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RESEARCH ARTICLE

Research on Risk Assessment of Container Operation Process in Ports Considering Functional Areas

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Abstract

The risk management of container ports has drawn significant attention recently in part because of recent high-profile accidents in global container ports and in part due to the increasing focus on port safety as a key element in sustainable maritime transportation. This research presented a novel, two-layer container port risk assessment model by partitioning the container port into four areas based on the process of container transportation: loading and unloading, in-port container transportation, storage, and gate areas. Failure mode and effects analysis (FMEA) and quantitative risk analysis modeling were combined for each part of the process to evaluate the risk of accidents in container ports. Historical container port accident data from the Port of Keelung, one of the international ports in Taiwan, were used to demonstrate the novel risk analysis method. The result revealed that risk mitigation should be prioritized to improve the safety of container storage and mitigate the risk of equipment-caused failures in the storage area of the container yard, as well as the risks of accidents on the receiving route for import containers. This study also proposed a standardized port accident data reporting form to enhance data quality and future resolution of quantitative risk analysis. The results of this study provide container port operators and regulators useful information for formulating port risk control strategies, thereby reducing the risk of the operation of port containers and improving port safety.

Keywords: Port risk assessment, Container operation process, Failure mode and effects analysis, Quantitative risk assessment

1. Introduction

1.1. Accident risks in container ports

Proper safety and risk management of container ports is crucial to the efficiency and reliability of maritime transportation, which necessitates an accurate assessment of risks in container ports. In 2015, a series of explosions occurred at the Tianjin Port Container Terminal in the Binhai New Area of Tianjin, China, causing more than 160 fatalities, hundreds of injuries, and economic losses of over 6.8 trillion Chinese Yuan [1]. The cause of the incident was the ignition of class 3 hazardous materials (hazmat or dangerous goods, DG), nitrocellulose from a container in the arrival area of the port, which, due to high temperature and other environmental factors, led to a series of explosions and, subsequently, large fires. The presence of other flammable hazmat containers in the vicinity increased the severity of the incident. Although the incident that occurred in the Tianjin Port Container Terminal in 2015 was a rare event, there are other accidents and incidents in container ports that could lead to more severe consequences under different circumstances, and therefore, mitigating and preventing more frequent but less severe container port accidents are important.

Container port facilities are generally divided into several functional areas, such as the loading and

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unloading area (from docks), the storage area, the gate area (connected to the roadway or railway), and the transportation routes within the port facilities, each having distinguishing functions and operational characteristics and environments. These differences predispose each area in the container port to different risks, including the type of accidents, causes, and potential consequences. Therefore, a risk evaluation of container ports should consider the different functional areas and their risk characteristics.

1.2. Research objectives

This research paper develops a novel area-specific risk assessment model for container ports, with a focus on the transportation of containers within the port. Risk assessment is conducted by partitioning the port into four functional areas based on typical container transportation processes: (1) container loading and unloading area on the dock, (2) container transportation routes between the dock and the storage area, (3) the storage area of the container yard, and (4) the gate area of the container port. Notably, transportation routes are linear "route areas" within the port terminals, where all the routes that containers can be transported to in the port area are considered. This area-specific container port risk assessment is performed in two stages. First, a failure mode and effect analysis (FMEA) is performed to identify key hazards in port areas and their relative qualitative risks. Thereafter, an empirical-based quantitative risk assessment model is developed for each of the four areas in the container port to calculate the risk of container transportation. A case study using historical container port accident data from the Port of Keelung, one of the international ports in Taiwan, is presented to demonstrate the new risk analysis method.

This study aims to construct a functional-area-specific risk assessment framework for the container operation process in ports. A combination of qualitative and quantitative risk analysis methods is implemented to evaluate and identify high-risk areas, route types, and accident types in the process, which has not been comprehensively conducted in previous research. The results of this research will provide useful information for port operators in developing risk control strategies for different areas of container ports to reduce the frequency and consequence of various types of accidents. This contributes to better allocation of risk mitigation resources and risk-informed decision-making for container port facilities. This study defines container risk as the multiplication of the probability of an accident during container transportation and the average severity of the consequences caused by the accident. The qualitative FMEA model identified and prioritized various types of accidents in different functional areas of the port based on expert opinions. The quantitative model uses the frequency and rate of accidents as the measure of likelihood and the economic loss as a measure of severity in the New Taiwan dollar (NTD) based on historical accident data. The results from these two models validate each other to improve the accuracy of risk evaluation and interpretation. In addition, this study also analyzed historical port accident data and identified opportunities to improve reporting and data collection procedures for container port accidents to facilitate detailed and accurate risk analyses. Accordingly, this study proposed a standardized accident record form for future accident data collection and research by referencing the past literature and experience in the maritime transportation industry on container port accidents for better risk management and risk-informed decision-making to improve container port safety.

2. Review of the literature

Common risk assessment methods include Formal Safety Assessment (FSA), fault tree analysis (FTA), Hazard Identification and Risk Assessment (HIRA), FMEA, analytical hierarchy process (AHP), Bayesian Networks (BN), evidential reasoning, risk matrix, fuzzy-based methods, and machine learning (ML) methods (Table 1), which have been utilized in many studies to address risks in port facilities. Mokhtari et al. [2] conducted a fuzzy-based FTA and bow tie risk analysis of seaports and offshore terminals considering hazmat releases. Ding and Tseng [3] developed a fuzzy risk assessment on safety operations for exclusive container terminals at Kaohsiung port in Taiwan. Several researchers utilized FSA to evaluate container port hazards [4−8]. BN was used to identify causal relationships between container port accidents and causative factors [9−12]. Yang et al. [13] analyzed the core risk factors influencing container terminals using the Decision-Making Trial and Evaluation Laboratory method. Mobrouki et al. [14] implemented the AHP multicriteria approach to analyze and assess operational risk within port terminals while focusing on roll-on/roll-off (RO−RO) activities. Lam and Su [15] used a semi-quantitative risk assessment method to assess the operational risk of Asian ports. Tseng and Pilcher [16] discussed container port safety and risk through formal, structured, and in-depth interviews

Table 1. *Summary of the literature on container port risk assessment research.*

Research	Risk Assessment Methods											Adopt Expert Opinions (Interview and/or Survey)	Case Study
	FSA	HIRA	FTA	AHP	FMEA	ER	BN	Risk Matrix	Other	Fuzzy-based Methods	ML-based methods		
[2]			○							Δ		✓	
[3]										■		✓	
[4]	●							■				✓	✓
[9]					●		■			■		✓	
[13]									●			✓	✓
[14]				■								✓	
[15]								Δ					
[5]	●							■				✓	✓
[11]							▲						
[6]	●							■				✓	
[16]									●			✓	✓
[17]		●	●					■					
[10]					●	▲	▲			▲			
[7]	●		●					■				✓	
[8]	●			■						■		✓	
[18]				■						■		✓	
[19]			▲										✓
[12]							■					✓	
[20]								■					
[21]											Δ		
[23]										▲			
[22]											▲		✓
[24]						□				□		✓	
General Port Risk Assessment:	○	*Qualitative*		□	*Semi-Quantitative*			Δ	*Quantitative*				
Container Port Risk Assessment:	●	*Qualitative*		■	*Semi-Quantitative*			▲	*Quantitative*				

with maritime experts. Sunaryo and Hamka [17] used a combination of HIRA, FTA, and risk index to derive risk evaluation models for container ports. Huang et al. [18] conducted a statistical analysis of the causes of container port accident cases and the fishbone diagram to obtain the risk assessment index set and used AHP to assign the weight values of the evaluation index for risk analysis. Hua et al. [19] conducted an FTA for the 2015 Tianjin Port Container Terminal incident. Ech-Cheikh et al. [20] evaluated the risks of container ports using a risk matrix based on empirical accident data in Morocco. ML methods were also attempted to predict container port hazards or classify key factors for container port accidents [21,22]. Atak [23] conducted a fuzzy-based risk analysis for a container port in Turkey. Jiang et al. [24] also conducted a fuzzy-based risk analysis for the general maritime port along the 21st century Maritime Silk Road (MSR).

Table 1 presents the risk assessments of many studies conducted qualitatively and semi-quantitatively, with a few being performed fully quantitatively. The general risk matrix approach, FSA, and fuzzy-related methods, which are all qualitative or semi-quantitative forms, are the most commonly applied methods. Common among the aforementioned studies is that they consider the container port as a whole while identifying and assessing the risk. Although these studies are comprehensive, they fail to provide more detailed risk analyses in the port area. Notably, many of the container port safety and risk analyses relied on expert opinions based on interviews and surveys. Some studies quantitatively analyzed maritime accidents but did not focus on container port activities. For example, Deng et al. [25] conducted a risk assessment of maritime accidents based on complex network models. A research gap here was the identification and prioritization of risks in different functional areas in a container port. Among the common risk assessment methods, FMEA is the most suitable because it uniquely combines two functions: identifying hazards and facilitating their prioritization using an initial assessment of their likelihood, consequence, and ease of detection. Furthermore, the implementation of the FMEA utilizes domain knowledge from experts in the field, which is essential to understand and interpret the results of subsequent detailed and quantitative risk assessments. Therefore, in this research, FMEA is implemented as the first step of the functional-area-based risk assessment for the container port.

Some studies addressed a particular aspect of container port risk. For example, Rix et al. [26] analyzed the seismic risk in container ports, focusing on berth, wharf, and crane structures. Shang and Tseng [27] analyzed the risk of stevedoring (loading, unloading, and transloading) containers in seaports. Zhang et al. [11] developed a risk estimation model for economic loss due to extreme wind events in ports. Cao and Lam [28] used the simulation method to analyze the severity of weather-induced container port accidents. Jian et al. [29] addressed the risk of cyclones in the container port via a vulnerability assessment and a risk exposure assessment. More recently, Balakrishnan et al. [30] conducted economic loss estimation as a risk measure for hurricane events in ports. Xiao and Bai [31] used a D-vine copula-based regression to evaluate the risk of port disruption. Gu and Liu [32] noted that certain factors related to ships can impact the safety of port operations. Liu et al. [33] studied the effects of the recent COVID-19 pandemic on ports, including safety, reliability, and resilience. Some studies on port resilience covered safety as part of the scope [34].

A review of past research demonstrated that most container port risk assessments were performed using qualitative or semi-quantitative methods. More importantly, all accidents in container ports in these studies were generalized, without analyzing risks in different functional areas within the container port. Hence, a research gap exists between the state-of-the-art and a container port risk analysis with a higher resolution level. The present research addressed the gap by developing a quantitative container port risk analysis with high resolution by dividing the container port into different functional areas.

3. Risk model of container operations in ports

The functional-area-specific risk assessment model was developed in two stages for the port container operation process (Fig. 1). The scope of the risk analysis is the land area of a container port terminal. A typical container port can be divided into four functional areas:

1) the unloading and loading area at the dock pier,
2) the storage area of the containers,
3) the gate area where the container is transported for road transportation,
4) the transportation routes between the three areas mentioned above.

The types of transportation routes vary according to the configurations of individual container ports. After partitioning the container port into four functional areas, the FMEA was conducted to

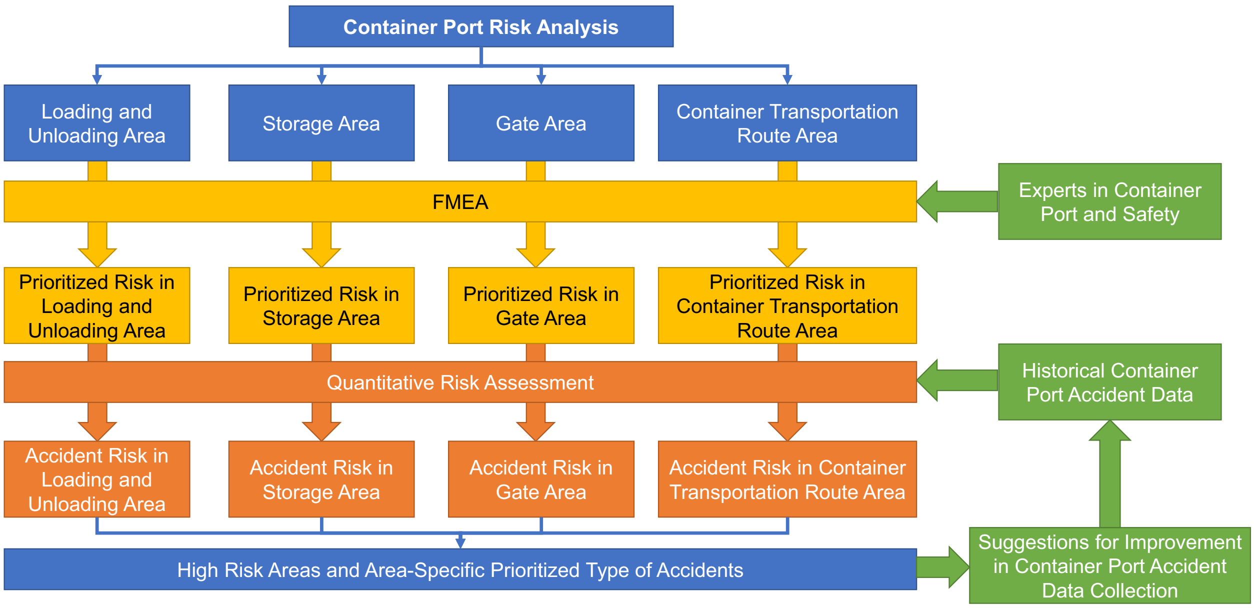

Fig. 1. Research methodology framework.

identify and prioritize important risks in each area based on input from experts with domain knowledge, which is a common practice, as shown in the literature review. The second stage develops a generalized quantitative risk assessment model to assess the accident risk of the four functional areas in a container port based on empirical data. The results are quantitative risk evaluations of different types of accidents in the four functional areas of the port. Quantitative analysis also provides information on how the accident data collection method can be improved for accurate and in-depth risk analysis in the future. The FMEA and quantitative risk assessment are complementary in container port risk management, where FMEA provides risk identification and prioritization, and quantitative risk assessment evaluates risk values and calculates the likelihood and consequence of various types of container port hazards. The combination of the two approaches comprehensively addresses the container port risk by considering functional areas. The results of the FMEA and the quantitative risk assessment can provide mutual validation and implications for safety. The methodology for the two parts of the risk assessment is described in Sections 3.1 and 3.2, respectively, and a case study is presented in Section 4 using one of the international ports in Taiwan to demonstrate the two-stage risk assessment model, which can be adapted to other container port facilities.

3.1. FMEA for port systems by functional areas

FMEA is a method to identify and summarize the potential failure modes (hazards) and the main factors affecting a system, as well as their causes and effects, and prioritize failure modes for further risk assessment and safety improvement. In this study, FMEA was used to evaluate and prioritize failure modes in a container port operation process by considering functional areas. The risk assessment of the port container operation process starts with a qualitative evaluation and analysis of possible risks, and failure modes are identified using past literature, field visits, domain experts, and port accident records. The risk of any identified failure mode is measured by the risk priority number (RPN):

$$RPN_i = S_i \times F_i \times D_i \tag{1}$$

where i denotes the ith failure mode, i = 1, 2, 3, …, n and n denote the total number of failure modes; S denotes the severity level of the failure mode; F denotes the frequency level of the failure mode; D denotes the level of ease of detection of the failure mode.

The severity, frequency and ease of detection levels of each failure mode in the container operation process in ports were evaluated by domain experts with practical experience and recorded in a table (Table 2). The evaluation was completed for

Table 2. Container port FMEA example.

Failure Mode and Effect Analysis (FMEA)							
System: container operation process in port							
Process Operation	Failure Mode	Failure Effect	Severity	Cause of Failure	Frequency	Ease of Detection	RPN
Loading and unloading area of the container at the dock	The gantry crane hits the typhoon lock cover plate when the operation was completed and moved.	Cover deformation, gantry crane brake system damage	2.4	Operation Error	1.6	1.6	6.1

each of the four functional areas in the container port; followed by the identification of the possible failure modes for each of them, their effects and causes; then, further evaluation of the severity, frequency, and ease of detection levels; and finally, the calculation of the RPNs. The definition of frequency, severity, and ease of detection levels for the particular container port under analysis should be chosen based on its operational environment, regions and countries, and operational practices so that these levels can properly reflect the situations in the port and distinguish high-risk from low-risk failure modes. For example, to assess port risk in Taiwan, severity and frequency levels are defined in the FSA methodology used by Pallis [6] and Budiyanto and Fernanda [7] (Table 3). To adjust for local regulations and occupational environment, the definition of the severity classification related to injuries and fatalities was also adjusted with reference to Article 37, Item 2 of the Taiwan Occupational Safety and Health Act [35], which is the basis for determining whether a major occupational disaster is considered in practice (Table 4). Definitions of the level of detectability were based on the common definitions introduced by Kiran [36] (Table 5). The RPN of each failure mode is the average of RPNs assigned by all experts, and the RPN of each port functional area is the average of RPNs from all failure modes in that functional area.

Table 3. Definition of the severity level.

Level	Description	Impact After Occurrence
1	Not Significant	There is no harm to people and the situation can be handled onsite No environmental impacts No loss of working days No equipment damage
2	Light	Minor injuries (depending on whether the patient is hospitalized) Employees are still available for work during the day/shift Equipment needs minor repair work
3	Moderate	Major injuries that require hospital treatments Employees unable to work for more than one day but less than three days Equipment needs major repair work
4	Severe	At least one fatality Three or more people having major injuries Employees unable to work for three days or more Equipment damage causes system to shut down
5	Very Severe	Multiple fatalities Employees no longer be able to work Equipment needs to be replaced

Table 4. Definition of the frequency level.

Level	Description	Frequency
1	Rare	Almost never occurs (only in extreme cases)
2	Low likelihood	Has not occurreed but may occur during the life cycle
3	Moderate likelihood	Expected to occur more than once during the life cycle
4	High likelihood	Likely to occur; occurs occasionally
5	Almost certain to occur	Can occur in most cases; occurs frequently

Table 5. Ease of defining the detection level.

Level	Description	Frequency
1	Almost certain	Reliable controls are known that can almost certainly detect the failure
2	High	High likelihood that the current controls will detect the failure
3	Moderate	Moderate likelihood that the current controls will detect the failure
4	Low	Low likelihood that the current controls will detect the failure
5	Less likely	No known controls available for detection

3.2. Quantitative risk models of container operations processes in ports

The quantitative risk modeling of the container operation process consists of two parts to account for the two types of functional areas in the port terminal:

$$R_P = R_{L,j} + R_T \tag{2}$$

where R_P is the risk of the port container operation process; $R_{L,j}$ is the risk of the fixed area j in the container port (j could be one of the following: loading and unloading area, storage area or container terminal gate area of container terminal); and R_T is the risk of the container transportation route between different fixed areas.

Considering that there are three fixed areas in the port terminal, the formula for calculating the risk value of the four functional areas in the port container operation process can be rewritten as follows:

$$R_P = R_{L,W} + R_{L,S} + R_{L,G} + R_T \tag{3}$$

where $R_{L,W}$ indicates the loading and unloading of containers at the dock, $R_{L,S}$ indicates the storage activities in the storage yard, $R_{L,G}$ indicates the container operation at the port gate, and R_T indicates the container transportation in the port area. The risk for individual functional areas can be calculated as follows:

$$R_{L,W} = P_W \times C_W \ (\text{risk of loading and unloading of containers at the dock}) \tag{4}$$

$$R_{L,S} = P_S \times C_S \ (\text{risk of container storage in the storage yard}) \tag{5}$$

$$R_{L,G} = P_G \times C_G \ (\text{risk of containers at the inspection gate}) \tag{6}$$

$$R_T = P_T \times C_T \ (\text{risk of container transportation}) \tag{7}$$

To calculate the risk in the fixed area, we first calculated their unit risk, that is, the average risk per unit traffic (container). The formula for the unit fixed-area risk value of the container is as follows:

$$R_{L,j} = P_{L,j} \times C_{L,j} \tag{8}$$

where j is the jth fixed area, $R_{L,j}$ is the unit risk value of an accident in fixed area j (measured in monetary loss per million containers), $P_{L,j}$ is the expected frequency (rate) of an accident in fixed area j (measured in number of accidents per million containers), and $C_{L,j}$ is the severity of an accident in fixed area j (measured in average monetary loss per accidents).

After calculating the unit risk for each area, the total fixed-area risk value for a given container traffic can be calculated as follows.

$$R^*_{L,j} = P_{L,j} \times C_{L,j} \times N^*_{L,j} \tag{9}$$

where $R^*_{L,j}$ is the total risk (measured in monetary loss) for a given container traffic in the fixed area j and $N^*_{L,j}$ is the traffic (measured in million containers) in the fixed area j for which the risk must be calculated.

The second portion of the risk, the risk of container transportation route in ports, can be expressed as follows:

$$R_T = P_T \times C_T \tag{10}$$

where R_T is the unit risk of accident on the port container transportation route (measured in monetary loss per million container-distance), P_T is the accident frequency (rate) on the port container transportation route (measured in number of accidents per million container-distance), and C_T is the accident severity on the port container transportation route (measured in monetary loss per number of accidents). The unit risk of port container transportation shown in Equation (10) implies that on a transportation route, the more the containers transported, the greater the exposure to the accident risk, whereas the longer the container is transported, the greater the risk to which it is exposed. The difference between the unit risk of the transportation route and the unit risk of fixed areas is transportation distance in the former. The distance can be expressed in kilometers (as shown in this paper) miles, or other units, as appropriate.

A container can be transported from one area to another by different routes. The risk value for different transportation paths is calculated as follows:

$$R_{T,k} = P_{T,k}^{*} \times C_{T,k} \tag{11}$$

where k is the kth transportation path, $R_{T,k}$ is the total risk value (measured in economic loss) of the transportation path k, $P_{T,k}^{*}$ is the average frequency of the accident of transportation path k, and $C_{T,k}$ is the average accident severity of transportation path k (measured in economic loss per number of accidents).

Given that there are m types of route in the port terminal, the total risk of the transportation route in the container port terminal is

$$R_T = \sum_{k=1}^{m} R_{T,k} \tag{12}$$

The average accident frequency per million container distance is calculated as follows:

$$P_{T,k} = \frac{A_k}{D_k \times N_k} \tag{13}$$

where k is the kth delivery route, $P_{T,k}$ is the average frequency of accidents per million container distance for transportation route k, A_k is the number of accidents occurred along transportation route k, D_k is the average container movement distance for transportation route k based on past data, and N_k is the number of containers (in million containers) for transportation route k based on past data. The risk of each transportation path is calculated separately when calculating the risk of container transportation within the port area. These risks can then be combined to obtain the total risk of container transportation routes.

The average frequency of accidents on a transportation path given its current operational conditions is calculated as follows.

$$P_{T,k}^{*} = \frac{A_k}{D_k \times N_k} \times D^{*} \times N^{*} \tag{14}$$

where $P_{T,k}^{*}$ is the average frequency of accidents on the kth transportation route, D^{*} is the current average distance of the transportation route, and N^{*} is the current traffic volume of the transportation route (millions of containers).

For each transportation route, the truck can take multiple paths to transport the container. Therefore, the average distance travelled by the container for the transportation route k is calculated as follows:

$$D_k = \sum_{l_k=1}^{p} P_{l_k} \times d_{l_k} \tag{15}$$

where l_k is the number of routes in the kth transportation route; $l_k = 1, 2, 3, \ldots$, p and p is the total number of paths available on the kth transportation route; and P_{l_k} is the probability of using the l_k th path in the kth route, $\sum_{l_k=1}^{p} P_{l_k} = 1$; d_{l_k} is the distance for path l_k.

The formula presented above jointly considers the risks of all accidents. If the risk of the individual type of accident is to be calculated, the risk value considering the specific type of accident, *t*, is given as

$$R_{P,t} = R_{L,j,t} + R_{T,t} \tag{16}$$

$$R_{L,t} = R_{W,t} + R_{S,t} + R_{G,t} \tag{17}$$

$$R_{W,t} = P_{W,t} \times C_{W,t} \tag{18}$$

$$R_{T,t} = P_{T,t} \times C_{T,t} \tag{19}$$

$$R_{S,t} = P_{S,t} \times C_{S,t} \tag{20}$$

$$R_{G,t} = P_{G,t} \times C_{G,t} \tag{21}$$

$$R_W = \sum_{t=1}^{q} R_{W,t} \tag{22}$$

$$R_T = \sum_{t=1}^{q} R_{T,t} \tag{23}$$

$$R_S = \sum_{t=1}^{q} R_{S,t} \tag{24}$$

$$R_G = \sum_{t=1}^{q} R_{G,t} \tag{25}$$

where t is the t-th accident type and t = 1, 2, …, q, where q is the total number of accident types.

4. Model demonstration using real-world data

4.1. Empirical data source

A case study was conducted on the port of Keelung, one of the international container ports in Taiwan. Port-related data used in this study were provided by the Port of Keelung, Taiwan International Ports Corporation, including a geographical location map, historical port accident reports, and container loading and unloading volume from 2017 to 2022. During this time, a total of 52 accidents were recorded in the four functional areas of the port, comprising 10 accidents in the loading and unloading area of the container at the dock, 7 accidents during container transportation between the dock and the storage yard, 11 accidents in the storage area of the container yard, 22 accidents in the gate area of the container terminal, and 2 accidents in unknown locations in the port. The total number of containers loaded and unloaded during the period the accidents were recorded was 7,621,402 twenty-foot equivalent units (TEU). It can be estimated, based on the ratio of ship-side containers to storage containers provided by the Port of Keelung, which is 65 %–35 %, that the total number of ship-side containers was 4,953,911 TEU, and the storage containers during the accident record period were 2,667,491 TEUs. Dock traffic was divided into import ship-side, import storage, export ship-side, and export storage containers, and the ratio of the four types of container traffic for each dock was then used to project the total container traffic during the accident record period for risk calculations. The severity was calculated from the insurance claims for each accident in New Taiwan dollars (NTD); the distance of each route was measured according to the actual movement of the truck in kilometers (km), which is done through the distance measurement function in Google Maps.

4.2. FMEA of the container operation process in port of Keelung

Using the research framework presented in section 3, the list of failure modes in each functional area, as well as their effects and causes, are identified and filled out in the aforementioned FMEA form (Table 2). With the help of staff and experts from the Port of Keelung, Taiwan International Ports Corporation, the failure mode list was adjusted to suit local port operation, and a panel of experts was invited to score the RPN according to all failure modes. Moreover, experts were asked to evaluate the risk of each failure mode, considering their levels of severity, frequency, and ease of detection, and quantify the practical experience of the experts to further calculate the risk priority of each functional area. The three RPN components of each failure mode were averaged (using the arithmetic mean) from the results of the expert evaluation and multiplied together to calculate the average RPN of each failure mode. The opinions of seven experts were collected, all of whom were familiar with the container business, operation safety, and container port safety in the port area; they also had rich experience in risk management (including accident records, follow-up reporting, and timely handling or follow-up recovery). The panel of seven experts consisted of five senior operators and supervisors with more than 30 years of experience each, who have handled multiple container port accidents in the past, and two junior operators who, though not very experienced, have undergone solid safety and risk management training. Expert opinions from junior and senior employees were surveyed to obtain a representative perception of container port risk within the company, with senior operators having greater weight, considering their deeper experiences. Junior experts were included to prevent bias, as senior employees tend to focus on more frequent risks based on experience and may miss opportunities to identify less common but potentially high-consequence scenarios.

The list of failure modes identified in each area of the container operation process is presented in Appendices A–D, and Table 6 lists the top five failure modes with the highest RPN in each functional area evaluated by the panel of experts for the Port of Keelung, where the causes of failure were divided into four categories: operational errors, which are human errors in loading and unloading containers; machine failures, which are accidents caused by mechanical problems during container operations; storage problems, which are damage caused by improper management of containers stored in the storage area; and worker health problems, which are related to the health conditions of the operators.

Considering the difference in the practical experience of the respondents, with five of the experts having between 30 and 40 years of practical experience and the other two experts having only two years of practical experience but experience in risk management in the port, the calculation results of the RPN for all seven experts and the five senior experts differ slightly (Table 7). The seven experts considered the container storage area to have the highest RPN, followed by the container transportation route from the dock to the storage area. The five senior experts evaluated the gate area of the container terminal to have a greater accident risk than the loading and unloading area of the container at the dock, whereas the seven experts combined determined that the loading and unloading area of the container at the dock had a greater accident risk than the gate area of the container terminal, although the RPNs of the two were very similar.

Table 6. List of high-risk failure modes in the four functional areas of the Port of Keelung.

Processes/Operations	Failure mode	Failure effect	Cause of failure	RPN
Loading and unloading area of the container at the dock	Fire in loading and unloading equipment	Machine and equipment damage, fire affects the surrounding area	machine failures	20.9
	Gantry crane spreader damage	The container is stuck and cannot be unloaded, the container falls	machine failures	17.2
	The overhead crane high-voltage cable falls off and the operator accidentally breaks the high-voltage cable during the movement of the head table	The entire power supply system of the container yard is cut off, and the instantaneous power failure causes the failure of the gantry crane panel in the original operation and the power module damage failure	machine failures	15.8
	The spreader fell and struck the people below	Personnel injuries	machine failures	15.6
	Container command operator struck by container during the gantry crane loading operation	Injuries to command operators	operational errors	14.3
Container transportation from the dock to the storage area	Truck overboard	Truck and container damage, casualties	operational errors	17.0
	Worker struck by truck	Personnel injuries	operational errors	16.3
	Truck fire at port operation	Damage to trucks and containers, fires affecting the surrounding area	machine failures	12.5
	Trucks collide with each other	Truck damage, container damage, casualties	operational errors	11.5
	Truck accidentally crashed into the perimeter fence of the rail-mounted gantry crane	Damage to the body of the fence	operational errors	11.1
Storage area of the container yard	Sudden breakage of the chain of the straddle loader when adjusting the container	Causes deformation of container cabinets	machine failures	17.7
	Fire in loading and unloading equipment	Machine and equipment damage, fire affects the surrounding area	machine failures	17.5
	The rail-mounted gantry cranes electrocuted	Worker injury or death	operational errors	16.7
	the spreader fell and struck the people below	Personnel injuries	machine failures	16.4
Gate area of container terminal	The truck accidentally knocked the guardrail of the driveway out of alignment	Control guardrail breakage	operational errors	12.1
	The truck accidentally broke the concrete post behind the gate in the gate driveway	The concrete column is damaged and the sign above it is skewed	operational errors	11.3
	The truck accidentally broke the speed sign in the lane	Damage to the body of the speed sign	operational errors	9.8
	Fire at the gate	Damage to buildings, fires affecting the surrounding area	machine failures	9.6
	The truck driver fell to the ground while preparing to go through the formalities	Ambulance emergency medical evacuation	worker health problems	7.5

Table 7. RPN for the four areas in the container port.

Functional Area in Container Port	RPN (five senior experts)	RPN (two junior experts)	RPN (total)
The storage area of the container yard	15.9	6.1	13.1
Container transportation from the dock to the storage area	12.3	8.5	11.2
The gate area of container terminal	10.8	6.6	9.6
Loading and unloading area of the container at the dock	10.2	8.5	9.7

In addition to the difference in risk ranking, the RPN values assessed by the five more experienced experts were all higher but decreased significantly with the inclusion of the two less experienced experts. The most experienced experts likely had more experience handling serious but infrequent risks, whereas the less experienced experts may have underestimated the risks due to their lack of experience. The container yard storage area was deemed the highest risk area by the experts, and its improvement needs to be prioritized, followed by the container transportation routes in the port area, for which risk management must be strengthened.

Furthermore, the five main failure modes ranked by the average RPN values are fire in the loading and unloading equipment in the storage area, sudden breakage of the straddle loader chain in the storage area when adjusting the container, fire in the loading and unloading equipment at the dock, gantry crane spreader damage at the dock, and truck overload. The top five failure modes ranked by the RPN values evaluated by all seven experts combined are sudden breakage of the chain of the straddle loader chain in the storage area when adjusting the container, fire in the loading and unloading equipment in the storage area, the truck falling into the sea while transporting the container in the port area, electrocution of the rail-mounted gantry cranes, and the spreader falling and striking the people below.

The result of the FMEA at the container port terminal served as the initial risk assessment of the four land areas in the container port and were used to qualitatively identify the hazardous events or activities. This part of the analysis can help the port operator and the safety regulator to focus on the specific container port hazard and perform detailed risk analysis. To provide a greater resolution of the accident risk of each area in the containment port and obtain more precise estimates of the risks in terms of monetary loss, a quantitative risk assessment was performed.

4.3. Quantitative risk models of the container operation process in Port of Keelung

The quantitative risk analysis of the container operation process was conducted in three parts. The first part calculated the risk in the fixed area (loading and unloading area of the container at the dock, the storage area of the container yard, and the gate area of the container terminal). The second part calculated the risk of the transportation route (the container transportation route between the dock and the storage yard). The total quantitative risk of container port operation can be calculated by combining the results of these two parts. The third part calculated the accident type-specific risk for each area in the container port.

4.3.1. Calculation of the risk of the fixed-point area

From the volume of containers and the number of accidents provided by the Port of Keelung, the accident rate can be calculated in the three fixed areas. The total volume of containers handled in the container loading and unloading area at the dock and the gate area of the container terminal includes all containers, with a volume of 7.62 million TEU; the volume of containers handled in the container yard storage area includes only storage containers, with a volume of 2.67 million TEU. The severity calculation is based on the amount of the insurance claim. Notably, some claim data were missing from accident reports, so they were estimated based on the average insurance claim from similar accidents. The estimation method aimed to classify the available data into categories and calculate the average monetary values as the expected consequence of this category of accident, and, if a similar type of accident does not have the actual insurance claim (consequence), the expected value of the similar type of accident is assumed for this accident. By multiplying the frequency and severity, the unit risk value for each area can be calculated, and it is multiplied by the total volume to obtain the total risk value for each area. The values of each variable are compiled in Table 8.

4.3.2. Calculation of transportation route risk

The main difference in calculating the risk of container transportation routes within the port area compared to the risk of the fixed area is the consideration of the distance the container is transported between the fixed areas in the port. There are six main types of container handling activities in the Port of Keelung: pickup of full container yard (CY) import containers from the storage area, submission of CY export containers to the storage area, delivery of CY import containers from the dock to the storage area for storage, pickup of CY export containers from the storage area to the dock for loading, direct pickup of containers from the south and north container yards from each dockside container ship, and delivery of containers from the gate directly to the dock side for loading (Fig. 2). Some of these activities have multiple paths because of multiple docks serving as origin and destination points. An onsite visit and survey were conducted to obtain the most commonly taken path for each container handling activity. The average distance from the route based on these paths was then measured using the distance measurement function of Google Maps (Fig. 3).

The calculation of frequency in each transportation route includes three variables: number of accidents, distance travelled, and volume of containers. The number of accidents is attributed to the location; as long as the route passes through the location of the accident, accident risk exists, so it is

Table 8. Risk calculation form for fixed-point areas in the Port of Keelung.

Fixed Area in Container Port	Rate (P)	Severity (S)	Volume (N)	Unit Risk (R)	Total Risk (R*)
Loading and Unloading Area	1.31	586,062	7.62	767,741	5,851,264
Storage Area in Container Yard	4.12	260,738	2.67	1,074,241	2,865,527
Gate Area of Container Terminal	2.89	4297	7.62	12,418	94,645

R* refers to the total fixed-area risk value for a given container traffic as shown in Eq. (9).

attributed to this route. The route distance is calculated by considering the frequency of different paths that the trucks will take for this route and calculating the average distances among these paths; the volume of containers is calculated by taking the ratio of ship-side containers to storage containers and the ratio of the volume of each dock, including the import and export storage containers and ship-side containers of each dock. The severity is determined by calculating the average severity of all accidents in the path and then calculating the average of all paths in the container movement activity. The variables in the route risk calculation are listed in Table 9.

Finally, the total risk of each container movement activity was calculated, as listed in Table 10.

4.3.3. Accident-type-specific risk calculation

In addition to calculating the risk by area, the risk was further calculated separately according to the type of accident, as listed in Tables 11–13, where the type of accident was classified according to the cause of the accident as operation error, equipment failure, storage problem, and worker health problem, among others. In addition, many accidents involve trucks hitting containers or equipment, which should be classified as operational errors; however, because they involve the human errors of truck drivers, which are not part of the port organization, they were specifically classified as collisions to distinguish them from operational errors associated with other port equipment. The -accident-type-specific risk of the container

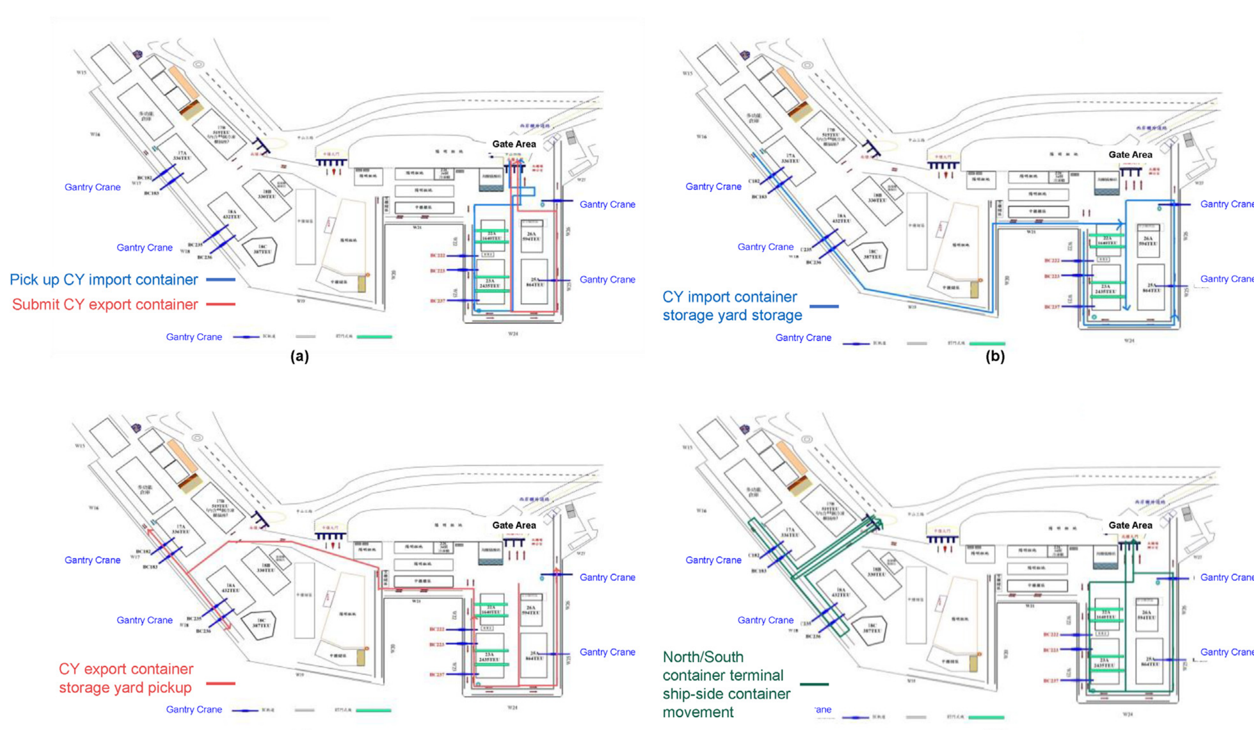

Fig. 2. Common container transportation paths between fixed areas in the Port of Keelung for the six major container handling activities: (a) pick up the import container and submit the export container, (b) import container to storage area, (c) export container storage pickup, and (d) north and south container terminal container movement.

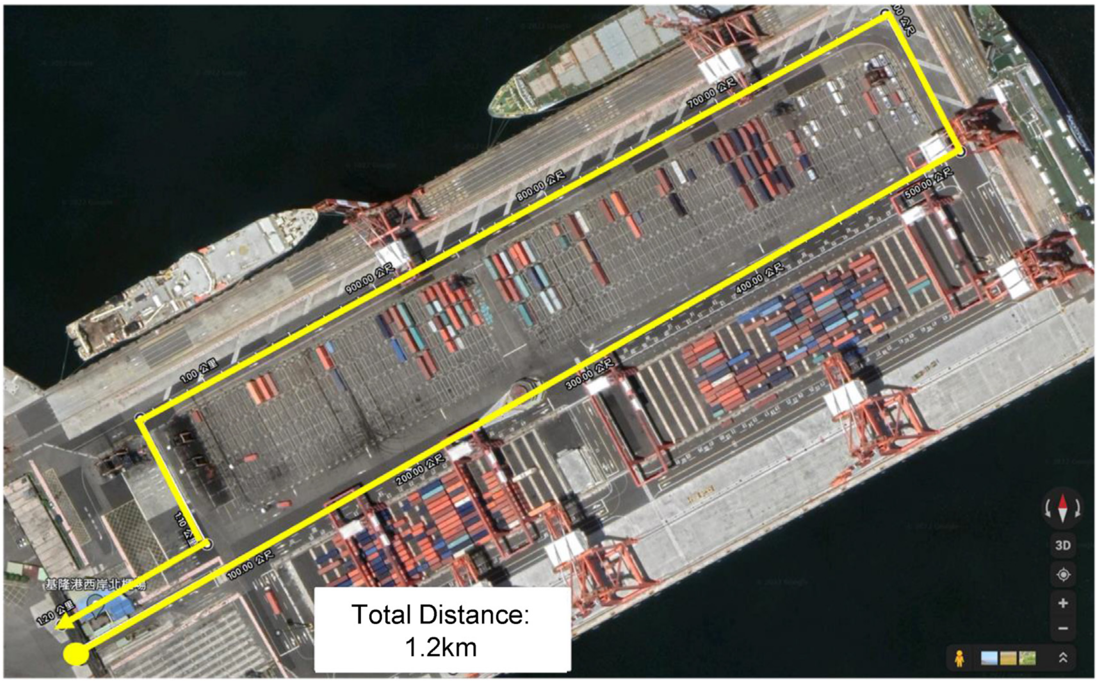

Fig. 3. Example of route distance measurement.

transportation route was not calculated because all accidents were collision accidents. Using the risk values for each type of accident in each area, the types of accidents in each area that should be prioritized for improvement can be determined and accurate management strategies developed (see Tables 11–13).

4.4. Standardized accident reporting form

In evaluating the quantitative risk of container transportation in the port terminal, it was discovered that the availability and completeness of the data affect the precision and resolution of the risk analysis (see Table 13). For example, the accident severity was measured from the total monetary damage based on the insurance claim. However, because some accidents did not merit an insurance claim (for instance, when conciliation is made or when the consequence does not exceed the threshold of filing a claim), such monetary damage information was unavailable, and therefore, they had to be assumed from the average of an accident of similar type and consequence of accidents in the past. Although the data still provided an estimate of the risk, its precision could be better if all reported accidents had an insurance claim documented. The lack of a systematic method for consistent accident data collection hinders in-depth risk assessments, which require consistent documentation of accident information to derive quantitatively the relationship between risk and affecting factors, such as regression analyses, time series analyses, and machine learning-based risk modeling. Due to this lack of data granularity, the quantification of risk level in this investigation focused on calculating the general likelihood, and consequence and risk of container port accidents. However, how individual factors quantitatively affect risk was not evaluated due to the lack of data resolution. To improve the future resolution and accuracy of quantitative risk analysis, this study proposes a standardized accident reporting form, for which the data entry fields include information that can be used for various qualitative and quantitative risk assessments (Table 14). This form was compiled by considering the data limitations identified in this study, with reference to the reporting forms of other types of transportation accidents, past literature, and valuable input from experts in maritime risk management. An example of a reference to the accident reporting form of a different transportation mode is the reference to the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) Rail

Table 9. Route risk calculation form.

Main Activity	Dock	Distance (km)	Container volume (million)		Percentage	The average distance (km)	Number of accidents	Average severity (NTD)	Routing type average severity	P frequency	R unit risk
Pick up CY import container		1.30	1.431836	Import storage containers			5	179,016	179,016	2.69	480,867
Submit CY export container		1.20	1.235655	Export storage containers			1	4333	4333	0.67	2922
CY import container storage yard storage	W17	1.78	0.357863	Using the ratio to calculate the import storage containers of each terminal in five years	0.250	1.33	4	222,687	222,687	2.10	468,077
	W18	1.51	0.400567		0.280		4	222,687			
	W22	1.22	0.01275		0.009		4	222,687			
	W23	1.04	0.555954		0.388		4	222,687			
	W25	0.65	0.101393		0.071		4	222,687			
	W26	0.45	0.003309		0.002		4	222,687			
CY export container storage yard pickup	W17	1.56	0.249237	Using the ratio to calculate the export storage containers of each terminal in five years	0.202	1.02	1	4333	4333	0.79	3439
	W18	1.60	0.368761		0.298		1	4333	(Truck hit the fence around the rail-mounted gantry crane)		
	W22	0.65	0.010731		0.009		1	4333			
	W23	0.45	0.509394		0.412		1	4333			
	W25	0.45	0.092612		0.075		1	4333			
	W26	0.65	0.00492		0.004		1	4333			
North container terminal ship-side container	W22	1.25	1.119807	Using the ratio to calculate the ship-side containers of each dock in five years	0.245	1.25	1	4333	4333	0.17	757
	W23	1.25	1.43172		0.313		1	4333			
	W25	1.25	0.043572	Total	0.010		1	4333			
	W26	1.25	1.982312	4.577411	0.433		1	4333			
South container terminal ship-side container	W17	0.50	0.360952	Total	0.959	0.51	1	92,295	92,295	5.18	478,423
	W18	0.80	0.015548	0.3765	0.041		1	92,295	(Truck scraping the freezer socket)		

Table 10. Unit risk and total risk for the six main container movement activities.

Main Activity	Routing type average severity (NTD)	P frequency	R unit risk	N^* volume	D^* Distance (km)	R^* total risk
Pick up CY import container	179,016	2.69	480,867.30	1.431836	1.30	895,080
Submit CY export container	4333	0.67	2922.20	1.235655	1.20	4333
CY import container storage yard storage	222,687	2.10	468,077.20	1.431836	1.33	891,379
CY export container storage yard pickup	4333	0.79	3439.15	1.235655	1.02	4335
North container terminal ship-side container	4333	0.17	757.28	4.577411	1.25	4333
South container terminal ship-side container	92,295	5.18	478,423.80	0.3765	0.51	91,864
Total						1,891,324

R^* refers to the total fixed-area risk value for a given container traffic as shown in Eq. (9).

Table 11. Accident-type-specific risk in dock area.

	Dock	
	Equipment failure	Operation error
Number of accidents	3	7
Average severity (NTD)	624,827	569,449
P	0.39	0.92
R	245,949.60	523,019.60
R^*	1,874,481	3,986,143

R^* refers to the total fixed-area risk value for a given container traffic as shown in Eq. (9).

Table 13. Accident-type-specific risk in gate area.

	Gate		
	Collision	Equipment failure	Worker health problem
Number of accidents	20	1	1
Average severity (NTD)	4333	7875	0
P	2.62	0.13	0.13
R	11370.74	1033.27	0.00
R^*	86,661	7875	0.00

R^* refers to the total fixed-area risk value for a given container traffic as shown in Eq. (9).

Equipment Accident/Incident (REA) database. This database comprises train accidents for which the total monetary damage exceeds a prespecified threshold [37]. For each recorded accident, more than 140 data fields were recorded, including train information, accident characteristics, consequences, environmental characteristics, and other information that is useful for risk assessments [38]. Due to such complete and high-resolution documentation of accidents, the database has been useful for conducting various quantitative risk assessments to address a wide range of rail safety problems [39,40]. In the context of assessing container port risk, recording accidents using this standardized form can allow certain factors that may affect the risk to be consistently recorded. For example, climate factors were not discussed in this investigation because weather conditions were not consistently recorded in previous accident records and, therefore, could not be analyzed. However, in past transportation safety studies, weather conditions were recognized as affecting operation risk. Therefore, in the proposed standardized accident reporting form, the authors included weather-related conditions. If port operators can adopt the standardized accident record form to record accidents or integrate it into the safety management information system, it will be easier to compile the form for risk and safety research and analysis while increasing operational efficiency and improving data integrity and the effectiveness of risk analysis.

Table 12. Accident-type-specific risk in storage area.

	Storage yard			
	Collision	Equipment failure	Operation error	Storage problem
Number of accidents	3	2	5	1
Average severity (NTD)	61,647	505,279	18,804	1,336,667
P	1.12	0.75	1.87	0.37
R	69,331.07	378,842.14	35,246.60	501,095.20
R^*	184,940	1,010,558	94,020	1,336,667

R^* refers to the total fixed-area risk value for a given container traffic as shown in Eq. (9).

Table 14. Standardized accident record form.

Time and Location				
Location (large area)	Accident location (detailed location)	Date of occurrence	Time of occurrence	Year
Time period	Month	Week	Season	
Climate				
Weather	Visibility	Temperature		
Parties				
Name of loading company/car company	Ship name			
Assignments				
Current operation/process	Route	Import/Export Operations	Container type	
Dangerous goods				
Whether dangerous goods are involved	Type	Whether the dangerous goods are leaked		
Accident information				
Occurrence (detailed summary)	Sequence of events in the accident	Accident type	Facilities involved	Facility location
Speed				
Cause of accident				
Cause of accident	Noncompliant items	Machine problems	Human factors	Other influencing factors
Other related information				
Loss and injury				
Damage condition	Number of injured	Number of deaths	Type of injury	Casualty worker role
Cause of injury	Number of days the person is unable to work	Number of people affected	Role of affected personnel	Number of evacuees
Aftercare				
Claims (amount of financial loss)	Severity	Processing method	Recovery time	Preventive measures taken
Other				
Worker experience	Worker attitude	Worker qualifications	Container management	Operation
Whether the workers have significant experience	Any poor attitude, such as failure to follow rules and use of drugs and alcohol.	Whether there is corresponding qualifications	Whether to store and manage effectively	Whether there is a relevant organizational team with the development of standard processes and rules and implementation
Emergency handling	Infrastructural facilities	Equipment	Security protocol	
Ability to resolve and manage accident situations in a timely manner	Whether to meet the operational requirements and standards	Whether the quantity, condition, and spare facility requirements are met	Whether to develop security processes and regulations	

5. Conclusion and future study

5.1. Concluding remarks

Considering the significant impact of container port accidents and the increasing emphasis on global container traffic, the containment risk of port terminals was highlighted. Previous container port-related studies considered container ports as a single unit in port and container supply chain risk management. This study contributes to the body of knowledge by developing a more in-depth risk assessment model for container ports. This novel risk analysis partitioned container ports into four functional areas and separately assessed their risks to consider differences in their characteristics. This study considered one of the major container ports in Taiwan as a case study to demonstrate the two-stage risk assessment framework that consists of a qualitative FMEA and a quantitative risk assessment. Risk was calculated quantitatively by considering the severity and frequency of occurrence and variables such as the number of accidents, transportation volume, monetary loss, route distance, and transportation volume. In addition to verifying the results of the quantitative analysis, the qualitative analysis integrates previous literature and actual accident data to establish a more comprehensive list of container transport failure modes in the port area than those in the previous literature. The findings and recommendations of this study are expected to provide useful risk management information for port-related organizations. The following are the main conclusions and contributions of this study:

1. Area-specific Risk Assessment in the Container Port

According to the FMEA results, the risk priority of each area in the container operation process was ranked highest in the storage area of the container yard, second in the route of containers from the dock to the storage yard, followed by the gate area of the container terminal, and the lowest RPN value in the loading and unloading area of the container at the dock.

According to the results of the quantitative risk model, in terms of fixed areas, the unit risk was highest in the storage area of the container yard, followed by the loading and unloading area of the container at the dock, and lowest in the gate area of the container terminal. The risk values of the three areas differed significantly in terms of unit and total risk. In the dock area, the risk of operational errors was higher; in the storage area, the risk of accidents caused by storage problems and equipment failure was higher; and in the gate area, the risk of collisions was higher.

In terms of the type of transportation routes, the unit risk was higher for the import container pickup route, followed by the south terminal ship-side container route, import container storage yard route, export container storage yard pickup route, and submit export container route. The north terminal ship-side container route was less risky, with the unit risk of the first three routes being much higher than that of the other three. The total risk was higher for the import container pickup route, followed by the import container storage yard route. The total risk values of these two routes were much higher than those of the others, followed by the south terminal ship-side container route and the export container storage yard pickup route, export container route, and north terminal ship-side container route, all of which had the same risk value.

In addition, the quantitative risk results were ranked according to the route and area according to the total risk from high to low as follows: the loading and unloading area of the container at the dock, the storage area of the container yard, the route of container transportation from the dock to the storage yard, and the gate area of the container terminal.

2. Comparison of qualitative and quantitative assessment results

Comparing the unit risk ranking according to the container operation process area, the container yard storage area was the highest risk area in both methods, but the container loading and unloading area on the dock and the container terminal gate area were ranked in the opposite order. The FMEA ranked the gate area as being at a higher risk, and the quantitative method ranked the loading and unloading area of the container on the dock as being at a higher risk. In practice, accidents at the gate are frequent, especially when a truck collides with the guardrail, and it is not easy to detect and prevent such collisions; however, accidents at the loading and unloading area of the container at the dock usually cause serious consequences, but they occur less frequently, and the detection mechanism is typically already developed. The qualitative method considers the ease of detection and balances the difference in severity, so the difference in RPN between the two areas was not significant; the quantitative method does not consider the ease of detection, so it fully reflects the difference in accident severity.

Comparing the total risk ranking of the container operation process areas revealed that, in the quantitative model, the loading and unloading area of the container at the dock is the riskiest part, whereas in the qualitative method, it is the least risky part, and the other three parts are ranked in the same order for both methods. Whether to consider the difference in the ease of detection was also considered. Because the severity of accidents in the loading and unloading area of the container at the dock is high, risk control is emphasized there, and many risk detection systems and methods have been developed. Therefore, considering the ease of detection in the qualitative method, the RPN value of the area was reduced.

Comparing the accident risks, sudden breakage of the straddle loader chain in the storage area when adjusting the container and breakage of the cable during the operation of the rail-mounted gantry cranes have higher risks in both the qualitative and quantitative methods.

3. Development of the standardized accident reporting form

It is recommended that port organizations refer to the standardized accident record form proposed in this study to record more accidents and items in more detail, as well as to record abnormalities or violations to facilitate a better risk study of the port area in the future.

4. Risk Mitigation Proposals

We were able to focus, based on the results of the aforementioned risk assessment, on the areas of highest risk for precise improvement and propose improvement strategies with reference to the revised version of the 109th edition of the Port District Occupational Accident Case Advocacy Manual of Taiwan International Ports Corporation. Accidents caused by storage problems and equipment failures in the container yard storage area should be ameliorated. The container may have been damaged before it was placed on the storage yard, or a minor accident may not have been recorded. Therefore, container inspection before storage and minor accidents records should be more strictly enforced to avoid delays in operation and labor costs caused by the attribution of responsibility. One of the high-risk accidents caused by equipment failure is the sudden breakage of the chain of the straddle loader chain in the storage area when adjusting the container and the breakage of the cable during the operation of the rail-mounted gantry cranes, causing damage to the spreader, falling or dumping of the container, and even affecting the adjacent containers. Therefore, it is necessary to strengthen the daily inspection of the equipment and check the equipment before operation, especially the chains and ropes, which are easily worn out. If there is a defective machine or equipment, it should be immediately reported to the operation supervisor for replacement or repair.

The risk of picking up the import container route should be lowered, where accidents include trucks hitting the guardrails of a rail-mounted gantry crane or storage yard and trucks hitting containers in the storage area. The route should be clearly marked, the truck should be guided to reduce speed, and a conductor should be available to help guide the truck when it is backing up, and so on.

In addition, in the FMEA, a truck falling into the sea and storage yard or dock loading and unloading equipment catching fire are failure modes that have not actually occurred in the Port of Keelung but are evaluated by experts to cause high risks and should be strictly prevented. For the first risk, truck maintenance and inspection should be strengthened, terminal road signs and markings should be clear and well-defined, and truck movement routes should be planned and evaluated in detail; for the latter, maintenance and inspection of loading and unloading equipment should be strengthened, disaster prevention education and training should be regularly implemented, and the ability of the port area to handle such accidents in an emergency should be enhanced.

5.2. Research limitations and opportunities for future research

One limitation identified in this research is the resolution of the accident data collected for the case study. Information collected for each container port accident can be improved to include more useful data for risk analyses. For example, the severity data in terms of monetary loss for each accident is based on the insurance claim, and therefore, monetary damage that is not considered in the insurance is not reported, which leads to a potential underestimation of the actual severity. Because the current accident reporting system only relies on the insurance claim for its severity information, this is the only available data for the quantitative risk assessment modeling. As proposed in subsection 4.4, an enhanced accident record form can help to capture more accurately the severity of the accident.

In this study, the existing accident data in the Port of Keelung were organized into tables and analyzed with statistics. If sufficient information is accumulated in the future, the accident severity and probability prediction model can be established via more advanced data analysis methods, such as BN models. The model can be used to analyze the severity of the accident based on the accident risk factors and then analyze the interdependence of the factors affecting the port accident. When an accident occurs, the model can also be used to explore the degree of influence of the accident factors to understand the probability of influencing factors that lead to serious consequences of the accident and understand the key factors of the accident for priority improvement. In addition, the potential of combining FMEA and various quantitative risk assessment methods can be further analyzed and improved to derive a methodologically more integrated process for container port operation.

Availability of data and material

The data sets analyzed during the current study are not publicly available due privacy reasons. The datasets contain personal data that may not be publicly available. Data generated for the research project are only used for this research context.

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Abbreviations

CY	Container Yard
FMEA	Failure Mode and Effect Analysis
NTD	New Taiwan Dollar
RPN	Risk Priority Number
TEU	Twenty-foot Equivalent Unit

Appendix.

A. List of failure modes of loading and unloading area of the container at the dock.

Failure mode	Failure effect	Cause of failure	RPN
The gantry crane hit the typhoon lock cover plate when the operation was completed and moved	Cover deformation, gantry crane head brake system damage	operational errors	6.1
Ship-side loading and unloading operations, the sea-side high voltage cable trough damage	Sea side high voltage cable trough collapse tilt, pressure damage, short circuit	operational errors	6.2
Ship-side loading and unloading operations, gantry cranes collide with each other	The two machines collide and bend, and the main platform limit switch frame collides and bends	operational errors	5.4
Inadvertent cutting of gantry crane cables during construction	Broken cable prevents gantry crane from operating	operational errors	8.3
Sudden fall of gantry crane during loading operation	Impacted container in the hold of the ship, the container was severely damaged and deformed	operational errors	10.2
In the case of container ships berthing at the dock, the ship's operation is inadvertent and damages the dock facilities (excluding gantry crane)	Damage to parapets, pads, piles, walls and stalls between docks	operational errors	11.6
The gantry crane spreader was lowered causing the spreader guide channel to hit the container on the truck below	Container tumbles from truck trailer rack to the ground	operational errors	12.7
Container command operator struck by container during gantry crane loading operation	Injuries to command operators	operational errors	14.3
When operating a gantry crane to lift a hatch from a cargo ship, the hatch falls to the ground	Damage to containers and injuries to operators caused by hitting containers	operational errors	7.8
Cargo ship berthing, hit the pier and gantry crane	Injuries, damage to docks, collapse of gantry cranes, damage to multiple containers, denting of vessel bows	operational errors	11.1
Gantry crane without lifting the crane boom to move the facility	Damage to the antenna, cab	operational errors	6.5
Weather conditions (e.g., typhoon) facilities without collision prevention measures	Facility displacement or collision damage	operational errors	6.3
The gantry crane was not far from the bow and stern of the ship, nor from the bridge or mast when in contact and off shore	The bow of the ship protrudes into the pier and hits the land-based machinery facilities	operational errors	9.2
Collision between the unreturned boom on the vessel and the gantry crane boom during loading and unloading	Ship boom damage, gantry crane boom damage	operational errors	9.0
Ship passing during loading and unloading, waves cause the ship to fall or the bow to be raised	The spreader rubs against the container or the facilities on board, the cable slips	operational errors	10.0
Gantry crane quick lift	Crane failure, rapid movement caused by shaking and collision	operational errors	7.8
Falling fence or boom during loading and unloading	Damage to deck or shipboard facilities	operational errors	9.5
Gantry crane collides with trailer while moving	Truck damage, gantry crane damage	operational errors	6.3
Truck not parked at a distance from the gantry crane	Loading and unloading is not easy, the container and the truck collide	operational errors	5.5
Weight imbalance or overweight containers	Collision during loading and unloading movement	operational errors	9.2
Inappropriate use of 40 and 20 foot spreader	Collision during loading and unloading movement	operational errors	6.1
The switch of the hatch is not well matched with the spreader interface	Easy to shake and scrape when moving the hatch, the hatch is not well placed, not stable and not waterproof	operational errors	7.0

(*continued on next page*)

A. (continued)

Failure mode	Failure effect	Cause of failure	RPN
No attention was paid to the loading height and actual draft of the ship	Causes risk to the ship while sailing	operational errors	12.7
The gantry cranes electrocuted	Worker injury or death	operational errors	13.4
The ship hit the dock while tilting	Damage to docks	operational errors	10.2
The overhead crane high-voltage cable falls off and the operator accidentally breaks the high-voltage cable during the movement of the head table	The entire power supply system of the container yard is cut off, and the instantaneous power failure causes the failure of the gantry crane panel in the original operation, and the power module damage failure	machine failures	15.8
When the gantry crane unloads the container to the ship, the spreader and the container fall down together	Hit the truck frame which was working on the side of the ship, causing damage to the front end and frame, and the container fell to the ground and was damaged	machine failures	11.1
Gantry crane oil tank valve seat broken oil leakage	Pollutant oil sprayed on the walkway and side of the cargo ship	machine failures	7.7
Gantry crane spreader damage	The container is stuck and cannot be unloaded, the container falls	machine failures	17.2
Insufficient spreader height during loading and unloading	Difficulty in loading and unloading containers under the deck, may not be placed in the guide channel, the container tilted and skewed	machine failures	13.2
Dock collapse	Collision of machinery and containers overturning or falling into the sea, casualties	machine failures	12.7
The spreader fell and struck the people below	Personnel injuries	machine failures	15.6
Fire in loading and unloading equipment	Machine and equipment damage, fire affects the surrounding area	machine failures	20.9

B. List of failure modes for container transportation from the dock to the storage area.

Failure mode	Failure effect	Cause of failure	RPN
Truck accidentally crashed into the perimeter fence of the rail-mounted gantry crane	Damage to the body of the fence	operational errors	11.1
The truck hit the stone pier and signboard when entering and leaving the storage yard	Displacement of stone pier and damage to the body of the sign	operational errors	9.0
Truck accidentally hit the refrigerated container socket in the storage yard	Socket and its outer box damage	operational errors	9.8
Truck collision storage refrigerated containers	Container displacement, container damage, damage to storage yard hardware facilities	operational errors	10.1
Trucks entering and leaving the CY storage area, not quite hitting the guardrail	Guardrail deformation	operational errors	7.8
Truck accidentally hit the storage container	Damage and displacement of containers, damage to trucks	operational errors	9.8
Truck hitting the dock movable facilities (such as tents, etc.)	Bodily injury and property damage	operational errors	8.3
Trucks collide with each other	Truck damage, container damage, casualties	operational errors	11.5
Worker struck by truck	Personnel injuries	operational errors	16.3
Truck fire at port operation	Damage to trucks and containers, fires affecting the surrounding area	machine failures	12.5
Truck overboard	Truck and container damage, casualties	operational errors	17.0
Container thrown out while truck is in motion	Damage to containers, containers hitting surrounding facilities	operational errors	10.6

C. List of failure modes in the storage area of the container yard.

Failure mode	Failure effect	Cause of failure	RPN
Straddle carrier accidentally hits dangerous goods container	Dangerous goods containers tilted and damaged	operational errors	12.6
Straddle carrier accidentally crashes into truck	Truck body damage	operational errors	14.2
Scrape and break frozen containers during straddle carrier operation	Damage to containers and goods	operational errors	12.7
Straddle carrier accidentally hits a container	Tilting of containers, damage to containers and goods	operational errors	11.2
sudden breakage of the chain of the straddle loader when adjusting the container	Causes deformation of container cabinets	machine failures	17.7
breakage of the cable during the operation of the rail-mounted gantry cranes	The spreader is damaged, the container is dumped and deformed, the heavy container is dropped and the side container is deformed	machine failures	15.9
the spreader falling and striking the people below	Personnel injuries	machine failures	16.4
Fire in loading and unloading equipment	Machine and equipment damage, fire affects the surrounding area	machine failures	17.5
The latch of the trailer frame is not pulled up when the container is lifted	Straddle carrier failure	operational errors	14.7
In the operation of portal crane, the spreader cable is too loose, so that when the spreader is raised, it hooks to the side of the container	Causing deformation and damage to the cable, tipping or skewing of the container	operational errors	10.4
When the straddle carrier is loading, the spreader is lowered and the container slides, hitting the truck frame	Bending down of the crossbeam of the container insert of the plate frame	operational errors	9.8
The straddle carrier is hitting the truck frame during operation	Tilt rupture of frame fixing pins	operational errors	12.6
Dropping of dangerous goods containers during loading operations	Damage to containers and leakage of contents	operational errors	13.5
The container slides directly onto the truck during loading and unloading	Damage to the container, damage to the body and frame of the truck	operational errors	11.5
The commander did not pay attention to the distance between the two rail-mounted gantry cranes and instructed the crane to move	Damage to the rail-mounted gantry cranes	operational errors	8.5
The rail-mounted gantry cranes electrocuted	Worker injury or death	operational errors	16.7
Containers received in a damaged state	Liability attribution costs, container compensation	operational errors	9.2
The container was stored at the container terminal area, and when the truck was being towed out of the terminal, it was found that the container was broken	Liability attribution costs, container compensation	storage problems	11.4

D. List of failure modes in the gate area of container terminal.

Failure mode	Failure effect	Cause of failure	RPN
The truck accidentally knocked the guardrail of the driveway out of alignment	Control guardrail breakage	operational errors	12.1
The truck accidentally broke the concrete post behind the gate in the gate driveway	The concrete column is damaged and the sign above it is skewed	operational errors	11.3
The truck accidentally broke the speed sign in the lane	Damage to the body of the speed sign	operational errors	9.8
The truck was hit by a metal gate blown by a strong wind	Car body damage dent	machine failures	7.3
Fire at the gate	Damage to buildings, fires affecting the surrounding area	machine failures	9.6
The truck driver fell to the ground while preparing to go through the formalities	Ambulance emergency medical evacuation	worker health problems	7.5

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