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Developing a decarbonization policy model of container terminal clusters

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Abstract

Purpose – The purpose of this research is to develop a set of policies to solve the decarbonization issues of container terminal clusters.

Design/methodology/approach – This research used the system dynamics approach to develop an integrated multi-issue policy model.

Findings – We found that the mandatory use of low-sulfur fuel can decrease GRDP and container throughput and hinder the growth of companies and workers due to high fuel prices. However, it can contribute to a significant reduction in SOx emissions.

Research limitations/implications – This research used the Tanjung Priok container terminal cluster in Jakarta, Indonesia, as its case study. Hence, some findings are attached to the characters of this container terminal cluster.

Practical implications – We found that an integrated policy approach that can tackle technical and social issues can be used to develop a novel approach to solving the complexity that arises in a complex socio-technical system such as container terminal clusters.

Social implications – As this research used the socio-technical systemic point of view, we found that solutions for major environmental issues should be coupled with significant social programs to (at least) maintain the welfare of society.

Originality/value – This research used the integrated complexity model approach, system dynamics, which can significantly increase society's ability to tackle multi-issue problems such as decarbonizing container terminal clusters.

Keywords System dynamics, Policy, Decarbonization, Container terminal cluster

Paper type Research paper

1. Introduction

As a maritime country, Indonesia is important for global trade routes. Of the 90% of world trade carried out by sea, 40% passes through Indonesian waters. With most national exports and imports transported via ship, ports are vital in supporting sea transportation connectivity.

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Ports activities produce considerable levels of emissions, and therefore, it is essential to recognize the relevance of seaport decarbonization. The International Maritime Organization (IMO) issued several crucial decarbonization policies. The most significant was IMO 2020, a policy regulating fuel use that took effect on January 1, 2020. The IMO 2020 policy limits the sulfur content in ship fuel to a maximum of 0.5% v/v. It is advisable to align the Indonesian Government's emissions reduction target to decarbonize sea transportation with the IMO policy on low carbon and sulfur fuel utilization.

There are several challenges to decarbonizing container terminal clusters. The IMO policy establishes an imperative to adopt low-sulfur fuel even though it is significantly more expensive. There are several methods of reducing emissions, such as adopting shore power technologies and designating specific areas within which companies are obligated to use low-sulfur fuel. However, container terminal clusters' economic and social aspects should also be considered. Therefore, research is needed on the most suitable policy alternatives for decarbonizing container terminal clusters, particularly in maritime countries such as Indonesia. Such an approach has the potential to significantly reduce emissions of CO_2, SOx, NOx, and more.

According to our preliminary survey, existing research does not integrate system dynamics with actor, scenario, and policy analysis to study decarbonization policies in the context of low-sulfur fuel regulations. Additionally, research on decarbonization policies targeting container terminal clusters remains limited, particularly in the Indonesian context, with few studies holistically addressing the economic, social, and environmental dimensions. Therefore, this paper bridges these gaps by developing a system dynamics model to study the decarbonization policy scenarios of container terminal clusters. Addressing these gaps is crucial to model the impacts of decarbonization policies that consider economic, social, and environmental sustainability, especially in developing maritime countries like Indonesia, where ports are essential to trade and urban development. System dynamics is used for this study since it is suitable for modeling a continuous system that can capture delays and feedback loops inherent in the actions taken as a decarbonization effort, making it ideal for policy modeling over time. Its ability to integrate multiple variables from different dimensions makes it well-suited for analyzing multidimensional trade-offs in container terminal clusters. This paper provides insights into the impact of policy interventions and the dynamics of decarbonization in critical container terminal clusters.

Tanjung Priok Port hosts a service facility in the form of a container terminal, where containers for export and import are dealt with. It has six terminals that accommodate the loading and unloading of containers. However, container terminal activities produce various greenhouse gas emissions at ports, including CO_2, SOx, NOx, CO, HC, and black carbon particles, and these gases slowly accumulate in the atmosphere. Continuous exposure to these pollutants risks public health, as they can cause several illnesses, particularly respiratory illnesses. Since Tanjung Priok Port is Indonesia's largest and busiest port, its complexity can represent the complexities of almost all ports in Indonesia. It is also supported by the fact that Jakarta is inhabited by more than 10 million people, according to the Statistical Planning Agency of Indonesia, in 2022. Therefore, what has been studied in Tanjung Priok Port can be a basis for other ports, making it a suitable reference for developing the container terminal cluster model.

This research is started by improving our previous study on the sustainability of port cluster development (Moeis *et al.*, 2020). This paper was used as our base model and expanded with a new sub-model, namely the fuel sub-model, and enhanced the environmental sub-model to cover deeper details of important container terminal cluster environmental indicators.

This paper explores robust decarbonization policies targeting container terminal clusters. This study adopts a system dynamics approach incorporating the actor, scenario, and policy analysis framework to develop a container terminal cluster decarbonization model appropriate for the current situation, particularly regarding the recently established low-sulfur fuel policy. Since the actor analysis is conducted, there is an opportunity to cover the details of the socio-technical aspects. The model is expected to consider not only the environmental aspects of the system but also the economic and social aspects, to maintain sustainability.

The structure of the paper is as follows. Section 2 is a literature review that summarizes existing research on port decarbonization. Section 3 discusses the methodology used to conduct the study. Section 4 contains the results and discussion. And lastly, Section 5 consists of the conclusion and policy implications.

2. Ports and decarbonization

A container terminal is an open material flow system with two external interfaces: One interface at the harbor where ships load and unload cargo and another on land where containers are transferred from ships to trains and vice versa. After the container ship is anchored at the container terminal, a machine equipped with a crane immediately loads and unloads containers from the ship (Steenken *et al*., 2004).

A cluster, according to Porter (2000), is a collection of businesses and related organizations associated with one another within a given industry due to their shared interests and complementary skills. Haezendock *et al*. (2000) define port clusters as the concentrations of industries and services networks that are situated in close proximity to a seaport. de Langen and Haezendonck (2012) emphasize the port cluster concept of collaboration and competition to improve ports' sustainability, competitiveness, and innovation. The cluster of economic activities connected to the arrival of cargo and ships is referred to as a container terminal cluster (Bai and Lam, 2015). de Langen (2020) then confirmed that a container terminal cluster could be understood as a network of interconnected businesses and organizations focused on port activities, logistics, and cargo handling that are geographically concentrated.

High activity at container terminal clusters produces a considerable amount of emissions. Therefore, there is an urgent need to implement decarbonization. There are several methods for reducing emissions at ports, and therefore, ports play an essential role in decarbonization. For example, ships could be connected to port power sources to transfer electricity to a boat barn. Connecting ships to the power grid when they are anchored will enable their auxiliary engines to be shut off, which will reduce emissions (Chang and Wang, 2012). Another decarbonization method involves using low-sulfur fuel and complying with maximum sulfur content regulations established by the IMO 2020 policy (Zhou and Yuen, 2021). However, these initiatives remain difficult to implement due to various economic and social constraints and the challenges of organizing all stakeholders to collaborate on decarbonization solutions.

Several studies discuss the policy implications of port decarbonization. For instance, Winnes *et al*. (2015) analyzed scenarios for reducing greenhouse gas emissions at ports. Based on quantifying the potential emissions reduction, different scenarios are performed if certain actions are implemented to see how they might impact the emissions reduction. Zhou and Yuen (2021) studied the policy implications of low-sulfur fuel utilization by applying game theory. They developed a two-stage game model, addressing low- and high-sulfur fuel pricing under an incentive scheme, to analyze the interactions between multiple stakeholders in the context of the IMO2020 regulation. Extending this discussion, Ismail *et al*. (2024) structured a framework to integrate ports into green shipping corridors. They provide guidance for overcoming its challenges, one of which is through collaborative actions between relevant stakeholders to achieve emissions reduction. Furthermore, Alamoush *et al.* (2021) analyze the implementation schemes to reduce greenhouse gas emissions in ports. They provide port policymakers with an understanding of emissions reduction decision-making by emphasizing the use of technical and operational measures. Meanwhile, Fadiga *et al*. (2024) have studied the literature on maritime port decarbonization. They categorize decarbonization measures into clusters, highlighting future research opportunities for each cluster.

3. Methodology

3.1 Actor analysis

For this study, actor analysis (Table 1) was carried out to improve the quality of the problem analysis; actor analysis was used to enhance knowledge and awareness of the actors within the system (Enserink *et al*., 2010). This study identified twelve actors involved in container terminal cluster decarbonization, including the Government of Indonesia, the Provincial Government of DKI Jakarta, the International Maritime Organization, Tanjung Priok Port Authority, PT Pelabuhan Indonesia (also known as Indonesian Port Company), container terminal companies, Coordinating Ministry for Maritime and Investments Affairs, Ministry of Transportation, Pertamina, other container companies, port workers, and Indonesian citizens.

3.2 Model conceptualization

(1) System Diagram

A system diagram can be helpful in conceptualizing complex situations (Van der Lei *et al*., 2011; Thissen and Walker, 2013). Figure 1 shows a system diagram of a sustainable container terminal cluster system. The output indicators involve the concept of sustainability, which includes economic, social, and environmental aspects.

(2) Causal loop diagram

A causality diagram visualizes the relationship between various factors and illustrates their interactions to demonstrate how they produce a dynamic, circular effect in the real world (Haraldsson, 2004). Figure 2 shows a causal loop diagram of the container terminal cluster.

Loop R1 is a reinforcing loop that models the gross regional domestic product (GRDP) growth of DKI Jakarta and the development of container terminal clusters according to container flow and throughput. Suppose a significant number of companies establish factories and offices in the container terminal cluster area, container throughput increases. The growth of this loop is limited by the capacity of the container terminal cluster and container handling.

Loop R2 is also a reinforcing loop that models the increase in GRDP caused by the development of container terminal clusters according to household expenditures, increasing the number of companies in the container terminal cluster. A rise in the number of container terminal clusters causes an increase in employment opportunities, which, in turn, boosts household expenditures. This loop represents a form of sustainable growth; however, it is limited by the capacity of the container terminal cluster.

Loop B1 is a balancing loop illustrating that when the flow of containers increases, emissions from port activities also increase. Increased emissions negatively impact health, reducing the welfare of the community and hampering worker productivity, thus reducing the level of container flow.

Loop B2 is a balancing loop that describes the use of low-sulfur fuel, which can reduce emissions at container terminal clusters and improve public health and welfare. However, the high costs of low-sulfur fuel can be prohibitive, and the resulting increased shipping fares can harm public welfare.

3.3 Model development and testing

3.3.1 SFD model description. The stock and flow diagram model was developed from the causality diagram, which is a simulation model that provides additional detail and quantitative measurements. This study divided the stock and flow model into four sub-modules to facilitate understanding of the model structure. The four sub-modules include the economy, container terminal operation, environment, and fuel sub-modules.

The economy sub-module is divided into three model structures: the structure of the economy (Figure 3), labor (Figure 4), and economic agglomeration (Figure 5). The economic structure models the primary stock in the economic sub-model: the GRDP of DKI Jakarta.

Table 1. Actors involved in the system of container terminal cluster

Actor	Interest	Conflict	Situations and gaps that are occurring or are expected to occur	Cause of problems
Government of Indonesia	Local economic development, community welfare, and a clean environment	Economic development versus regulation compliance	There is a need for appropriate decarbonization policies to be implemented at container terminal clusters	High emission levels from container terminal activities, the obligation to use low-sulfur fuel, and economic and social aspects all must be considered
Provincial Government of DKI Jakarta	Local economic development, community welfare, and a clean environment	Urban development versus environmental sustainability	The air in Jakarta contains relatively high levels of Sox	Port activities, particularly the activities of ships docked at ports, generate considerable levels of emissions
The International Maritime Organization	Clean environment	Emissions reduction versus low-emission fuel price	Various efforts have been made to reduce emissions, but it still faces multiple obstacles	Low-sulfur fuel is more expensive, and there are costs for adapting ships to use new fuel
Tanjung Priok Port Authority	Port development and a clean environment	Port development versus environmental sustainability	There is a potential decrease in the volume of import and export goods	Increased costs that companies and customers must incur due to the adoption of low-sulfur fuel
PT Pelabuhan Indonesia or Indonesian Port Company	Affordable prices, business benefits, and port development progress	Port development versus increasing operational costs	Increased operating costs following the implementation of the low-sulfur fuel policy	Low-sulfur fuel is more expensive, and there are costs for adapting ships to new fuel
Container Terminal Companies	Business profit and port development	Business growth versus environmental sustainability	Each year, a new target is set for increasing the flow of containers; however, the resulting levels of emissions generated by these goals are very high	No decarbonization policy has considered the economic and social aspects, which is applied to the container terminal cluster
Coordinating Ministry for Maritime and Investment Affairs	Port development and a clean environment	Port development versus regulatory compliance	There is pressure to implement the latest policies, even though they generate various obstacles, especially for ports and shipping companies	Port and shipping companies must adjust to the use of low-sulfur fuel, which has the potential to increase port and shipping company expenses and shipping rates
Ministry of Transportation	Relations with international maritime organizations, port development progress, and a clean environment	Regulatory compliance versus shipping companies' interests	There is increasing pressure to adopt a low-sulfur fuel policy	Port and shipping companies must adjust to the use of low-sulfur fuel, which has the potential to increase port and shipping company expenses and shipping rates

(*continued*)

Table 1. Continued

Actor	Interest	Conflict	Situations and gaps that are occurring or are expected to occur	Cause of problems
Pertamina	Business profit and a clean environment	Regulatory compliance versus cost competitiveness	The company succeeded in producing low-sulfur fuel by the established policy standards, but this fuel is more expensive than fuel with high sulfur content	Low-sulfur fuel is more expensive to produce, and therefore, the sale price of the product will also increase
Container Companies	Business profit	Global competitiveness versus regulatory compliance	Container companies experienced a significant increase in spending	The necessity of using low-sulfur fuel, which is more expensive
Port Workers	Clean environment and community welfare	Welfare versus high emissions produced by ports	Workers work in an environment where air pollution is high enough to endanger their health	Port activities that generate emissions, mainly from ships while in port
Indonesian Citizens	Affordable prices, a clean environment, and community welfare	Affordable service price versus regulatory compliance	Increased costs in the delivery and transportation of goods due to the adoption of low-sulfur fuel	The use of low-sulfur fuel results in higher prices, and therefore, container rates for fuel are applied to customers

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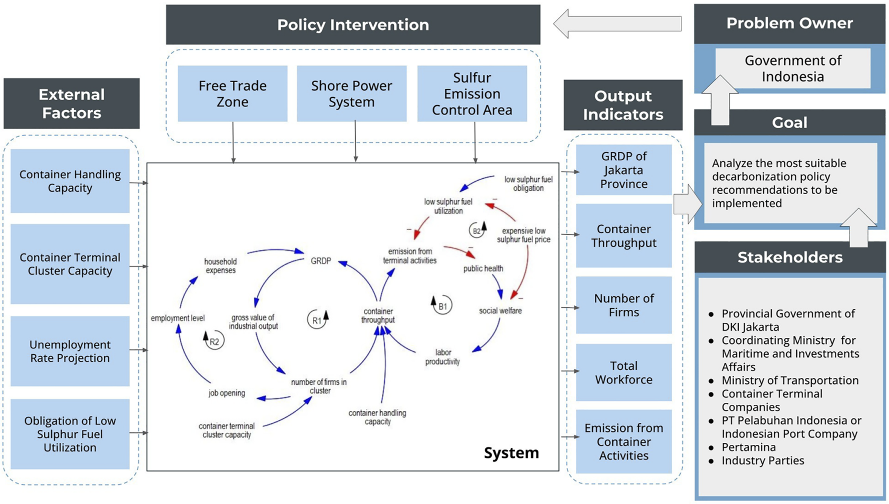

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Figure 1. Conceptual model of the container terminal cluster

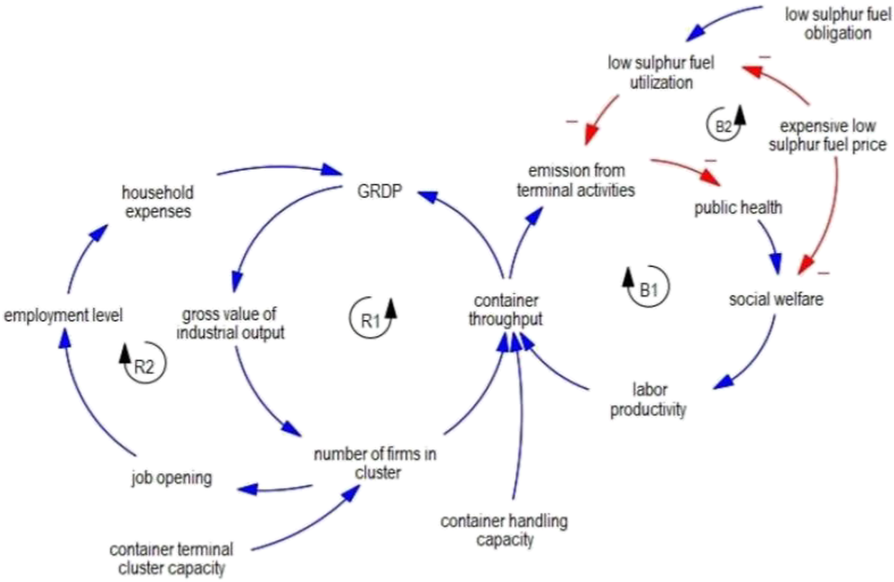

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Figure 2. Causal loop diagram of the container terminal cluster

The economic structure describes the effect of increasing container terminal activity at ports on economic growth as represented by GRDP. Container throughput and the income of workers employed within the container terminal cluster will increase annual GRDP growth. Moreover, GRDP stock increases through GDP flows in year t and decreases with GRDP flow in year $t-1$. The value of GRDP in year t is obtained from GRDP growth, household consumption, and the contribution of container export activities to GRDP.

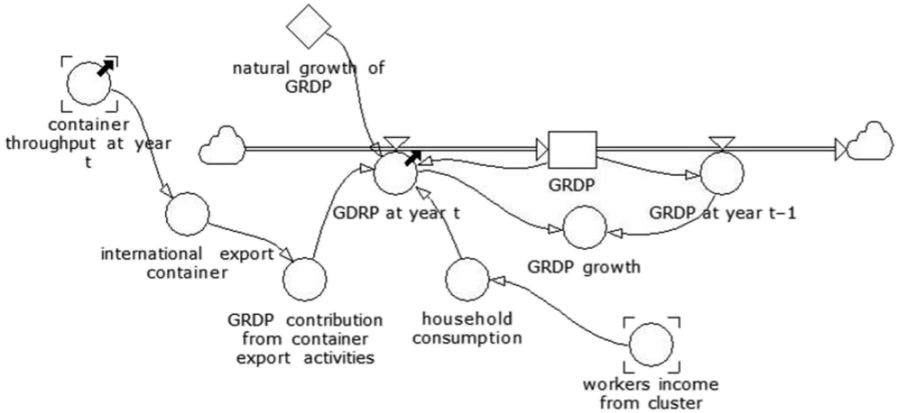

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Figure 3. Economic structure

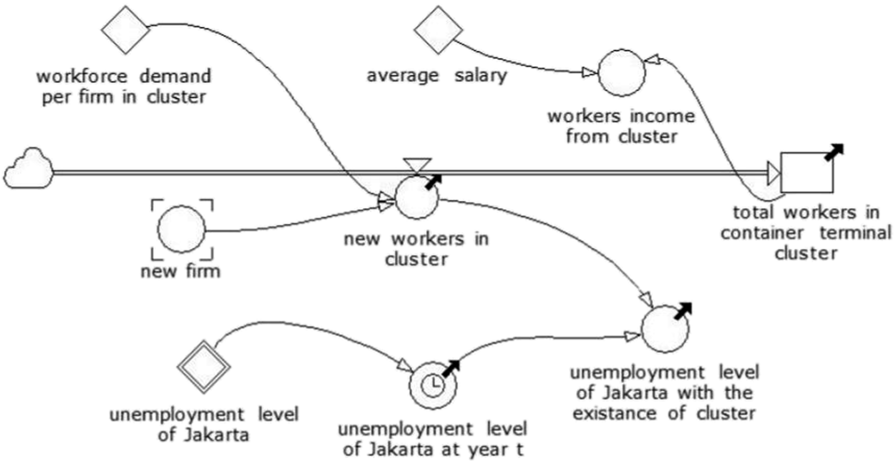

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Figure 4. Workforce structure

The workforce structure analyzes the number of workers employed at the container terminal cluster. This number of workers is obtained by adding the number of new workers in the container terminal cluster, which is obtained from the existence of new companies and the labor requirements of each company in the container terminal cluster.

The economic agglomeration structure describes an increase in the number of companies in the container terminal cluster due to economic growth. Although the number of companies is expected to increase alongside GRDP growth, the growth rate for the number of companies is limited by the available capacity for the companies.

The container terminal operation sub-model (Figure 6) models the flow of containers in the container terminal cluster. The value of container flows was obtained from the increase in container flows in year t, and it decreases with the presence of container flows in year $t-1$, where the value of container flows in year t is obtained from the growth rate of container flows, international container exports, and capacity container handling in year t.

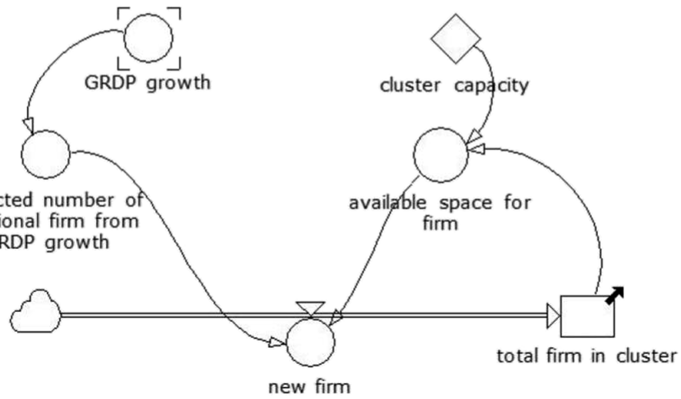

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Figure 5. Agglomeration economic structure

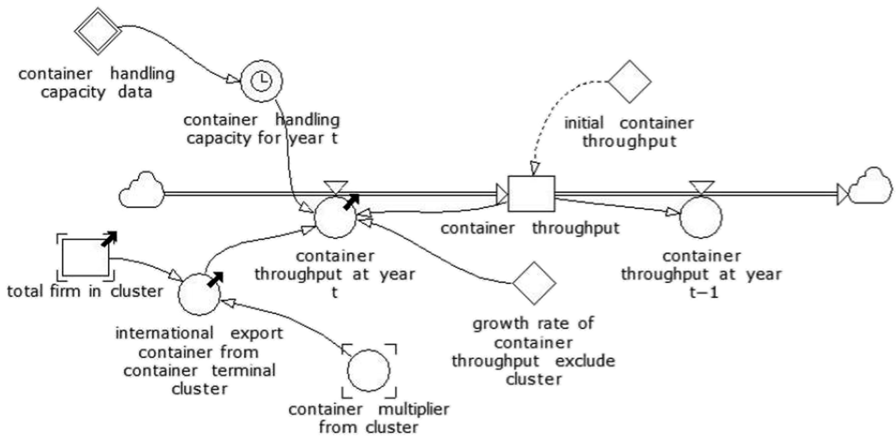

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Figure 6. Container terminal operation sub-model

The environmental sub-model (Figure 7) models various emissions produced by container terminal activities, including CO_2, SOx, NOx, PM, HC, and black carbon. High CO_2 emissions can lead to restricted activity days, including days spent in bed, days absent from work, and other days of limited activity due to illness. Any change in emissions concentration will affect the number of restricted activity days per person yearly.

The fuel sub-model (Figure 8) models the amount of emissions at container terminal clusters that could be avoided if ships were to use low-sulfur fuel, where emissions in year *t* are obtained from the emissions of each container ship, the average number of ships berthing at container terminal containers at the Tanjung Priok Port annually, and the percentage of emissions reduction that can be achieved by adopting low-sulfur fuel.

3.3.2 Model testing (verification and validation). Sterman (2000) has introduced several methods that can be used to test whether a model is verified and valid. The first method is dimension analysis, which aims to test whether the units used in the equations of the simulation model are consistent with one another. For this study, the model was built using PowerSim

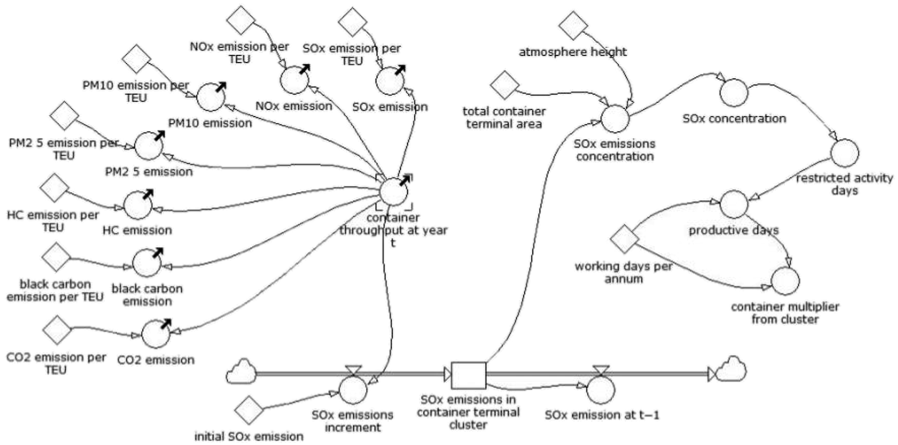

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Figure 7. Environment sub-model

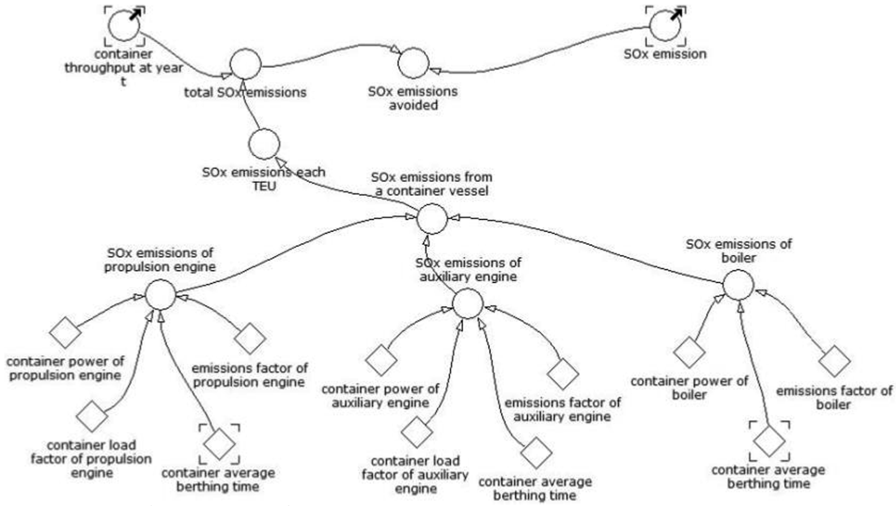

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Figure 8. Fuel sub-model

software, where the software no longer shows a red question mark. Thus, it can be concluded that the units used in the model were consistent with each other.

The second test is the error integration test (Figure 9), which aims to test the sensitivity level of the model simulation results for a certain simulation period. The variables tested in this validation test were DKI Jakarta's GRDP and container throughput variables. Models were simulated with time spans of 90, 180, and 360 days. The simulation results show that the variable values do not change significantly even when the model is simulated using different timeframes.

The behavioral reproduction test (Table 2, Figure 10) aims to test whether the relationship between variables in the simulation model is consistent with data in the real world. This test

Source(s): Authors' own work

Figure 9. Error integration test results of GRDP and container throughput

Table 2. Behavioral reproduction test result

	2016	2017	2018	2019	2020
GRDP (million rupiah)					
Real	14,109,948	14,984,765	15,900,334	16,825,733	16,428,646
Model	14,105,157	14,758,045	15,383,873	16,018,672	16,676,136
	0.03%	1.51%	3.25%	4.80%	1.51%
Final result	2.22%				
Container throughput (TEU)					
Real	6,222,798	6,925,046	7,640,312	7,660,485	6,921,750
Model	6,229,842	6,549,101	6,883,920	7,234,997	7,602,928
	0.11%	5.43%	9.90%	5.55%	9.84%
Final result	6.17%				

Source(s): Authors' own work

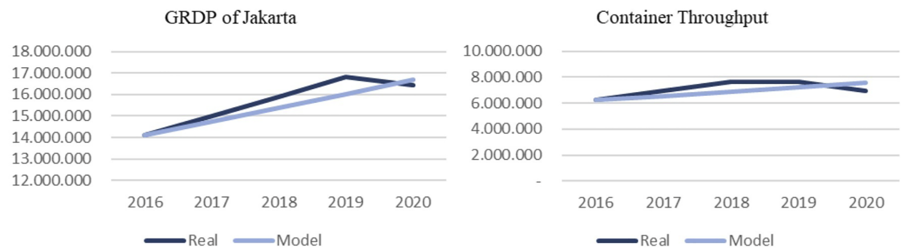

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Figure 10. Behavioral reproduction test results of GRDP and container throughput

compares variable values from real-world historical data with the simulated values in the model.

3.4 Scenario development

Due to future uncertainties, modelers cannot predict how a problem currently being analyzed will develop in the future. However, a modeler can investigate potential future outcomes by producing alternative scenarios (de Haan and de Heer, 2012). Using a PESTLE matrix, uncertain variables that can impact the container terminal cluster system at Tanjung Priok Port were identified. The identified variables are based on five categories:

politics, the economy, society, technology, law, and the environment. Subsequently, each variable was analyzed and placed within the impact matrix according to whether it possessed a high or low level of uncertainty and according to its impact on business development. This revealed five variables with high uncertainty levels and a strong impact on business development. Next, variables that are likely to be affected by various hypothetical scenarios were identified among these five variables. Table 3 shows the variables that will be affected by the hypothetical scenarios.

After the variables were identified, scenarios (Table 4) were developed by mapping the level of change for each variable based on the three phases that may occur in each scenario.

The first scenario, titled “All Things Get Better,” describes a situation where people in Indonesia have a higher level of immunity, and therefore, the situation improves, and industrial activities return to normal. Due to pandemic conditions, restrictions have been placed on people’s activities in recent years. In this scenario, when the situation normalizes, public consumption increases. This increase has a positive impact on increasing GRDP and container throughput. Positive economic growth also causes more investors to identify business opportunities and become interested in establishing businesses in the container terminal cluster. Meanwhile, the use of low-sulfur fuel begins to be implemented.

The second scenario, “Economic Down Trend,” describes an economic recession that changes people’s behaviors. Economic recessions occur suddenly and often unexpectedly. They also slow economic growth, reduce public consumption levels, and negatively impact public welfare. Due to financial stress, people are hesitant to spend money. This situation will motivate people to choose the cheapest option to meet their needs. Therefore, the adoption of low-sulfur fuel is hampered by its higher price, especially during unfavorable economic conditions.

The third scenario, titled “New Waves Emerge!” describes a situation where a new variant of the dangerous COVID-19 virus emerges. COVID-19 is a virus that continues to mutate and produce new variants. In this scenario, a dangerous, quickly spreading variant impacts operational activities at the container terminal. The economy experiences a significant downturn, and the potential for a crisis emerges. Many companies reduce their number of employees due to reduced income. Consequently, as people’s disposable income decreases, so does their consumption. Moreover, low-sulfur fuel is not widely adopted because shipping companies suffer from a poor economy.

After the scenarios were created, experimental variables were formulated to be used as interventions in the model. The variables formulated are the five predetermined affected variables, and each variable value is divided into three phases: initial, middle, and final. The initial phase encompasses 2020–2025, the middle phase is 2026–2032, and the final is 2033–2039.

Table 3. Table of variables that will be affected by the hypothetical scenarios

Variables with high levels of uncertainty and high impact on business	Variables in the affected model
Increased growth of GRDP	The natural growth of GRDP
Increased growth in container flows	Growth rates of container throughput
The growth rate of workforce absorption	Workforce demand per firm in the container terminal cluster
Growth in the number of firms establishing their business in container terminal clusters	Total firms in the cluster
Increased emissions due to container terminal activities	SOx emissions per TEU

Source(s): Authors’ own work

Table 4. Experiment variables for scenario analysis

Scenario	Title	Phase	Natural growth of GRDP (%)		Growth rate of throughput (%)		Workforce demand (%)		Total firm in cluster (%)		SOx emission (%)	
Scenario 1	All Things Get Better	Initial	High	101–102	High	102–103	Low	0	Low	0	Minus	20–25
		Middle	High	105–106	High	106–107	High	105–107	High	103–105	Minus	40
		Final	High	106–107	High	115–120	High	109–112	High	107–110	Minus	50
Scenario 2	Economic Down Trend	Initial	Minus	10–15	Minus	5–10	Low	0	Low	0	Minus	15–20
		Middle	Minus	5–10	Minus	1–5	Low	0	Low	0	Minus	20–25
		Final	Minus	1–5	Low	0	Low	0	Low	0	Minus	30–35
Scenario 3	New Waves Emerge!	Initial	Minus	40–45	Minus	20	Minus	20–25	Minus	5–7	Minus	5–10
		Middle	Minus	20–25	Minus	10–15	Minus	15–20	Minus	2–3	Minus	10–15
		Final	Minus	10–15	Minus	5–10	Minus	5–10	Low	0	Minus	15–20

Source(s): Authors' own work

4. Results and discussion

The model simulation covers a period of 20 years, from 2020 to 2039. The results are then presented in the business-as-usual condition, the scenario analysis conditions, and the policy analysis conditions.

4.1 Scenario analysis

In the first scenario (Figure 11), the GRDP value and container throughput initially experienced a slight increase. And then, in the following years, both values increased significantly. The number of companies and workers remained constant in the initial phase. Moreover, although these numbers should have increased during the middle and final stages, their growth was limited by the capacity of the container terminal cluster. Meanwhile, SOx emissions decreased significantly and further during the final phase.

In scenario 2 (Figure 12), the GRDP value and container throughput both decreased. The number of companies and workers remained constant with no recorded change. Meanwhile, SOx emissions decreased rather significantly, although not as significant as the emissions

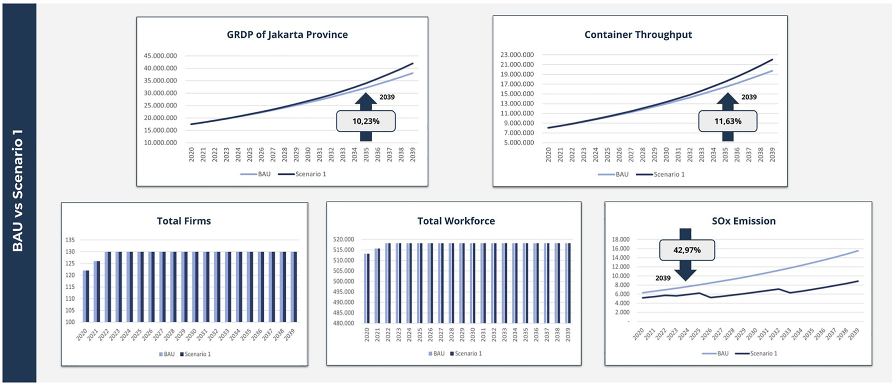

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Figure 11. Simulation results of BAU vs Scenario 1

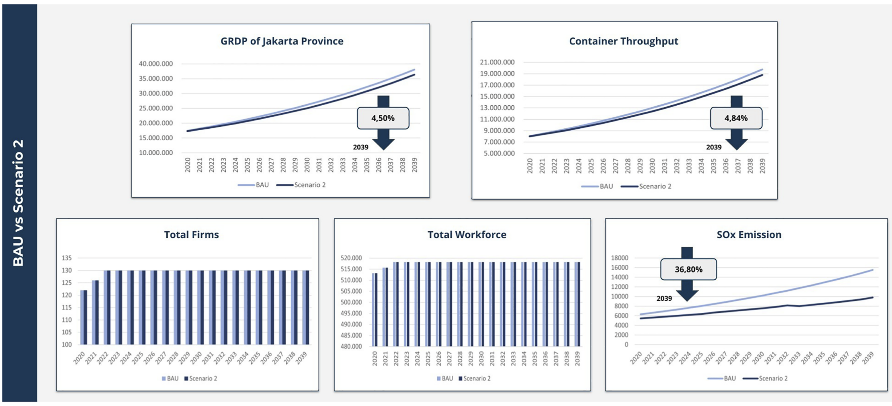

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Figure 12. Simulation results of BAU vsddd Scenario 2

reduction in Scenario 1. This is because, in Scenario 2, the adoption of low-sulfur fuel was hampered by an economic downturn.

In the third scenario (Figure 13), the GRDP value and container throughput decreased significantly. The number of companies decreased but then began to recover the following year. The number of workers decreased quite considerably due to companies laying off workers. SOx emissions also decreased because of a decrease in container throughput. In addition, the reduction in SOx emissions was due to using low-sulfur fuel, which has been implemented on a limited scale.

4.2 Policy analysis

This study developed three policy alternatives—the free-trade zone, shore power system, and sulfur emission control area policies—while exploring various combinations of these policies. The free-trade zone policy is designed to establish import duty exemptions. The shore power system policy is intended to supply electricity to ship barns to reduce emissions generated when ships are anchored at port. Finally, the sulfur emission control area policy establishes areas where low-sulfur fuel must be used.

According to the simulation, implementing the free-trade zone policy would increase the number of container terminal clusters from 130 to 250. Moreover, it would cause an increase in the number of firms, which is represented by the conversion factor in the estimated variable of additional firms. The simulation also found that the free-trade zone policy would increase both GRDP and container throughput. The level of emissions would also increase accordingly. Total workforce growth would increase significantly alongside the number of firms.

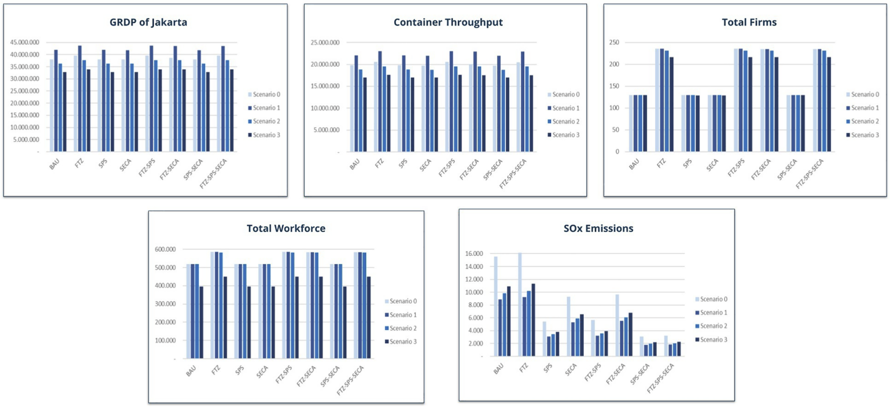
Implementing the shore power system policy would decrease the levels of various types of emissions. More specifically, it would decrease SOx emissions by as much as 65%, CO_2 by 55%, NOx by 50%, PM by 40%, HC by 30%, and black carbon by 65%. Indeed, the shore power system policy would significantly minimize various emissions.

Implementing the sulfur emission control area policy would decrease SOx emissions by as much as 40%. It would also reduce GRDP during the initial phase and cause the impact of low-sulfur fuel surcharge against the decrease in container throughput to emerge. Therefore, the sulfur emission control area policy would significantly minimize SOx emissions and slightly decrease GRDP and container throughput.

After each policy's simulation results were obtained, the combinations of the policies were simulated (Figure 14). The combination of the three policy alternatives is the most advantageous policy alternative because it provided the most robust simulation results and produced the second lowest emission levels, the second highest economic value, and the

Source(s): Authors' own work

Figure 13. Simulation results of BAU vs Scenario 3



Source(s): Authors' own work

Figure 14. The combination of various scenarios and simulated policies

second highest social value. The second-best policy alternative is the combination of the free-trade zone and shore power system policies because this combination produced the highest GRDP and container throughput, as well as the highest number of companies and workers while also achieving the fourth-lowest emission levels. In addition, the third-best policy alternative is the combination of the free-trade zone and sulfur emission control area policies because this combination produced the third-highest economic value and the second-highest social value while also achieving the sixth-lowest emission levels.

This study bridges the gap in integrating system dynamics with actor, scenario, and policy analysis in studying decarbonization policies in the context of low-sulfur fuel regulations in container terminal clusters, considering economic, social, and environmental impacts. System dynamics enabled the exploration of feedback loops and trade-offs across economic, social, and environmental dimensions. For instance, although the top policy alternative did not achieve the lowest emissions, its robust economic and social outcomes make it the most advantageous choice. This finding provides policymakers with a clear understanding of the trade-offs between various policy interventions and their outcomes, offering a framework for sustainable decision-making in the maritime industry.

5. Conclusions and policy implications

The International Maritime Organization (IMO) established a policy on January 01, 2020, that calls for adopting low-sulfur fuel. This regulation sets the maximum sulfur content of ship fuel at 0.5% v/v. Mandating the use of this fuel is designed to significantly reduce the emissions generated by port activities, especially SOx emissions. Tanjung Priok Port, Indonesia's largest and busiest container terminal, was used as a reference for developing a decarbonization implementation model. This study discussed the issue of decarbonization at container terminal clusters following the establishment of a policy mandating the use of low-sulfur fuel. In this study, decarbonization is addressed in relation to questions of sustainability, mainly environmental, economic, and social sustainability.

This study employed a system dynamics method to produce a container terminal decarbonization model that describes how decarbonization policies affect various economic and social aspects of container terminal clusters. In addition, actor and scenario analysis were incorporated into this study to gain a deeper understanding of decarbonization at container terminal clusters. The actor analysis revealed that 12 actors played a role in sustainability issues at the Tanjung Priok Port after a low-sulfur fuel policy was implemented.

The system dynamics model developed in this study demonstrated that decarbonization policies impact economic growth (reflected in DKI Jakarta's GRDP and container throughput), social welfare (the number of companies and employment growth), and environmental quality (emissions reduction). Several scenarios were analyzed, reflecting different future conditions, including economic recovery, downturn, and pandemic emergence.

Several policies were developed and analyzed to identify the policy that can best optimize economic, social, and environmental factors. These policies include the free-trade zone, shore power systems, sulfur emission control areas policies, and a combination of them. The simulation results show that mandatory low-sulfur fuel can raise fuel prices and negatively impact GRDP and container throughput, hindering the growth of companies and employment. However, it can contribute to a significant reduction in SOx emissions.

The scenario and policy analyses found that a combination of the three analyzed policies is the most advantageous policy for container terminal clusters because it can support sustainability, including economic, social, and environmental sustainability. The combination of the free-trade zone and shore power system policies produced the second-best results. Finally, the combination of the free-trade zone and sulfur emission control area policies produced the third-best results. However, it should be noted that the use of low-sulfur fuel is a requirement that has been established internationally by the IMO. At the same time, the shore power system is not required.

On its own, the free-trade zone policy can support economic growth by increasing container throughput and GRDP. The shore power system policy can significantly reduce various types of emissions. Meanwhile, the sulfur emission control area policy can significantly reduce SOx emissions; it does, however, slightly reduce economic value. However, the sulfur emission control area policy can help optimize the use of low-sulfur fuel because the use of this fuel is mandatory.

The findings offer valuable insights for policymakers, government, and port authorities to design and implement effective decarbonization strategies. Combining multiple policy measures supported by technological advancements can help balance the economic, social, and environmental goals. Future research could explore the integration of technology adoption into port operations, its economic feasibility, and the effectiveness of government subsidies in fostering the adoption. In addition, research should investigate the resilience of decarbonization policies under dynamic economic and environmental conditions, such as fluctuating fuel prices or changing decarbonization pathways.

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Further reading

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