Maritime Stakeholder Model-Based Decision-Making for Accelerated Adoption of Autonomous Vessels by Analyzing Tradeoffs in R&D Investment, Manufacturing, and Operational Experience

Takuya Nakashima, Tomohiro Sugimoto, Keisuke Kimura and Bryan Moser

September 22, 2022

Model-based decision-making for accelerated adoption of autonomous vessels by analyzing tradeoffs in R&D investment, manufacturing, and operational experience

Takuya Nakashima, Tomohiro Sugimoto, Keisuke Kimura, Bryan Moser

Abstract Maritime autonomous surface ships (MASS) have been proposed to significantly transform the maritime industry. While research and development are underway worldwide, fully autonomous ships have yet to be commercialized, hindered by technical, economic, and legal constraints. Shipbuilders and ship owners together must weigh how to invest limited budgets and attention to adopt MASS. This research demonstrates a model and simulation to explore the interplay of decisions and actions by maritime stakeholders, including R&D investment, technology readiness of various autonomy subsystems, and learning curves in manufacturing and operation. These factors are examined across specific types of ships to bend the adoption curve, so that industrial capability and adoption of MASS are accelerated. By exploring the tradespace of combined decisions toward the introduction of MASS, roadmaps are crafted which can be tuned to particular industrial maturity, resources, and market. Simulation results for a specific ship type and market are shown.

1 Introduction

1.1 Background

The Japanese shipbuilding industry is in a critical situation, losing competitiveness and market share [1]. Looking at the bulk carriers that have been built by Japanese shipyards, considering the tradeoff between safety (structural strength) and construction cost, they have designed and built rational bulk carriers based on their experience. However, since the IACS adopted Common Structural Rules for Bulk

---

Takuya Nakashima
Graduate School of Frontier Science, The University of Tokyo
5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8568, Japan
nakashima@s.otpe.k.u-tokyo.ac.jp

Bryan Moser
System Design & Management, Massachusetts Institute of Technology
77 Massachusetts Avenue, Building E40-315, Cambridge, MA 02139, U.S.A.
bry@mit.edu

Carriers (CSR-BC) and began applying them in 2006, the structural strength of bulk carriers has been standardized worldwide [2], which may have led to the "price war." In order to break out of this situation, they must find significance in technological innovations other than structural strength. However, the decrease in Research and Development (R&D) expenses due to small profit results in less money available for technological improvement, not leading to innovation. Japanese shipbuilding companies tend to take a more cowardly stance toward the R&D of new technologies.

New concept ships are expected to transform the maritime industry making a quality difference in shipbuilding. Autonomous ships can be one of the candidates for "industrial transformers." They can enhance maritime safety by decreasing human error, accounting for 80% of maritime accidents [3]. Also, they can eliminate crew shortages and provide economic advantages such as the improvement of fuel efficiency due to the elimination of the navigation bridge and accommodation and the ability to expand the cargo hold. Currently, the technological development of autonomous vessels is underway worldwide. However, fully autonomous ships have yet to be commercialized, hindered by technical, economic, and legal constraints.

Fig.1 shows the stakeholder value network of the maritime industry. Shipowners select the specifications of the ships they purchase from the manufacturers (shipbuilding companies and equipment manufacturers). The policymakers (the government and classification societies) make policy-related decisions. These three play essential roles in the development of autonomous vessels.

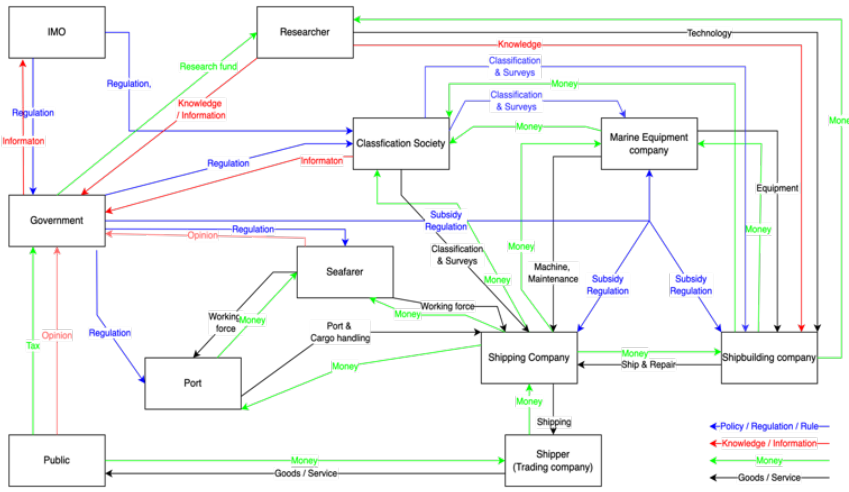

Fig. 1. Stakeholder Value Network of Maritime Industries.

Shipowners are unwilling to adopt new technologies actively without verifying their profitability and safety. On the other hand, the manufacturers hesitate to invest in R&D activities due to a lack of confidence in ROI (return on investment). This

"chicken-and-egg" condition leads the Japanese maritime industry to be stuck in local minima, missing out on business opportunities. Therefore, various mechanisms, including the strategies of policymakers and regulators, shall be considered to create a positive cycle between R&D investment, adoption, the improvement of technological capabilities, cost reduction, and high profitability.
Looking at the aerospace industry in the United States, SpaceX conducted agile prototyping activities for developing Starship, culminating in a successful flight in May 2021[4]. Although their R&D resources are not as abundant as NASA's, they successfully implement this complex system into the world faster. These prototyping activities and gaining engineering experience are critical factors for fast implementation and technology development. This learning-from-experience factor should be considered to solve the maritime industry problem.

1.2 Objective

In this study, we examine how incorporating the dynamic feedback of the industrial experience, which are the manufacturing experience on the production cost and the operation experience on the technical capability and safety, can improve the fidelity of autonomous technology development and adoption model. After that, we use the model to determine the critical decision set of the various stakeholders for the autonomous ship introduction, including policy makers' subsidy and regulation, manufacturers' R&D investment strategy, and shipowners' adoption criteria.
The objective of this study is shown below, using 'to-by-using' statement [5];
To *enhance the introduction of a high level of autonomous ships, which can significantly transform the maritime industry,*
By *changing the decisions of ship adoption, technology investment, and policymaking, which have interactions with each other, by providing the appropriate decision set,*
Using *a model and simulator which can emulate autonomous technology readiness and benefits, considering the effects of R&D activities and manufacturing and operational experiences.*

2 Method

2.1 Model Overview

A model overview represented as system dynamics is shown in Fig.2. This model was constructed by referring to a case study introducing new concept vehicles such as electric vehicles [6][7][8]. A fleet of vessels is assumed to be stock, and new

shipbuilding and scrapping flow is considered. New vessels are introduced according to the shipowner's technology adoption model.
As technologies are developed through R&D activities, the utility and safety of ships with the technology will increase. In addition, the experience gained by building and operating ships with the new technology will be accumulated. This experience will lower construction costs and improve the safety of the technology. The introduction of external subsidies, subsidized projects, and regulations are also assumed. Although it is assumed that R&D activities will be further developed when profits increase, this model avoids modeling the relationship because the profit is often attributed to external factors such as the shipping market.

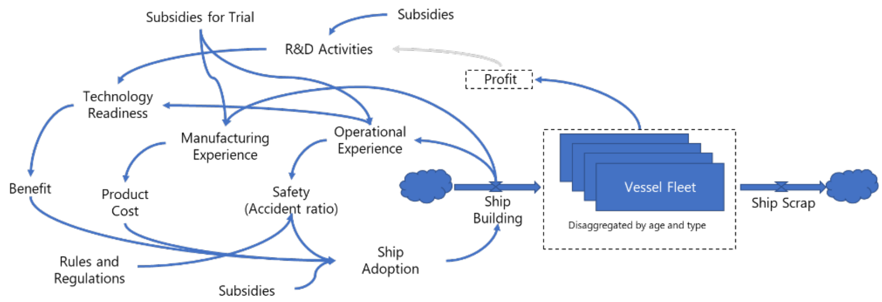

Fig. 2. Schematic image of the model.

2.1.1. Assumption
This research targets ocean-going Bulk Carriers built in Japan (Averaged them out to the Panamax size). The initial number of ships (vessels) is assumed as 1,000, and the annual growth of ship demand is 1%. The expected ship lifetime is 25 years, and the simulation duration is from 2022 to 2050. Autonomous technologies are divided into three types, berthing, navigation, and monitoring, as shown in Table 1. Here, navigation technology has the step of semi-automation considering its technological gap and current development project status [9]. As shown in Table 2, each technology type and step combination makes 12 ship configuration types. Additional and reduced costs of each autonomous technology for Panamax bulkers are shown in Table 3.

Table 1. Autonomous technology type, level, and example.

Technology	Level	Example of technology and equipment
Berthing	Full	Visual Sensors, LDR / LRS, Weather Buoy, Autonomous Tugboat, Automatic Mooring
Navigation	Semi	LiDAR, Shore Control Center (SCC), Situation Awareness
	Full	Efficient Scheduling, Motion Control, Collision Avoidance
Monitoring	Full	Machinery & Hull Sensors, Shore Monitoring Center (SMC), Digital Twin

Table 2. Ship configuration and each technology type (0: Not used, 0.5: Semi, 1: Full).

Configuration	0	1	2	3	4	5	6	7	8	9	10	11
Berthing	0	1	0	0	0	1	1	1	0	0	1	1
Navigation	0	0	0.5	1	0	0.5	1	0	0.5	1	0.5	1
Monitoring	0	0	0	0	1	0	0	1	1	1	1	1

Several studies have estimated the economic benefit of introducing autonomous ships [10]. For example, Kretschmann et al. [11] discuss a cost comparison between an autonomous and a conventional Panamax bulk carrier. In this research, we assume 67% of the total production cost is the material cost, and the rest is the integration cost.

Technology Readiness Level (TRL) [12] is used to evaluate the maturity of technologies in various areas. Devaraju et al. [9] shows the overview of TRL of autonomous ship technology. In this research, the TRL-cost model and the current status of TRL of autonomous technology are set; for TRL8(7), it is assumed that 50% (75%) of backup crew members are needed to compensate for the less feasibility compared to TRL 9. The cost reduction is calculated based on the assumption. TRL6 or below cannot be adopted for actual operation in this model. The current TRLs of the autonomous technologies for berthing, navigation (semi), and monitoring are assumed as 6, 3 (6), and 4, respectively, based on the current industrial status and Devaraju et al. [9].

Table 3. Additional and reduced cost of each autonomous technology. [11]

Technology	Level	Benefits and additional costs (except safety aspects)
Berthing	Full	Less Port calls fee (assumed Pilot fee USD4,000/time) Additional equipment fee (USD34,000)
Navigation	Semi	Less Maintenance & Repair fee (USD6,700) Less Construction fee (USD17,000) Additional Shore Control/Monitoring fee (USD167,514) Additional equipment fee (USD17,000)
	Full	Less Maintenance & Repair fee (USD13,400) Less Construction fee (USD34,000) Less Fuel cost for the main engine (USD66,240) Additional Shore Control/Monitoring fee (USD167,514) Additional equipment fee (USD34,000)
Monitoring	Full	Less Maintenance & Repair fee (USD46,900) Less Construction fee (USD34,000) Less Fuel cost for aux engine (USD78,400) Additional Maintenance Crew cost (USD155,250) Additional Shore Control/Monitoring fee (USD167,514) Additional equipment fee (USD136,000)

2.1.2. Experience-Cost Model

It is revealed that direct labor hours decrease along with the manufacturing experience [13]. In this research, the following equation is introduced as the model between ship manufacturing experience and the integration cost of each technology.

$$c = \left\{ \sum_{i=B,N,M} max(a{x_i}^{-b},\ 1) - 2 \right\} c_0$$

c indicates the integration cost to produce an autonomous vessel, including x_Bth unit of berthing, x_Nth unit of navigation, and x_Mth unit of monitoring subsystem. $c_0$is the integration cost for a conventional ship. a and b are assumed as 1.33 and 0.05 respectively in this research, considering production cost can be doubled if made by a shipbuilder without experience.

2.1.3. TRL-Experience-Safety Model

Accident probabilities due to the failure of berthing, navigation, or monitoring are expressed as follows. These probabilities decrease according to the operation experience and TRL.

$$P = \sum_{i=B,N,M} max\, Pini_{i,j} \cdot {x_i}^{-\beta}$$

i and j are the subscript for each technology and TRL, respectively. x_i is the operation experience of each technology, calculated by multiplying its operating number and operating duration. P is the probability of accidents for a ship. $Pini_{i,j}$ indicates the accident probability without any operational experience shown in Table 4, which is made based on [14]. β is decreasing rate in the probability of accidents for the technology, assuming 0.02 in this study. Operational experience is assumed to be accumulated even when TRL is upgraded.

2.1.4. R&D Activities-TRL Model

TRL of each technology is assumed to increase by R&D activities and operational experience [15][16]. Although the effect of R&D expense and operation experience can be different based on TRL, these effects are assumed constant.

$$\Delta TRL_i = \frac{1}{\mathrm{a}_i} (r_i + b_i x_i)$$

r_i is R&D expenditure for each technology during the same TRL level. a_i is a total R&D expenditure needed for upgrading one TRL for each technology, and b_i is an operation experience conversion factor into R&D expense (USD). Based on the current situation and industrial experience, a_i and b_i are set as 20 million and 10 thousand, respectively.

Table 4. Probability of marine accidents for each technology and TRL.

	TRL1-6	TRL7	TRL8	TRL9
Accident related to Berthing	0.94	0.75	0.56	0.19
Accident related to Navigation	0.64	0.51	0.38	0.13
Accident related to Monitoring	2.90	2.32	1.74	0.58

2.1.5. Stakeholder's Decision Options

Architectural decisions (ADs) are decision items in a system that have a dominant effect on the system architecture.

(1) Adoption model (shipowner)

This model represents the decision-making process by which a shipping company selects its vessels. Adoption is determined by each configuration's total cost and expected accident loss (the product of the probability of occurrence and the average loss) [17]. The decision-making process depends on the safety factor multiplied by the expected loss in the event of an accident, emulating where the shipowner places more emphasis on safety or more emphasis on profit.

(2) Investment model (manufacturer)

The manufacturer (industry as a whole) makes decisions within a limited budget. There are two significant cases: one is to invest in each technology equally, and the other is to invest intensively in one of the technologies. When the readiness level of particular technology reaches 9, they invest in other immature technologies. Investment ends when the level of all technologies reaches 9.

(3) Subsidy (policymaker)

There are mainly three kinds of subsidies provided by the policymaker.

a) R&D grant: Increase the budget for investment explained above.
b) Adoption subsidy: When implementing an adoption, the subsidy will support the difference between the most cost-competitive ship type at the time and the ship with the highest level of automation among those ships whose TRLs for each technology exceed the specified value.
c) Prototyping: Budget to increase manufacturing and operational experience by creating prototypes. We presume manufacturing and operational experience is increased by dividing the budget by the technology price and creating a prototype of that amount, assuming subsidies that support prototyping [18].

(4) Regulation (policymaker)

Assuming that the TRL8 ("actual system completed and qualified") level is currently in place, Policy Maker has the option to allow the introduction of a lower TRL. This permission is envisioned to relax actual regulations and includes safe implementation in specific sea areas, for example, by setting up test routes.

In this study, the decisions are made by key stakeholders in the maritime industry shown in Table 5.

Table 5. Architectural Decisions (ADs).

AD	Description	Option1	Option2	Option3	Option4
AD1	Subsidy (Policymaker)	R&D activities	R&D and Adoption	R&D and Prototyping	
AD2	Regulation (Policymaker)	As-is	Relaxation		
AD3	Investment (Manufacturer)	Covering all technologies	Focusing on Berthing	Focusing on Navigation	Focusing on Monitoring
AD4	Adoption (Shipowner)	Safety oriented	Profit oriented		

2.1.6. Evaluation Criteria

Performance metrics, shown in Table 6, are the criteria for evaluating the system architecture, a decision set of the key stakeholders. The appropriate weights will be discussed among stakeholders using the simulator.

Table 6. Performance Metrics.

No.	Performance Metric	Description
PM1	Introduction	The year of the first crewless ship (or a certain type of autonomous ship) is adopted
PM2	Profitability	ROI of investment or subsidy
PM3	Maritime safety	Amount of possible maritime accidents
PM4	Human Resource	Total number of seafarers

2.2 Model Validation

The model's validity was checked by the test evaluating whether the model exhibits more realistic behavior by incorporating experience effects into the model. The base case shown in Table 7 was set up based on Japan's current state of development and considering the opinions of experts in the maritime industry.

Table 7. The setting of Base-case.

Parameters	Setting
Safety weight compared to profitability	10
Investment Strategy	All
Annual private investment amount (USD)	5,000,000
Annual subsidy for R&D activities (USD)	5,000,000
Minimum TRL for technology adoption	TRL8

We confirmed the improvement in safety over time by introducing the effects of experience into the model. The accident reduction curve became similar to the Airbus cockpit's accident reduction curve by adding the experience effect [19]. We also observed the behavior of the integration cost reduction curve. We concluded that incorporating the dynamic feedback of the industrial experience (manufacturing experience on the production cost, operational experience on technical capability, and safety) makes the autonomous vessel introduction model realistic.

The result of the base case is shown in Fig. 3. In this case, semi-autonomous navigating ships will start in 2034, and fully autonomous ships will be introduced in 2045.

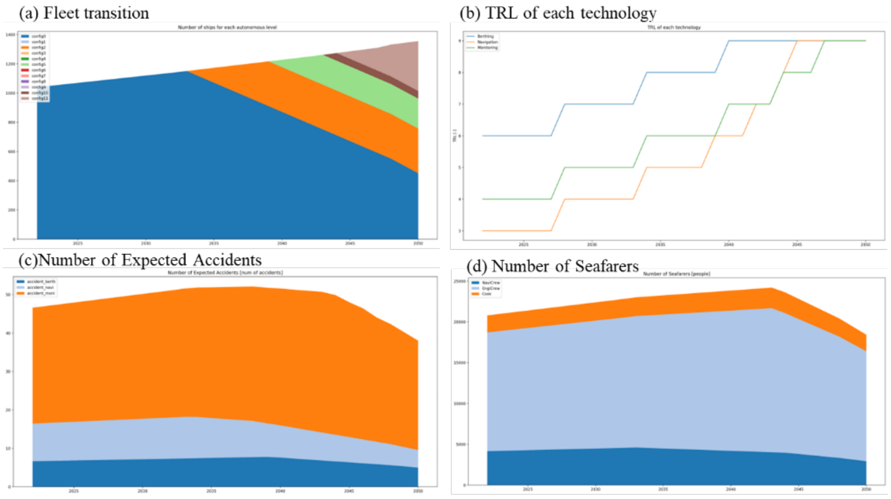

Fig. 3. Simulation result of the base case

3 Results and Discussions

First, the unit tests are conducted, where each AD is changed from the base case. These tests are conducted to see the effect of each AD on the performance metrics. The unit test cases are shown in Table 8.

The results of unit tests are shown in Fig. 4. Additional subsidy for the adoption and prototyping enhances the introduction of the autonomous ship. In this case, the subsidy for adoption leads to better ROI, and the subsidy for prototyping increases safety (1-1, 1-2). Furthermore, the relaxation of regulations promotes technological development and, consequently, contributes to safety (2-1). In addition, focusing on the investment in navigation and monitoring technologies can enhance the ROI and safety, while the introduction of the fully autonomous ship is delayed (3-2, 3-3). Finally, If ship owners take safety lightly, the introduction cannot be enhanced, resulting in smaller profits (4-1).

Table 8. Unit test cases.

Case	AD1 (Subsidy)	AD2 (Reg.)	AD3 (Investment)	AD4 (Adoption)
Base	For R&D	As-is	Cover a wide range	Safety oriented
1-1	+ Adoption	As-is	Cover a wide range	Safety oriented
1-2	+ prototyping	As-is	Cover a wide range	Safety oriented
2-1	For R&D	Relaxation	Cover a wide range	Safety oriented
3-1	For R&D	As-is	Focusing on Berthing	Safety oriented
3-2	For R&D	As-is	Focusing on Navigation	Safety oriented
3-3	For R&D	As-is	Focusing on Monitoring	Safety oriented
4-1	For R&D	As-is	Cover a wide range	Profit oriented

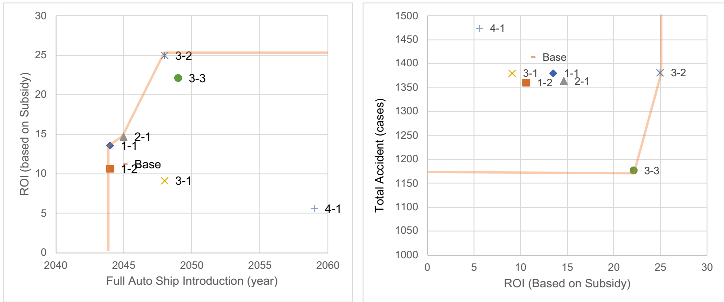

Fig. 4. Results of unit tests (left: Introduction year of the fully autonomous ship vs. ROI, right: ROI vs. expected number of accidents)

After that, all combinations of ADs are examined to find the optimal combination of decision options. A combination of additional subsidies for prototyping and relaxing the regulation can enhance the introduction of autonomous ships, ROI, and safety. We chose "'Exp' (AD1: Option 3), 'Relax' (AD2: Option 2), 'All' (AD3: Option 1), 'Safety' (AD4: Option 1)" as the best case, realizing the fastest implementation of the fully autonomous ship and competent ROI and safety. This case is on the Pareto front of the tradespace in Fig. 5.

The best-case result is shown in Fig. 6. Fully autonomous ship (and autonomous ship) is introduced seven years faster, and ROI becomes 2.5 times bigger than the base case, though the total subsidy is just a 7.7% increase. Expected accidents and seafarers also decrease to approximately two-thirds of the base case.

4 Conclusion

In this study, a model simulator was constructed to simulate the introduction of automated vessels by simulating the decision-making process of shipyards and equipment manufacturers, shipowners and operators, and government and classification societies, all of which are essential stakeholders in the maritime industry. The model includes the factors of increasing the level of technology through R&D and increasing the level of experience in ship construction and operation. The combination of each stakeholder's decision-making was evaluated through the introduction timing, ROI, and safety of the automatic vessel.

Through this study, we reaffirm the importance of considering experience when modeling the improvement of new technology levels and the introduction of such technology. It was also suggested that by appropriately combining the decisions of different stakeholders, we could approach a situation closer to the ideal.

On the other hand, there are still several issues that need to be considered. Considering the operational time difference among the technologies can upgrade the fidelity of the experience learning model. Furthermore, as most accidents related to monitoring are relatively minor, taking these factors into account shall improve the fidelity of the safety estimation. Uncertainty and future risk can be considered by Monte-Carlo simulation assuming parameter distributions. Introducing the actual decision-making by social experiment with the stakeholders can validate the results. In addition, considering different ship types besides Panamax Bulk Carrier and technology development of foreign countries and assuming several types of shipowners and manufacturers can be effective for a more realistic industry model. Finally, shipowners and shipyards are modeled as a single entity in this study, although several different firms exist. If the characteristic parameters of these companies can be extracted, it may be possible to reproduce more realistic behavior through multi-agent simulation.

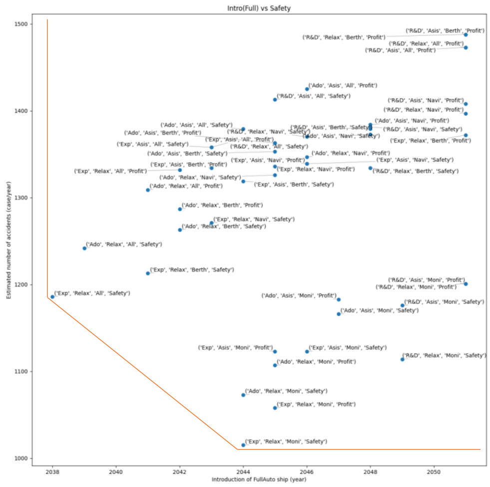

Fig. 5. Simulation result of all combinations (Introduction year of the fully autonomous ship vs. expected number of accident (cases))

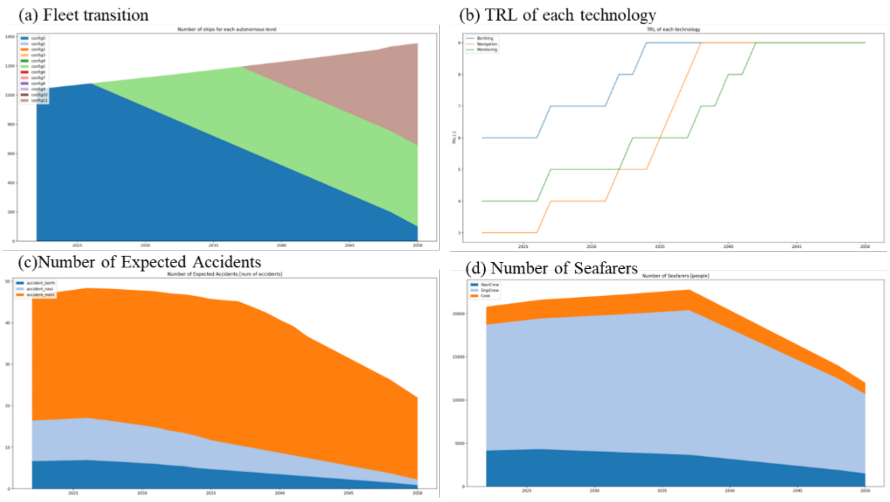

Fig. 6. Simulation result of best-case.

References

1. Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT): Shipbuilding Industry: Current Status and Issues. (in Japanese) Accessed May 2022
2. Fuya, S.: Impact and issues of the Common Structural Rules (CSR) on Shipyards. (in Japanese) The Japan Society of Naval Architects and Ocean Engineers KANRIN **12**, pp. 14-16 (2007)
3. Matsuda, K.: Voice Interactive Voyage Support System Prevents from Human Error. (in Japanese) The Japan Association of Marine Safety **40**(531), pp. 42-45 (2006)
4. Foust, J.: "Nasa's Space Launch System Will Lift Off: But with rival rockets readying for flight, the ultimate value of SLS is murky," in IEEE Spectrum 59(1), pp. 36-39 (2022)
5. Crawley, E., Cameron, B., Selva, D.: System Architecture: Strategy and Product Development for Complex Systems. (2016)
6. Keith, D., Naumov, S., Sterman, J.: Driving the Future: A Management Flight Simulator of the US Automobile Market. Simulation & Gaming 48(6), (2017)
7. Moser, B., Singh, A., Zhanga, Y.: Systems Dynamics and Empirical Studies of Innovation in the Automotive Industry. Transdisciplinary Engineering for Resilience: Responding to System Disruptions (2021)
8. Sun, X., Liu, X., Wang, Y., Yuan, F.,: The effects of public subsidies on emerging industry: An agent-based model of the electric vehicle industry. Technological Forecasting and Social Change **140**, pp. 281–295 (2019)
9. Devaraju, A., Chen, L., Negenborn, R.: Autonomous Surface Vessels in Ports: Applications, Technologies and Port Infrastructures. International Conference on Computational Logistics, pp. 88–105 (2018)
10. Ghaderi, H.: Autonomous technologies in short sea shipping: trends, feasibility and implications. Transport Reviews **39**, pp. 152–173 (2019)
11. Kretschman, L., Burmeister, H., Jahn, C.: Analyzing the economic benefit of unmanned autonomous ships: An exploratory cost comparison between an autonomous and a conventional bulk carrier. Research in Transportation Business & Management **25**, pp. 76–86 (2017)
12. National Aeronautics and Space Administration (NASA): Robotics and Autonomous Systems. NASA Technology Roadmaps TA4 (2015)
13. Argote, L., Epple, D.: Learning Curves in Manufacturing. Science **247**, pp. 920–924 (1990)
14. Malone, P., Smoker, R., Apger, H., Wolfarth, L.: The application of TRL metrics to existing cost prediction models. IEEE International Conference on Aerospace, pp. 1-12 (2011)
15. Crespo, A.: Less automation and full autonomy in aviation, dilemma or conundrum? IEEE/SMC International Conference on Systems, Man and Cybernetics, pp. 4245-4250 (2019)
16. Fonseca, T., Lagdami, K., Schröder-Hinrichs, J.: Assessing innovation in transport: An application of the Technology Adoption (TechAdo) model to Maritime Autonomous Surface Ships (MASS). Transport Policy **114**, pp. 182–195 (2021)
17. Shiobara, R.: Ship Reliability and Marine accidents. (in Japanese) Nihon Hakuyō Kikan Gakkai **18**(9), pp. 699-706 (1983)
18. DARPA Grand Challenge web page (https://www.darpa.mil/about-us/timeline/-grand-challenge-for-autonomous-vehicles) Accessed May 2022
19. Airbus web page (https://accidentstats.airbus.com/statistics/fatal-accidents) Accessed May 2022