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System Dynamics Based Analysis Of Multimodal Port Accidents

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Abstract

The resilience of Container Supply Chains (CSCs) has gathered increasing interests in maritime transportation research. However, as a multimodal transshipment hub, the influence of port failures is underemphasized, leaving a persistent challenge. Therefore, this paper aims to develop a novel framework to examine the impact of port accident on operations across diverse transportation sectors in port. Implemented with various variables, indictors, relationships, a micro-level system dynamics model is established. According to the discovery of field investigation, real accidents data is analyzed to create disruptive scenarios. The findings reveal the that accidents damaging quay cranes failure and causing traffic congestion in the yard have a more crucial impact on the efficiency of port operation. Notably, congestion in the yard area is observed to propagate via internal trucks, leading to delays in seaside operations. The presence of ripple effect further underscores the significance of this research. By analyzing various scenarios, the model enhances the understanding of risk propagation mechanisms in the multimodal container terminal, highlighting the critical need for rational port safety management.

Keywords: port disruption, container supply chain, system dynamics, ripple effect, maritime resilience

1. Introduction

Recent advancements in container supply chains (CSCs) accessibility have significantly impacted the international logistics industry. Seaports, critical for container transshipment and connecting various transportation modes (Zhou et al., 2022), are pivotal for CSCs resilience against disruptions. However, ports, due to their high uncertainty and risk susceptibility (Jiang et al., 2021), are considered a major bottleneck in CSCs efficiency. In addition, their strategic location and role in multimodal CSCs not only expose them to diverse risks but also facilitate risk propagation across the CSCs, amplifying both direct and indirect losses (Verschuur et al., 2022, Koks and Thissen, 2016). Therefore, it is essential to investigate how the failure in one element of port operations affects other parts.

Port resilience has suffered due to catastrophic events like climate change, disease outbreaks, and economic crises, causing disruptions and economic losses in CSCs. In the meantime, secondary failures from these disruptions often surpass the direct damage, as indicated by multiple studies illustrated in Table 1. In order to prevent the influence of potential accidents, this paper aims to develop a novel model that can facilitate the understanding of risk propagation mechanism of port operations.

Table 1. Indirect and direct cost CSC disruptions.

	Risk Type	Direct Damage	Network Damage
Hurricane Katrina 2005 (Trepte et al., 2014)	Natural Disaster	1,833 fatalities; $108 billion	45% cargo tonnage; $882 million loss on agriculture; food price surged
Typhoon Maemi 2004 (Lam et al., 2017)	Natural Disaster	107 injured; $4.8 billion	91 days port close; $96 million

Tropical Cyclone Debbie 2017 (Lenzen et al., 2019)	Natural Disaster	14 fatalities; $2.67 billion	8487 jobs; AUD 2203 million
Piracy (Gong et al., 2023)	Man made	Cargo loss; crew kidnaped or killed	$7-12 billion per year including ransoms, insurance, rerouting, security cost

A comprehensive review of CSCs resilience literature highlights three main research gaps. First, the role of ports as multimodal transshipment hubs is often underexplored compared to vessel collisions, complex waters, and shipping routes (Angeloudis et al., 2013, He et al., 2015, Guerrero et al., 2022, Verschuur et al., 2022, Wan et al., 2022). Second, while existing studies focus on a macro perspective of port resilience (Liu et al., 2023, Wang and Wang, 2023), there's a lack of detailed analysis on straightforward cause and effect rules. Third, the cascading effects of port disruptions on other CSCs transportation modes requires further research. These findings underline the urgent need for a new model that quantifies the causal relationships of disruptions in multimodal CSCs from a port-centric view.

Port operations are highly dynamic and sensitive to disruptions. Equipment failure can lead to vehicle and vessel accumulations and potentially causing widespread congestion. Addressing the resilience of port operations from a CSCs perspective requires understanding multiple causal relationships within a complex system. While various methods, such as scenario-based preference modelling (Almutairi et al., 2019), digital twin (Zhou et al., 2021), heuristic method (Zohoori et al., 2023), micro-simulation (Dhanak et al., 2021), focus group (Islam et al., 2021), mathematical modelling (Xiao and Bai, 2022, Zhen et al., 2022), case study (Rogerson et al., 2022, Kim et al., 2021), network theory (Rousset and Ducruet, 2020) have been used in port resilience analysis, system dynamic (SD) emerges as particularly effective in representing complex causation through feedback loops, depicting variables evolution over time, modeling risks and uncertainties through various scenarios. Therefore, SD is chosen for analyzing port operations and potential risk propagation, offering a comprehensive view of system behaviors and interactions.

The aim of this paper is to model and investigate the impact of port accidents on container terminal operation. Therefore, an SD model is constructed to simulate the performance of port operations. This study can fill in the gaps under the context of a multimodal CSCs of port resilience analysis, highlighting the unconsidered but necessary effect of risk propagation. In addition, quantitative data based on real operation provides practical insights. Besides, the risk mitigation strategies derived in this research are beneficial for various stakeholders, where systematic countermeasures can be generated to stabilize and promote the development of CSCs. The contributions of this research are outlined below.

1. An innovative port-based system dynamics model is designed to simulate the repercussions of port accidents across multiple segments of the CSCs. The outcomes of the simulation underscore the crucial role of port as a transshipment hub, establishing the significance of this research.
2. This research introduces a pioneering framework for modelling port operations from a micro-level perspective. It comprehensively integrates various quantitative variables and performance indicators, including feedback mechanisms and interdependent relationships derived from field investigation, thereby ensuring the precision and reliability of the model’s construction and simulation.
3. To accurately examine the impact of port accidents, this model accounts for the ripple effect across different segments of port operations. It demonstrates the indirect damage and enhances the comprehension of risk propagation dynamics across the entire port ecosystem.

The research is structured as follows. In Section 2, the causal loop diagram and stock and flow chart of container terminal are established based on real operation logic; key variables and performance indicators are determined based on expert opinions. In Section 3, risk scenarios and numerical experiments are carried out for sensitivity analysis. In Section 4, the conclusions are summarised.

2. Methodology: Port-based system dynamics model

The research framework is shown in Figure 1, outlining the key steps towards the research aim defined above. They include the analysis of effect of disruptions, indicator identification and relationship analysis, SD model development, and scenario design and implication generation.

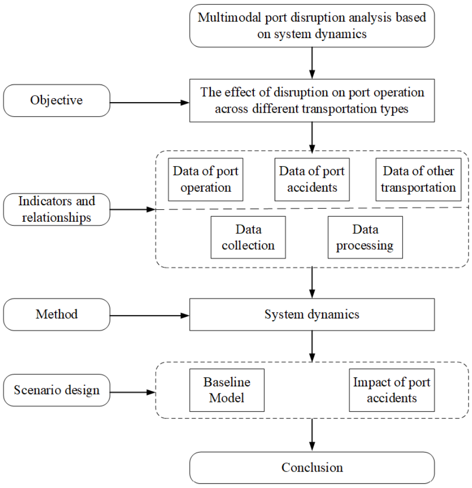


Fig. 1. Research framework.

2.1. Model framework: causal loop diagram

A system dynamic model is developed based on the following settings according to a real case study: 1) In terms of requiring loading and unloading services, there are two types of major transportation considered in this research: international liner vessels and trucks; 2) Two types of activities share the service of internal trucks; 3) The condition of terminal resources can influence the working efficiency of loading and unloading activities; 4) Key variables, performance indicators are all generated based on the past literature and expert experience; 5) As a transportation hub, inbound containers are received by deep-sea vessels and further distributed through trucks; conversely, outbound containers are accumulated in storage yards by trucks and subsequently shipped out by linear ships.

Based on above settings, the causal loop diagram of this research in shown in Figure 2.

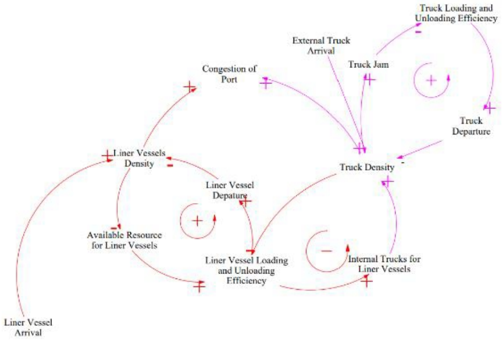
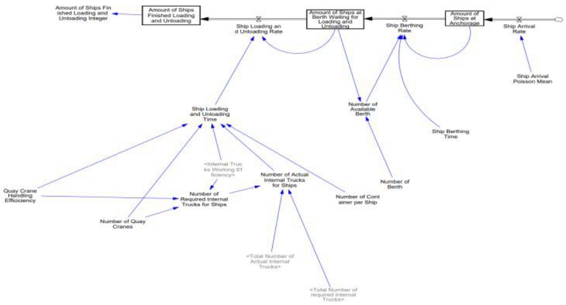


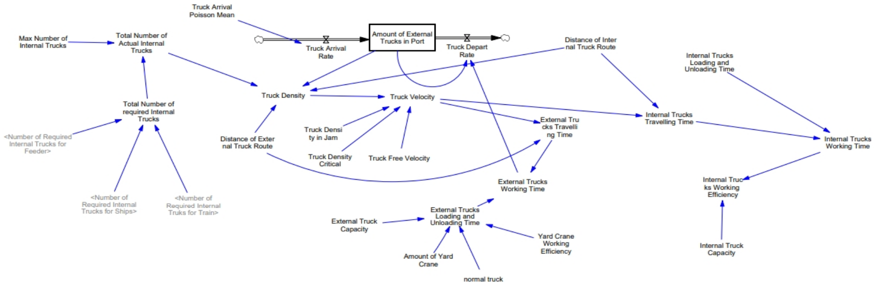
Fig. 2. Causal loop diagram of the model.

2.2. Stock and flow diagram

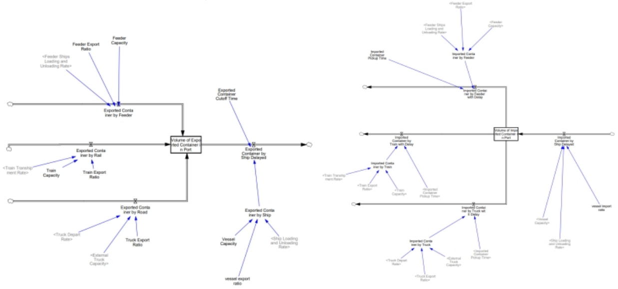
Based on the causal loop diagram, the dominating modules impacting the efficiency of port operations are identified. Then the abstract causal loop diagram is expanded to a stock and flow diagram representing quantitative variables. The stock and flow diagram is constructed using Vensim PLE, as illustrated in Figure 3. According to industrial standards and expert opinions, the key performance indicators for port operations are related to the service level, the usage of port equipment, and the accumulation of container inventory. This research involves 2 different transportation types, therefore stock variables are set to reflect the efficiency of handling linear vessels and container trucks, as detailed in Table 2. Due to space limitation, only the main equations are listed in Table 2.



(a) linear shipping vessels



(b) external and internal trucks



(c) container inventory

Fig. 3. Stock and flow diagram.

Table 2. Main performance indicators.

Category	Variable	Corresponding Index	Unit
Liner vessels	Number of waiting linear vessels	Amount of Ships at Anchorage = INTEG(INTEGER(Ship Arrival Rate - Ship Berthing Rate), 0)	Vessels
	Number of occupied liner vessels berth	Amount of Ships at Berth Waiting for Loading and Unloading = INTEG(INTEGER(Ship Berthing Rate - Ship Loading and Unloading Rate)), 0)	Vessels
Trucks	Number of external trucks in port	Amount of External Trucks in Port = INTEG(INTEGER(Truck Arrival Rate - Truck Depart Rate),0)	Trucks
	External truck turnaround time	External Trucks Working Time = Distance of External Truck Route/Truck Velocity + External Trucks Loading and Unloading Time	Hours
	Truck Density	Truck Density = (Amount of External Trucks in Port + Total Number of Actual Internal Trucks)/MAX(Distance of External Truck Route × 4, Distance of Internal Truck Route × 4)	Trucks/km
Containers	Number of export containers	Volume of Exported Container in Port = INTEG(Exported Container by Road - Exported Container by Ship Delayed, 0)	Containers
	Number of import containers	Volume of Imported Container in Port = INTEG(Imported Container by Ship Delayed - Imported Container by Truck with Delay, 0)	Containers

3. Case study and analysis

3.1. Data collection and data process

In order to assess the effectiveness and vadality of the proposed system dyanmics model, a worlding leading multimodal container terminal is selected as the researched subject. This particular port plays an important role in integrating and distribuing containers in East-Northen Asia. It represents typical operations in a container terminal and the analysis of accidents occurred in this terminal offers valuable insights and lessons. In order to gather the relavant data for the research, field investigation combined with export interviews over a long-time span was conducted. The data is grouped into four subsystems: trucking subsystem, liner shipping subsystem, export and import containers subsystem and port accident subsystem. Collected data are used as input in the model to generate exogenous variables. A detailed setting of main exogenous variables is shown in Table 3.

Table 3. Exogenous Variables (Main).

Subsystems	Variable	Unit	Estimation	Source
Trucking system (Yard system)	External truck arrival rate	TEU/hour	RANDOM POISSON(0, 1500, 500, 0, 1, 1)	Statistics based on real data
	Distance of external truck route	Km	5	Real data
	Truck density in Jam	Trucks/km	60	Average real data
	Internal truck loading and unloading time	Hour	0.05	Averaged real data
	Amount of yard crane	Cranes	48	Real data
Liner Shipping system	Liner ship arrival rate	TEU/hour	RANDOM POISSON(0, 3, 1.5, 0, 1, 0)	Statistics based on real data
	Number of berth	Vessels	16	Real data
	Number of quay cranes	Cranes	6	Real data
	Number of containers per ship	Containers/ vessel	RANDOM UNIFORM(1000, 3000, 4)	Statistics based on real data
Import and export system	Export container cutoff time	Hour	120	Averaged real data
	Import container pickup time	Hour	72	Averaged real data

Firstly, port accident data, spanning the past 20 years from 1998 to 2021, are collected through accident reports. Secondly, these accidents are further categorized based on the responsible party. Thirdly, given the unique and sudden nature of these risks, the causes and their impact of typical incidents are determined with the assistance of expert opinions, as presented in Table 4. Accidents caused by yard cranes, truck drivers and quay cranes are specifically selected and given much attention due to their frequent occurrence, typical resemblance, and siginificant consequence.

Table 4. Consequence of typical accidents.

Consequence	Cause	Quay crane	Yard crane	Container trucks
Liner Shipping	Quay crane out of order	√		√
	Inefficiency of quay cranes	√		√
Yard area	Yard crane out of order		√	√
	Inefficiency of yard crane		√	√
	Traffic jam		√	√

3.2. Model verification

As an essential component of the system dynamics model, model verification and validation are conducted following the established steps from previous literature.

- **Structure and parameter test**

Based on expert opinions from industries and academia, the selection of variables and performance indicators are confirmed to be reasonable. In addition, the causal relationships and feedback loops are authenticated according to actual situation of the port.

- **Extreme condition test**

In order to examine whether the performance of the model coincides with expectations under extreme situation, some input values are altered. The result shows that the behaviors of the model are predictable, for instance, the number of waiting vessels grow exponentially when the number of yard cranes is low.

- **Dimensional consistency test**

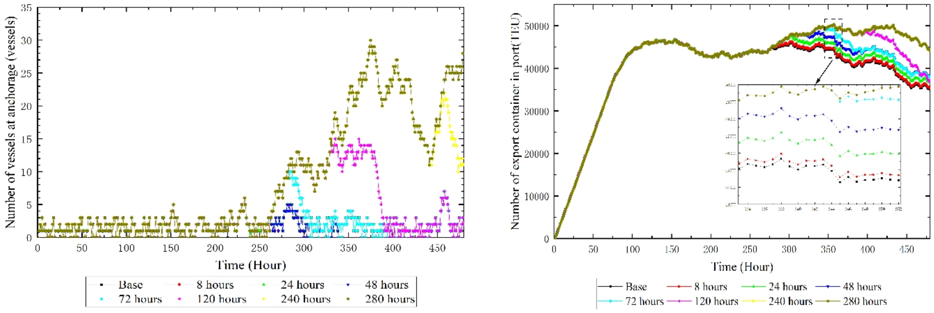
The proposed model has passed the dimensional consistency test by deploying “UNIT CHECK” tool provided in Vensim PLE.

- **Validity test**

To prove that the proposed model can simulate port operations accurately, simulated data is compared to real data. The simulated results exhibit variations within the range of -10% and 10% which falls within an acceptable range. It is important to note that this limitation is possibly caused by potential data accuracy loss associated with the use of statistical data and averaged data. However, it does not interference with the development of conclusions as the trends of disruption remain discernible.

3.3. Liner shipping accident scenario

Accidents occurring in the liner shipping area can cause the loss of quay cranes or disruptions in loading and unloading efficiency. In aligning with the structure of the model, the impact of accidents is reflected by a reduction in the operational quay cranes and a limitation in quay crane handling efficiency. All of these changes will take effect after the operation flow is rather stable (at the 200-hour time point). In order to illustrate different scales of failure and the lasting time of failures, the number of quay crane is reduced by 1 lasting for 8 hours, 24 hours, 48 hours, 72 hours, 120 hours, 240 hours and 20 hours (simulation terminates), as shown in Figure 4. Additionally, the quay crane handling efficiency is altered from 0% to -40% with 10% decrease for 8 hours (one shift), as shown in Figure 5.



a b

Fig. 4. (a) Number of vessels waiting in anchorage; (b) number of export containers stored in the yard when the number of quay crane decreases by 1.

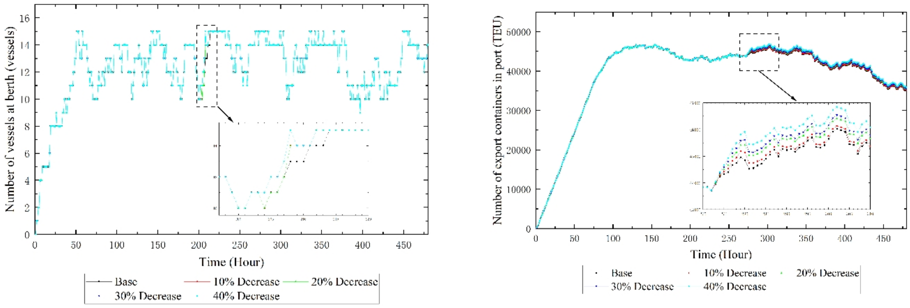


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Fig. 5. (a) Number of vessels in the berth; (b) number of export containers stored in the yard when the efficiency of quay crane decreases from 0% to 40%.

Notably, as seen in Figure 4, the loss of 1 quay crane leads to longer waiting time for vessels spend in the anchorage and significantly growth in the accumulation of vessels, peaking at 30 ships when exceeding120 hours. Meanwhile, the damage of quay crane not only affects seaside operations but also lead to an increase in container volume within the yard, with an increase of up to 5000 TEUs, thereby occupying limited port resources. As shown in Figure 5(a), more berths and extending berth time are needed as the efficiency of the quay crane decreases over an 8-hour period. Although the disruption is short and comparably mild, the inventory of containers still depicts an upward trend. Moreover, with the passage of time, the impact becomes more evident, indicating the existence of potential bullwhip effect. These observations underline the importance of quay crane as an indispensable port asset which should be preserved and maintained with care.

3.4. Yard area accident scenario

Incidents happened in yard area can cause reduction in yard crane quantity, restriction in yard crane handling efficiency and more importantly, traffic congestion which could spread to other components. To evaluate the effect of yard area accidents and demonstrate the scale and duration of the disruptions, the value of the following key variables is adjusted: the number of yard cranes is reduced by 1 for 8 hours, 24 hours, 48 hours, 72 hours, 120 hours, 240 hours and 20 hours (simulation terminates), shown in Figure 6; the efficiency of yard cranes is modified for 8 hours from 0% to -40% with 10% decrease, seen in Figure 7.

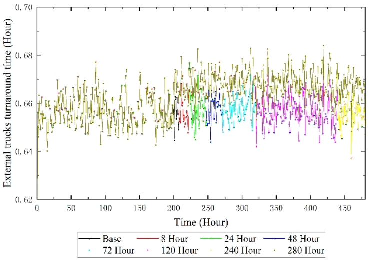
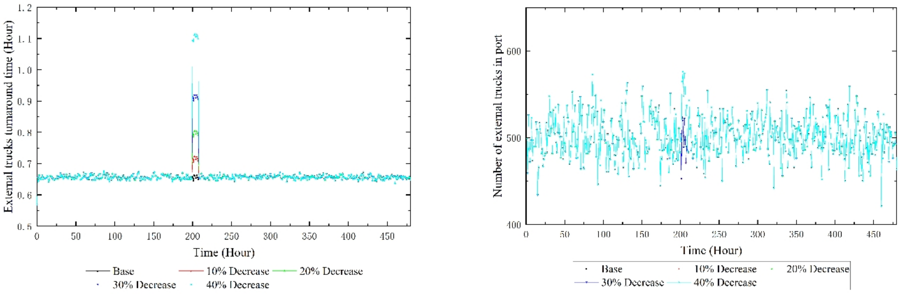


Fig. 6. External truck turnaround time when the yard crane is decreased by 1.



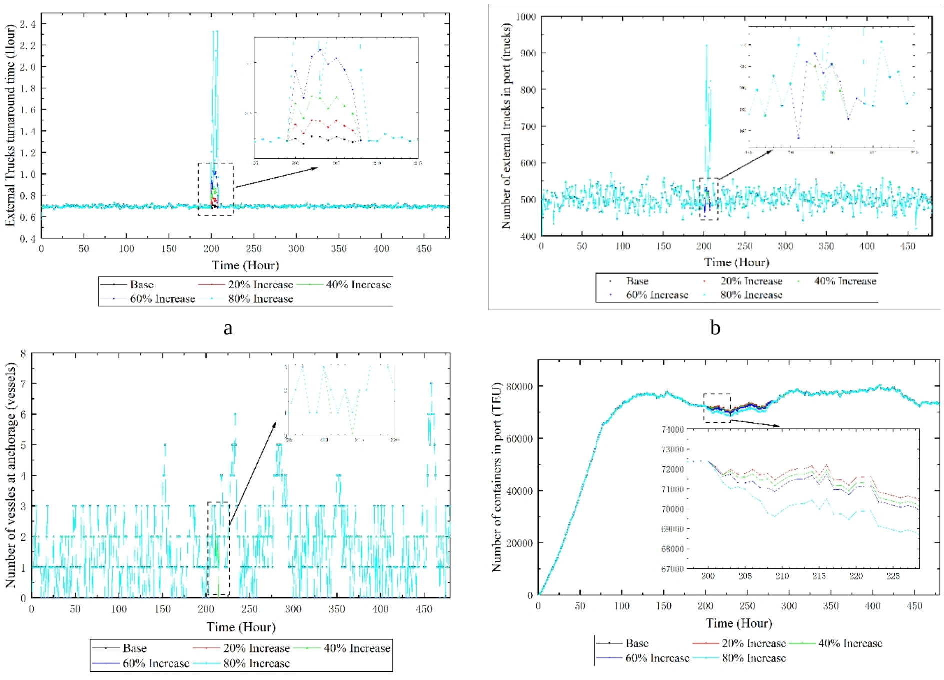
a

b

Fig. 7. (a) External truck turnaround time; (b) Number of external trucks in port when the efficiency of yard crane is decreased for 8 hours.

As shown in Figure 6, the truck turnaround time, as an essential indicator concerned by multiple stakeholders, increases by about 5% (about 2 minutes) when 1 less functional yard crane is available. This result coincides with the actual observation when investigating the optimal yard cranes number to achieve desired truck turn time (Huynh et al., 2004), further validating the effectiveness of the proposed model. Meanwhile, as depicted in Figure 7(a), the turn time increases from about 40 minutes to over 1 hour gradually when the efficiency of yard crane is decreased. Additionally, extended turnaround time causes the accumulation of external trucks in the port. However, compared with the disfunction of quay cranes, the influence of yard cranes breakdown is controllable, reflecting the resilience of port operations when facing yard crane risks.

Particularly, in order to understand the negative impact of traffic jam in port, the severity is measured in two ways. In the perspective of scale, truck density is altered from 0 % (normal traffic flow) to 80% (congestion) with 20% increase, seen in Figure 8. While in the perspective of duration, the traffic jam is modelled to last from 8 hours to 48 hours with 8 hours increase, as shown in Figure 9.



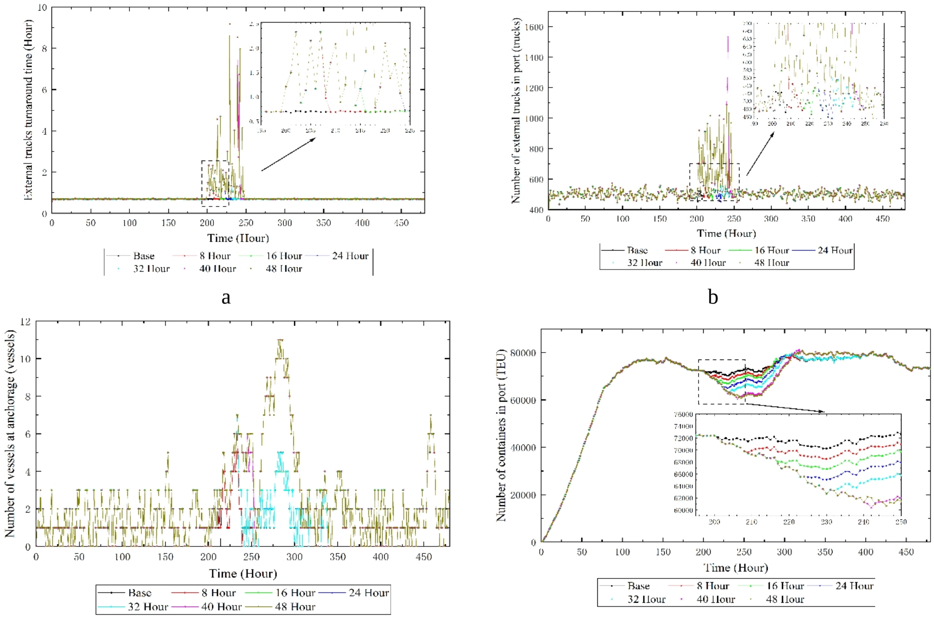
a

b

c

d

Fig. 8. (a) External truck turnaround time; (b) number of external trucks in port; (c) number of vessels at anchorage; (d) number of containers in port when truck density increases for 8 hours.



a

b

c

d

Fig. 9. (a) External truck turnaround time; (b) number of external trucks in port; (c) number of vessels at anchorage; (d) number of containers in port when truck density increases by 80%.

As shown in Figure 8(a), congestion within port area directly leads to an increase in the turnaround time for external trucks, rising from about 40 minutes (well-regulated traffic) to over 2 hours (heavily congested). Consequently, in Figure 8(b), the number of external trucks in port doubles, forming a negative feedback loop. These results not only affect the traffic condition in the yard area, but also spread to the seaside operations as shown in Figure 8(c) where more berths are occupied by vessels due to decreasing loading and unloading efficiency. In addition, the impact of the accident occurred in one section has a delayed effect on other parts. For instance, as illustrated in Figure 8(d), due to the accident happens between 200th and 208th hour, the quantity of containers at the port fluctuated between the 200th and 300th hour, subsequently returning to a normal state gradually.

Furthermore, Figure 9 offers a depiction of scenarios where the truck density is increased by 80% over varying durations, aimed at examining the robustness of port operations under disruptive events of different time scales. As shown in Figure 9(a), the turnaround time for external trucks rises exponentially from 40 minutes to over 8 hours when the disruption extends, causing massive truck blockage in the port, as illustrated in Figure 9(b). Above all, the disruption propagates to seaside operations where the number of waiting vessels in the anchorage raises from an average of 2 to over 10. Meanwhile, the performance of seaside operations rebounds to normal levels 100 hours following the cessation of the disturbance, demonstrating the lagging effect and ripple effect at the same time. Similar phenomenon is observed when investigating the volume of container inventory. As a whole, these figures prove the lagging effect and ripple effect across multiple operational areas in port, revealing the vulnerability of port when faced with accidents. This insight provides valuable guidance for port operators in understanding the potential consequence of certain risks, thereby boosting their awareness for risk prevention and the deployment of risk mitigation measures.

4. Conclusion

In this study, a novel system dynamics model is developed aimed at facilitating the comprehensive understanding of how port accidents can impact the operations of a multimodal container terminal. This methodology introduces several innovative features, including 1) this research proposes a system dynamics model to investigate the resilience of CSCs in the context of often underdiscussed yet essential port accidents; 2) this study illustrates the port operations in a micro-level view, enabling a more detailed characterization of quantitative port activities; 3) the proposed model not only considers the direct damage of port accidents, but also the ripple effect across different transportation sectors. The model is validated through several tests using real operational data. According to the experiment, the result demonstrates the effectiveness and superiority of the proposed model. More importantly, it reveals the bottleneck and weakness of current port operations through sensitivity analysis of different risky areas. In addition, the lagging effect and ripple effect of port accidents are illustrated in the simulation through prolonged destructive indirect damage, promoting the understanding of risk aversion for relevant stakeholders. Consequently, the proposed methodology contributes to risk reduction countermeasures and port safety management. Furthermore, it provides valuable insights for transforming container terminals towards a resilient transshipment hub in the near future.

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