Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220648

International Regulation Design for Reduction of GHG Emission in Maritime Shipping by Agent-Based Simulation

Kazuho NONOMURA[a,1] , Kazuo HIEKATA[a] and Junki YOSHIDA[b]
[a] *The University of Tokyo, Japan*
[b] *Nippon Kaiji Kyokai, Japan*

Abstract. In order to reduce carbon dioxide emissions from international shipping, the International Maritime Organization (IMO) is discussing the future strengthening of EEDI/EEXI and the introduction of subsidies and carbon taxes. However, the stakes in international shipping are so complex that it is difficult for the IMO to predict how regulations will affect shipping companies' decisions and markets in the future, making it difficult to determine effective regulations.In this study, we develop an agent simulator that simulates the decision-making process of actual shipping companies, and propose a method to quantitatively evaluate the response of international shipping to various regulations, thereby supporting the decision-making process of policy makers. The developed simulator outputs simulation results from 2023 to 2050 when the EEDI/EEXI reduction rate, subsidy rate, and carbon tax rate are input.In this study, we conducted simulations for 100 different regulatory proposals and plotted the results of all the proposals on a scatter plot of total carbon dioxide emissions and total benefits to support the decision making of regulatory decision makers. Furthermore, we were able to support effective regulatory decisions even when the assumptions were that the carbon emission reduction targets set by the IMO would be met and that carbon tax revenues would exceed subsidy expenditures.

Keywords. Agent based simulation, maritime transportation, reduction of carbon dioxide emissions, policy making, decision making

Introduction

In recent years, global warming has led to a rise in sea levels and the spread of damage from extreme weather events. In response, countries around the world are considering and implementing policies to curb the emission of greenhouse gases that are believed to be the cause of such emissions. In particular, the 2015 Paris Agreement set greenhouse gas emission reduction targets for each industry and promoted cross-national cooperation. International shipping is no exception, and the industry as a whole is required to reduce greenhouse gas emissions. 2018 carbon dioxide emissions from international shipping accounted for about 2.1% of global carbon dioxide emissions [1], making international shipping one of the industries that emit large amounts of greenhouse gases. Furthermore, it is estimated that future demand for international shipping will increase as the world population continues to grow. A study [2] has shown that if no action is taken,

[1] Corresponding Author, Mail: kazuho8986@g.ecc.u-tokyo.ac.jp.

greenhouse gas emissions from the maritime transportation industry in 2050 will be 250% of the 2008 level.

To improve this situation, the International Maritime Organization (IMO) has conducted a total of four surveys since 2000, and based on the results of the surveys, announced a reduction target of halving the greenhouse gas emissions from international shipping by 2050 from 2008 levels. The company has been in the process of developing a new business model. As a stepping stone to achieving that goal, the IMO proposed the EEDI, which came into effect with the publication of the Energy Efficiency Convention [3] in 2013. Shipping companies are now only allowed to operate new ships ordered after 2013 that meet the standard, and those that do not meet the standard are forced to reduce their speed or retrofit their engines to reduce their greenhouse gas emissions below the standard.

In addition, the IMO has strengthened the EEDI regulations approximately every five years, defining 2013-2015, 2015-2020, and 2020-2025 as Phase 1, Phase 2, and Phase 3, respectively, and proposed a new regulation, EEXI, for 2020, which would require that all ships that have been in the EEXI program up to that point be regulated by the IMO. The company announced that all vessels, including those completed in 2012 or earlier, to which EEDI did not apply, would be subject to the same fuel efficiency standards as EEDI. It has already been decided that EEXI will come into effect from Phase 3, which will start in 2023, ahead of schedule, and the IMO will be more fully engaged in reducing greenhouse gas emissions in the maritime transport industry. In addition, a carbon tax and fines for excess greenhouse gas emissions are being considered for Phase 4 and beyond.

The IMO identified alternative fuels and additional equipment as measures that shipping companies can take to comply with these regulations. Heavy Fuel Oil (HFO) is the fuel used in most ships today, and its exhaust emissions contain many substances that have a very high greenhouse effect. On the other hand, fuels such as Liquefied Natural Gas (LNG), ammonia (NH3), and hydrogen (H2) emit fewer greenhouse gases when burned, and IMO is encouraging shipping companies to introduce ships fueled by these substances. In addition, the IMO has developed a number of new technologies such as Wind Propulsion System (WPS), Solar Propulsion System (SPS), and Carbon Dioxide Capture and Storage (CCS). WPS and SPS are systems that use onboard wind and solar power, respectively, to supplement part of the energy consumed by the ship, thereby reducing fuel consumption. Research and development has been conducted in recent years.

The IMO is expected to take aggressive measures to reduce greenhouse gas emissions. However, the stakes in international shipping are so complex that it is difficult to predict how regulations will affect the decisions of shipping companies and what the future scenario will be. Insufficient regulation may not curb greenhouse gas emissions very much, while too strong regulation may curb the economic activities of shipping companies, resulting in a shortage of supply in the international shipping market. A major challenge for the IMO in the future will be to accurately determine the efficacy of regulations and to implement them with as little uncertainty as possible.

Therefore, this study develops an agent simulation to estimate the impact of IMO's regulations on greenhouse gas emissions and markets in the maritime transportation industry in 2050. Furthermore, the purpose of this study is to propose a method to support the IMO in considering the most effective regulations and policies by evaluating the response of the maritime transport industry to various regulations using the developed simulator.

1. Previous study

1.1. Simulation in international shipping

A study by Toratani et al [4] can be cited as a simulation to predict the impact of regulations to reduce carbon dioxide emissions in international shipping. In this study, the interests of ships, shipping companies, IMO, etc. were organized as shown in Figure 1 below for a route between Japan and the west coast of North America, and a simulator was developed based on a model of market supply and demand, freight rates, and fuel prices based on this relationship diagram. The user of the simulator is a regulator and multiple shipping companies, and the user in the shipping company role makes decisions in response to regulations imposed by the user in the regulator role. The simulator developed by Toratani et al. is not an agent simulator, but a simulator in which humans actually take on the roles of regulators and shipping companies to make decisions.

In this study, the simulator will be developed as a means to evaluate the response of the international shipping industry to various regulations and to propose ways to assist the IMO in considering the most effective regulations and policies to be implemented, and the simulator developed by Toratani et al. will be used as a model for this study. The simulator of Toratani et al. is one in which actual humans participate in the simulation and make decisions. In this study, however, we develop a multi-agent simulator in which the players who participate as shipping companies are agents and the simulation proceeds automatically when the regulator inputs regulations.

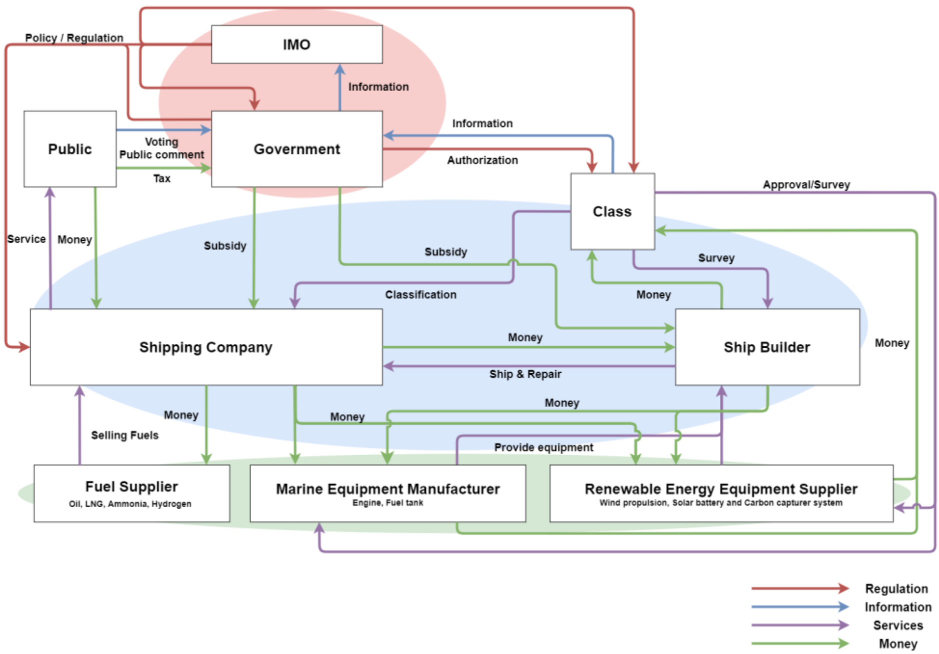

Figure 1. Stakeholder value network in international shipping [4].

2. Proposed method

2.1. Outline

As shown in Figure 2 below, simulations are performed with multiple regulatory proposals listed as input variables, and the results of each simulation are output together in a figure to support efficient consideration of regulatory proposals. The output is a scatter plot of total carbon dioxide emissions and total profits of all shipping companies from the start to the end of the simulation. In this study, effective regulations are defined as those that protect shipping company profits while reducing carbon dioxide emissions.

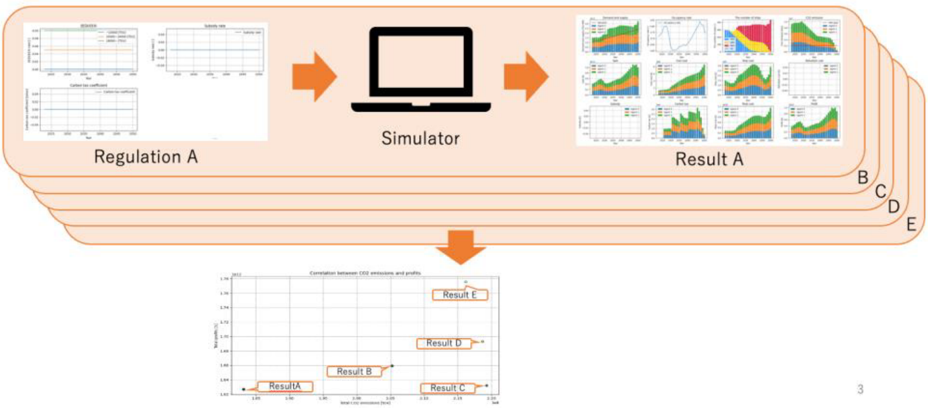

Figure 2. Proposal method.

2.2. Simulator

The general flow of the simulation proposed in this study is shown in Figure 3 below. The simulation is an agent simulation that takes as input the various regulations imposed on shipping companies and produces as output the final results of international shipping's carbon dioxide emissions and market supply and demand from the start to end years. The agents involved are one regulator and one or more shipping companies.

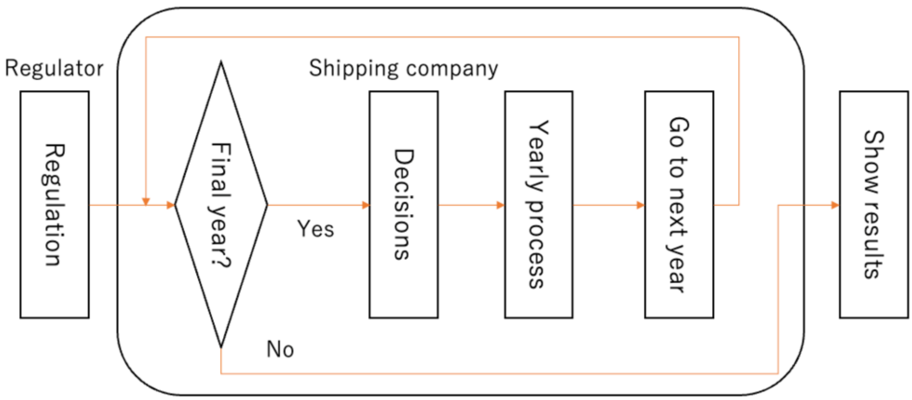

Figure 3. Flowchart of the simulation.

First, the simulation runner inputs the regulations. Once the regulations are entered, the simulation begins. The simulation makes decisions for the shipping company each year, then moves on to the next year once the annual data has been computed. The smallest unit of time in the simulation is one year, and the simulation runner repeats this cycle until the final year to obtain the final results. From the final results, the simulator can see how the imposition of the regulation has changed the supply-demand balance in the international shipping market, the number of vessels by fuel, and the profits of shipping companies.

2.3. Shipping company agent

Figure 4 below shows the decision-making process of a shipping company. The four main decisions are whether to order new vessels, refurbish owned vessels, scrapping owned vessels, and how to set the operating speed of owned vessels. In this simulation, the shipping company is an intelligent agent, making decisions that maximize the company's expected profit each year. After all shipping companies have made their decisions, data on supply, demand, and carbon dioxide emissions for the year are compiled and calculated, and the year comes to an end. This cycle is repeated from the start year to the final year, and the simulation ends at the end of the final year.

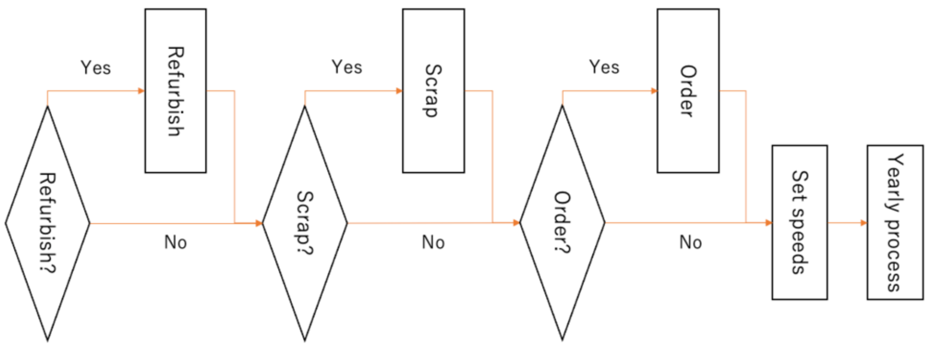

Figure 4. Flowchart of shipping company's decision.

The shipping company in this simulation is a decision-making agent that takes into account regulatory and market trends. Since actual shipping companies are thought to make decisions in order to maximize profits, in this simulation, the agents of the shipping companies are assumed to make decisions in order to maximize expected future profits. Figure 3 5 below shows the flow of decisions made by a shipping company agent during a given year. As shown in the figure, the shipping company agent in this simulation makes four decisions: the decision on the ship's speed, the decision on the ship's modification, the decision on the ship's scrapping, and the decision on the ship's order. The decision-making algorithm for each agent is the same, but the agents are diversified by applying different thresholds to their decisions. This reflects the real market, which has a wide variety of decision making under the same conditions.

3. Case study

The model described in the previous section is implemented and simulated. By running simulations under conditions that reproduce actual international shipping conditions, we aim to predict how the introduction of certain regulations will affect international shipping market trends and the management of shipping companies, and to propose better regulations for international shipping. The starting year of the simulation is 2023 and the ending year is 2050.

3.1. Case 1

First, in Case 1, simulations are performed under simple conditions to confirm that the developed simulator does not behave in an unnatural manner. Hydrogen-fueled vessels and additional equipment are excluded from the model, and the decision-making algorithms of the shipping company agents are standardized among the agents. Furthermore, the EEDI/EEXI reduction rate is fixed at the Phase 3 value until 2050, when the simulation ends. In this case, the validity of the simulator is verified by changing only the carbon tax rate without changing the EEDI/EEXI reduction rate or the subsidy.

Figure 5 below shows the simulation results without a carbon tax, and Figure 6 shows the simulation results with a carbon tax at a constant carbon rate. Intuitively, one would expect a carbon tax to reduce carbon dioxide emissions more than before, but in fact, Figures 5 and 6 show that the higher the carbon tax rate, the more ammonia-fueled ships were ordered and the lower the overall carbon dioxide emissions of international shipping. This result fits our intuition and confirms that the simulator does not exhibit unnatural behavior.

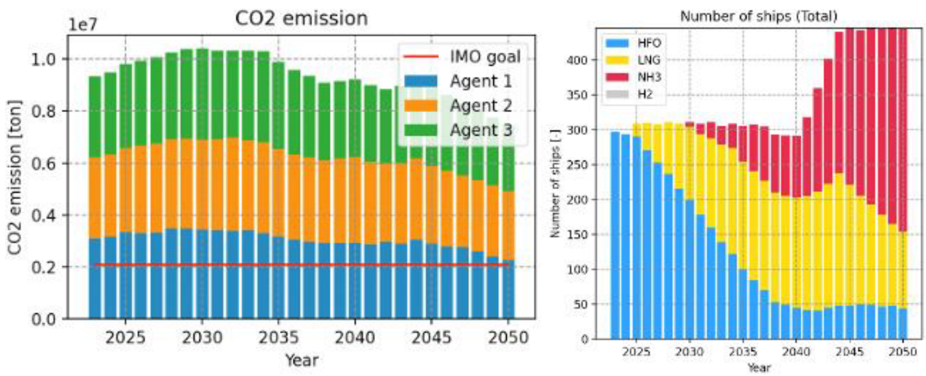

Figure 5. Results 1.

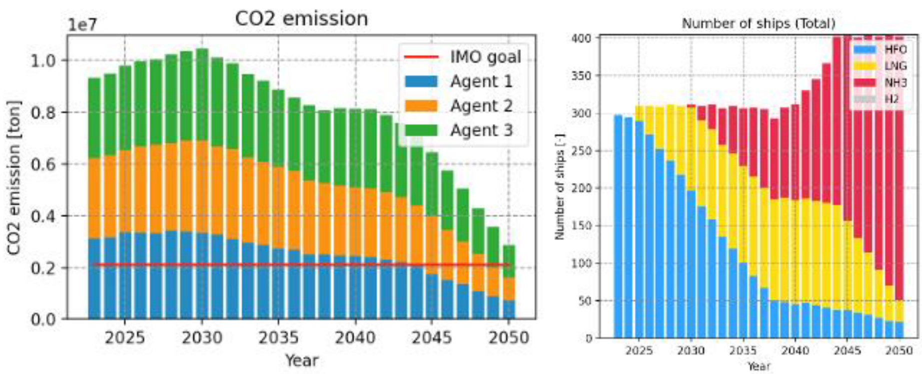

Figure 6. Results 2.

3.2. Case 2

Having confirmed the basic behavior of the simulator in Case 1, Case 2 is a more complex simulation that takes into account hydrogen-fueled vessels and additional equipment. In this case, the number of shipping agents is set to five, and their respective discount rates are 0.01, 0.06, 0.11, 0.16, and 0.21. The discount rate is a value by which shipping agents discount uncertain future profits when calculating their expected future profits.

The three independent variables that are the input values for the simulation are the EEDI/EEXI reduction rate, the carbon tax rate, and the subsidy rate. First, the EEDI/EEXI reduction rate is assumed to be +0, +0.025, +0.05, and +0.075 for every five years after Phase 4. Next, the subsidy rate is set to [α, β], where [0, -0], [1, -0], [1, -0.2], [0.5, -0], and [0.5, -0.1] in this case, assuming that the subsidy rate is expressed as α in Phase 4 and β is updated every five years after that. Finally, let the carbon tax rate be expressed as [α, β], where α$/ton in Phase 4 and β$/ton every five years thereafter, and the five types of carbon tax rates in this case are [0, +0], [100, +0], [100, +50], [100, +100], and [100, +150]. Simulation is performed. Simulate 100 combinations of all of the above EEDI/EEXI reduction rates, subsidy rates, and carbon tax rates.

Table 1. Examples of regulation.

Regulation	2023	2026	2031	2036	2041	2046
EEDI/EEXI +0.05 (Large ship)	0.45	0.5	0.55	0.6	0.65	0.7
Subsidy rate [1, -0]	0	1	1	1	1	1
Subsidy rate [0.5, -0.1]	0	0.5	0.4	0.3	0.2	0.1
Tax rate [100, +0]	0	100	100	100	100	100
Tax rate [100, +150]	0	100	250	400	550	700

Figure 7 below shows a scatter plot of the total carbon dioxide emissions and total profits of all shipping companies from start to finish for the 100 simulation results. The red dots in the figure indicate overspending by the regulator, indicating that the subsidies exceed the revenue from the carbon tax. Conversely, green dots indicate excess revenue, i.e., revenue from the carbon tax is greater than expenditure on subsidies. The correlation coefficient is 0.11, indicating little correlation between total carbon emissions and total benefits. Since this study defines effective regulations as those that reduce carbon dioxide emissions and do not reduce shipping company profits more, the regulations in the upper left of the scatterplot are more effective. In Figure 7 below, the proposed regulations that are relatively far to the upper left and could be candidates for effective regulation are, for example, the three with the speech bubbles.

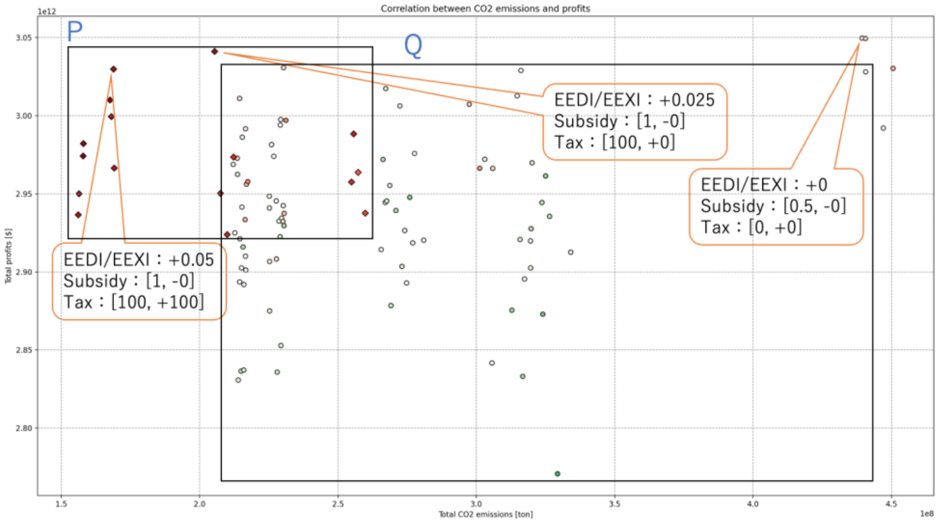

Figure 7. Scatter plot.

Next, let us consider the minimum requirement for effective regulations to meet the carbon dioxide emission reduction target, and consider what kind of regulations can be regarded as effective regulations within this minimum requirement, and extract only those regulations that meet the reduction target from the simulation results of Figure 7, as shown in Figure 8 below, which is Efficient regulations in Figure 8 include the two proposed regulations with the balloon.

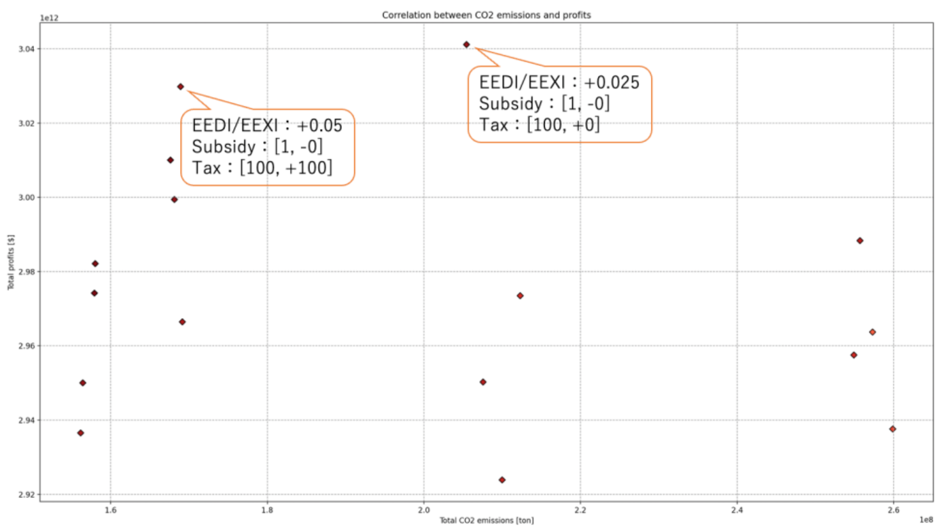

Figure 8. Scatter plot (IMO goal).

Finally, a subsidy policy for shipping companies is considered important for meeting carbon dioxide emission reduction targets, but subsidies require financial resources. If it is difficult to secure new financial resources to provide subsidies, then the regulation of excess revenue, in which carbon tax revenues are larger than subsidy expenditures, would be highly valued. Therefore, we consider the minimum requirement for effective regulation to be revenue overruns, regardless of whether or not carbon dioxide emission reduction targets are met, and consider what types of regulation can be considered effective within that context. The proposed regulations that would result in excess revenue are shown in Figure 9 below, which is the range of box Q in Figure 7. Among the results of these simulations, plotted in the upper left corner are four possible candidates for effective regulation, for example, the four regulation proposals with the balloon.

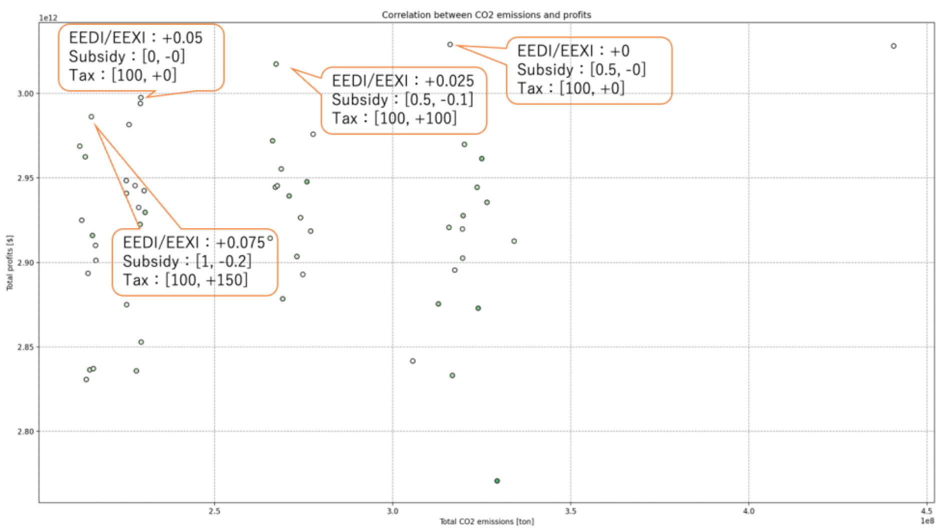

Figure 9. Scatter plot (Surplus).

4. Discussion

The simulation of Case 2 in the previous chapter suggested that a larger EEDI/EEXI reduction rate would reduce carbon dioxide emissions. However, in many cases, it also reduces the profits of shipping companies, so regulatory decision makers also need to make better use of subsidies to ensure that shipping companies' profits are not reduced. The scatterplot also shows that a strict carbon tax rate of 100$/ton or more is required to meet the carbon emission reduction target. On the other hand, it was found that there are many regulatory proposals that do not rely on external sources of funding, and that only carbon tax revenues are used to cover subsidy expenditures.

Finally, in the two cases described in the previous chapter, the simulation results differed greatly depending on the availability of CCS, which can cut 85% of carbon dioxide emissions. Future development of CCS may delay the widespread use of ammonia-fueled vessels and thus hinder the reduction of carbon dioxide emissions.

5. Conclusion

In the design of the simulator, the vessel's operating speed, extinction rate, fuel consumption, and other factors were modeled with reference to actual data. As a result, the developed agent simulator does not show behavior that deviates significantly from reality, and the validity of the simulation results can be asserted. Furthermore, simulations were performed using the developed agent simulator and the results were plotted on scatter plots. The scatter plots are two-dimensional (total carbon dioxide emissions and total benefits), and we propose a method that can assist in the evaluation of quantitative regulations. In summary, we have developed an agent simulator to estimate the impact of IMO regulations on greenhouse gas emissions and markets in international shipping in 2050, and to evaluate the response of the maritime transport industry to various regulations, thereby providing a method to assist the IMO in considering the most effective regulations and policies to be implemented by the IMO.

Acknowledgement

This study is supported by ClassNK (Nippon Kaiji Kyokai)

References

[1] N.N., *Japan sets a target for global shipping of achieving net-zero GHG emissions by 2050*, Ministry of Land, Infrastructure, Transport and Tourism, 2021. https://www.mlit.go.jp/en/report/press/kaiji07_hh_000001.html accessed June 20, 2022.

[2] N.N., *IMO ACTION TO REDUCE GHG EMISSIONS FROM INTERNATIONAL SHIPPING*, International Maritime Organization, 2021, https://sustainabledevelopment.un.org/content/documents/26620IMO_ACTION_TO_REDUCE_GHG_EMISSIONS_FROM_INTERNATIONAL_SHIPPING.pdf, accessed June 20, 2022.
N.N.,EEDI regulation, ClassNK, 2021, https://www.classnk.or.jp/hp/en/activities/statutory/eedi/index.html, accessed June 20, 2022.

[3] H. Kawabe, Team workshop with interactive simulation for industry stakeholders and policy makers towards reduction of GHG emission in maritime transportation, *3rd Global Alliance of Universities on Climate*, 2021, https://climatex2021.gauc.net/article2.html, accessed June 20, 2022.

[4] Hiekata K, Zhao Z. Decision Support System for Technology Deployment Considering Emergent Behaviors in the Maritime Industry, *Journal of Marine Science and Engineering*, 2022, 10(2), 263. https://doi.org/10.3390/jmse10020263.

[5] K. Hiekata, S. Wanaka, T. Mitsuyuki, Ryuji Ueno, Ryota Wada, Bryan Moser System Analysis for Deployment of Internet of Things(IoT) in the Maritime Industry, *Journal of Marine Science and Technology*, 2021, https://doi.org/10.1007/s00773-020-00750-5.