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System dynamics modeling for greenhouse gas emissions from passenger and roll on-roll off ships

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ABSTRACT

Tanjung Perak Port in Surabaya plays a key role in Indonesia's maritime economy through the Jamrud Utara Pier, serving passenger and roll on-roll off ships. Ship berthing activities contribute to greenhouse gas emissions, particularly CO_2. This study estimated the emissions from 2021–2022, developed a dynamic model of ship behavior, and analyzed berthing duration scenarios until 2030 using the European MEET methodology. Research stages include system identification, model creation, validation, and scenario simulation. Validation uses the Behavior Pattern Test and Mean Absolute Percentage Error. Results estimate emissions at 10,502,847 kg CO_2 in 2021 and 10,341,740 kg CO_2 in 2022. The model shows emissions increasing with ship gross tonnage, number, and berthing duration. Reducing berthing duration by 15% can cut emissions by 17% in 2030, while a 20% reduction can lower emissions by 25%.

Keywords: CO_2 emissions, forecasting, modeling, system dynamics, water transportation.

INTRODUCTION

Indonesia is a maritime country where shipping and sea transportation activities play a role as one of its economic wheels. Strategic ports such as Belawan in Medan, Tanjung Priok in Jakarta, Tanjung Perak in Surabaya, Soekarno-Hatta in Makassar, and Sorong also play a role in the country's economy (Arsasiwi, 2016). Tanjung Perak Port in Surabaya, as part of PT Pelabuhan Indonesia (Persero) Sub Regional Java, has a special terminal such as the Jamrud Utara Pier. Ship activities at this pier produce exhaust emissions, such as CO_2, PM_{10}, $PM_{2.5}$, VOC, NO_x, and SO_x, which have negative impacts on the environment and health (Cullinane et al., 2016). Regarding that, the ship movements at Busan Port were evaluated to contribute 32% of greenhouse gases due to high shipping traffic (Cheong et al., 2007).

Indonesia is committed to supporting the target of reducing greenhouse gas emissions by 29% by 2030 with its own efforts, and 41% with international support (Baroleh et al., 2023). The European MEET methodology is often used to estimate air pollution emissions based on gross tonnage (GT) of ships, including ship operating fuel consumption (Trozzi and Vaccaro, 1999). Research on greenhouse gas inventories from ships, such as the study by Johansson et al., (2017) inventoried global shipping emissions by analyzing spatial data on ship traffic. However, this study was limited to one year and modeling only on gas dispersion patterns in certain areas. To address the complexity of the system, an approach model is needed.

Models are a way of representing a system to evaluate the performance of a real system and make improvements if necessary so that it can build a complex system simulation (Kusumawardani, 2014). The simulated system is ideally projected for up to 10 years (medium term) for reasons of balance between accuracy and time. The simulation results are used to support decision making by providing better solutions (Petropoulos et al., 2022). System dynamics study changes in an entity over time. In system dynamics modeling, the relationships between elements such as causal loops are used to study system behavior. Simulations with dynamic models can provide an explanation of the processes in the system and allow prediction of the results of various scenarios (Elsawah et al., 2012).

Validation is an important stage before applying scenarios to the model to ensure the accuracy of the analysis results. Common validation methods used are Behavior Pattern Test (BPT) and Mean Absolute Percentage Error (MAPE). BPT evaluates the conformity of behavioral patterns between predicted data and observed data, while MAPE measures the relative error between predictions and actual values. Both methods provide an overview of the quality of the model against actual data (Muhammadi et al., 2001). If the validation test results meet the criteria, scenario development can be carried out. Scenario development through simulation allows for future impact analysis by adding new parameters or changing existing models. Software such as STELLA (Structural Thinking Experiential Learning Laboratory with Animation) has become a common tool in system dynamics modeling (Widodo, 2011).

On the basis of the description, this study focuses on estimating the CO_2 emission from the operational berthing mode of passenger ships and roll on-roll off (Ro-Ro) ships at the Jamrud Utara Pier, Tanjung Perak Port in 2021–2022 using the European MEET methodology (Methodologies For Estimating Air Pollution Emissions From Transport) from the research of Trozzi and Vaccaro (1999) based on ship fuel consumption while at the pier. From this estimate, modeling was carried out related to the greenhouse gas system of ship berthing activities at the pier. The model that has been created was validated using BPT and MAPE. The system dynamics approach is expected to obtain greenhouse gas behavior patterns from ship activities under existing conditions, so that scenarios can be applied to the duration of ship berthing.

METHODS

Data collection

This study used secondary data in the form of ship arrival data at Jamrud Utara Pier in 2021-2022 by PT Pelabuhan Indonesia (Persero) Sub Regional Jawa, which included the data on the number of ship arrivals and ship berthing duration (days). The data of the ships GT and classes were collected from official websites of Equasis C/O, Vesseltracker, Marinetraffic, and Nippon Kaiji Kyokai. The number of arrivals of each ship in 2021 and the duration of ship berthing that has been analyzed for each GT of the ship as the average duration of ship berthing in one year were used as initial input. The initial input was used in the simulation of greenhouse gas behavior from ship berthing activities.

Greenhouse gas emission estimation

The calculation of greenhouse gas estimates using the MEET methodology was carried out on passenger ships and Ro-Ro ships. The process began by estimating daily fuel consumption based on the GT of the ship. Then, the daily fuel consumption of the ship in berthing mode was calculated with a factor of 0.32 for passenger ships and 0.12 for Ro-Ro ships. Using a CO_2 emission factor of 3.200 kg per ton of fuel, the daily greenhouse gas estimate was obtained. The annual estimate was calculated by considering the number of ships arriving in that year and the average duration of their berthing while at the pier. Formula 1 was used to estimate the greenhouse gas (GHG) emission of passenger ships and Ro-Ro ships.

$$\mathrm{GHG\ GT.X} = \mathrm{Daily\ GHG\ GT.X} \times \times \mathrm{GT.X\ Ships} \times \mathrm{t} \tag{1}$$

where: *GHG GT.X* – estimated greenhouse gas emission of *GT.X ships* (kg/year), *Daily GHG GT. X* – daily estimated greenhouse gas emission of *GT.X ships* (kg/day), *GT.X Ships* – total of berthing ships (unit/year), *t* – average berthing duration of *GT.X ships* (day/year).

System dynamics modeling

Modeling aims to understand how the system works in depth. This process used STELLA (Structural Thinking, Experiential Learning Laboratory With Animation) software. The system dynamics modeling process included problem formulation by identifying factors in a system, system conceptualization by creating causal loop diagrams, model formulation through stock-flow diagrams, model simulation, and model testing (verification and validation) through model structure tests, model parameter tests, extreme conditions, as well as behavioral tests/model replication using behavior pattern test (BPT) and MAPE validation tests. If the model is "valid", then the scenario can be applied to the model.

RESULTS

Greenhouse gas emission estimation

The total greenhouse gas (GHG) emissions are calculated as the sum of emissions from both ship types. In 2021, the combined greenhouse gas emissions from passenger ships and Ro-Ro ships amounted to 10,502,847 kg CO_2, with passenger ships contributing the majority of the emissions. In 2022, the total emissions decreased to 10,341,740 kg CO_2, with passenger ships continuing to dominate the emission contributions. The difference in GHG emissions between passenger ships and Ro-Ro ships was 72,667 kg CO_2 in 2021 and 104,176 kg CO_2 in 2022.

Among passenger ships, the highest number of arrivals occurred in May 2022, with a total of 613 ships, including 73 arrivals in May alone, marking the peak of passenger ship traffic. This surge was associated with the 2022 Eid homecoming period, coinciding with the government's implementation of the "new normal" policy. During this phase, the public was permitted to engage in outdoor activities, including travel, under the condition of adhering to recommended health protocols (Kendek, 2022).

For Ro-Ro ships, the number of arrivals in 2021 was followed by a 2.8% decrease in 2022. Despite this decline, the cumulative number of Ro-Ro ship arrivals in 2022 remained higher than that of passenger ships. The lowest number of Ro-Ro ship arrivals was recorded in May 2022, with only 123 ships docking. In 2022, several companies experienced supply chain disruptions linked to a global container shortage, which also impacted the use of Ro-Ro ships. This issue arose as a cascading effect of the COVID-19 pandemic, during which manufacturers scaled down production, leading to reduced shipments to ports. Shipping companies also continued to face escalating operational costs, including a sharp increase in fuel prices – rising to double the rates of previous years and 20–30% higher than international prices (Widyanto et al., 2022).

On the basis of Figure 1, the berthing duration for Ro-Ro ships is generally longer than for passenger ships, with passenger ships averaging 5 hours at the pier and Ro-Ro ships averaging up to 6 hours. The extended berthing duration for Ro-Ro ships is attributed to the loading and unloading processes of wheeled vehicles, which require specialized entry and exit doors that can be raised and lowered for vehicle movement (Ventura et al., 2020). Additionally, some Ro-Ro ships may require extra time at the pier for routine maintenance, repairs, or inspections, extending their berthing duration compared to passenger ships, which often follow a more flexible repair

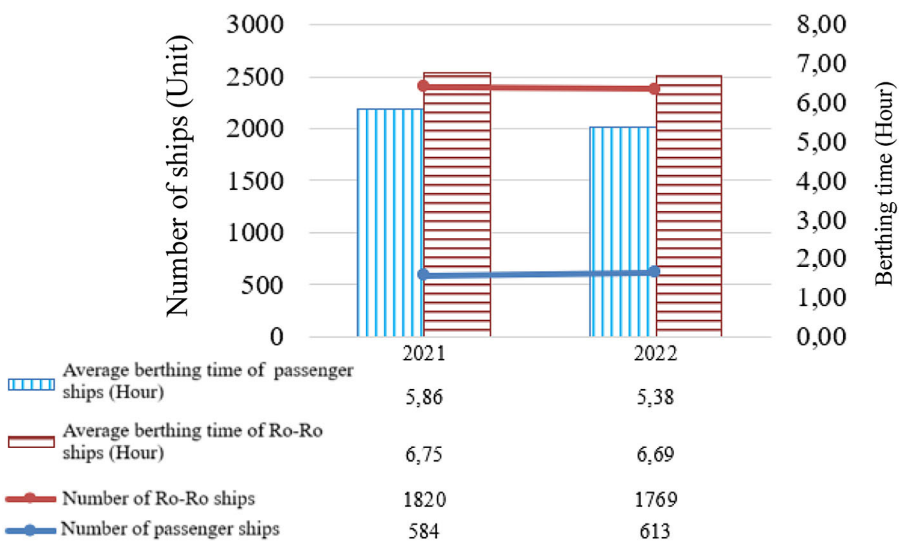

Figure 1. Numbers of ship arrival and berthing time at Jamrud Utara Pier in 2021 and 2022

schedule (Pramita and Sari, 2020). From 2021 to 2022, the berthing duration for both types of ships ranged from five to six hours, reflecting an improvement compared to historical data. This reduction in berthing time is likely a result of operational management restructuring following the merger of PT Pelabuhan Indonesia as a unified port service provider in October 2021.

Following the merger, PT Pelabuhan Indonesia has prioritized operational transformation through the standardization and systematization of port operations. This effort is evident in the increased efficiency of berthing and loading/unloading times. The resulting improvements have led to enhanced operational cost efficiency, which is anticipated to boost ship traffic volumes. Notable performance gains are observed at TPK Makassar and Makassar New Port Terminal, where berthing durations have been reduced by more than 50%. Comprehensive service standardization has been implemented across various sectors, including container and non-container operations, marine services, as well as logistics (Kusumaningrum and Heikal, 2023).

Model simulation

The model simulations presented cover the period 2021 to 2030. The simulations include greenhouse gas estimates from passenger ships, Ro-Ro ships, and the total accumulated greenhouse gas estimates from both types of ships. The projections are made with the consideration that the projections that are too short may not provide a picture of long-term trends, while the projections that are too long may be less accurate due to increasing uncertainty (Athanasopoulos et al., 2017). Not only that, economic cycles often last for several years, and the projections with almost 10 years can cover one or more of these cycles so that they can provide a better picture of potential economic changes. In some cases, public policies take time to be implemented and show their impact. A 10-year projection can help in accurately evaluating the effects of these policies (Petropoulos et al., 2022).

The model created consists of two main submodels, the daily ship fuel consumption submodel which contains the daily ship greenhouse gas estimation component and the sub-model of greenhouse gas estimation at the dock for passenger ships and Ro-Ro ships. A sub-model of total greenhouse gas estimation which is the accumulation of greenhouse gas estimation by both types of ships is also present. The main model can be seen in Figure 2. On the basis of the simulation results, the total greenhouse gas estimation before the scenario in 2023 was initially 10,597,313 kg CO_2. However, in 2030 the total greenhouse gas estimation increased to 16,013,769 kg CO_2.

Model testing results indicate that the obtained error values comply with the established standards for the model behavior test. The mean comparison value (E1) demonstrates validation results of ≤ 5%, while the amplitude variation comparison (E2) yields validation results of ≤ 30%. Likewise with the MAPE validation results, all validated variables show validation results of less than 10%. Therefore, all model test results demonstrate strong quantitative validity (Michalak, 2017). This indicates that all variables in the

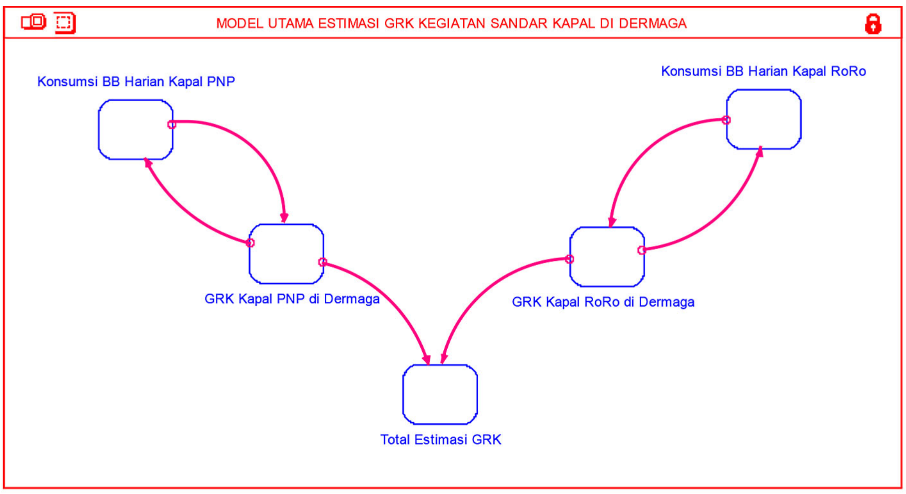

Figure 2. Main model for estimating the greenhouse gases from ship berthing activities at the pier

greenhouse gas estimation system model from ship berthing activities have a behavioral pattern that is consistent with the actual situation. Thus, the developed model is valid for representing and predicting the behavior of greenhouse gases from ship berthing activities.

The relationship between the number of ships and the annual greenhouse gas estimation is shown in Table 1.

Figures 3 and 4 show the simulation results of passenger ship and Ro-Ro ship greenhouse gas estimation based on the number of ships in a graphical form.

Alternative scenarios are expected to be the key solution offered based on the existing analysis pattern that has been taken previously. Formulating a scenario is essential to identify the key variables for determining the optimal equilibrium within the scope of the study (Rebs et al., 2019). The application of the scenario was carried out on the berthing duration of 15% and 20% supported by the reason (Styhre et al., 2017) that optimizing the berthing and departure schedules of ships can increase operational efficiency, reduce ship queues, and ensure compliance with the schedule that has been set. Labor gang performance influences loading and unloading productivity, where reducing berthing time enhances efficiency (Saleeshya et al., 2017). The results of the simulation of existing conditions from 2023 to 2030 can be seen in Figure 5.

After applying the scenarios to the model, the results of scenario I (Figure 6) with a 15% reduction in the berthing duration show that the total estimated greenhouse gas in 2023 will be 9,007,716.53 kg CO_2. Meanwhile, the estimated greenhouse gas in 2030 can be reduced to 13,611,704.12 kg CO_2. The results of scenario

Table 1. Simulation results of the total estimation of greenhouse gas from ship berthing activity

Year	Passenger Ship		Ro-Ro Ship		Total estimated GHG emission (kg.year^{-1})
	Number of ship arrival (unit.year^{-1})	Estimated GHG (kg.year^{-1})	Number of ship Arrival (unit.year^{-1})	Estimated GHG (kg.year^{-1})	
2021	584	5,284,511	1,820	5,213,605	10,498,116
2022	613	5,225,674	1,769	5,120,741	10,346,416
2023	650	5,273,096	1,850	5,324,217	10,597,313
2024	700	5,405,634	2,002	5,692,914	11,098,548
2025	750	5,538,171	2,224	6,208,415	11,746,587
2026	801	5,681,491	2,460	6,754,667	12,436,159
2027	861	5,921,851	2,703	7,338,712	13,260,564
2028	929	6,233,944	2,950	7,944,354	14,178,299
2029	997	6,546,038	3,197	8,549,996	15,096,03
2030	1,065	6,858,131	3,444	9,155,637	16,013,769

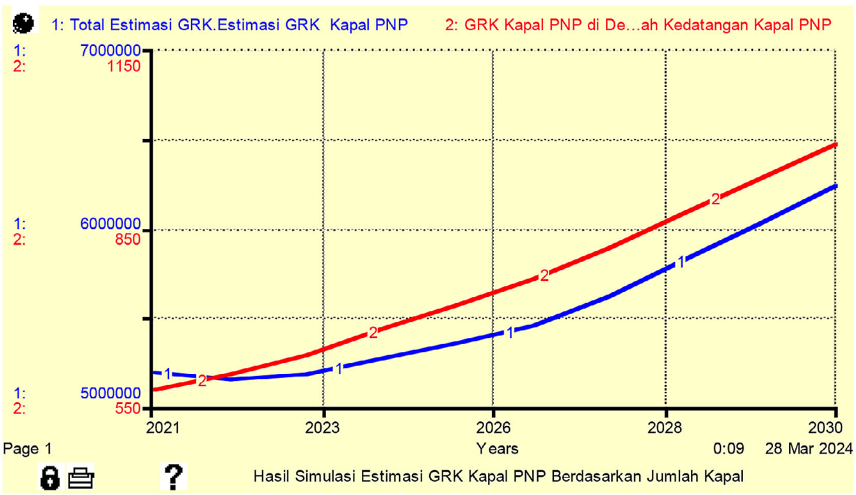

Figure 3. Simulation results of passenger ship greenhouse gas estimation based on number of ships

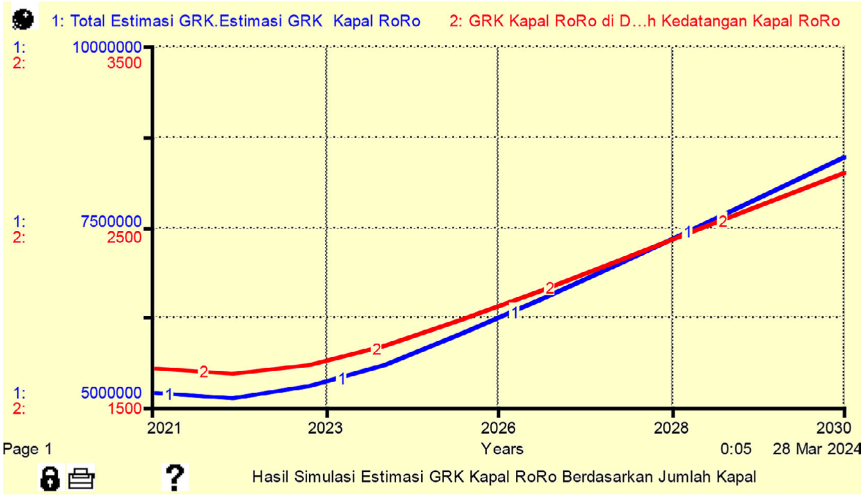

Figure 4. Simulation results of Ro-Ro ship greenhouse gas estimation based on number of ships

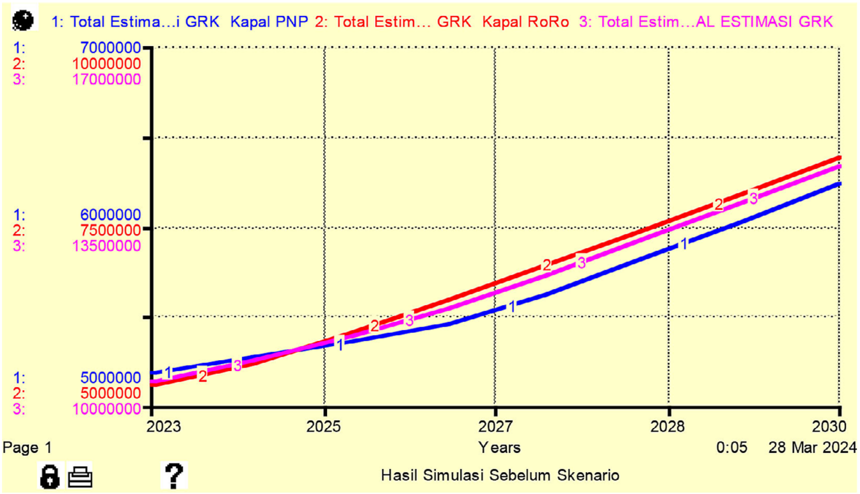

Figure 5. The results of the simulation of existing conditions from 2023 to 2030

II with a 20% reduction in the berthing duration (Figure 7) show that the total estimated greenhouse gas in 2023 will be 8,477,850.85 kg CO_2. Meanwhile, the estimated greenhouse gas in 2030 can be reduced to 12,811,015.65 kg CO_2.

DISCUSSION

Greenhouse gas emission from berthing activity of passenger and roll on-roll off ships

Tanjung Perak Port serves as a key hub for inter-island passenger and goods distribution, particularly within Eastern Indonesia (Maryam and Handayani, 2015). The Gapura Surya Nusantara Passenger and Ro-Ro Ship Terminal, located within Tanjung Perak Port in Surabaya, operates as one of the largest passenger terminals in the region. It facilitates both domestic and international ship routes, with the Jamrud Utara Pier dedicated to handling international vessels. The ship berthing activities at this pier not only influence operational efficiency but also contribute to greenhouse gas emissions, primarily carbon dioxide (CO_2), resulting from the combustion of fossil fuels (Issa et al., 2022). Estimating greenhouse gas emissions is essential for assessing the environmental impact of the pier's operations.

Variations in greenhouse gas estimation results are influenced by several factors, including the number of ship arrivals, the gross tonnage (GT) of ships, and the duration of ship berthing at the dock (Ekmekçioğlu et al., 2022). The frequency of ship arrivals affects annual greenhouse gas estimates through the cumulative emissions

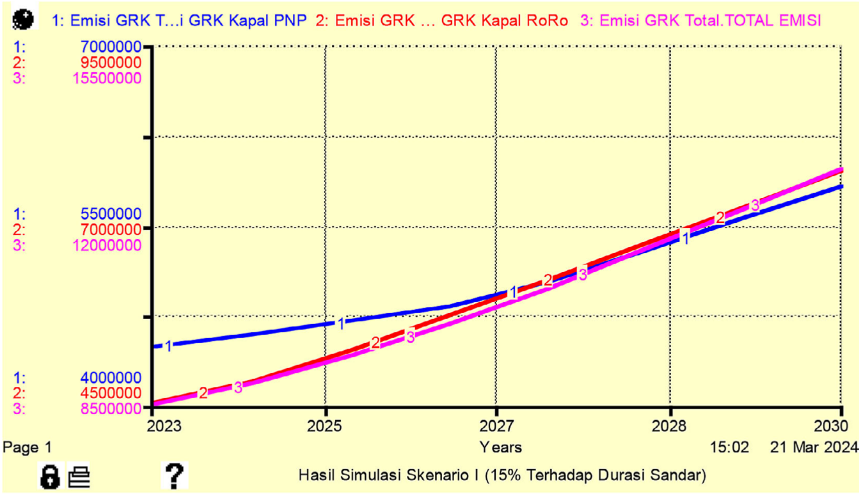

Figure 6. The results of the simulation of scenario 1

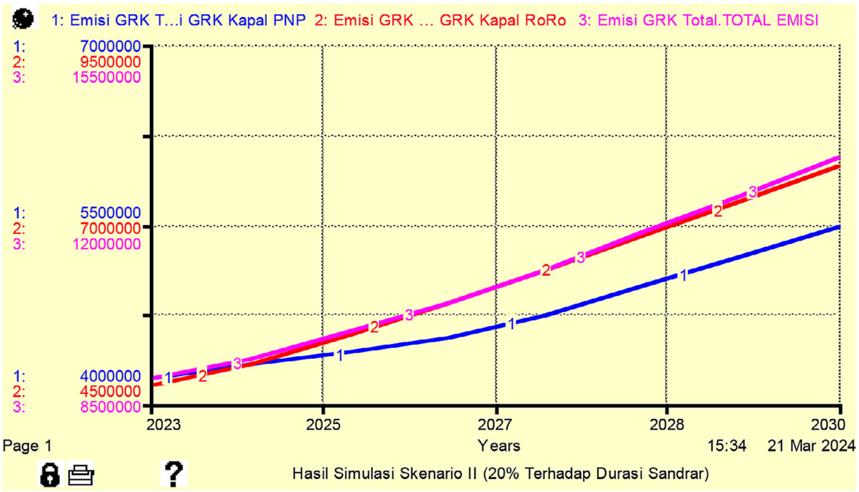

Figure 7. The results of the simulation of scenario 2

from daily operations. Ship type also plays a critical role, as larger or older ships often have less efficient engines, resulting in higher greenhouse gas emissions per vessel (Wijaya, 2020). Additionally, Perdana et al. (2018) demonstrated that an increase in ship arrivals impacts berthing duration, as higher traffic can limit the number of ships that can be serviced simultaneously. Berthing duration has a direct, linear relationship with fuel consumption at the dock, as longer berthing times lead to increased fuel use to power onboard systems and generate electricity (Fitria, 2022).

The GT of a ship significantly influences its fuel consumption while at the dock, as fuel usage is directly related to the ship type, size, and engine power requirements. Larger ships with higher GT generally consume more fuel due to their greater power demands for operation (Sa'id, 2011). Passenger ships, in particular, tend to have higher fuel consumption at the dock compared to Ro-Ro ships, primarily because passenger ships have greater electricity requirements. These ships must maintain onboard facilities, such as lighting, air conditioning, and other amenities, necessitating the continuous operation of their engines and resulting in higher fuel consumption than Ro-Ro ships (Firdaus and Utomo, 2016). Table 2 shows the GT of passenger and Ro-Ro ships with their daily fuel consumptions.

The total GT of ships docked at a pier is directly influenced by the number and type of ship arrivals. When large ships with high GT dominate, the total GT increases significantly. Conversely, if arrivals consist mainly of smaller ships with lower GT, the total GT will be comparatively lower. This dynamic indicates that variations in

Table 2. Total of ship gross tonnage and daily fuel consumption

Year	Total of ship GT (Ton)		Total daily fuel consumption (Ton.Day^{-1})	
	Passenger Ship	Ro-Ro Ship	Passenger Ship	Ro-Ro Ship
2021	5,901,262	15,308,417	6,898	5,668
2022	5,997,903	15,174,986	7,116	5,565

the number and type of ships docking at the pier directly impact the total GT (Sasono, 2021). At Jamrud Utara Pier, passenger ships range from conventional vessels to cruise ships, with GT sizes between 856 GT and 150,695 GT. Similarly, Ro-Ro ships docking at the same pier vary in size and cargo volume, with GT values ranging from 994 GT to 20,563 GT.

The number of ship arrivals is a contributing factor in estimating the total greenhouse gas emissions at a pier, but its impact is influenced by additional variables, such as the berthing duration of each ship and its gross tonnage (GT). These factors affect fuel consumption based on the operational mode of a ship, making the effect of ship arrivals on greenhouse gas emissions non-absolute (Ekmekçioğlu et al., 2020). Research by Albo- López et al. (2023) examining the adjustment of ship GT parameters and berthing duration through multiple regression analysis indicates that berthing duration has a greater influence on total greenhouse gas emissions than ship GT. Moreover, greenhouse gas emissions increase with the growing number of ship arrivals, highlighting the cumulative effect of these factors.

Model behavior and scenarios for optimization of greenhouse gas emission from berthing activity of passenger and roll on-roll off ships

The behavioral patterns related to the estimation of greenhouse gases from ship berthing activities at the pier are described through a model structure diagram. By using the model structure, a system description can be revealed and allows for detailed model formulation and simulation (Velten et al., 2024). These behavioral patterns describe existing conditions, allowing for the development of specific scenarios to reduce the greenhouse gas impacts of each type of ship (Schwarzkopf et al., 2021).

The simulation of the system dynamics model indicates a trend of increasing incoming passenger ship traffic over time. In the absence of regulatory policies restricting shipping activities, this trend is expected to persist, driven by the expansion of the tourism and trade sectors (Lamb et al., 2021). Furthermore, the estimated greenhouse gas emissions from passenger ships at the dock exhibit a corresponding increase as ship arrivals rise. If the average berthing duration remains constant or continues to increase, as suggested by historical data, the resulting emissions will escalate further (Wang and Li, 2023). These interrelated factors collectively contribute to the projected increase in greenhouse gas emissions.

A similar pattern is observed in the greenhouse gas estimation model for Ro-Ro ships. Although historical data indicate a decline in the total number of Ro-Ro ship arrivals, the trend suggests that the majority of Ro-Ro ships within a specific GT range continue to increase. In the absence of policies regulating shipping activities, this trend is expected to persist in line with the expansion of the logistics and distribution industry (Raza et al., 2019). Wang et al. (2018) emphasized the importance of analyzing historical trends and projecting future developments to formulate effective policies for reducing greenhouse gas emissions in the maritime transportation sector. By recognizing the increasing trends in ship arrivals and berthing duration, more proactive policies can be designed to align with these dynamics.

The increase in service duration significantly influences total greenhouse gas emissions. The ships that remain docked for extended periods consume more fuel, leading to higher emission levels (Balcombe et al., 2019). Analysis of this behavioral pattern reveals a complex system dynamics in which rising ship arrivals and prolonged berthing durations collectively drive the overall increase in greenhouse gas emissions from both passenger and Ro-Ro ship sectors. Addressing substantial shifts in these patterns may necessitate comprehensive interventions and coordinated strategies to mitigate their environmental impact effectively.

System dynamics modeling scenarios are expected to play a crucial role in formulating solutions based on previously analyzed patterns. The policies that promote the adoption of renewable energy and sustainable practices in ship operations are essential for mitigating the environmental impact of the maritime transportation sector (Jing et al., 2021). One proactive approach is the implementation of berthing duration reduction strategies, which can effectively decrease greenhouse gas emissions (Hoang et al., 2022). By minimizing the time ships spend at the port, fuel consumption can be proportionally reduced, contributing to overall emission reductions.

A 15% reduction in berthing duration, as proposed in Scenario I, represents a feasible and practical measure that allows the maritime industry to adapt to changes without significantly disrupting operations. Calculations indicate that this scenario could reduce the estimated greenhouse gas emissions by approximately 17% compared to current conditions. In contrast, Scenario II, which proposes a 20% reduction in berthing duration, is more ambitious but has the potential to achieve a 25% reduction in greenhouse gas emissions. However, reducing berthing duration may not be universally applicable to all vessel types due to constraints such as operational safety, maritime regulatory compliance, and customer service requirements (Mba, 2025).

CONCLUSIONS

This study shows the estimated greenhouse gas emissions from the berthing activities of passenger ships and roll on-roll off ships. The total estimated greenhouse gas emissions from both types of ships is 10,502,847 kg CO_2 for 2021 and 10,341,740 kg CO_2 for 2022. The results of this estimate are influenced by the number of ship arrivals, ship size, fuel consumption patterns, and the duration of ship berthing at the pier. The application of the ship berthing duration scenario can reduce the estimated greenhouse gas emissions by 17% (Scenario I) and 25% (Scenario II).

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