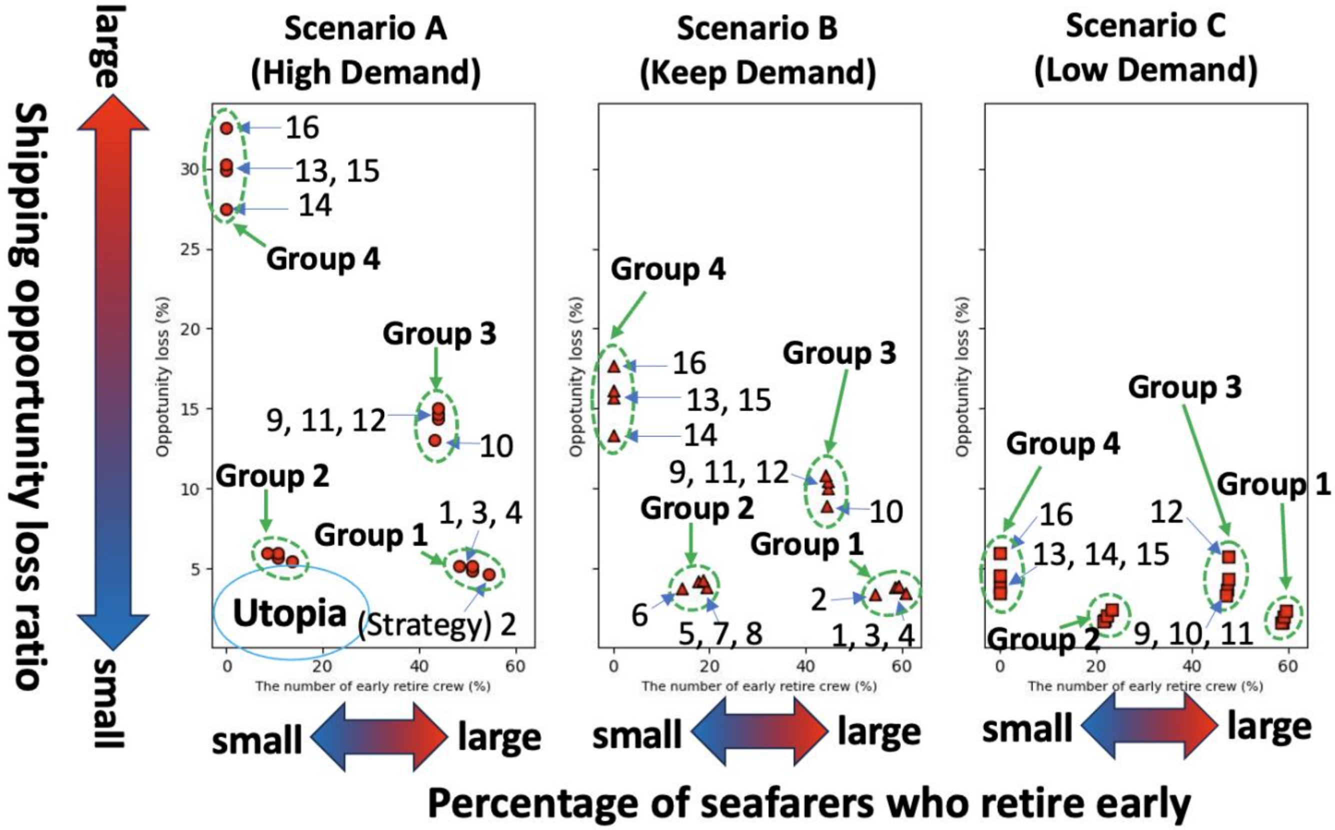

Figure 12: The results by case in Model B

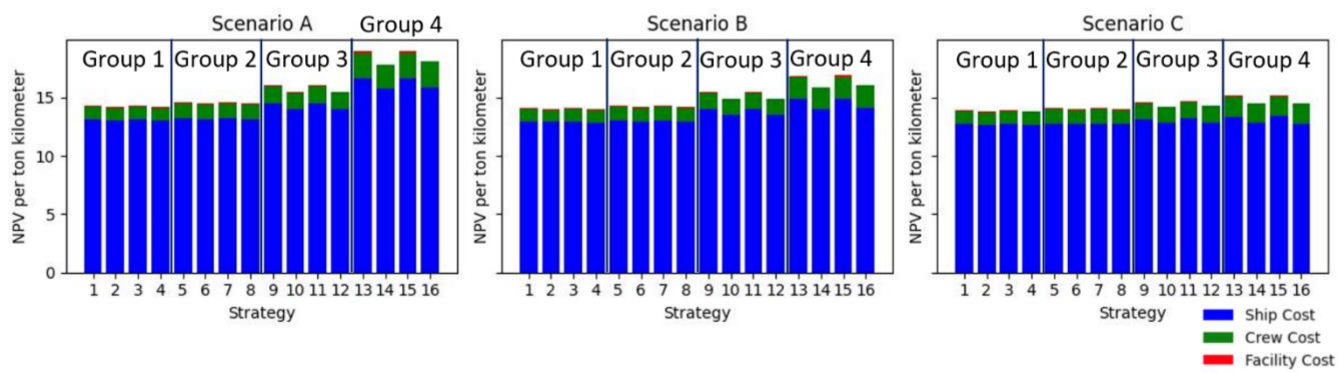

Figure 13: The results by case in Model B

The general shape of the results for Model B (Figure12, 13) was similar to Model A (Figure 6, 7). However, some differences were observed. In Groups 1, 2, and 3 with CA or FA, Scenario B, where transport demand is maintained, and Scenario C, where it decreases, the case with AO only has smaller values for all three indicators than the cases with both AO and RC. In comparison with the case with neither AO nor RC, the case with only AO showed smaller values for the loss of transport opportunities and the ratio of early retired seafarers, but only for the NPV of transport costs in the case with neither AO nor RC. On the other hand, in Scenario A, where total transportation demand increased, the case with AO only, the case with both AO and RC, and the case with RC only were compared, and the case with AO only showed smaller transportation cost and opportunity loss ratio, but the case with AO only showed smaller NPV in the ratio of early retired crews. However, the percentage of seafarers who retired early was higher in the AO-only case.

These results show that when total transport demand is maintained or decreases, AO implementation benefits shipping companies in all three indicators, but when total transport demand increases, AO implementation adversely affects shipping companies only in terms of seafarer employment.

Initially, as a consideration of the improvement in transportation costs due to the introduction of AO that was seen in the results of Model B but not seen in the results of Model A. This phenomenon is caused by a decrease in demand for marine transportation and seafarers is triggered by the increase in costs due to the introduction of AO (Figure 14). This is a decrease not seen much in the Model A due to the smaller impact of the cost term (Figure 15). The timing of this decline coincides with the retirement of seafarers currently aged 60 and over, as discussed before, causing a shortage of seafarers, which combined with the effect of the reduction in seafarer demand per vessel due to the introduction of AO, alleviates the seafarer shortage. This, in turn, is thought to have reduced the cost of shipping per ton-kilometer by reducing the rising labor costs of seafarers.

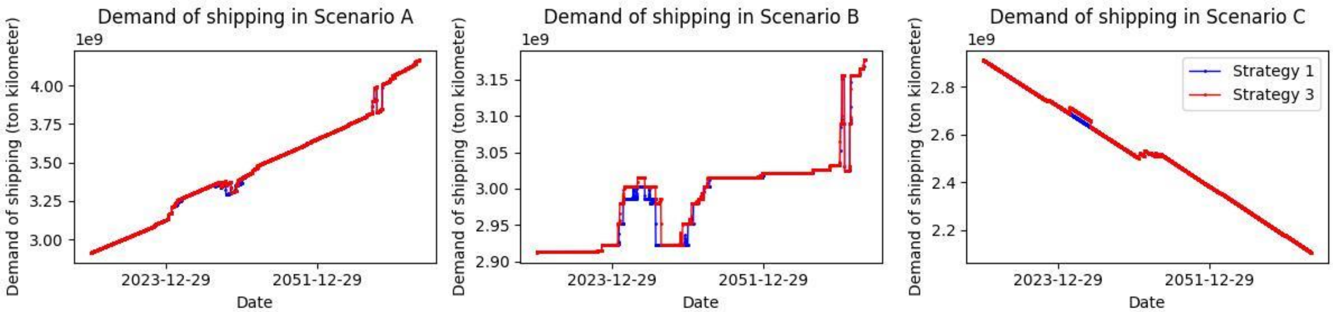

Figure 14: Result of shipping demand in Model B.

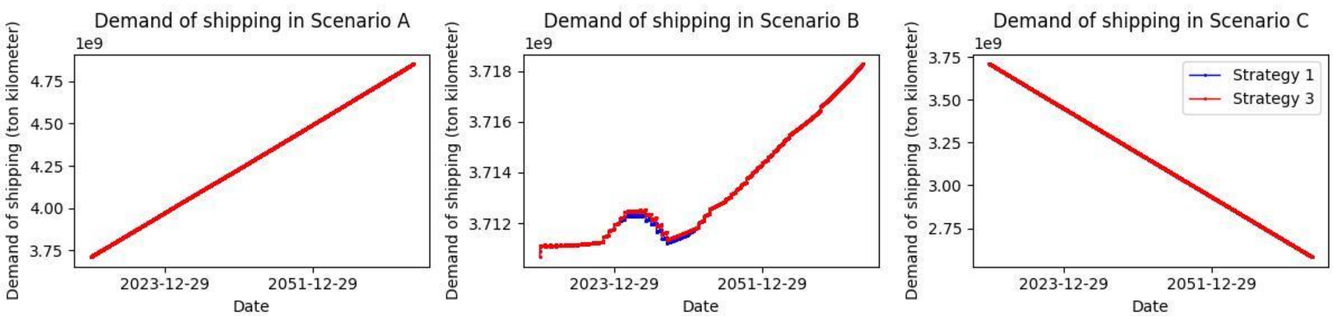

Figure 15: Result of shipping demand in Model A.

The next part discusses the cases in Model B where the introduction of AO has a positive impact on seafarer employment in scenarios where aggregate transport demand is maintained (Scenario B) or reduced (Scenario C), and where the introduction of AO has a negative impact in scenarios where aggregate transport demand is increased (Scenario A). In Model A, the introduction of AO had a positive impact on seafarer employment in all scenarios. This is one of the advantages of phasing in automation technology. Furthermore, as discussed in the previous part, the percentage of early retired seafarers decreased when aggregate transport demand increased, but there was no significant difference in the percentage of Scenario B and C. In Model B, the latter phenomenon is confirmed, but the former phenomenon, in which the ratio of early retired seafarers improves as aggregate demand increases, is not observed in the case where AO is introduced.

One factor contributing to this is that the recruitment of seafarers is done on an annual basis rather than in one time step. As a result, in Model A, the seafarer shortage is eliminated one year earlier in the case where AO were introduced (left graph in Figure 16). On the other hand, in Model B, the seafarer shortage was eliminated in the same year regardless of introduction of AO (right graph in Figure 16). This means that in Model A, where the seafarer shortage was solved a year earlier by the introduction of AO, the working environment for seafarers improved, while in Model B, where the seafarer shortage was solved in the same year regardless of the introduction of AO, the working environment for seafarers worsened in Strategy 1, which employed the same number of seafarers in both cases but introduced more automation through the introduction of AO. This suggests that even a one-year delay in eliminating the seafarer shortage by introducing automated technology can have a significant impact on the employment environment for seafarers, and that it is necessary to introduce automated technology with caution.

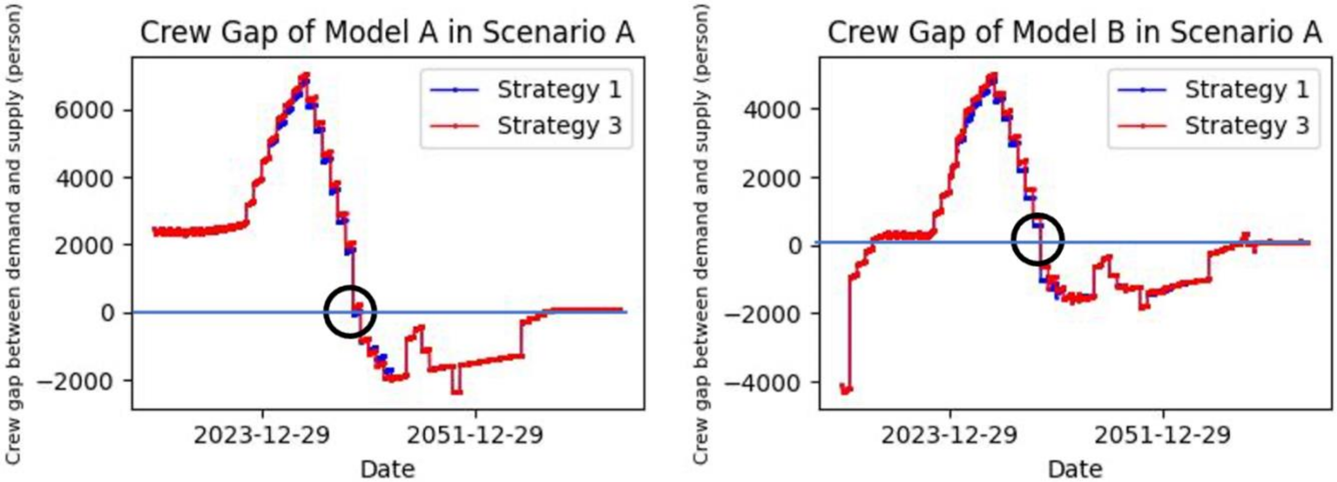

Figure 16: Result of crew gap (Left is Model A. Right is Model B).