Vulnerability assessment of ports and industrial clusters against catastrophes

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**VULNERABILITY ASSESSMENT
OF PORTS AND INDUSTRIAL CLUSTERS
AGAINST CATASTROPHES**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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**VULNERABILITY ASSESSMENT
OF PORTS AND INDUSTRIAL CLUSTERS
AGAINST CATASTROPHES**

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ABSTRACT

Catastrophes, with the features of high negative impact and low frequency, are causing increasing losses to the human society due to the increasing exposure and vulnerability. Seaports are critical lifeline infrastructures in coastal cities and are at the same time vulnerable to both natural and man-made catastrophes, such as typhoon, earthquake, fire, and explosion. Any disruptions to a seaport will have a direct impact on the supply chain where the port lies and have a second order or even a third order propagation to the industrial clusters in the hinterland.

A literature review reveals a research gap on port multi-dimensional vulnerability assessment against catastrophes, which includes assessments of physical, functional, institutional, economic and interdependency aspects of port vulnerability. Therefore, to fill the gap, this study firstly identifies the major port catastrophic hazards by literature review. Based on the framework, port vulnerability is assessed against non-repetitive catastrophes by utilizing the method of vulnerability index which integrates the fuzzy evidential reasoning (ER) and the fuzzy technique for order preference by similarity ideal solution (TOPSIS). By using Tianjin Port Explosion in 2015 as the case study, vulnerability estimates of the four port sub-systems as well as the whole port system in two assessment periods are obtained. It is found that the storage system is the most vulnerable subsystem after the explosion, while the vulnerability condition of the loading and unloading system improves the most after the first round of port recovery. Further, port vulnerability assessment against repetitive catastrophes is conducted by using the developed port operation simulation-based model. The relationship between catastrophe magnitude and port loss is revealed by quantifying decreased port throughput and physical damages. The typhoon hazard and the Port of Shenzhen, China is selected as the case study. It is estimated that a worst-case scenario typhoon attack could cause a total loss of 0.91 USD billion in the studied terminal, which is approximately three times the terminal net profit in 2015. Finally, the research takes a further step in considering the hinterland industrial clusters into the research scope.

Propagation of port vulnerability to hinterland industrial clusters is evaluated by an original three-layer port-cargo-industrial cluster model. The key seaports and industrial clusters in Guangdong province, China as well as the typhoon hazard are used as examples. It is identified that the most vulnerable industrial cluster of Guangdong is the petrochemical industrial cluster when facing typhoon-induced port disruptions in the import mode, while the textile and apparel industrial cluster is the most vulnerable one in the export mode. Consequently, the port and industrial clusters vulnerability estimates obtained from this study could be used by decision makers in identifying and prioritizing critical port protection targets, ship route planning, and risk mitigation strategy formulating.

LIST OF PUBLICATIONS

Published peer reviewed paper:

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LIST OF SYMBOLS

The following symbols are used in this thesis:

A^* - fuzzy positive idea solution (FPIS);

A^- - fuzzy negative idea solution (FNIS);

A_i^* - linguistic variable of the i th antecedent;

A_{ij} - the j th linguistic term of the i th attribute;

A_{ki} - linguistic variable of the i th antecedent attribute in R_k ;

(a_{ij}, b_{ij}, c_{ij}) - aggregated fuzzy triangular number of the i th assessment unit's j th criterion;

$(a_{ijk}, b_{ijk}, c_{ijk})$ - fuzzy triangular number given by the k th analyst to the i th assessment unit's j th criterion;

BC_i - bottleneck coefficient of the i th assessment unit;

$C_i^{load \& unload}$ - loading and unloading charge per TEU at the i th terminal;

CC_i - closeness coefficient of the i th assessment unit;

d - great circle distance between the geographical latitude and longitude of two points;

$(x_1, y_1), (x_2, y_2)$ - latitude and longitude of the two points;

$\tilde{D}$ - fuzzy decision matrix;

D_j - the j th consequence;

$d_v(.,.)$ - distance between two fuzzy numbers;

d_i^* - distance between the i th assessment unit and FPIS;

d_i^- - distance between the i th assessment unit and FNIS;

EL - direct economic loss of the port caused by one catastrophe event;

h - ideal half width;

h_0 - half width of the results obtained from the n_0 replications;

H_{ij} - number of components of the j th type in the i th terminal;

IV - defuzzified index value;

K_u - number of analysts;

L - number of rules in the rule base;
 L_{ijk} - loss potential of k th component of the j th type in i th terminal;
 M - number of antecedent attributes;
 m_{kD} - unassigned probability mass to any individual output D_j ;
 $\bar{m}_{kD}$ - unassigned probability mass due to the relative importance of the k th packet antecedent A_k ;
 $\tilde{m}_{kD}$ - unassigned probability mass due to the incompleteness of the k th packet antecedent A_k ;
 m_{kj} - individual degrees to which each R_k supports the final conclusion D_j ;
 M_u - number of assessment units;
 MC_i - types of components of i th terminal;
 MP - number of studied ports;
 MQ - number of the types of studied cargos;
 MR - number of studied industrial clusters;
 n – replication number of running;
 N - number of belief degrees;
 N_u - number of selected criteria;
 n_0 - initial replication number of the simulation model;
 NP - number of terminals in the studied port;
 P_i - probability of damage of the i th terminal;
 PD - number of disrupted scenarios;
 PL - direct physical loss of the port caused by one catastrophe event;
 r - radius of the earth;
 $\tilde{R}$ - normalized fuzzy decision matrix;
 R_k - the k th rule in the rule base;
 $\tilde{r}_{ij}$ - normalized fuzzy rating to the the i th assessment unit's j th criterion;
 S_{ij} - frequency of the i th disrupted scenario in the j th year;

$S(A^*)$ - final conclusion generated by fusing the rules;
 $S((A_1^*, \varepsilon_i))$ - linguistic-termed distribution representation using belief degrees;
 $T_{base\ year}$ - throughput of the port in the base year;
 T_j - predictive throughput of the port in the j th year;
 T_i^{de} - decreased container throughput at the i th terminal;
 T_i^{dis} - container throughput at the i th terminal under disrupted scenario;
 T_i^{int} - container throughput at the i th terminal under intact condition;
 TL - total loss of the port caused by one catastrophe event;
 TL_{ij} - expected total loss of the i th disrupted scenario in the j th year;
 TL_{sum} - total port loss over predictive period against one type of catastrophe;
 TLP_i - total loss potential of the i th terminal;
 UC_j - utility centroid value of the j th consequence;
 $\tilde{V}$ - weighted normalized decision matrix;
 $\tilde{v}_{ij}$ - element in the i th row and j th column of the matrix $\tilde{V}$;
 $(v_{ij1}, v_{ij2}, v_{ij3})$ - fuzzy number of the element in the i th row and j th column of the matrix $\tilde{V}$;
 $V_{\hat{W}_{(n)}}$ – variance of point estimate of the difference and observed difference;
 $\tilde{W}$ - aggregated fuzzy weight matrix;
 W_i – observed difference of the terminal throughput and the model output of the i th replication;
 $\tilde{w}_j$ - aggregated fuzzy weight for the j th criterion;
 (w_{j1}, w_{j2}, w_{j3}) - aggregated fuzzy triangular number of the fuzzy weight of the j th criterion;
 $\tilde{w}_{jk}$ - fuzzy rating given by the k th analysts to the fuzzy weight of the j th criterion;
 $(w_{jk1}, w_{jk2}, w_{jk3})$ - fuzzy triangular number given by the k th analyst to the fuzzy weight of the j th criterion;
 $\hat{W}_{(n)}$ – the point estimate of the difference between the terminal throughput and the sample mean of the model output;

$\widehat{W}_{(n)} \pm t_{n-1, (1-(\alpha/2))} \sqrt{V_{\widehat{W}_{(n)}}}$ – the 100(1- α)% confidence interval of the variance;

X_1 – terminal throughput;

$\tilde{x}_{ij}$ - aggregated fuzzy rating to the i th assessment unit's j th criterion;

$\tilde{x}_{ijk}$ - fuzzy rating given by the k th analyst to the i th assessment unit's j th criterion;

Y - predictive period;

Y_i – model output of the i th replication;

$\hat{Y}_n$ – sample mean of the n replications;

α_i - catastrophe risk input of the i th port;

α_{ij} - degree to which the input (ε_i, A_i^*) for U_i belongs to the linguistic term A_{ij}

with $\alpha_{ij} \geq 0$ and $\sum_j \alpha_{ij} \leq 1$;

β_D - remained belief degrees unassigned to any D_j ;

β_j - overall fused degree of belief for the j th consequence;

β_i^j - cargo value proportion of the j th type of cargo among all types of cargoes imported through the i th port;

β_j^i - cargo value proportion of the j th type of cargo among all types of cargoes exported through the i th port;

β_{kj} - belief degree to which D_j is believed to be the consequence in the k th rule;

β_{kj}' - updated belief degree considering the incompleteness of input data;

δ_{ki} - weight of the i th antecedent attribute in the k th rule;

(ε_i, A_i^*) - actual input of the i th antecedent;

φ_k - initial weight of the k th rule;

λ_j^k - cargo value proportion of the j th type of cargo among all types of cargoes consumed by the k th industrial cluster;

λ_k^j - cargo value proportion of the j th type of cargo among all types of cargoes produced by the k th industrial cluster;

μ_k - activation weight of the k th rule;

θ_k - relative weight of the k th rule;

σ_j - adjustment coefficient of total loss for the j th year;

τ - a matching function, $\tau(A_{ij}, A_i^*)$ stands for the matching degree to which A_i^* belongs to A_{ij} ;

ω^k - propagation vulnerability output of the k th industrial cluster in the import model;

ω_k - propagation vulnerability output of the k th industrial cluster in the export model.

CHAPTER 1 INTRODUCTION

Seaports are critical infrastructure systems in global supply chains, whose smooth operations safeguard the movement of around 90% of world trade cargo. Despite the importance, seaports are vulnerable to a number of natural and man-made catastrophes from both sea-side and land-side. Different from daily operational risks, catastrophe risks feature high negative impacts and low probabilities. Once being attacked by catastrophes, seaport structures and equipment tend to suffer serious physical damages, which may result in long-term port downtime and tremendous port economic loss. Any port inoperability will then propagate along supply chains to the industrial clusters served by the port, and thus negatively impact the local, regional, and even global economy. Assessing vulnerability is a core task in quantitative risk assessment. However, to assess vulnerability at a port's level is a challenging work due to (1) the multi-dimensional feature of port vulnerability, (2) the complexity and confidentiality feature of port operation, and (3) the limitation of publicly available data on port catastrophe hazards. Therefore, this research aims to deal with such difficulties by conducting port and industrial cluster vulnerability assessments against catastrophes from multi-dimensions. The research background, objectives, scope, significance, and thesis structure are introduced in this chapter.

1.1 Research background

Catastrophe risks are risks that feature high negative impact and low frequency (Bier et al., 1999; Banks, 2005). Despite the low frequency, society is suffering increasing losses from both natural and man-made catastrophes as time goes on. This is evidenced by many catastrophes happened in the last few decades, as shown in Table 1.1.

Table 1.1 Major catastrophes sorted by direct loss (1985-2017)

Rank	Year	Catastrophe event	Country/Region	Direct loss (in USD billion)	Reference
1	2011	Tōhoku earthquake and tsunami	Japan	300	Ridgwell, 2011
2	2017	Hurricane Harvey	The U.S.	198	Hicks and Burton, 2017
3	2017	Hurricane Maria	The U.S.	103	Masters, 2017
4	1995	Great Hanshin Earthquake	Japan	102	Smith, 2015
5	2010	Deepwater Horizon oil spill	The Gulf of Mexico	100	Cohen, 2010
6	2008	Sichuan earthquake	China	86	Ranasinghe, 2013
7	2017	Hurricane Irma	The U.S.	100	Harrington, 2017
8	2011	Thailand floods	Thailand	46	The World Bank, 2011
9	2005	Hurricane Katrina	The U.S.	45	History, 2009a
10	2011	Christchurch earthquake	New Zealand	40	Newshub, 2013
11	2008	Hurricane Ike	The U.S.	30	Texas Engineering Extension Service, 2008
12	1998	Yangtze River floods	China	26	You, 2012
13	1992	Hurricane Andrew	The U.S.	25	National Oceanic and Atmospheric Administration, 2002
14	2001	9.11 attack	The U.S.	21	Institute for the Analysis of Global Security, 2003
15	1994	Northridge earthquake	The U.S.	20	Northridge virtual exhibit, 2015
16	1986	Chernobyl disaster	Ukraine/Belarus	15	GreenFacts, 2017

Cont'd Table 1.1

Rank	Year	Catastrophe event	Country/Region	Direct loss (in USD billion)	Reference
17	2004	Indian Ocean earthquake and tsunami	Many nations	15	Pudney, 2015
18	1985	Armero tragedy	Colombia	7	Nevado, 1985
19	2013	Alberta floods	Canada	5	Athukorala and Resosudarmo, 2005
20	1989	Exxon Valdez oil spill	Prince William Sound	3	National Oceanic and Atmospheric Administration, 2015
Sum				1287	

As can be seen from Figure 1.1, during the last three decades, the frequency of catastrophes remained more or less constant, while the direct losses on societies experienced a huge increase. The reason lies in the increasing exposure and vulnerability of human societies to natural and man-made catastrophes.

Figure 1.1 World's largest catastrophes (1985-2017)

Source: Drawn by author, based on references as shown in Table 1.1.

Cities are the centres of politics, economy, science, and culture. Coastal cities are areas of the largest population density (McGranahan et al., 2007). Worldwide, more than sixty percent of the cities with a population larger than five million are distributed along the coastal areas (Doukakis, 2005). Of the top twenty catastrophes in the last three decades, many caused huge damages to coastal cities, such as the Tōhoku earthquake and tsunami, the Great Hanshin earthquake, the Deepwater Horizon oil spill, Hurricane Katrina, the Indian Ocean earthquake and tsunami, as

well as the Yangtze River floods (Lloyd's list, 2000; Rao, 2001; Chambers, 2003a; History, 2009b; Murphy, 2011; Faucon, 2015).

Seaports are critical infrastructures in coastal cities (Moteff et al., 2003). Seaports play important roles as nodes not only along the physical maritime supply chains but also in the economic networks. Most of the international metropolises around the world flourished because of ports (Taylor and Kwok, 1989; Nicholls et al., 2008). However, seaports face a number of catastrophic hazards from both seaside and landside due to their special locations. The catastrophic hazards will not only cause huge damage to the port infrastructure and people's lives but will also lead to long term port operation disruption. Any disruption to a seaport will have a direct impact on the supply chain that the seaport is a part of and have a second order or even a third order propagation to the industry as a whole.

Clusters are defined as “geographic concentrations of interconnected companies and institutions in a particular field” (Porter, 1998, p.3). A number of industrial clusters are formed near seaports in order to achieve lower costs of transportation (Hamilton and Atkins, 2008). Among the thirty-three major industrial clusters in the United States, nineteen are located in port cities (Porter, 1998). The location advantage of hinterland industrial clusters is manifest. However, interdependency between port clusters and industrial clusters would also pose tremendous threats to the hinterland industrial clusters during port failure times.

On 11th March 2011, the Tōhoku earthquake and tsunami hit the northeast part of Japan, causing severe damages to fifteen major ports. The loss of seaborne trade for Japan on that day alone was estimated to be more than 3 USD billions. The overall loss, including the loss of port immediate closure and the secondary impacts on the global just-in-time supply chain, was inestimable (Osler, 2011). On 12th August 2015, two catastrophic blasts occurred in a dangerous cargo warehouse within the port area of Tianjin, China, leaving one hundred and sixty-five people dead and more than seven hundred people injured. This catastrophic chemical explosion not only damaged physical properties and cargoes within the port area, but also caused disruptions to the shipping network of chemicals in China. Port users, such as shippers, carriers, and chemical factories were seriously affected (Leander and Lin,

2015).

Vulnerability is viewed as an internal state of a system before a hazard event and the system's ability to cope with such shocks, which affects the amount of damages to the affected system bringing by the hazard event. Assessing vulnerability is the first step and a critical task in any quantitative risk assessment and reduction against natural and man-made catastrophic hazards. Many nations have launched and conducted comprehensive vulnerability assessments from physical and/or socioeconomic aspects (Clark et al., 1998; Tapsell et al., 2002; Wu et al., 2002; Cutter et al., 2003; Kleinosky et al., 2007). However, most of the assessments focus on a scale of community, city, region, and even the whole world. Very few focus specifically on ports and maritime transportation network (Hsieh, 2014; Hsieh et al., 2014; Chhetri et al., 2015). Even fewer focused on port vulnerability assessment against catastrophes (Hsieh, 2014). To author's knowledge, there is no study addressing the propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port inoperability. To assess port vulnerability is a challenging work due to three major reasons. Firstly, the in-depth discussion of the concept of port vulnerability is insufficient in the existing literature. Secondly, the structure of port systems and the process of port operations are complex. Thirdly, there is limited publicly available data on port catastrophes. Therefore, this work is motivated by the literature gap, the increasing interest of how catastrophes affect port and industry cluster operations, as well as the urgent need for sound vulnerability reduction plans for ports operators and port stakeholders. The research objectives, the scope of research, the research significance, and the organization of this study are shown in the following sections.

1.2 Research questions and objectives

To bridge the mentioned gaps in the current literature, four research questions with sub-questions are raised:

1. How do we define port vulnerability?
2. What types of hazards have posed catastrophic risks and will pose potential catastrophic risks to ports?

3. How can we measure port vulnerability against catastrophes?
 - a. How to measure port vulnerability against non-repetitive catastrophes?
 - b. How to measure the port vulnerability against repetitive catastrophes?
4. How should propagation of port vulnerability be measured for hinterland industrial clusters, resulting from catastrophe induced port disruptions?

By answering the four raised questions, this study aims to achieve the following five research objectives:

- (1) To give definitions of port vulnerability from a multi-dimensional perspective;
- (2) To identify the types of major catastrophic hazards that affect port operation;
- (3) To assess port vulnerability against non-repetitive catastrophes;
- (4) To assess port vulnerability against repetitive catastrophes;
- (5) To assess propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port operational disruptions.

1.3 Research scope

The research scope is discussed from three aspects in this section, namely the type of catastrophe, the dimension of port vulnerability, and the affected body. Firstly, catastrophe could be classified into natural catastrophe and man-made catastrophe by its source. It could also be classified into repetitive catastrophe and non-repetitive catastrophe by its frequency. In order to conduct port vulnerability assessments in a comprehensive manner, this study covers both natural and man-made, as well as repetitive and non-repetitive. In detail, port vulnerability assessment against man-made, non-repetitive catastrophes is carried out in Chapter 4 by using 2015 Tianjin Port explosion as the case study. Against natural, repetitive catastrophes, the hazard of typhoon is used as an illustration example of the applicability and feasibility of the proposed method. Secondly, port vulnerability is assessed in this study from multi-dimensions. To be more specific, functional, economic, institutional aspects of port vulnerability are examined in Chapter 4.

Chapter 5 focuses on port vulnerability from perspectives of physical, functional, and economic dimensions. Lastly, the study expands its research scope from solely seaports to the network of seaports and hinterland industrial clusters. In Chapter 6, propagation of port vulnerability to industrial clusters is assessed by evaluating the interdependency between ports and industrial clusters. The detailed descriptions of natural and man-made, repetitive and non-repetitive catastrophes, as well as the dimensions of port vulnerability are illustrated in Chapter 2.

1.4 Research significance

There has been a growing international attention on port catastrophes after the 2015 Tianjin Port explosion, which calls for realistic yet effective methods to assess port vulnerability against catastrophes and its further impacts on the economy. Research concerning port vulnerability assessment is progressively increasing but inadequate, especially against catastrophes. Since maritime transportation is a derived demand of global trades, assessing port vulnerability alone is insufficient. The propagation of port vulnerability to the industrial cluster resulting from catastrophe-induced port disruptions should also be assessed. This study proposes three vulnerability assessment frameworks in tackling port and hinterland industrial cluster vulnerability assessments against catastrophes. The three research frameworks as a whole examine port and hinterland industrial cluster vulnerability from a multi-dimensional perspective and from different assessment periods for the first time. Moreover, the scarcity of data is a major challenge in catastrophe risk analysis and related research. A port catastrophe database is firstly established in this study in an effort to overcome this challenge. The established database supplements the current catastrophe-related databases by including the less studied infrastructure of seaports.

The significance of the port vulnerability assessment results could also be shown in the practical usages for various types of port stakeholders. For example, for port operators, the results can be used for prioritizing mitigation options for different subsystems of ports in a cost-effective manner. Furthermore, the outputs can be useful references for port users in decision making, such as route planning, and

selecting bunkering ports. The assessment results of the propagation of port vulnerability can serve as city planning references for city planners and port designers when selecting industrial cluster locations and port locations. For port-dependent industry managers, the outputs offer access to the knowledge of interdependency between the ports and their industries. Managers could adjust procurement and inventory plans accordingly. Faster reaction is thus achieved when they face catastrophe-induced port disruptions.

1.5 Organization of research

This thesis is organized into seven chapters.

Chapter 1 discusses the background and significance of port vulnerability studies, as well as the scope of the research, objectives, and research questions.

Chapter 2 presents a systematic literature review of the current status of research regarding catastrophe risk, port risk, port vulnerability, and industry risk with major research gaps identified. It also presents answers to the first and second research questions.

Chapter 3 explains in detail the proposed research methodologies for the achievement of the research objectives.

Chapter 4 answers question 3.a by applying the method of vulnerability index based on the fuzzy evidential reasoning (ER) and fuzzy technique for order preference by similarity ideal solution (TOPSIS). The 2015 Tianjin Port explosion is used as the case study.

Chapter 5 answers question 3.b by developing a simulation-based port vulnerability assessment framework. As a real-world application, a case study on the Port of Shenzhen and the hazard of typhoon is carried out.

Chapter 6 answers question 4 by proposing a three-layer port-cargo-industrial cluster (PCI) network model. The propagation of port vulnerability to major industrial clusters in Guangdong Province, China resulting from typhoon-induced port disruptions is examined.

Chapter 7 concludes the thesis with major finding and contributions presented. Limitations and directions for future works are also provided in this chapter.

CHAPTER 2 LITERATURE REVIEW

As stated in Chapter 1, this study is motivated by the current research gaps in the scientific domain of port and industrial cluster vulnerability assessment against catastrophes. The first half of this chapter (Sections 2.1 to 2.5) shows how these research gaps are identified by systematically and comprehensively investigating literature covering catastrophe risk, port risk, port vulnerability, and industrial cluster risk. The key words used for the advanced search are “catastrophe”, “maritime disruption”, “port disruption”, “industrial cluster risk”, “risk assessment”, “vulnerability assessment”, “propagation vulnerability”, “infrastructure interdependency”, “supply chain disruption”, “safety”, and “fire and explosion”. The literature review shows that there is a substantial need for the assessment of port vulnerability against catastrophes from a multi-dimensional perspective. Based on the research gaps identified and the future research directions discussed in Section 2.5, Chapters 4, 5, and 6 demonstrate how these research gaps are filled. In order to shape the research scope, in the second half of this chapter (Section 2.6), major port catastrophic hazards are identified. This is achieved by a detailed review of the literature, news records, and related port documents. “Port catastrophe”, “port risk”, “coastal area risk”, and “coastal area disaster” are used as keywords in the reviewing process.

The following publications from the author are based on part of this chapter:

- Cao, X., & Lam, J. S. L. (2018). Simulation-based Catastrophe-induced Port Loss Estimation. *Reliability Engineering & System Safety*, 175, 1-12. Cao, X., & Lam, J. S. L. (2018).
Cao, X., & Lam, J. S. L. (2018). Simulation-based Severe Weather-induced Container Terminal Economic Loss Estimation. *Maritime Policy & Management*. DOI: 10.1080/03088839.2018.1516049.
Cao, X., and Lam, J.S.L., 2018, Catastrophe Risk Assessment Framework of Ports and Industrial Clusters: A Case Study of the Guangdong Province. *International Journal of Shipping Transport and Logistics*. Accepted.
Cao, X., and Lam, J.S.L., 2017, Simulation-Based Catastrophe-Induced Port Loss Estimation. *The International Association of Maritime Economists Conference*, Kyoto, Japan, 27-30, June 2017.
Cao, X., and Lam, J.S.L., 2017, Catastrophe Risk Analysis of Ports and Industrial Clusters: A Framework and Case Study. *The International Association of Maritime Economists Conference*, Kyoto, Japan, 27-30, June 2017.
Cao, X., and Lam, J.S.L., 2015, A framework for port and industrial cluster catastrophe risk analysis. *The International Association of Maritime Economists Conference*, Kuala Lumpur, Malaysia, 24-26, August 2015.

2.1 Vulnerability, risk and catastrophe

2.1.1 Definition and research framework of vulnerability

The concept of vulnerability has experienced a growing study trend in the field of natural hazards, social science and climate change in the last few decades (Brooks, 2003). A number of review papers are collected and analysed considering descriptions/definitions/concepts/measurements of vulnerability, such as Cutter (1996), Brooks (2003), Adger (2000), and Fuchs et al. (2007). Table 2.1 shows a summary of selected definitions of vulnerability.

Table 2.1 Summary of vulnerability definition and research framework

Vulnerability definition	Research framework	Reference
"vulnerability is the degree of loss to a given element or set of elements at risk resulting from the occurrence of a hazard of a given magnitude in a given area"	$V = \text{Degree of loss} = f(\text{Exposure, Hazard})$	Varnes, 1984
"... the ability of an element to withstand hazards of a given type or size"	$V = f(\text{Exposure, Hazard, Coping capacity})$	Alexander, 2005
"Vulnerability depends upon the degree of loss to a given element at risk at a certain severity level. Generally, it is expressed as the percentage of loss (between 0: no damage, to 1: total damage) caused by given hazards"	$V = \text{Percentage of loss} = f(\text{Exposure, Hazard})$	UNDP, 1994
"... a measure of the robustness or the fragility of an element"	$V = \text{Robustness or Fragility}$	Vandine et al., 2004
"characteristics of a person or group in terms of their capacity to anticipate, cope with, resist against, and recover from the impact of natural hazards"	$V = f(\text{Exposure, Hazard, Coping capacity})$	Blaikie et al., 1994
"the presence or lack of ability to withstand shocks and stresses to livelihood"	$V = f(\text{Exposure, Hazard, Coping capacity})$	Adger, 2000
A complex set of characteristics that includes a person's initial wellbeing, livelihood and resilience, self-protection, social protection and social and political networks and institutions.	$V = f(\text{Wellbeing, Resilience, Protection, Networks})$	Cannon et al., 2003
"a multidimensional concept that helps to identify those characteristics and experiences of communities (and individuals) that enable them to respond to and recover from natural hazards"	$V = f(\text{Exposure, Hazard, Coping capacity})$	Cutter et al., 2003

As shown in Table 2.1, some works view vulnerability as an internal state of a system before a hazard event and the system's ability to cope with such shocks (e.g. Blaikie et al., 1994; Adger, 2000; Cannon et al., 2003; Cutter et al., 2003). Vulnerability plays a role of 'translator' who translates the level of hazard to the level of risk (Sterlacchini et al., 2014). The purpose of conducting vulnerability assessment is to identify the most vulnerability part of a system and to examine vulnerability variables (Vandine et al., 2004). For example, the measures of a social system could include poverty, inequality, marginalization, food entitlement, access to insurance, and housing quality, etc (Blaikie et al., 1994; UNDP, 1994; Brooks, 2003; Vandine et al., 2004).

There also exist some works quantifying vulnerability with the degree of loss (e.g. Varnes, 1984; UNDP, 1994; Alexander, 2005). As such, the measure of vulnerability is similar as the measure of risk (see definition in Section 2.1.2), for example, monetary cost, human mortality, production cost, and ecosystem damage (Brooks, 2003). It should be noted that, vulnerability is an intrinsic function of a system and could be independent of exposure and hazard. Thus, the degree of loss is used as a measure of vulnerability when analysts have an incomplete understanding of the studied system.

The concept of vulnerability is multi-dimensional. Sterlacchini et al. (2014) identified five dimensions of vulnerability of human society, which includes physical/functional vulnerability, socio-economic vulnerability, socio-cultural vulnerability, ecological/environmental vulnerability, and political/institutional vulnerability. The authors argue that it is the multi-dimensional nature of vulnerability that makes the assessment of vulnerability a challenging work. In addition, vulnerability assessment is end user-oriented. Analysts are required to investigate the end-users, specifically, the facets of vulnerability that the end-users are interested in, before conducting any systematic vulnerability assessments (Sterlacchini et al., 2014).

2.1.2 Definition and research framework of risk

In the content of risk analysis, there exist various definitions and research frameworks (Mokhtari et al., 1990; United Nations Department of Humanitarian Affairs [UNDHA], 1992; Stenchion, 1997; Crichton, 1999; Ahmad et al., 2001; Downing et al., 2001; United Nations Environment Programme [UNEP], 2002; United Nations International Strategy for Disaster Reduction [UNISDR], 2002; UNISDR, 2004; UNISDR, 2009; United Nations Development Programme [UNDP], 2010). Table 2.2 shows a collection of selected definitions and research frameworks from the existing publications. It can be seen from the table that most of the organizations or scholars use “probability” when describing risk, whether referring to the probability of occurrence of an undesired event or the probability of expected losses/consequences. Regarding the research framework, four typical models can be found:

- (1) $R = f(\text{Probability, Consequence})$ (Ahmad et al., 2001; UNISDR, 2009);
- (2) $R = f(\text{Hazard, Vulnerability})$ (UNDHA, 1992; Stenchion, 1997; UNDP, 2010);
- (3) $R = f(\text{Hazard, Vulnerability, Exposure})$ (Crichton, 1999; UNISDR, 2004);
- (4) $R = f(\text{Hazard, Vulnerability, Capacity})$ (UNISDR, 2002).

Framework (1) evaluate risk as consequences of different levels under different probabilities; frameworks (2), (3), and (4) view risk as the result of interaction between hazards and affected bodies from a system’s opinion. The main focus of debate on frameworks (2), (3) and (4) lies in whether exposure and coping capacity are a part of vulnerability. For the purpose of this paper, we define risk as the negative impacts resulting from the interactions among natural or human-made hazards, the exposure of the affected body and, the affected body’s vulnerable conditions, which could be measured by the probability of expected losses/consequences. We see exposure as an independent, external attribute from vulnerability while coping capacity or the concept of resilience as an internal

attribute of vulnerability.

Table 2.2 Summary of risk definition and research framework

Risk definition	Research framework	Reference
“Expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability.”	$R = f(\text{Hazard, Vulnerability})$	UNDHA, 1992
“Risk might be defined simply as the probability of occurrence of an undesired event, but might be better described as the probability of a hazard contributing to a potential disaster...importantly, it involves consideration of vulnerability to the hazard.”	$R = f(\text{Hazard, Vulnerability})$	Stenchion, 1997
“Risk” is the probability of a loss, and depends on three elements: hazard, vulnerability and exposure.”	$R = f(\text{Hazard, Vulnerability, Exposure})$	Crichton, 1999
Function of probability and magnitude of different impacts	$R = f(\text{Probability, Consequence})$	Ahmad et al., 2001
"Risk involves an exposure to a chance injury or loss"	$R = f(\text{Exposure, Loss})$	Mokhtari et al., 1990
"the combination of the probability of an event and its negative consequences"	$R = f(\text{Probability, Consequence})$	UNISDR, 2009
The probability of harmful consequences, or expected loss (of lives, people injured, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable/capable conditions. Conventionally, risk is expressed by the equation $\text{Risk} = \text{Hazards} \times \text{Vulnerability} / \text{Capacity}$	$R = f(\text{Hazard, Vulnerability, Capacity})$	UNISDR, 2002
Probability of hazard occurrence	$R = f(\text{Probability, Hazard})$	Downing et al., 2001

Cont'd Table 2.2

Risk definition	Research framework	Reference
The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions.	Conventionally: $R = f(\text{Hazard, Vulnerability})$; some disciplines $R = f(\text{Hazard, Vulnerability, Exposure})$	UNISDR, 2004
The probability of harmful consequences-casualties, damaged property, lost livelihoods, disrupted economic activity, and damage to the environment-resulting from interactions between natural or human-induced hazards and vulnerable conditions.	$R = f(\text{Hazard, Vulnerability})$	UNDP, 2010

2.1.3 Definition of catastrophe

Currently, the term catastrophe lacks a sharp definition from the academia. Different fields define catastrophe in different ways. For example, Swiss Re (e.g., Swiss Re, 1996) defines a natural catastrophe as an event caused by natural forces and a man-made catastrophe as a major event associated with human activities. Bank (2005, p.5) expands this definition to “a low probability natural or man-made event that creates shocks to the existing social, economic, and/or environmental frameworks, and has the potential of producing very significant human and/or financial losses” and “instances where a gradual accumulation of many small incidents, perhaps precipitated by the same catalyst, leads to the same scale of damage/losses”. On this definition, a wide range of man-made or natural events including earthquake, volcano eruption, flood, cyclones, pandemic infection, nuclear accidents, and climate change constitute catastrophes (Bostrom and Cirkovic, 2011). Although catastrophe is defined in many ways, catastrophic events share a common characteristic of low frequency/high severity.

Extreme events and HILP events are two terms shown in the literature which have trivial and vague distinctions between catastrophes (Bier et al., 1999; Lee et al., 2012;

Ord et al., 2010). Bier et al. (1999) describe extreme events as rare, severe, and outside the normal range of experience, while HILP events are the abbreviation of “high-impact, low-probability” events. From the descriptions, we can conclude that the common feature of the three types of events is low probability. Distinctions are found in terms of impacts and affected bodies. Concerning impacts, extreme events and HILP events are not necessarily catastrophic (Bier et al., 1999; Lee et al., 2012), unlike catastrophes which stress negative impacts. With regard to affected bodies, the affected body in extreme events and HILP events can vary from small to large systems such as a person, a computer, a dam, or a nuclear reactor, while the range of influences is usually broad for catastrophes (Bostrom and Cirkovic, 2011). Thus, based on the above analysis and Bank’s definition in 2005, this study proposes a definition of catastrophe as the theoretical foundation of this research. We define catastrophe as a low probability and high negative impact natural or man-made event that causes large scales of losses to the existing social, economic, and/or environmental frameworks.

It is noteworthy that a catastrophic event does not always lead to human and/or financial losses. If a high-magnitude earthquake happens in an unpopulated desert, no human and/or financial losses will occur. However, great influences on geology and/or zoology may take place. However, these impacts are beyond our research scope.

Regarding the classification of catastrophes, Bank (2005), Bostrom and Cirkovic, (2011), and Lee et al. (2012) propose three classification angles from catastrophe frequency, source, and the degree of human preparation. By frequency, catastrophe could be classified into non-repetitive catastrophe, irregular catastrophe, regular catastrophe, and seasonal catastrophe (Bank, 2005). In details, a non-repetitive catastrophe is a one-off event that only occurs once in a particular location, for example, the 2015 Tianjin Port explosion, the 9.11 attack, and the Chernobyl disaster. An irregular catastrophe refers to a disaster without a statistical regularity, however,

it can reoccur in the same location. Examples could be the 2014 Indian Ocean tsunami. A regular catastrophe is a disaster led by a regular cause, such as an eruption from an active volcano. A seasonal catastrophe indicates disaster that can reoccur in a given space and on a regular time basis. Examples induce typhoons, floods, and storm surges. It should be noted that the listed natural disasters do not always lead to catastrophes. In this thesis, only the seasonal disasters that lead to large scale losses to the human society are considered. By source, catastrophe could be classified into natural catastrophe, unintended consequence-induced catastrophe, and hostile act-induced catastrophe (Bostrom and Cirkovic, 2011). Catastrophes could also be classified by the degree of human preparedness into black swans (which means unknown events, whether being prepared or unprepared for), “known and prepared for” events, and “known but unprepared for” events (Lee et al., 2012). In this study, by taking references to the classification methods in Bank (2005) and Bostrom and Cirkovic (2011), we classify catastrophe into repetitive and non-repetitive catastrophe by frequency and into natural and man-made catastrophe by hazard source. Although more detailed classifications are possible, these granularities are suitable enough for our research purposes.

2.1.4 Catastrophe risk research methods

Since catastrophes and extreme events share a common feature of low probability, methods for assessing and managing extreme events are used as references. Table 2.3 summarizes the methods which have been used in the assessment of extreme event risks with partial references from Bier et al. (1999). The approaches could be categorized into the explicitly probabilistic manner, the semi-probabilistic manner (quasi-probabilistic manner), the non-probabilistic but quantitative approach, the qualitative approach, and the simulation-based approach. In circumstances of sparse data and the tail distribution of catastrophes, the Bayesian method becomes more popular than classical statistical methods. Some updates have been made to the Bayesian which act better in coping with the scarcity of data and the tail distribution.

Such methods include the updated method of the hierarchical Bayesian method, the empirical Bayesian methods, the standardized or “reference priors”, the “ignorance” or “non-informative” priors, and the maximum entropy priors (Bigün, 1995; Li et al., 2010). The bounding approach is a relatively new method to overcome the limitations of the approaches discussed above. In this approach, analysts specify bounds on the cumulative distribution functions of the various input parameters, rather than a single informative distribution for each input value. The fuzzy set theory and the theory of interval-valued probabilities related approaches are classified under such kind of methods (Kaufmann and Gupta, 1991; Walley, 1991).

Table 2.3 Approaches in extreme event studies

Method type	Method	Reference
Explicitly probabilistic manner	Bayesian method	Bigün, 1995; Li et al., 2010
	Fuzzy set logic	Zadeh, 1965; Kaufmann and Gupta, 1991
Semi-probabilistic/quasi-probabilistic	D-S theory	Shafer, 1976; Mu et al., 2008
	The theory of interval valued probabilistic	Walley, 1991
Non-probabilistic but quantitative approach	Chaos theory	Gleick, 1987; Sellnow et al., 2002
	Catastrophe theory	Poston and Stewart, 2014; Su et al., 2011
Qualitative approach	Surprise theory	Fiering and Kindler, 1984

In particular, Bigün (1995) uses an explicitly probabilistic manner to predict future catastrophes based on Bayesian. Since data is insufficient, subjective assessments which are experts’ opinions on catastrophe risks and consequences are naturally used in decision making. Two calibration methods based on probability assessment and interval assessment are given to adjust the experts’ prediction.

Ord et al. (2010) talk about the serious consequences of probability estimation of catastrophe risks by using a scientific analysis’s estimate. They argue that the use of the scientific report’s estimate of one in a billion directly is naïve. As can be seen

from the work of Ord's (2010), the accuracy of an estimation of a HILP event may result from a flaw in the report's argument. In the dichotomous study of catastrophe risks, consequence calculation is much more important than the calculation of a specific possibility or a probability distribution. It is not only because the accuracy of probability estimation cannot be guaranteed, but also the consequence of catastrophes is usually extremely enormous. Specifically, for ports, due to the interdependency between ports and port-reliant industrial areas, the second-order even third-order impacts to the national economy make port-related catastrophe risks more important.

The other method analysing catastrophe risks and their economic loss is the simulation technique. Clark (1986) proposes a formal approach based on Monte Carlo simulation to assess and manage catastrophe risks. Simulation is used to avoid drawbacks of using historical data. Methods such as time series regression can only give poor estimations to catastrophes due to the rarity of catastrophes which would lead to the actual loss data sparse and inaccurate. Besides, external variables such as changing population distributions, changing building codes, and changing building repair costs could be significantly changed in the long time interval between occurrences. Kozlowski and Mathewson (1995) also discuss the problem of using historic data. They summarize the simulation model for catastrophe risks into three modules: (1) the science module which indicates the physical characteristics of natural disasters such as the wind speed of a specific hurricane and the magnitude of earthquakes; (2) the engineering module which denotes as the percent damage from a specific catastrophe; and (3) the insurance coverage module which translates the damaged exposure to insured damaged exposure.

2.2 Port risk

2.2.1 Port risk, classified by hazard types

Hazards that lead to port risks shown in the earlier literature include security events,

fire and explosion, overtopping, oil spill, collision, grounding, earthquake, and climate change (Werner, 1998; Atsushi et al., 2004; Pachakis and Kiremidjian, 2004; Roeder et al., 2005; Pinto and Talley, 2006; Bichou, 2008; Moser et al., 2009; Na and Shinozuka, 2009; Yang et al., 2009; Zhang and Lam, 2015). There also exists a few literature which does not specify hazard types (Ronza et al., 2003; Darbra and Casal, 2004; Yip, 2008; Mokhtari et al., 2011; John et al., 2014). Figure 2.1 shows the distribution of the number of port risk literature classified by hazard types.

Figure 2.1 Maritime risk literature, classified by hazard types

Source: Author, based on databases of ScienceDirect, ISI Web of Knowledge and SCOPUS

As can be seen from Figure 2.1, we find that the man-induced risk studies outnumber the natural disaster-induced risk studies to a large extent. Among the studies of man-induced risks, security events and accidents are on the top list. Port risk analysis against natural disasters is seldom studied except for the hazard of earthquake. Port risk analysis against common disasters happened in coastal areas, for example, typhoon, storm surge, and tsunami, are absent from the literature.

As mentioned in Section 2.1.2, man-induced risks could be categorized into risks from unintended consequences and risks from hostile acts (Bostrom and Cirkovic, 2011). Port accidents, also shown as port operational risks (in John et al., 2014), are unintended events and may include foundering, fire/explosion, collision, contact, wrecking/stranding, and miscellaneous (Ronza et al., 2003; Darbra and Casal, 2004).

Studies on port accidents mainly contain two aspects: (1) the studies of previous accidents in order to explore accidents' causes, damages and consequences (Darbra, and Casal, 2004; Yip, 2008; Ronza et al., 2003) and (2) the studies using the probability of various accidents' scenarios to predict the future frequency of accidents (Ronza et al., 2003).

Unlike accidents, security incidents are risks from hostile acts. McGill et al. (2007) identify terrorist attack, sabotage, arson, and surveillance system failure as major security incident types. Earlier research focuses are laid on the identification of terrorist targets (Pinto and Talley, 2006), the discussion of potential risk assessment methods (Yang et al., 2009), and the estimation of ex-ante costs of international anti-terrorist initiatives (Bichou, 2008). Pinto and Talley (2006) find that the potential terrorists' targets may include ships, underwater mines, channels, oil tanks, and even containers. The authors also argue that regarding the four phases of security incident cycle of ports, more emphases are placed on the phases of prevention and detection, but little has been done to the phases of response and recovery. Yang et al. (2009) state that several security-related initiatives are launched after the "9.11" attack to enhance maritime and port security. These regulatory measures involve the International Ship and Port Facility Security code (ISPS), the IMO/ILO code of practice on security in ports, and the Framework of Standards to Secure and Facilitate Global Trade (SAFE Framework). In recent works, the research focus has been transferred from the studies of the prescriptive details of the measures and their ex-ante costs of compliance to the maritime risk assessment and management models (Bichou, 2008). Another type of events that will cause short-term or long-term port disruptions caused by intended purposes is labour strike. However, labour strike is only mentioned in some works (John et al., 2014; Mokhtari et al., 2011), there is no literature conducting special studies on the adverse effects of labour strike to port operations currently.

In terms of natural disaster risks, two major research topics are addressed: the

quantification of port risks against natural disasters (Pachakis and Kiremidjian, 2004; Na and Shinozuka, 2009; Lam and Su, 2015; Zhang and Lam, 2015; Burden et al., 2016; Lam and Lassa, 2017) and the selection of optimal risk reduction methods (Werner et al., 1997; Lam and Su, 2015).

Regarding the first topic, Chang (2000) analyzes the impacts of the 1995 Great Hanshin earthquake to the Port of Kobe by comparing the container throughput before and after the earthquake. By using an integrated method of simulation and fragility curve, Na and Shinozuka (2009) quantify a container terminal's revenue loss induced by an earthquake. However, the impact of trade's long-term trend and annual cycle to the throughput was not considered in their work. Lam and Su (2015) quantify port risks by adopting the method of risk matrix. The frequency and severity of disruption events are examined simultaneously. It is noteworthy that this study considers not only natural disasters, but also man-made incidents. With consideration of daily variations in the international trade volume, Zhang and Lam (2015) conduct a regression analysis to identify the relationship between port economic losses and port disruptions caused by extreme wind events. In 2017, Lam and Lassa (2017) propose a multi-hazard risk assessment framework for ports and cargoes exposing to natural catastrophes. Hazard, exposure, vulnerability, and risk management measures are considered in the proposed framework.

With regard to the second research question, Werner et al. (1997) carry out an assumed benefit-cost analysis of port seismic risk reduction methods by using the 1995 Great Hanshin earthquake as the case study. Lam and Su (2015) propose several mitigation strategies for port operators in dealing with natural disasters with a discussion of the pros and cons of each strategy.

Through analyzing the existing literature, it is found that regarding the causes of port disruptions, only man-made accidents, extreme wind events and earthquake are covered. This may result from the availability of some specific port risk databases,

such as the port accidents database established by local maritime bureaus and the extensive research on hydraulic structures seismic behavior in the discipline of harbour engineering (for example, Werner, 1998; Atsushi et al., 2004; Roeder et al., 2005). The research of other causes, such as severe weather events are limited. In addition, the above-mentioned works mainly analyzed the relationship between the cause and the consequence, to be specific, the hazards and the damages/economic losses. Those dedicated to revealing the mechanism of how losses come into being, which indicates the vulnerability of the elements and/or the systems at risks have, so far, remained limited.

Several papers and reports study the slow-motion effects of climate changes to ports as well as the associated adaptation strategies (Moser et al., 2009; United Nations Conference on Trade and Development [UNCTAD], 2011; Becker et al., 2012; Ng, et al., 2013). Rising sea levels, increasing temperature, as well as increasing frequency and magnitude of extreme phenomena are potential threats bringing to ports by climate change (UNCTAD, 2011). These hazardous events pose serious direct and indirect impacts to both port physical infrastructures and related services. Direct impacts are addressed in works of Rahmstorf (2007), Bromirski and Kossin (2008), Fiore et al. (2009), and Ruggiero et al. (2010). Direct impacts are identified, which include increasing siltation in channels, access restrictions to wharfs, deterioration of the structural integrity of port roads/railways, road inundation, and problems in water supply systems. Indirect impacts are harder to be assessed, for the reason that they impact on a larger scale than just a port, e.g. international transportation patterns (Pinnegar et al., 2006; Borgerson, 2008; Hansen, 2008). In addition, several studies have addressed climate impacts on transportation infrastructures and possible adaptation measures (Inner City Fund International, 2008; Savonis et al., 2008; Eisenack et al., 2012). It can be found that, most of them are not mode-specific and very few focus specifically on ports.

2.2.2 Port risk, classified by processes of MTS

In this section, the literature on port risks analysis is investigated from a broader perspective of the different processes in Maritime Transportation System (MTS). MTS is defined in Berle et al. (2011) as a set of vessels, navigable waterways, ports, intermodal connections and users. In this study, as shown in Figure 2.2, the components of MTS are merged into three main groups in order to facilitate the collection of documents. In details, vessels and waterways are merged into one group as navigable waterways. Terminal is solely considered as a part. All roads, bridges to intermodal connections and the intermodal connections are seen as a part called port landside. The user is not considered explicitly, for the reason that the interest of the user is covered by the mission of the transportation system.

Figure 2.2 Process of MTS

Source: Drawn by author, based on Berle et al. (2011).

In general, as shown in Figure 2.3, the number of studies focusing on waterway risks exceeds the number of studies focusing on terminal risks and intermodal connection risks as a whole to a large extent. However, Ronza et al. (2003) find that 40% of port accidents occurred at the waterside of a port, while 60% occurred at port landsides. The mismatch between the numbers of accidents and the numbers of the literature reveals a lack of studies of the port land-side risks.

Figure 2.3 Port risk literature, classified by process of MTS

Source: Author, based on databases of ScienceDirect, ISI Web of Knowledge and SCOPUS

In terms of navigable waterway risks, several ship collision and grounding models have been proposed and used in practice, such as the Macduff's model (Macduff, 1974), the Fuji's model (Fuji et al., 1974), the Pedersen's model (Pedersen, 2002), the Kaneko's model (Kaneko, 2002), and the COWI models (Lyngby, 2008). However, there is a gap in the quantification of the impacts of human errors in the waterway quantitative risk assessment models.

Figure 2.3 indicates that there appear to be virtually very few studies specifically for terminal risks and port land-side risks. Indeed, some studies focus on the integration of all the risks instead of studying one specific risk (Yang et al., 2009; Mokhtari et al., 2011; John et al., 2014). Terrorism attacks, seismic damages, fire/explosion and climate change related risks are the common risk events that have been shown in the literature. The complexity of the port landside system may contribute to one of the reasons for the low number of studies. To be more specific, in the waterway risks analysis, the vessel is the main hazard-affect body; while in the terminal and port landside risk analysis, the hazard-affect bodies varies from the quay crane and other cargo handling equipment, roads and vehicles on roads, railways, pipelines, to yards, warehouses, and buildings.

2.3 Port vulnerability assessment

2.3.1 Definition of port vulnerability

Very few literature provide sharp definitions of port vulnerability. By taking reference from the definition of vulnerability in Section 2.1.1, this research defines port vulnerability as the internal characteristics of a port system that make it susceptible to negative effects of any natural or man-made hazard.

To the best of author's knowledge, there is no study mentioning the dimensions of port vulnerability. In accordance with the classification of human society vulnerability dimensions discussed in Sterlacchini et al. (2014), this research proposes five dimensions of port vulnerability, including

- the physical dimension of port vulnerability, related to the predisposition of port infrastructures, systems, and equipment, such as berth, quay, warehouse, water/power supply system, storage equipment, to be damaged or partially affected during a hazard event;
- the functional dimension of port vulnerability, related to the predisposition of port functions, such as loading and unloading, storage, cargo collection and distribution, to be damaged or partially affected during a hazard event;
- the economic dimension of port vulnerability, related to a decline in port income or in port production due to the occurrence of a hazard event, shown in forms of currency, container throughput, cargo tonnage or number of units;
- the environmental dimension of port vulnerability, related to the interrelation between the environment and port operations, such as environmental pollution due to crude ship collisions within port areas;
- the institutional dimension of port vulnerability, related to proactive and active institutional actions that prevent or reduce the negative effects of a hazard event, such as container lashing, dangerous cargo partitioning, evacuation, and relief

supplies distribution;

-the interdependency dimension of port vulnerability, related to interdependency between ports and other sectors, such as port users and other critical infrastructures.

As shown in Figure 2.4, it can be seen that it is the multi-dimensional feature of port vulnerability as a whole play a role of a mediator between the evaluated level of hazards and the assessed level of risks. Thus, assessing vulnerability is a prerequisite and core step in quantitative risk assessment. Until this section, the first research question raised in Chapter 1 has been answered.

Figure 2.4 Relationship of hazard, port vulnerability, and risk

Source: Author.

2.3.2 Port vulnerability assessment method

Previous literatures focused more on the assessment of the physical dimension of port vulnerability (Nozu et al., 2004; Yang et al., 2012; Kakderi and Pitilakis, 2014; Chhetri et al., 2015), while insufficient prior studies addressed other dimensions (Earnest et al., 2012; Nursey-Bray et al., 2013; Hsieh, 2014; Hsieh et al., 2014).

Regarding the assessment of the physical dimension of port vulnerability, Kakderi and Pitilakis (2014) propose adequate fragility curves of waterfront structures, cargo handling and storage components within the European context against seismic hazards. Yang et al. (2012) develop seismic fragility curves for vertical-pile-supported wharves with nonlinear time-history analyses. Also against seismic hazards, Nozu et al. (2004) conduct an effective-stress analysis for quay

walls and a pushover analysis for pile-supported wharves. Against sea-level rise, Chhetri et al. (2015) use a 3D model to assess the infrastructure vulnerability of Port Kembla in different emission scenarios. A vulnerability rating from one to five is used to evaluate the performance of each asset. In a related study, Voisin et al. (2004) conduct experiments to test the tower crane behavior in strong winds. It can be seen that, most of the port physical vulnerability assessments focus on the development of seismic fragility curves of quay walls. Limited literature assesses port vulnerability against other natural hazards, even few consider man-made hazards.

Regarding port functional vulnerability, Hsieh (2014) select seven vulnerability indicators based on Hsieh et al. (2014). The value of transport diversity is adopted as a proxy measurement of port functional vulnerability, which is derived by calculating the Shannon-Weaver index (entropy). Results show that the efficiency of gantry cranes, labour productivity, free trade zone business volume, and ground access networks are the most significant port vulnerability factors. The risk map of the Port of Taipei and neighbouring areas is obtained by overlapping the vulnerability map and the hazard map of debris flow and tsunami inundation.

On port institutional vulnerability, Nursey-Bray et al. (2013) analyze several Australia ports against climate changes in three aspects: (1) the real and/or potential climate change impacts to the ports; (2) the ports' coping ability and adaption capacity to these impacts; (3) to what extent the coping capacity may be restricted by social and environment constraints.

From a perspective of interdependency, Hsieh et al. (2014) assess port vulnerability against natural disasters by selecting fourteen vulnerability factors as vulnerability indicators. By integrating the fuzzy cognitive maps and the sensitivity model, vulnerability scores are calculated with and without the consideration of interdependency between the port system and other critical infrastructure systems. Four Taiwan ports are used as case studies. Results show that vulnerability of a port

is underestimated by excluding the consideration of interdependency. Regarding the port dependency of industries, Pant et al. (2011) estimate losses for eight industries across ten primary states due to a two-week inland terminal closure. An integrated method of simulation and multi-regional inoperability input-output model (Leontief, 1986) is used. Zhang and Lam (2016) propose a three-stage framework for the estimation of economic losses of industrial clusters due to port disruptions.

It can be seen that, while the literature on port vulnerability is growing, many research topics remain untouched, especially from perspectives of economic and environmental dimensions. Hsieh (2014) argues that the reason for the low number of research on port vulnerability may lie in the complexity and professionalism feature of port operations, as well as the fierce competition among ports. Additionally, it is revealed that the challenge of data collection grows along with the decrease of the study unit scale. We find a number of studies that provide vulnerability assessment on a larger scale, such as port communities, port city or coastlines (El-Raey, et al., 1999; Wood and Good, 2004; De Andrade et al., 2010; Akukwe and Ogbodo, 2015). These studies are investigated in the rest of this section.

In terms of earthquake and tsunami hazards, Wood and Good (2004) use GIS to integrate natural, socioeconomic, and hazard features to assess community vulnerability to natural hazards. These features include hazard potential, built environment, community services, and economic health. The authors use Oregon port and harbour community and earthquake and tsunami as the study case.

As for the oil spill hazard in a port complex, De Andrade et al. (2010) aim at mapping the physical vulnerability and socioeconomic vulnerability around Itaquí-Bacanga port complex (IBC) by using the technique of GIS and high-resolution remote sensing. The vulnerability index obtained based on the relationship among four variables which include geomorphological units, income,

education, and dependence on fishing. The results reflect the most vulnerable neighbourhoods in the area relate to the low-lying locations, the strong reliance on fishing and low education and income level.

Regarding sea-level rise vulnerability assessment to the port city, El-Raey et al. (1999) use remote sensing and GIS technique to assess the physical and economic impact of sea-level rise to the city of Port Said, Egypt. By overlaying horizontal retreat and land use, the authors could obtain the losses and socioeconomic impacts.

Akukwe and Ogbodo (2015) study the spatial vulnerability to flooding in Port Harcourt Metropolis, Nigeria. Vulnerability indices including adaptive capacity, sensitivity, and exposure have been used to compare flood vulnerability across thirteen zones in the port city. Principal component analysis has been used to get the weight for each variable. Cluster analysis was used to obtain a vulnerability map distinguishing flood vulnerability levels by grouping the various vulnerability indices. The result could be used in the spatial planning and emergency planning.

2.4 Industry risk

2.4.1 Safety management

Several safety indices for industrial areas have been developed with the development of the insurance industry. They rank different chemical installations based on the possible risks these installations may pose, such as fire, boiling liquid expanding vapor explosion (BLEVE), explosion, toxic releases. They are now extensively used in insurance premium setting, plant design, site selection, system design, accident prevention, and emergency planning. Well-known examples are the Dow fire and explosion index (DOW F&EI) (Chemical engineering progress and American Institute of Chemical Engineers (CEPAICE), 1967), Dow chemical exposure index CEI (American Institute of Chemical Engineers, 1994) and the Mond fire, explosion and toxicity index (Lewis, 1979). These methods aim to quantify the harm, identify

the main hazardous source and communicate the risk by analysing historical industrial near-misses and accident data. Modifications of the DOW F&EI could be found in Gupta (1997), Gupta et al. (2003). Other examples include the Wash 1400-Reactor safety study (Burns, 1980), which is for the assessment of the nuclear reactor explosion risks. Khan and Abbasi (1997) propose an accident hazard index for rapidly assessing potential chemistry industry accident risks. Khan et al. (2001) take into consideration the impact of safety measures, adding the accuracy of the chemical installations ranking. An inherent safety index module is developed by Leong and Shariff (2008), in which the preliminary design stage safety levels are assessed. Tugnoli et al. (2008a, 2008b) propose a domino hazard index as a reference for the designing of the industrial area layout.

Our academic review finds that there exists simplicity in the index computation algorithm in the above literature where only the single installation is taken into consideration. However, a trend of gathering multiple installations data to obtain an index of the industrial area as a whole as well as involving security risks and supply chain risks is observed. Moreover, to the best of author's knowledge, the methods used in the standard assessment procedures are mostly base on the dichotomous definition of risks ($\text{risk} = f(\text{possibility}, \text{consequence})$), which is proved to be not appropriate for the assessment of catastrophe risk. Novel assessment methods based on risk definition of $\text{risk} = f(\text{hazard}, \text{vulnerability}, \text{exposure})$ should be explored specifically for the estimation of catastrophe risks.

2.4.2 Supply chain management

Kleindorfer and Saad (2005) categorize supply chain risks into supply and demand risks (low-impact, high-frequency risks) and disruptions risks to normal activities (high-impact, low-frequency risks). There is a wide acknowledgment of articles addressing low impact, high-frequency risks in supply chains (Wilson, 2007; Sanchez-Rodrigues et al., 2010; Vilko and Hallikas, 2012) and a wide range of

operations research methods aims to solve the problem such as stochastic programming, stochastic dynamic programming, robust optimization, fuzzy programming, see reviews like Tang (2006) and Marquès et al. (2010).

Traditional operations research methods seem less appropriate to solve the problem featuring with high impact, low-frequency risks. Regarding this type of risks, a conceptual framework - Specifying risks, Assessment and Mitigation (SAM) offered by Kleindorfer and Saad (2005) aims to firstly identify the hazards which have the potential to lead risks, then quantify the risks by identifying the pathways by which the risks may be triggered and lastly offer the assessment and mitigation strategy guidelines to meet the decision requirement. The authors use chemical supply chains as an example, setting ten principles which should be simultaneously implemented to avoid or decrease disruption risks. However, as a conceptual framework, this approach does not provide models or risk ranking methods. Wilson (2007) investigates effects of transportation disruptions on traditional and vendor managed inventory (VMI) supply chain with three performance measures: unfilled customer orders, maximum and average inventory levels and maximum goods in transit. Four types of disruption cases occurring between two adjacent points inside a five-echelon supply chain are simulated by a system dynamics models. Results indicate that the disruption occurs between tier one supplier and the warehouse creates the most threats.

Although the literature on supply chain disruption risks is informative, the study on catastrophic supply chain risks with features of high impact, low frequency is still in its infancy. Fewer is on supply and demand disruptions led by a port disruption. Moreover, to the best of the author's knowledge, none of the developed models and algorithms so far can be used to evaluate industry supply chain risks as a whole and none of them incorporates industry losses into the models.

2.5 Summary of research gaps

In this literature review, a total of a hundred and nine previous publications regarding

the risk assessment-related fundamental concepts (Section 2.1), port risk (Section 2.2), port vulnerability (Section 2.3), and industrial risk (Section 2.4) are investigated, which were published between 1967 and 2017 with a forty-year time span. Literature gaps in the research area of port and industrial cluster vulnerability assessment against catastrophes are identified. Future studies are suggested based on the identified literature gaps, thereby assisting in the development of academic and practical perspectives in port and industrial cluster catastrophe risk assessment.

2.5.1 Major literature gaps in catastrophe risk assessment

There exist two prevailing definitions of risk and research frameworks for risk assessment in the earlier literature: (1) the dichotomous quantitative definition which sees risk as the product of hazard probability and severity of consequences, and (2) the definition from a system's point of view which defines risk as the negative results of interactions between hazards and affected bodies. Vulnerability is defined as an internal state of a system before a hazard event and the system's ability to cope with such shocks, which plays a role of 'translator' who translates the level of hazard to the level of risk. Catastrophe is defined in many ways in literature and by (re)insurance companies, however, these definitions share common characteristics of high negative impact and low probability. Catastrophe events could be classified according to the frequency, the source, and the degree of human preparedness. In order to deal with the scarcity of data and the tail distribution in catastrophe risk assessment, updated methods are used for the quantification of catastrophe risks instead of classical statistical methods. These methods include the hierarchical Bayesian method, the empirical Bayesian methods, the fuzzy set theory related approaches, the interval-valued probabilities related approaches, and the simulation technique. Most of the studies regarding catastrophe risks emphasis on catastrophe insurance product pricing, catastrophe risk modelling, and infrastructure behaviour in disasters. Although ports are critical nodes in the global maritime transportation system, which underpin economy development, there are few studies addressing

catastrophe risk on a scale of a port.

2.5.2 Major literature gaps in port risk assessment

This section investigates port risks analysis literature from angles of hazard types and MTS processes. From the angle of hazard types, port risks could be classified into man-induced risks and natural disaster-induced risks. It is found that more works emphasis man-induced port risks than natural disaster-induced port risks. Most of the unintended consequence man-induced port risks studies focus on the accident frequency analysis, while major research topics pertaining to port risks from hostile acts are the qualitative analysis of prescriptive details of the security-related regulatory measures. However, for both risk sources, very few researchers provide quantitative risk assessment methods. Although loss quantifications are conducted for natural disaster-induced port risks, there are limited studies discussing the mechanism of how the losses come into being, namely, port vulnerability, not to mention the study of hazard-specific port vulnerability. In addition, regarding hazard types leading to port disruptions, only seismic and typhoon hazards are covered. Other common hazard types in coastal areas, such as flood, storm surge, tsunami, and fog, are absent from the current literature. From the aspect of the processes in MTS, port risks are classified into navigable waterway risks, terminal risks, and landside risks. Port accidents happen more frequently at landside, however, there are fewer works addressing terminal risks than waterway risks. Vessels are the main affected body in waterways. A number of ship collision and grounding models are developed. In contrast, affected body varies on port landside, which may consist one of the reasons for the lower number of studies.

2.5.3 Major literature gaps in port vulnerability assessment

Few previous studies propose sharp definitions of port vulnerability, and no study has discussed the multi-dimensional characteristic of port vulnerability. Although port vulnerability is not defined from a multi-dimensional perspective in the earlier

literature, the assessment of port vulnerability targets one or more dimensions of vulnerability. The physical dimension of port vulnerability is well assessed, while assessments of other dimensions of port vulnerability are less addressed, especially the economic, environmental, interdependent dimension. Vulnerability is hazard-specific, however, except for earthquake and climate change-induced hazards, few studies assess port vulnerability against other natural catastrophes that may cause tremendous losses to ports. No study is found which attempts to assess port vulnerability against man-made catastrophes.

2.5.4 Major literature gaps in industry risk assessment

Industrial risks, by source, can be classified into internal risks and external risks. Regarding internal risks assessment, several safety indicator systems for industrial areas have been developed to assess potential risks of fire, boiling liquid expanding vapor explosion, other types of explosion, and toxic releases. However, most of these systems focus on a single installation rather than on an industrial cluster. Safety index of industrial cluster as a whole is almost missing from the literature. Additionally, the methods used in the safety indices for the quantification of risk is based on the dichotomous definition of risks ($\text{risk} = f(\text{possibility, consequence})$), which is not appropriate for the assessment of catastrophe risks. Supply and demand risks, as one of the major external risks, have been studied to a large extent regarding the low-impact, high-frequency risks. Analysis of high-impact, low-frequency industry risks is less conducted. The origins and destinations of supplies and demands of industries are not specified in most of the literature. Thus, mitigation strategies are not able to be given according to particular risk sources. Although maritime transport plays a key role in the movement of raw materials and final products for industries, industrial losses due to port disruptions are insufficiently studied.

Having identified the major research gaps in this study, the next section identifies major catastrophic hazards in order to narrow down the research scope.

2.6 Identification of catastrophic hazards occurred in seaport areas

This section aims to answer the second research question raised in Chapter 1. At this first phase of seaport vulnerability assessment against catastrophe, analysts are required to identify and analyze all types of catastrophic hazards that have led to or could potentially lead to severe consequences for a specific port.

In fact, there exist controversies in the definition of hazard. For example, Banks (2005) defines a hazard as an event that can lead to or intensify a peril/threat. A peril/threat, in turn, is the actual event that has the potential to cause damage to an area. For example, gasoline spilled on the ground of a warehouse is a hazard that can lead to an increased probability of damage by fire, which is the peril/threat. However, in the field of climate change-related studies, the real sources, the gasoline in the above example, is ignored. Only the actual event that causes the damage is referred to as a hazard (Brooks, 2003), for example, the fire. Moreover, sometimes one principal hazard can lead to one or several secondary hazards and thus a hazard chain is formed (Brooks, 2003). For example, a flood related to a heavy rainfall may be viewed as an outcome of that rainfall, and coastal floods may be viewed as the outcome of storm surges. In these cases, the rainfall and the storm surge are viewed as the principal hazards, while the flood and the coastal floods are viewed as secondary hazards. In this study, referring to Brooks (2003), a hazard is an actual event which causes the damage. All hazards on the hazards chain, involving all the principal hazards and the secondary hazards are collected in the hazards list.

Due to the different types, sizes, locations, hinterland population/asset, different ports are susceptible to different hazards. To identify hazards which pose potential risks to ports needs systematically searching the literature, news records, and port documents. “Port catastrophe”, “port risk”, “and coastal area risk”, “coastal area disaster” are used as the keywords during the reviewing process. Port contingency plans are used as a second channel. Contingency plans for the world large ports and the dangerous

cargoes terminals were given priority during the collection period for their rich experiences in risk management. These contingency plans involve port comprehensive emergency contingency plans, passenger emergency evacuation and rescue plan for major production safety accidents, port blackout emergency contingency plans, dangerous goods accident emergency plan, typhoon and flood prevention plan, port natural disaster emergency plan. News that reported port catastrophes are collected as a third channel. By taking references to the natural disaster classification of EM-DAT (EM-DAT, 2009), eight natural hazard main types, ten natural hazard sub-types, and eleven man-made hazard types have been identified as port hazards, as shown in Table 2.4 and Table 2.5. It is noteworthy that the structure of the natural hazards listed in Table 2.4 does not mean the associated or secondary relationships among hazards but only indicates the subordinate relationship among the definitions.

Table 2.4 Port natural hazards identification and classification

Hazard group	Hazard sub-group	Hazard main type	Hazard sub-type	Reference
Geophysical	Earthquake	Tsunami	nil	Prescott, 1996; Tinsley, 1996; Lloyd's list, 2000; Flinders Ports, 2004; Lloyd's list, 2004; Kelly, 2011; Leander and Murphy, 2011; Murphy, 2011; Osler, 2011; Ridgwell, 2011; Zhuhai Port Authority, 2011; Dalian Port, 2015; Oskin, 2015
Meteorological	Storm	Tropical cyclone	Typhoon/Hurricane	Brooke, 2003; Chambers, 2003a; Zhuhai Port Authority, 2011; Dalian Port, 2015
		Convection storm	Hail	Dalian Port, 2015
			Lightning/thunderstorm	Flinders Ports, 2004; Dalian Port, 2015
			Rain	Zhuhai Port Authority, 2011; Dalian Port, 2015
			Sand/dust storm	Dalian Port, 2015
			Winter storm/blizzard	Dalian Port, 2015
			Storm/surge	Flinders Ports, 2004; Zhuhai Port Authority, 2011
			Wind	Dalian Port, 2015
	Extreme temperature	Cold wave	nil	Dalian Port, 2015
		Heat wave	nil	Zhuhai Port Authority, 2011; Dalian Port, 2015
		Severe winter conditions	Snow/ice	Dalian Port, 2015
			Frost/freeze	Zhuhai Port Authority, 2011; Dalian Port, 2015

Cont'd Table 2.4

Hazard group	Hazard sub-group	Hazard main type	Hazard sub-type	Reference
Hydrological	Fog	nil	nil	Zhuhai Port Authority, 2011; Dalian Port, 2015
	Flood	Coastal flood	nil	Flinders Ports, 2004; Zhuhai Port Authority, 2011
		Riverine flood	nil	Flinders Ports, 2004; Zhuhai Port Authority, 2011
	Landslide	nil	nil	Zhuhai Port Authority, 2011
Climatological	Drought	nil	nil	Dalian Port, 2015
Biological	Epidemic	nil	nil	Dalian Port, 2015

Note: "nil" denotes no hazard main types/hazards sub-types fall under the column of hazard sub-group/hazard main type.

Table 2.5 Port man-made hazards identification

Hazard Group	Hazard type	Reference
Man-made	Labor strike	Dalian Port, 2015; Hutchins, 2015
	Dangerous substances spill	Flinders Ports, 2004; Port of Tauranga, 2008; Forth ports, 2010
	Explosion	Flinders Ports, 2004; Port of Fowey, 2008; Forth ports, 2010; History, 2009b; History, 2010; Burns, 2015; Leander and Lin, 2015; Osler, 2015; Taizhou Port, 2015
	War	History, 2009b; History, 2010
	Fire	Flinders Ports, 2004; Port of Fowey, 2008; Forth ports, 2010; Dalian Port, 2015; Taizhou Port, 2015
	Food poisoning	Dalian Port, 2015
	Terrorism	Flinders Ports, 2004
	Blackout	Dalian Port, 2015
	Ship grounding	Flinders Ports, 2004; Forth ports, 2010
	Ship sinking	Flinders Ports, 2004; Port of Fowey, 2008; Forth ports, 2010
	Ship capsize	Flinders Ports, 2004
	Ship collision	Darbra and Casal, 2004; Flinders Ports, 2004; Port of Fowey, 2008; Forth ports, 2010

Just as catastrophe does not have a universally agreed definition, port catastrophe does not lend itself to a simple and commonly-agreed definition. For the purpose of the research, we define a port catastrophe as a low probability natural or man-made event that creates shocks to existing port infrastructure, operation, reputation, and has the potential of producing very significant human and/or financial losses to the port and stakeholders.

It is admitted that, given high enough magnitudes and/or long enough durations, all of those identified hazards are able to lead to catastrophic consequences to ports. By investigating ten global worst natural catastrophes that caused losses to seaports, as seen in Figure 2.5, it is found that typhoon and earthquake are the two major hazard types that account for around 94% of the total insured losses. Thus, in this study, earthquake and typhoon are identified as the two major natural disasters that have the potential to cause catastrophic losses to seaports. Regarding man-made hazards, the same method for the identification of major natural hazards is not applicable, since insured losses for a single event are not able to be found in public databases. However, yearly average major maritime insured losses are recorded and used as references. From Table 2.6, it can be seen that from 2007 to 2016, yearly average maritime insured losses range from 6 USD millions to 68 USD millions with an average of 34 USD millions. Thus, in this study, we only focus on man-made catastrophe with an insured loss of 34 USD millions or above. It is found that, major fire and explosion, oil spill, and war are recorded to have caused such scale of loss to seaports in the past (Allen and Vogel, 1996; History, 2009b; History, 2010; Swiss Re, 2016).

Figure 2.5 Insured loss percentage of each natural hazard type affected ports

Source: Computation by author, based on Swiss Re (2016).

Table 2.6 List of major maritime insured losses (2007-2016)

Source: Compiled by author, based on Swiss Re (2008-2017).

Year	Number	Insured loss (in USD million)	Average (in USD million)
2007	52	582	11
2008	41	548	13
2009	39	1359	35
2010	27	162	6
2011	39	1833	47
2012	43	2208	51
2013	25	814	33
2014	39	783	20
2015	31	1679	54
2016	36	2463	68
Average	37	1243	34

Up to this step, typhoon, earthquake, major fire and explosion, oil spill, and war are identified as major hazard types that could lead to catastrophic impacts on ports. The list is then validated through interviews with selected maritime experts from worldwide and various port-related fields, whose organization, working location, and job title are listed in Appendix A. It was suggested to remove war from the list in this study, as hostile acts will require different research methods from other unintended consequence events. Thus, the scope of this study is adjusted and determined as shown in Figure 2.6, with principle hazards and secondary hazards presented.

Figure 2.6 Major port catastrophic hazards

Source: Author.

2.7 Chapter summary

This chapter firstly presents a comprehensive literature review regarding the research field of port vulnerability assessment. In general, future research should be focused on port risk assessment against catastrophes, especially port vulnerability assessment, taking hinterland industrial clusters into consideration. Studies on port vulnerability assessment are in progress but inadequate. In details, firstly, there is a substantial need for assessing port vulnerability against catastrophes with features of high negative impacts and low probabilities. Port vulnerability is better assessed against repetitive catastrophes than non-repetitive catastrophes and is better assess against natural disasters than man-made hazards. The hazard of earthquake, in particular, is well considered in the earlier literature, while other coastal repetitive natural disasters are seldom addressed, such as typhoon, storm surge, flooding, not to mention non-repetitive and/or man-made hazards. Secondly, port vulnerability is assessed from a single dimension and single assessment period. In order to meet the need of end-users, it is more suitable to conduct port vulnerability assessment from multi-dimension and in different assessment periods. Thus, diversity usage of the results could be achieved. Thirdly, since the demand for transport is a derived demand for fulfilling functions of production and consumption, to assess port vulnerability alone is not comprehensive. Interdependency between ports and

industrial clusters should be addressed in order to assess the propagation of port vulnerability to industrial clusters.

In the second half of the chapter, major catastrophic hazards threatening seaport operations are identified by methods of literature review and interview. These hazards include typhoon, earthquake, major fire and explosion, as well as oil spill.

CHAPTER 3 RESEARCH METHODOLOGY

As discussed in Chapter 1, this research aims to assess port and hinterland industrial cluster vulnerability against both natural and man-made catastrophes from a multi-dimensional perspective. This chapter presents the methodology design for systematically solving the proposed research topic, based on the vulnerability index system, the simulation-based model, and the input-output model, by using both primary and secondary data. The overall research process is illustrated in Section 3.1. The detailed explanations regarding particular components are discussed later in this chapter. Justification of the selected methods used in this study is also provided. Focusing on the whole method framework, this chapter can be used as a road map of the following chapters.

3.1 Research process

The overall research process of the thesis is shown in Figure 3.1. The study starts with a literature review covering studies on catastrophe risk, port risk, port vulnerability, and industry risk. This literature review supplements the current literature on catastrophe risk studies from facets of ports and industrial clusters. In order to shape the research scope, major catastrophe types that have occurred in seaport areas are identified by means of secondary data analysis. Subsequently, the study assesses port vulnerability from functional, economic, and institutional dimensions against non-repetitive catastrophes. A simulation-based port vulnerability assessment is then carried out against repetitive catastrophes, aiming physical, functional, and economic dimensions of port vulnerability. At last, the study takes a further step in the assessment of propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions. Based on both qualitative and quantitative methods, this study provides insights for industry practitioners and policy makers with regard to catastrophe-induced port disruptions and port-industrial cluster interdependency analysis.

The various methods proposed are illustrated in the following sections.

Figure 3.1 The overall research process

Source: Author.

3.2 Vulnerability assessment methods

Descriptive statistics methods, the vulnerability index, the vulnerability mapping, the vulnerability matrix, and the simulation-based modelling are used in the existing studies on coastal area, port city, and port vulnerability assessment (El-Raey et al., 1999; Pethick and Crooks, 2000; Rashed and Weeks, 2003; Wood and Good, 2004; Coffman and Noy, 2010; McLaughlin and Cooper, 2010; Hsieh, 2014; Hsieh et al., 2014; Chhetri et al., 2015). The comparison of these methods is listed in Table 3.1.

Descriptive statistic method is used to describe the basic features of data collected from experiments, surveys, or historical records. With graph drawing, a brief summary of the sample measurements can be obtained, which form the basis of quantitative analyses. Coffman and Noy (2010) assess ex-post Hawaii Island economic vulnerability against hurricanes. The unemployment rate, the resident population, and the tourist arrivals are examined as vulnerability measures in the study.

Vulnerability index method firstly selects representative vulnerability indicators to generate a vulnerability index system, then synthesises the collected data for each indicator to obtain one aggregated indicator as the vulnerability value or vulnerability level (Füssel, 2010). Hsieh et al. (2014) develop a port vulnerability index system containing fourteen indicators to evaluate port functional vulnerability against natural hazards. Port vulnerability is calculated by vulnerability indicator rating and the ANP method. In the same work, the authors also use fuzzy cognitive maps to examine the spatial-functional interdependent vulnerability among fourteen vulnerability indicators. Based on the work of Hsieh et al. (2014), Hsieh (2014) selects seven indicators to assess port functional vulnerability against natural hazards. The Shannon – Weaver index, a major transport diversity indicator is used as the port vulnerability indicator. Earnest et al. (2012) develop a port vulnerability index system which consists of three indicators. The economic impacts to international container transportation network resulting from container terminal failures are obtained through simulations.

Table 3.1 Comparison of vulnerability assessment methods performing in coastal areas, port cities, and ports

Method	Feature	Application	Reference
Descriptive statistic method	<ul style="list-style-type: none"> •For macro scale assessments •A deductive way of reasoning 	<ul style="list-style-type: none"> •Assess economic vulnerability against hurricane 	Coffman and Noy, 2010
Vulnerability index	<ul style="list-style-type: none"> •For macro scale and micro scale assessments •Inductive and deductive ways of reasoning •For multi-dimensional vulnerability assessment 	<ul style="list-style-type: none"> •Assess resilience and susceptibility of the coast against erosion, wave-induced erosion, assess the infrastructure vulnerability at coastal area •Compare vulnerability among various coastal features (e.g. cliffs, beach, sand dune, etc.) •Identify lead factors among port vulnerability factors 	McLaughlin and Cooper, 2010; Pethick and Crooks, 2000; Hsieh, 2014; Hsieh et al., 2014
Vulnerability mapping	<ul style="list-style-type: none"> •For macro scale and micro scale assessments •An inductive way of reasoning •Based on indices and Geographic information systems (GIS) •Visual presentation • For multi-dimensional vulnerability assessment 	<ul style="list-style-type: none"> •Assess vulnerability against earthquake, identify hot spots •Identify port and harbor community areas that are susceptible to earthquake and tsunami hazards and contain valued resources. •Assess port city loss against sea level rise and compare losses among areas with various functions (e.g. urban, beach, industry, agriculture, etc.) •Evaluate port operation vulnerability to debris flows and tsunami inundation 	Rashed and Weeks, 2003; Wood and Good, 2004; El-Raey et al., 1999; Hsieh, 2014; Hsieh et al., 2014

Cont'd Table 3.1

Method	Feature	Application	Reference
Vulnerability matrix	<ul style="list-style-type: none"> •For micro scale assessments •For ex ante assessments •A deductive way of reasoning •Simple, fast assessment 	<ul style="list-style-type: none"> •Examine the impact of extreme weather events (e.g. flash flooding, stream and creek flooding, heat waves, storm surges, high-speed winds, fog, tidal change and sea-level rise) on key port logistics operations and infrastructures 	•Chhetri et al., 2015
Simulation-based model	<ul style="list-style-type: none"> •For micro scale assessments •For ex ante and ex post assessments •An inductive way of reasoning •Flexible, visual representation •Tool: Google SketchUp Pro, field photographs, drawings and oblique aerial photographs 	<ul style="list-style-type: none"> •Examine the degree of vulnerability of key port logistics operations and infrastructures to sea level rise 	•Chhetri et al., 2015

Vulnerability mapping is a commonly used, visualized vulnerability assessment tool. With the support of geographic information system (GIS) technique, vulnerability mapping is able to integrate various layers that stand for different aspects of vulnerability. Thus, a combined vulnerability map can be obtained. Wood and Good (2004) combine layers of area portrayal, hazard potential, community assets, and community vulnerability for the purpose of assessing the vulnerability of an Oregon port and harbor community against earthquake and tsunami hazards. In order to estimate possible losses and socioeconomic impacts of sea level rise, El-Raey et al. (1999) overlay retreat distances with land use on well-registered GIS layers to get vulnerable classes. In aspects of port vulnerability mapping, by combining layers of the layout of the Port of Taipei and the natural hazards maps, Hsieh (2014) is able to get vulnerability maps of the Port of Taipei against debris flow and tsunami inundation.

Vulnerability matrix is designed to generate perceived vulnerability magnitudes for identified assets/components of a system, given exposures to observed and predicted hazards. In particular, port vulnerability magnitudes are estimated by port experts who have accesses to various port operation sources, such as logged records, failure reports, port contingency plans, port administrative documents, and personal experiences (Chhetri et al., 2015). Chhetri et al. (2015) assess port assets vulnerability against 8 types of natural hazards. Assets are divided into sea-side assets, sea-land interface assets, and land-side assets. The research shows locations of port assets affect assets' vulnerability against different types of hazards. The method is also adopted by local port authorities in the port disaster contingency plans in order to assess negative impacts of hazards bringing to local ports (Zhuhai Port Authority, 2011).

Simulation-based modelling is widely used in port and terminal operation planning (Dragović et al., 2017). Chhetri et al. (2015) adopt a 3D spatial model to examine the possible impacts of sea level rise to ports in a normal condition of 2010 and a high tide condition of 2100, respectively. In their work, a 3D environment asset register database is firstly created, then the spatial model is developed which simulates the impact of identified hazards on assets based on the results of

perceived vulnerability.

As stated in Chapter 1, four research questions are raised for the fulfillment of the research objectives. Having solving research question 1 and 2 in Chapter 2 by carrying out an in-depth discussion of the concept of port vulnerability and the identification of port major catastrophic hazards, methods of vulnerability index and simulation-based model are selected to tackle question 3.a and 3.b, respectively.

Vulnerability index method is chosen to evaluate the port vulnerability against non-repetitive catastrophes. It is a common method used to perform the vulnerability assessment of coastal areas, port communities/cities and port (Pethick and Crooks, 2000; McLaughlin and Cooper, 2010; Hsieh, 2014; Hsieh et al., 2014). One reason for choosing vulnerability index is because this method enables port vulnerability indicator selection in a flexible way. Since vulnerability assessment is end user-oriented, it is important to take into consideration the method's capability in customization when choosing the assessment method. Another reason is that this method allows port vulnerability to be assessed in different assessment periods and in multi-dimension. Comparison among results in different assessment periods could be obtained for realizing the recovery progress and determining the recovery investment schemes. In this process, leading factors in port vulnerability could also be identified. Lastly, the availability of several imperfection data fusion methods within the framework is another reason for choosing this method for the assessment of port vulnerability against non-repetitive catastrophes. The imperfection nature of non-repetitive catastrophe data, the comparison of several data fusion methods that treat imperfect data, and the rationale for the selected data fusion methods for the vulnerability indicator are elaborated in detail in Section 3.4.4.

Simulation technique is adopted for the assessment of port vulnerability against repetitive catastrophes. It is widely used in port and terminal operation planning. This method is selected for its merit in simulating catastrophes that can rarely happen in real life. Although the scarcity nature of port catastrophe risk data is inevitable, comparing to the assessments of non-repetitive catastrophe risks, the higher frequency of repetitive catastrophes makes the acquisition of input data more accessible. Thus, by adopting the collected port operation and hazards information

as the input, various results could be obtained by using the established port operation simulation model. These results include the quantification of catastrophe-induced port infrastructure physical damages and port economic losses.

In this study, the software package of ARENA (Rockwell Automation, 2006) is used for the development of the simulation model. Processes of ship arrival, berth allocation, quay crane deployment, cargo loading and unloading and ship departure are simulated by the modules in ARENA, such as “Create”, “Hold”, “Assign”, “Delay”, “Process” and “Dispose”. The developed terminal operation model is verified and validated with actual terminal records. Detailed model development is illustrated in Section 5.1.1.

3.3 Methods for studying infrastructure interdependency

In Chapter 6, propagation of port vulnerability resulting from the interdependency between ports and hinterland industrial clusters is assessed. Methods that have been used in studying the interdependency between two infrastructure systems are collected and analyzed in this section. These methods include surveys (National Petroleum Council, 2001; Pederson et al., 2006; The White House, 2003), simulation-based models (Brown et al., 2004; Los Alamos National Laboratory [LANL], 2005; North, 2001), the input-output model (Leontief, 1986; Haines and Jiang, 2001; Pant et al., 2011), the network-based approach (Nozick et al., 2005; Qiao et al., 2007), and the system-of-systems approach (Nagurney and Dong, 2002; Zhang et al., 2005). Table 3.2 shows the features and applications of each of the method.

From Table 3.2, it can be found that, the existing methods that address infrastructure system interdependency have some shortcomings. Economics models like the input-output model do not capture the network and physical characteristics of the infrastructure system, while those that consider the network layout (network-based approach and system-of-systems approach) do not leverage the economic and functional aspects.

In order to solve the last research question raised in Chapter 1, this study proposes a three-layer PCI model which links ports, cargos, and industrial clusters within the

same region. The PCI model is developed based on the input-output model and the fuzzy-link-based (FLB) transformation technique (Yang et al., 2009). By using cargoes as intermediaries, the PCI model allows the conversion of catastrophe inputs of ports into outputs of the propagation of port vulnerability to industrial clusters. The FLB technique and the input-output model compensate each other. To be more specific, the utilization of the FLB technique enables the capture of network and physical characteristics of interdependencies, while the input-output model shows its advantage in depicting the economic interdependencies. The detailed description of the PCI model is presented in Chapter 6.

Table 3.2 Comparison of methods for studying infrastructure system interdependency

Method	Feature	Application	Reference
Simulation-based model	<ul style="list-style-type: none"> •Used to model large-scale infrastructure systems •Enable scenario-based analyses •Apply to both short-term and long-term analyses •Visual presentation •Lack of theoretical analyses •Do not focus on all aspects of interdependencies 	<ul style="list-style-type: none"> •Explore interdependencies between energy and power systems •Explore economic interactions between decisionmakers in the infrastructure systems •Simulate input–output commodity flows 	North, 2001; Brown et al., 2004; LANL, 2005
Input-output model	<ul style="list-style-type: none"> •Enable theoretical analyses •Do not capture spatial characteristics •Assume a linear risk transmission input–output relationship •Static input–output factors and other coefficients 	<ul style="list-style-type: none"> •Study risk transmission/cascading risk among interdependent infrastructure systems •Quantify demand reduction of interconnected infrastructures due to terrorist attacks •Quantify industry losses due to container terminal closures 	Haimes and Jiang, 2001; Jiang and Haimes, 2004; Santos and Haimes, 2004; Haimes et al., 2005a; Haimes et al., 2005b; Pant et al., 2011

Cont'd Table 3.2

Method	Feature	Application	Reference
Network-based approach	<ul style="list-style-type: none"> •Capture spacial characteristics and topological characteristics, such as connectivity, vertex degree, path length, clustering coefficient, and redundancy ratio •Do not leverage the economy and functional aspects •Rely on probabilities and/or conditional probabilities of disruptions of network components 	<ul style="list-style-type: none"> •Analyze physical interdependencies and cascading failures in interdependent networks against earthquakes •Estimate system performances and make optimized investment decisions for electric power and gas systems •Address security issues for water systems 	Nozick et al., 2005; Dueñas-Orsorio et al., 2007a; Dueñas-Orsorio et al., 2007b; Qiao et al., 2007
System-of-systems approach	<ul style="list-style-type: none"> •Hybrid a broad range of methodological domains, including graph theory, network modeling, operations research, mathematical programming, nonlinear science, and behavioral science •Do not leverage economy and functional aspects 	<ul style="list-style-type: none"> •Model interactions among transportation, telecommunication, energy, and financial networks •Solve the flow equilibrium and optimal budget allocation problem for three layers networks of automobiles, urban freight, and data 	Nagurney and Dong, 2002; Zhang et al., 2005

3.4 Port vulnerability assessment based on vulnerability index

3.4.1 Research flow

As shown in Figure 3.2, after the port in question is selected, a hierarchical port vulnerability assessment model is established. The assessment units and the assessment periods are determined during this step. Then the port vulnerability indicators are selected by taking into considerations of the dimensions of port vulnerability that needed to be examined. In the next step, the fuzzy ER approach is used to fuse the selected vulnerability indicators in order to obtain comprehensive vulnerability estimates for each assessment unit. A sensitivity analysis of the input parameters is then performed to test the robustness and sensitivity of the proposed method. Once the method passes the sensitivity analysis, the vulnerability estimates of each assessment unit are combined into an integrated vulnerability estimate for the port as a whole. In Chapter 4, a seaport is modelled as a complex system consisting of subsystems of ship navigation system, loading and unloading system, storage system, and collection and distribution system. Each subsystem is treated as an assessment unit in this study. Since each subsystem contributes differently to the vulnerability of the whole port, it is not suited to take equal weighting for every assessment unit in the combination process. A bottleneck subsystem, referring to the weakest subsystem which restricts the outputs of the whole system, exists in every port. It is believed if Subsystem A is the bottleneck system during the normal operation period, the crash of this subsystem will worsen the failure of the whole port during the inoperable period. Thus, bottleneck coefficients are adopted here as the weightings for each assessment unit during the vulnerability estimate combination process. In this research, the bottleneck coefficients are generated by fusing the selected bottleneck indicators using the fuzzy TOPSIS method. Detailed steps, along with the justification of selected data fusion methods are illustrated in the following sections.

Figure 3.2 Port vulnerability assessment framework against non-repetitive catastrophes

Source: Author.

3.4.2 Establish hierarchical port vulnerability assessment model

Since port systems are complex systems containing a huge number of elements, it is not possible to conduct vulnerability assessments for each element (Ronza et al., 2009). Therefore, a feasible and common practice is to divide a port system into several assessment units (Dragović et al., 2017). Generally, as shown in Figure 3.3, a port system can be seen as the combination of four subsystems: ship navigation system, loading and unloading system, storage system, as well as collection and distribution

system. Thus, these four subsystems are identified as the four assessment units in this study. As a second step, port vulnerability assessment periods are determined. Vulnerability assessment and reassessment should be performed at the beginning and end of each round of recovery plans. Hence, port operators are able to determine whether to terminate investments for further recovery plans based on the assessment results. In this study, the assessment periods are set to be the starting and ending of the first round of the recovery of Tianjin Port, which is one day and four months after the explosion. Until this step, as seen in Figure 3.4, a hierarchical port vulnerability assessment model, combining four assessment units and two assessment periods, is established.

Figure 3.3 A typical layout of subsystems in a seaport

Source: Drawn by author.

Figure 3.4 Port vulnerability hierarchy for the case of 2015 Tianjin Port explosion

Source: Author.

3.4.3 Selection of port vulnerability indicators

As discussed in Chapter 2, the concept of port vulnerability is multi-dimensional. Vulnerability analysts are required to investigate the interests of end-users before conducting the assessments. Table 3.3 lists the port vulnerability indicators selected in the earlier literature. It can be seen that few works talk about the selection of port vulnerability indicators. However, multi-dimensional port vulnerability has been assessed, including the functional dimension, the economic dimension, the institutional dimension, and the interdependency dimension. Depending on the data availability, port vulnerability indicators provided by Earnest et al. (2012) are adopted. Thus, efficiency (EF), resilience (RE) and robustness (RO) are determined as the vulnerability indicators in this study.

Table 3.3 Port vulnerability indicators used in previous literature

Indicator	Application and feature	Reference
Shipping route density, investment growth in hinter, land-related industries, free trade zone business volume, electric power supply facility, gas supply system, EDI system, labor productivity, ground access network, average travel time, internal operations, container gantry crane productivity, wharf productivity, facility supportability, turnaround time, berth occupancy rate	<ul style="list-style-type: none"> •For vulnerability assessment against natural disasters •Assess port functional and interdependent vulnerability 	Hsieh et al., 2014
Ground access travel time, gantry crane efficiency, wharf productivity, EDI connectivity, labor productivity, free trade zone business volume, electric power supply	<ul style="list-style-type: none"> •For vulnerability assessment against natural disasters •Assess port functional vulnerability 	Hsieh, 2014
Efficiency, robustness, resilience	<ul style="list-style-type: none"> •Assess port functional, economic, and institutional vulnerability 	Earnest et al., 2012

A variety of studies discussed the relationship between port choice and port efficiency (Clark et al., 2004; Lam and Dai, 2012; Ducruet et al., 2014). Port efficiency also represents the capabilities of providing sufficient operational functions after a disturbance (Yuen et al., 2012). The efficiency of a port is measured by the actual average volume of inbound and outbound cargoes as a percentage of the total capacity. A vulnerable port is one that suffers a loss of efficiency after a catastrophe happened. The measurement of port efficiency is consistent with the description of the economic dimension of port vulnerability stated in Chapter 2. Thus, port vulnerability from an economic dimension is examined.

Generally, the concept of vulnerability includes an adaptive capacity, which is mostly seen as a dynamic concept that relates to a certain period of time (Scholz et al., 2012). Resilience expresses a system's capability to cope with the hazards that the system exposes to (Brooks, 2003). Resilience defines the time required for the port to recover after a disruption. A vulnerable port is one that takes a long time to return to full capacity after a catastrophe. Resilience is concerned with ports' performance over time, rather than simply their abilities to resist disruptions. Robustness concerns the maintenance of a system state within a narrow range of performance (Mumby et al.,

2014). The adaptive capacity within the concept of resilience matches with the description of the institutional dimension of port vulnerability. Hence, port vulnerability from an institutional dimension is also considered in Chapter 4.

Robustness concerns the maintenance of a system state within a narrow range of performance (Mumby et al., 2014). It does not only imply rigidity but also describes the ability of the system to adapt and innovate in anticipation or in response to a disturbance (DiGiano and Racelis, 2012). Robustness describes the degree to which ports can resist disruptions. A vulnerable port is one that suffers a loss of throughputs after a catastrophe while a robust port's throughput does not decline appreciably when a port is disabled. In some studies, robustness is seen as an antonym to vulnerability (Aven, 2011), which negatively represents the vulnerability in the case of a scalar measurement (Scholz et al., 2012). Since robustness measures a port's performance after the shock, which reflects the functional dimension of port vulnerability discussed in Chapter 2. Thus, port vulnerability from a functional dimension is assessed in this study.

3.4.4 Selection of data fusion methods

After the selection of vulnerability indicators, indicator fusion is considered to be the second step of in the whole assessment procedures. The two major tasks in this framework, namely the generation of vulnerability estimates for each assessment unit and the quantification of port bottleneck coefficients, can both be viewed as multi-criteria decision making (MCDM) problems (Linkov et al., 2006). The quantity and quality of the available input, as well as the requirement of the fineness of the output determine the selection of the data fusion methods for the indicators/factors/attributes/criteria. The scarcity of critical mass in statistical data in the realm of port catastrophes decides the imprecision nature of the data to be fused. Through several rounds of data acquisition from port operators, we find that the data to be analysed are associated with different types of imprecision resulting from unclear information (vagueness and ambiguity) or partial information (ignorance), for example:

- (1) The recovery period needed for the port storage system is long (vagueness);
- (2) The recovery period needed for the port storage system is 30 days with a certainty of

0.8 (ignorance);

- (3) The recovery period needed for the port storage system could be 30 days, or it could be 40 days (ambiguity).

It is further found, most of the data demanded by the quantification of port bottlenecks coefficients are available within the port, however, they are confidential to the public sectors. The requested data are ignorant and ambiguous even for the port operators. Moreover, most of the data required for the assessment of vulnerability are ill-recorded, or even unavailable within the port operators. Thus, such data is characterized by vagueness, ignorance, and ambiguity.

Another difficulty arises in the fusion process when the collected data may not be of the same type. To be more specific, they could be quantitative or qualitative in essence. For example, of the three typical parameters used to describe risk, failure rate and failure consequence probability are quantitative in nature while consequence severity is qualitative in nature. Therefore, the use of traditional vulnerability assessment to deal with catastrophe vulnerability in a port system reveals two major difficulties (1) the inoperability in dealing with vulnerability data's high level of imprecision and (2) the inoperability in fusing diverse data formations in a utility vulnerability inference mechanism.

Thus, the essences of the work in Chapter 4 are reconsidered and defined as the standardizing of the use of expert ratings supplementing the limitation of objective port catastrophe failure data. In order to tackle this problem, this section reviews several data processing methods which are commonly used in dealing with the imprecision of data. The features of each of the methods are listed in Table 3.4. It can be found that, these methods deal with different aspects of data imperfection in a complimentary manner, rather than a competition manner. By comparing the features of each method, a fuzzy ER method is chosen as the indicators fusion technique used in this study.

Table 3.4 Comparison of imperfect data fusion methods

Methods	Feature	Reference
Probabilistic fusion	<ul style="list-style-type: none"> • Use probability distribution/density functions to express data uncertainty • Fuse data by Bayes estimator which enables to calculate the posterior (conditional) probability distribution/density • Recursive way of fusion • Approximation probability can be generated from Monte Carlo simulation-based techniques 	Hoeting et al., 1999; Bayraktarli et al., 2005; Straub, 2005; Grêt-Regamey and Straub, 2006; Li et al., 2010; Korb and Nicholson, 2010
Evidential reasoning	<ul style="list-style-type: none"> • Base on belief function theory, characterize data using beliefs and plausibilities based on probability mass • Deal with uncertainty and imprecision data • Fuse data with Dempsters' combination rule • A general form of the Bayesian theory that deals with probability mass functions • Allow each data source to contribute information in different levels 	Dempster, 1968; Shafer, 1976; Sii et al., 2001; Sentz and Ferson, 2002; Sun et al., 2006; Awasthi and Chauhan, 2011
Fuzzy reasoning	<ul style="list-style-type: none"> • Use fuzzy membership to express data vagueness • Fuse data based on fuzzy rules • Able to deal with conflict data • Suit to model the fuzzy membership in an ill-defined class • Require prior membership functions for different fuzzy sets 	Zadeh, 1965; Gaines, 1976; Mizumoto, 1995; Liu and Yu, 2009

Cont'd Table 3.4

Methods	Feature	Reference
Fuzzy reasoning	<ul style="list-style-type: none"> •Can be used to represent and fuse vague data produced by human experts in a linguistic fashion •Various integrations with probabilistic and D-S evidential reasoning 	An et al., 2011
Possibilistic fusion	<ul style="list-style-type: none"> •Use possibility distribution to present data imperfection •Deal with incomplete data, rather than vague data •Similar data fusion rule as the fuzzy reasoning •Not commonly used in the data fusion community yet 	Negoita et al., 1978; Darby, 2004; Dubois and Prade, 2012; Georgescu, 2012
Rough set based fusion	<ul style="list-style-type: none"> •Deal with data granularity •Apply classic set theory conjunctive and disjunctive fusion operators •Do not rely on data distribution or membership function •Rarely applied to data fusion problems at present 	Pawlak et al., 1995; Yong et al., 2004; Li and Zhou, 2011
Hybrid fusion	<ul style="list-style-type: none"> •Hybrid the algorithms in a complimentary manner, rather than a competition manner •Combine fuzzy set theory with probabilistic fusion •Hybridization of fuzzy set theory with D-S evidential reasoning •Combination of fuzzy set theory with rough set theory 	Yen, 1990; Yeung et al., 2005; Karimi and Hüllermeier, 2007; Yang et al., 2009; Alyami et al., 2014

Fuzzy set theory is chosen mainly because it is a powerful theory to represent and fuse vague information offered by human experts in a linguistic form (Khaleghi et al., 2013). Fuzzy set theory-based methods do not require an expert to provide a precise point at which a vulnerability factor exists, and the reasoning process does not employ precise quantitative analysis. Thus, it is an ideal tool for representing risk factors and carrying out risk/safety/vulnerability assessments when working with the linguistic information (Wang et al., 1995; Wang et al., 1996; Sii et al., 2001). Another advantage of the fuzzy set theory lies in the capability of modelling the fuzzy membership of a target in an ill-defined class while the probabilistic and evidential reasoning work well in a well-defined class (Khaleghi et al., 2013).

ER is chosen mainly because of its attractiveness in dealing with the fuse of various formats of data obtained/evaluated. This method does not assign priori probabilities to unknown propositions, while probability theory requires prior knowledge of probability distributions. ER is superior to the traditional fuzzy inference mechanisms (i.e., max-min fuzzy operation) in avoiding losing the useful information in the fusion process (Yang et al., 2009). The hybrid of fuzzy set theory and the ER allows for the use of fuzzy linguistic variables in an evidential reasoning mechanism. Hence, it offers a more flexible way to deal with (1) the different kinds of input data imperfection (e.g. uncertainty, ambiguity and vagueness) and (2) the various types of input data in forms of quantitative and qualitative in the process of port vulnerability assessment to catastrophes.

Having selected the hybrid fuzzy ER for the data fusing process in the vulnerability assessment for each assessment unit, the data fusion method is selected for another major task in Chapter 4, namely the quantification of port bottleneck coefficients. Since this problem is treated as an MCDM problem, several popular MCDM developed in the recent decades are analyzed in this section. These MCDM methods include utility models (Manski, 1977), the data envelopment analysis (DEA) (Charnes et al., 1978), the TOPSIS (Hwang and Yoon, 1981), the PROMETHEE (Brans, 1986), the analytic hierarchy process (AHP) (Saaty, 1990), the ELECTRE (Roy, 1990), and the analytic network process (ANP) (Saaty, 2008).

Utility models select the alternative with the best performance based on the decision maker's utility preference structure. The utility preference structure, namely the utility function for each attribute is firstly built. Weightings for each attribute are decided in the following step. After the determination of utility model types (additive or multiplicative), the best alternative is selected as the one that provides maximum utility according to the utility preference structures proposed by the decision makers (Manski, 1977).

DEA aims to measure the efficiency of a decision-making unit. It is a nonparametric method, which generates input and output weights for the assessed decision-making unit automatically by adopting operations research techniques. Subsequently, the obtained weights are multiplied with input and output value to calculate the final efficiency scores. The nonparametric nature of this method determines a large amount of data required. Additionally, there are no production, cost, and/or profit functions estimating from the model results (Charnes et al., 1978).

AHP deals with attribute weighting problem. It allows users to quantify the importance weights for various attributes for an alternative concurrently. This is achieved by making a set of pairwise comparisons between each pair of competing attributes (Saaty, 1990). This method is widely reviewed and used in the publications. Several software packages developed elevate its applicability in both academic and commercial environment. However, this method has its shortcoming in treating problems with diversified attributes for different alternatives. Thus, ANP is introduced to overcome this difficulty, in which the local weights of attributes could be different for each alternative (Saaty, 2008).

Outranking method, including ELECTRE and PROMETHEE, select the best performed alternative by making a pairwise comparison between every alternative pair. Decision makers may declare confirms or contradict to the pairwise dominance relationship between every alternative pair based on their judgements (Brans, 1986; Roy, 1990).

TOPSIS is developed based on the idea that the distance between the selected alternative and the positive ideal solution should be the shortest, while the distance

should be the longest for the case of the negative ideal solution. The positive ideal solution is obtained by integrating the best performance value for each attribute contributed by any alternatives, while the negative ideal solution is the aggregation of worst performance values (Hwang and Yoon, 1981). The distance is calculated in the Euclidean distance, with or without importance weightings for each attribute (Kahraman, 2008). In this study, TOPSIS is selected for the quantification of the bottleneck coefficients for its straightforward computation processes. Another reason for choosing this method is because it is easy to be understood by analysts or decision-makers, which is an important selecting criterion when choosing MCDM methods during the assessment period of just after the occurrence of the catastrophe. In the following sections, the detailed procedures in the fuzzy ER and the fuzzy TOPSIS are illustrated.

3.4.5 The fuzzy ER

3.4.5.1 Determination of the fuzzy input and output variables

Setting up granularities for linguistic terms for each vulnerability input and output is the first step. The second step is to decide the types of fuzzy membership functions used in defining each input and output. The determinations of the vulnerability linguistic terms and the fuzzy membership functions are presented in detail in the case study in Section 4.2.

3.4.5.2 Construct a fuzzy rule-base with belief structure

A fuzzy IF-THEN rule with degrees of belief (Yang et al., 2009; Yang et al., 2014) is preferred here because it shows its advantage in building a correlation between the premise and the conclusion when the available information is not enough for experts to make certainty judgements. A fuzzy IF-THEN rule with degrees of belief is shown as Equation (3.1), which is comprised of two parts: the antecedent and the consequence. The distribution of degrees of belief $\{(\beta_{k1}, D_1), (\beta_{k2}, D_2), \dots, (\beta_{kj}, D_j), \dots, (\beta_{kN}, D_N)\}$ is assigned by the same group of experts.

$$\begin{aligned}
 R_k : & \text{ IF } A_{k1} \text{ and } A_{k2} \dots \text{ and } A_{ki} \dots \text{ and } A_{kM}, \\
 & \text{ THEN } \{(\beta_{k1}, D_1), (\beta_{k2}, D_2), \dots, (\beta_{kj}, D_j), \dots, (\beta_{kN}, D_N)\}, \\
 & \forall i \in \{1, \dots, M\}, \forall j \in \{1, \dots, N\}, \forall k \in \{1, \dots, L\}.
 \end{aligned} \tag{3.1}$$

R_k - the k th rule in the rule base;

L - number of rules in the rule base;

A_{ki} - linguistic variable of the i th antecedent attribute in R_k ;

M - number of input variables;

β_{kj} - belief degree to which D_j is believed to be the consequence;

D_j - the j th consequence;

N - number of belief degrees.

3.4.5.3 Fuzzy rule-base inference by using the ER

The procedure is for discretizing the input into the distributed representation by using belief degrees in antecedents. Based on ruled-base (3.1), the corresponding general input form of an antecedent attribute in the k th rule is shown as follows, assuming the antecedent contains three attributes:

$$(\varepsilon_1, A_1^*) \text{ AND } (\varepsilon_2, A_2^*) \text{ AND } (\varepsilon_3, A_3^*) \tag{3.2}$$

ε_i - the degree of belief of A_i^* ($i = 1, \dots, 3$) assigned by an expert which expresses the input uncertainty. For instance, $(0.9, A_1^*)$ means that the expert is ninety percent sure that the input data could take the linguistic term A_1^* .

The input (ε_i, A_i^*) for any one of the antecedent attributes (U_i) is then mapped to a linguistic-termed distribution representation using belief degrees by Equations (3.3)–(3.5). When generating $S((\varepsilon_i, A_i^*))$, there are several matching functions available. In this paper, we choose the following max-min operation matching function, as shown in Equation (3.5), for it is a classical tool and its wide range of applications (Zimmerman, 2001).

$$S((\varepsilon_i, A_i^*)) = \{(\alpha_{ij}, A_{ij}^*), i = 1, 2, 3, j = 1, \dots, J_i; \tag{3.3}$$

$$\alpha_{ij} = \frac{\tau(A_{ij}, A_i^*) \cdot \varepsilon_i}{\sum_{j=1}^{J_i} [\tau(A_{ij}, A_i^*)]}, i = 1, 2, 3, j = 1, \dots, J_i; \quad (3.4)$$

$$\tau(A_{ij}, A_i^*) = \max_x [\min(A_i^*(x) \wedge A_{ij}(x))], i = 1, 2, 3, j = 1, \dots, J_i. \quad (3.5)$$

A_{ij} - the j th linguistic term of the i th attribute;

α_{ij} - degree to which the input (ε_i, A_i^*) for U_i belongs to the linguistic

term A_{ij} with $\alpha_{ij} \geq 0$ and $\sum_{j=1}^{J_i} \alpha_{ij} \leq 1$;

(ε_i, A_i^*) - actual input of the i th antecedent;

τ - a matching function, $\tau(A_{ij}, A_i^*)$ stands for the matching degree to which A_i^* belongs to A_{ij} .

Then, generate the activation weight for the packet antecedent by using Equations (3.6)–(3.8).

$$\varphi_k = \prod_{i=1}^3 (\delta_{ki})^{\overline{\delta_{ki}}}, \forall k \in \{1, \dots, L\}; \quad (3.6)$$

$$\overline{\delta_{ki}} = \frac{\delta_{ki}}{\max_{i=1,2,3}(\delta_{ki})}, \forall i \in \{1, \dots, M\}, \forall k \in \{1, \dots, L\}; \quad (3.7)$$

$$\mu_k = (\theta_k \cdot \varphi_k) / \sum_{k=1}^L \theta_k \varphi_k. \quad (3.8)$$

φ_k - initial weight of the k th rule;

δ_{ki} - weight of the i th antecedent attribute in the k th rule;

θ_k - relative weight of the k th rule;

μ_k - activation weight of the k th rule.

The incomplete antecedent attributes input will lead to the incompleteness of the consequents. Such incompleteness should be considered in the inference process (Liu et al., 2004). By using Equation (3.9), the original belief degree of the j th consequent term of the k th rule in Equation (3.1) is updated on a basis of the

incompleteness of the input data by:

$$\beta_{kj}' = \overline{\beta_{kj}} \cdot \left[\sum_{t=1}^3 (\tau(t, k) \cdot \sum_{j=1}^{J_i} \alpha_{ij}) \right] / \left[\sum_{t=1}^3 \tau(t, k) \right], \quad (3.9)$$

$$\forall k \in \{1, \dots, K\}, \forall j \in \{1, \dots, N\}, \forall t \in \{1, 2, 3\},$$

β_{kj}' - updated belief degree considering the incompleteness of the input data;

$$\tau(t, k) = \begin{cases} 1 & \text{if } U_t \text{ is used in defining } R_k \\ 0 & \text{otherwise} \end{cases}.$$

Until this step, a fuzzy rule-base with degrees of belief could be expressed in the rule expression matrix. Having obtained the rule expression matrix, the evidential reasoning algorithm (Yang and Xu, 2002) is used to synthesize rules in order to draw the conclusions. Starting from the transformation of the updated degrees of belief β_{kj}' to basic probability masses, as shown in Equations (3.10)–(3.14):

$$m_{kj} = \mu_k \beta_{kj}', \forall k \in \{1, \dots, L\}, \forall j \in \{1, \dots, N\}; \quad (3.10)$$

$$m_{kD} = 1 - \sum_{j=1}^N m_{kj} = 1 - \mu_k \sum_{j=1}^N \beta_{kj}', \forall k \in \{1, \dots, L\}; \quad (3.11)$$

$$\bar{m}_{kD} = 1 - \mu_k, \forall k \in \{1, \dots, L\}; \quad (3.12)$$

$$\tilde{m}_{kD} = \mu_k (1 - \sum_{j=1}^N \beta_{kj}'), \forall k \in \{1, \dots, L\}; \quad (3.13)$$

$$\sum_{k=1}^L \mu_k = 1. \quad (3.14)$$

m_{kj} - individual degrees to which each R_k supports the final conclusion D ;

m_{kD} - unassigned probability mass to any individual output D_j ;

$\bar{m}_{kD}$ - unassigned probability mass due to the relative importance of the k th packet antecedent A_k ;

$\tilde{m}_{kD}$ - unassigned probability mass due to the incompleteness of the k th packet antecedent A_k .

For $\forall k \in \{1, \dots, L\}$, we could get Equation (3.15),

$$m_{kD} = \bar{m}_{kD} + \tilde{m}_{kD}; \quad (3.15)$$

Next, it is possible to synthesize all the L rules to get the fused degree of belief β_j of all the activated rule for each consequence term D_j in D . Let $m_{I(k)j}$ be the fused degree of belief by combining the first k packet antecedents $(A_1, \dots, A_k)$ and $m_{I(k)D}$ be the remaining degree of belief unassigned to any D_j . Let $m_{I(1)j} = m_{1j}$, $m_{I(1)D} = m_{1D}$. Thus, the overall fused degree of belief β_j of D_j is obtained by using Equations (3.16)–(3.22):

$$\{D_j\}: m_{I(k+1)j} = K_{I(k+1)}[m_{I(k)j}m_{(k+1)j} + m_{I(k)j}m_{(k+1)D} + m_{I(k)D}m_{(k+1)j}], \quad (3.16)$$

$$\forall k \in \{1, \dots, L\}, \forall j \in \{1, \dots, N\};$$

$$m_{I(k)D} = \bar{m}_{I(k)D} + \tilde{m}_{I(k)D}, \forall k \in \{1, \dots, L\}; \quad (3.17)$$

$$\{D\}: \tilde{m}_{I(k+1)D} = K_{I(k+1)}[\tilde{m}_{I(k)D}\tilde{m}_{(k+1)D} + \tilde{m}_{I(k)D}\bar{m}_{(k+1)D} + \bar{m}_{I(k)D}\tilde{m}_{(k+1)D}], \quad (3.18)$$

$$\forall k \in \{1, \dots, L\};$$

$$\{D\}: \bar{m}_{I(k+1)D} = K_{I(k+1)}[\bar{m}_{I(k)D}\bar{m}_{(k+1)D}], \forall k \in \{1, \dots, L\}; \quad (3.19)$$

$$K_{I(k+1)} = [1 - \sum_{j=1}^N \sum_{t=1, t \neq j}^N m_{I(k)j}m_{(k+1)t}]^{-1}, \forall k \in \{1, \dots, L\}; \quad (3.20)$$

$$\{D_n\}: \beta_j = m_{I(L)j} / (1 - \bar{m}_{I(L)D}), \forall j \in \{1, \dots, N\}; \quad (3.21)$$

$$\{D\}: \beta_D = \tilde{m}_{I(L)D} / (1 - \bar{m}_{I(L)D}). \quad (3.22)$$

β_D denotes the remained belief degrees unassigned to any D_j . The final conclusion generated by fusing the L rules is represented as follows:

$$S(A^*) = \{(\beta_j, D_j)\}, \forall j \in \{1, \dots, N\}. \quad (3.23)$$

Finally, results expressed by fuzzy sets need to be defuzzified in order to get the

rank of the vulnerability assessment results of each assessment unit. The defuzzification method of centroid approach is selected here for the suitability of modeling fuzzy vulnerability expressions (Mizumoto, 1995). The defuzzified index value (IV) of the vulnerability assessment results is calculated by Equation (3.24).

$$IV = \sum_{j=1}^N \beta_j \times UC_j \quad (3.24)$$

UC_j - utility centroid value of the j th consequence.

3.4.6 Identification of port bottleneck indicators

Table 3.5 reviews the port bottleneck indicators adopted in the previous literature (Yeo et al., 2007; Ji and Zhou, 2010). Since there are no reference bottleneck indicators for the collection and distribution systems, this chapter proposes three indicators for the assessment of bottleneck effects for this assessment unit. Thus, three indicators are determined for each of the assessment units: the average number of waiting vessels/trucks (queue length), the average waiting time of vessels/trucks, and the average service time of vessels/trucks. Until this step, an MCDM model containing four alternatives (assessment units) and three criteria (bottleneck indicators) is established.

Table 3.5 Review of port bottleneck indicators

Assessment unit	Bottleneck indicator	Reference
Navigation system	Average waiting time of vessels	Yeo et al., 2007
	Average number of waiting vessels	
	Maximum waiting vessels	
	Average use rate	
Loading and unloading system	Average number of vehicles of the system	Ji and Zhou, 2010
	Average number of non-load vehicles	
	Average sojourn time of vehicles	
	Average waiting time for vehicles	
	Operating factor of shore container crane	
Storage system	Average number of vehicles of the system	Ji and Zhou, 2010
	Average number of on-load vehicles	
	Average sojourn time of vehicles	
	Average waiting time for vehicles	
	Operating factor of gantry crane	
Collection and distribution system	Average numbers of waiting vehicles	Original indicators
	Average waiting time for vehicles	
	Average service time of vehicles	

3.4.7 The fuzzy TOPSIS

In this work, the extension TOPSIS proposed by Chen et al., (2006) was considered. In the method, fuzzy numbers are used to describe the weights of criteria and ratings of the alternatives. The analysts' ratings for each assessment unit under each indicator are collected and aggregated to construct the fuzzy decision matrix by using Equations (3.25)–(3.32). Fuzzy triangular number ($\tilde{x}_{ijk}$) is used for its widely usage and convenience (Ertuğrul and Karakaşoğlu, 2008).

$$\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}), \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}, \forall k \in \{1, 2, \dots, K_u\}; \quad (3.25)$$

$$a_{ij} = \frac{1}{K} \sum_{k=1}^K a_{ijk}, \quad b_{ij} = \frac{1}{K} \sum_{k=1}^K b_{ijk}, \quad c_{ij} = \frac{1}{K} \sum_{k=1}^K c_{ijk}, \quad (3.26)$$

$$\forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}, \forall k \in \{1, 2, \dots, K_u\};$$

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}), \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.27)$$

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1N_u} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2N_u} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{M_u 1} & \tilde{x}_{M_u 2} & \cdots & \tilde{x}_{M_u N_u} \end{bmatrix}; \quad (3.28)$$

$$\tilde{w}_{jk} = (w_{jk1}, w_{jk2}, w_{jk3}), \forall j \in \{1, 2, \dots, N_u\}, \forall k \in \{1, 2, \dots, K_u\}; \quad (3.29)$$

$$w_{j1} = \min_k \{w_{jk1}\}, \quad w_{j2} = \frac{1}{K} \sum_{k=1}^K w_{jk2}, \quad w_{j3} = \max_k \{w_{jk3}\}, \quad (3.30)$$

$$\forall j \in \{1, 2, \dots, N_u\}, \forall k \in \{1, 2, \dots, K_u\};$$

$$\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}), \forall j \in \{1, 2, \dots, N_u\}; \quad (3.31)$$

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_j], \forall j \in \{1, 2, \dots, N_u\}. \quad (3.32)$$

M_u - number of assessment units;

N_u - number of selected criterion;

K_u - number of analysts;

$\tilde{x}_{ijk}$ - fuzzy rating given by the k th analyst to the i th assessment unit's j th criterion;

$(a_{ijk}, b_{ijk}, c_{ijk})$ - fuzzy triangular number given by the k th analyst to the i th assessment unit's j th criterion;

$\tilde{x}_{ij}$ - aggregated fuzzy rating to the i th assessment unit's j th criterion;

(a_{ij}, b_{ij}, c_{ij}) - aggregated fuzzy triangular number of the i th assessment unit's j th criterion;

$\tilde{D}$ - fuzzy decision matrix;

$\tilde{w}_{jk}$ - fuzzy rating given by the k th analyst to the fuzzy weight of the j th criterion;

$(w_{jk1}, w_{jk2}, w_{jk3})$ - fuzzy triangular number given by the k th analyst to the fuzzy weight of the j th criterion;

$\tilde{w}_j$ - aggregated fuzzy weights for the j th criteria;

(w_{j1}, w_{j2}, w_{j3}) - aggregated fuzzy triangular number of the fuzzy weight of the j th criterion;

$\tilde{W}$ - aggregated fuzzy weight matrix.

Then, by using Equations (3.33)–(3.36), the normalized fuzzy decision matrix and the weighted normalized decision matrix are obtained.

$$c_j^* = \max_i c_{ij}, \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}. \quad (3.33)$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.34)$$

$$\tilde{R} = [\tilde{r}_{ij}]_{M_u \times N_u}, \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.35)$$

$$\tilde{V} = [\tilde{r}_{ij}(\cdot) \tilde{w}_j]_{M_u \times N_u}, \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}. \quad (3.36)$$

$\tilde{r}_{ij}$ - normalized fuzzy rating to the the i th assessment unit's j th criterion;

$\tilde{R}$ - the normalized fuzzy decision matrix;

$\tilde{V}$ - the weighted normalized decision matrix.

The calculations of the fuzzy positive ideal solution (FPIS), the fuzzy negative ideal solution (FNIS), the distance between each alternative and FPIS, as well as the distance between each alternative and FNIS are next steps, using Equations (3.37)–(3.44).

$$\tilde{v}_{ij} = (v_{ij1}, v_{ij2}, v_{ij3}), \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.37)$$

$$\tilde{v}_j^* = \max_i \{v_{ij3}\}, \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.38)$$

$$\tilde{v}_j^- = \min_i \{v_{ij1}\}, \forall i \in \{1, 2, \dots, M_u\}, \forall j \in \{1, 2, \dots, N_u\}; \quad (3.39)$$

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_j^*), \forall j \in \{1, 2, \dots, N_u\}; \quad (3.40)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_j^-), \forall j \in \{1, 2, \dots, N_u\}; \quad (3.41)$$

$$d_i^* = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^*), \forall i \in \{1, 2, \dots, M_u\}; \quad (3.42)$$

$$d_i^- = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^-), \forall i \in \{1, 2, \dots, M_u\}; \quad (3.43)$$

$$d_v(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}. \quad (3.44)$$

$\tilde{v}_{ij}$ - element in the i th row and j th column of the matrix $\tilde{V}$;

$(v_{ij1}, v_{ij2}, v_{ij3})$ - fuzzy number of the element in the i th row and j th column of the matrix $\tilde{V}$;

A^* - fuzzy positive idea solution (FPIS);

A^- - fuzzy negative idea solution (FNIS);

d_i^* - distance between the i th assessment unit and FPIS;

d_i^- - distance between the i th assessment unit and FNIS;

$d_v(.,.)$ - distance between two fuzzy numbers, $\tilde{m} = (a_1, b_1, c_1)$, $\tilde{n} = (a_2, b_2, c_2)$.

Lastly, the weightings of the assessment units, namely the bottleneck coefficients (BC_i) are obtained by computing the closeness coefficient and normalize the closeness coefficients (CC_i), as shown by Equations (3.45) and (3.46).

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-}, \forall i \in \{1, 2, \dots, M_u\}. \quad (3.45)$$

$$BC_i = \frac{CC_i}{\sum_{i=1}^m CC_i}, \forall i \in \{1, 2, \dots, M_u\}. \quad (3.46)$$

CC_i - closeness coefficient of the i th assessment unit;

BC_i - bottleneck coefficient of the i th assessment unit.

In Chapter 4, the 2015 Tianjin Port explosion is used as the case study for the illustration of the proposed vulnerability index method, with the sensitivity analysis of the input parameters, results, discussion, and the policy implications shown in Section 4.4.

3.5 Simulation-based port vulnerability assessment

This section presents the research flow proposed for the port vulnerability assessment against repetitive-catastrophes. The economic dimension of port vulnerability is assessed by the estimation of catastrophe-induced port economic losses. Port physical vulnerability is also examined in order to obtain the physical damage estimates of the port system. As the bridge between the estimated amount of

physical damages and the evaluated economic losses, port functional vulnerability is assessed in the measurement of port disrupted periods. To achieve this, as shown in Figure 3.5, a terminal operation simulation model is firstly established under intact conditions, which is validated through the actual terminal operation records and container throughput. By considering various identified disrupted scenarios, terminal operations under disrupted conditions are then simulated. The decreased container throughput is obtained by comparing container throughput obtained from intact and disrupted scenarios (as shown in the green box), based on which, the container throughput vulnerability surface and the estimation of direct port economic loss are obtained. Direct physical loss is calculated by performing the probabilistic estimates of physical damages and Monte Carlo technique. Finally, the total port direct loss induced by one catastrophe event is estimated as the sum of physical loss and economic loss (shown by the yellow box).

The detailed procedures of the research flow are presented in Chapter 5, including the development of the port operation simulation model (Section 5.1.1), model verification and validation (Section 5.1.2), the hazard-specific model input (Section 5.1.3), and the process for port loss estimation (Section 5.1.5). A real-world application of the proposed method is carried out (Section 5.2 to 5.3). The Port of Shenzhen and the hazard of typhoon is taken as the case study. The results, discussion, and the policy implications to different stakeholders are presented in Section 5.4.

Figure 3.5 Method flow chart for the assessment of port vulnerability against repetitive catastrophes

Source: Author.

3.6 Port-cargo-industrial cluster model

In order to assess the propagation of vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions, a three-layer PCI model is proposed, which hybrids the input-output model and the fuzzy-link-based (FLB) transformation technique (Yang et al., 2009). An input-output model enables the quantification of interdependencies between different sectors of national or regional economies (Leontief, 1986). Based on the concept of equivalent rules, the FLB model allows different evaluation grades of each criterion in multi-criteria decision making to convert into the same form of grades for further data fusion process. By adopting the same equivalent rules, a three-layer PCI model linking the port layer, the cargo layer, and the industrial cluster layer is developed in this study.

In Chapter 6, the detailed procedures of the PCI model are shown for the import and export modes, respectively. The major seaports and the key industrial clusters in Guangdong Province, China are selected as the case study for the illustration of the PCI model. The data acquisition process for this case is illustrated in Section 6.2. Finally, the results, discussion, and the implications for practice are presented in Section 6.3.

3.7 Chapter summary

This chapter presents the proposed methods for solving research question 3 and 4 raised in Chapter 1, with the overall research process elaborated in Section 3.1 and the detailed explanations regarding particular components presented in the following sections. In detail, a vulnerability index system integrating the fuzzy ER and the fuzzy TOPSIS (Section 3.4) is proposed for the assessment of port vulnerability against non-repetitive catastrophes. Further, a simulation-based port operation model (Section 3.5) is developed for assessing port vulnerability against repetitive catastrophes. Finally, the propagation of vulnerability between ports and hinterland industrial clusters is evaluated by an input-output model-based PCI model (Section 3.6). Their real-world applications and research findings will be presented in Chapter 4, Chapter 5 and Chapter 6, respectively.

CHAPTER 4 PORT VULNERABILITY ASSESSMENT AGAINST NON-REPETITIVE CATASTROPHES

This chapter aims to assess port vulnerability against non-repetitive catastrophes by utilizing the vulnerability index method. Particularly, port vulnerability is evaluated by performing an application on the case of the 2015 Tianjin Port Explosion. The fuzzy ER and fuzzy TOPSIS are used for the fusion of the selected port vulnerability indicators. Multi-dimensional vulnerability assessment is achieved by evaluating port vulnerability from perspectives of economic, functional, and institutional dimensions. Additionally, from a dynamic point of view, port vulnerability is assessed in two assessment periods: one day and four months after the explosion. Comparisons of the results obtained from the two assessment periods could be used as indicators of the effectiveness of the implemented port recovery plans. Following this, recommendations for prioritizing risk mitigation options are proposed to the port operators. The method also shows its applicability for port users in route planning and bunkering port selection.

The event review, the data acquisition process, as well as the application of the fuzzy ER and fuzzy TOPSIS are presented in the following sections. The results, discussion, as well as the implications of results are also presented.

4.1 Event review

On 12th August 2015, two blasts occurred in a dangerous cargo warehouse within the area of Tianjin Dongjiang Bonded Port at 2330 hrs. Even though only a relatively small area of the port was damaged, the explosion left more than one hundred people dead and more than seven hundred people injured. Apart from the casualties, terminal equipment, warehouses, port buildings, thousands of containers and more than ten thousand cars waiting to be transported within the affected area were totally destroyed. Though the physical damages were severe, the business impacts were even larger. The explosion led to a six hours' closure of the whole port. One day after the event, Tianjin Municipal Transportation Committee required all dangerous cargo ships, including tankers, chemical bulk ships, and fertilizer ships, to call at other ports without transshipment. However, except very few dangerous cargo terminals, such as Shanghai and Ningbo, most of the dangerous cargo terminals in China began to ban the dangerous ships for the reason of self-inspection. Shipping companies were seriously affected due to the difficulty in rescheduling shipment. This impact rippled along the supply chain from the port to shippers, causing serious delays in shippers' production schedules. An Australian iron ore miner, BHP Billiton announced disruption of its iron ore transportation (Burns, 2015). This catastrophic event also left many insurance companies and reinsurance companies on the sharp end of claims (Burns, 2015). It is reported that this event caused a direct economic loss of nearly 7000 RMB millions (about 1000 USD millions).

4.2 Application of the fuzzy ER

As shown in Section 3.4.2, a hierarchical port vulnerability assessment model is established for the event of the 2015 Tianjin Port explosion, combining four assessment units of the port and two assessment periods. The four assessment units include the ship navigation system, the loading and unloading system, the storage system, as well as the collection and distribution system. The two assessment periods are determined to be the first day and four months after the occurrence of the catastrophic explosion. In Section 3.4.3, three port vulnerability indicators are

determined, including efficiency (EF), robustness (RO), and resilience (RE).

In this section, the fuzzy ER approach is used to fuse the selected indicators for the generation of the vulnerability estimates for each assessment unit. A fuzzy rule-base with belief structure is established by a group of ten analysts from the operation department of the Tianjin Port. The profile of the ten analysts and the established fuzzy rule-base is shown in Appendix B and C. Within the rule-base, the vulnerability linguistic terms and the fuzzy membership functions constituting the antecedent part, as well as the fuzzy output variables and the degrees of belief constituting the consequence part are determined. Regarding setting up the vulnerability linguistic terms, according to Bowles and Peláez (1995), a granularity from four to seven is used. The straight-line membership functions, including the triangular membership function and the trapezoidal membership function are used because of the advantage of simplicity and the wide range of applications in risk assessments (Wang, 1997). A psychometric scale, which is also called a subjective scale (Cox, 1998) is adopted here to establish the fuzzy membership functions for each indicator.

As a result, as shown in Figures 4.1-4.3, the vulnerability linguistic terms for EF has been determined as “Low, Medium, High”. RO is described as “Very low, Low, High, Very high”, and RE is described as “Very easy, Easy, Difficult, Very difficult”. Detailed interpretations for each vulnerability linguistic term of the three vulnerability indicators are shown in Appendices D-F. The vulnerability estimates, as shown in Figure 4.4, demonstrate the fuzzy output variables, which are described by the linguistic terms of “Very vulnerable, Vulnerable, Strong, Very strong”.

The established fuzzy rule-base is validated by another five analysts from the same department, whose profile is shown in Appendix G. During the validation process, the fuzzy linguistic terms for RE were suggested to change from “Very large, Large, Small, Very small” to “Very Easy, Easy, Difficult, Very difficult” for ease understanding. The rest of the determined vulnerability linguistic terms, the fuzzy membership functions, as well as the degrees of belief for each output variable remain the same. In the rest of this section, the case of Navigation System-One Day after the explosion (NS-OD) is carried out for illustration. Similar computations are

performed for the other seven cases.

Figure 4.1 Fuzzy EF set definition

Source: Author.

Figure 4.2 Fuzzy RO set definition

Source: Author.

Figure 4.3 Fuzzy RE set definition

Source: Author.

Figure 4.4 Membership functions for vulnerability estimates

Source: Author.

Fuzzy ratings are collected from port experts selected from security and operation-related departments within the Tianjin Port, the vicinity shipping companies, and the public sectors. The experts who give opinions should be able to get access to various port sources, such as port log books, daily reports, and accident records. Additionally, personal experience is also a critical consideration when selecting experts. In order to meet these requirements, twelve experts (whose profiles are shown in Appendix H) are selected and invited make their fuzzy judgements on each vulnerability indicator for each assessment unit during the two assessment periods. The selected experts are all from the directorial or managerial level of operation and safety-related departments. Thus, all of them have the same importance weighting.

The fuzzy ratings collected for the case of NS-OD are shown in Table 4.1. Using Equation (3.5), the ratings in Table 4.1 are transformed into the unique linguistic variables shown in the first twelve lines in Table 4.2. Further, by using Equation (3.4), aggregated linguistic variables are obtained for further computations, as shown in the last line of Table 4.2. The original fuzzy ratings and the transformed fuzzy ratings for the other seven cases are presented in Appendix I.

Table 4.1 Fuzzy ratings of the vulnerability indicators, Case of Navigation system—One day after explosion

Expert	Efficiency	Robustness	Resilience
E1	0.9 M, 0.1 H	0.7 VL, 0.3 L	0.8 D, 0.2 E
E2	[0.3, 0.4]	(0, 0.2, 0.4)	1 D
E3	[0.7, 1]	[0.7, 0.9]	0.7 E, 0.3 VE
E4	0.6 M, 0.4 H	0.3 VL, 0.7 L	0.2 VD, 0.8 D
E5	0.2 M, 0.8 H	[0.7, 0.8]	[0.7, 0.9]
E6	0.8 M, 0.2 H	0.5 L, 0.5 H	0.6 D, 0.4 E
E7	0.8 L, 0.2 M	0.7 L, 0.2 H, 0.1 VH	0.1 D, 0.1 E, 0.8 VE
E8	[0.6, 0.8]	(0.6, 0.8, 1)	E 0.4, VE 0.6
E9	0.8 L, 0.2 M	0.6 VH, 0.4 H	0.9 D, 0.1 E
E10	0.7 L, 0.3 M	0.6 L, 0.4 H	0.6 D, 0.4 E
E11	1 L	1 L	1 VD
E12	0.2 L 0.5 M, 0.3 H	0.7 H, 0.3 VH	0.4 E, 0.6 VE

Table 4.2 Transformed ratings, Case of Navigation system—One day after the explosion

Expert	Efficiency	Robustness	Resilience
E1	0.9 M, 0.1 H	0.7 VL, 0.3 L	0.2 E, 0.8 D
E2	0.5 L, 0.5 M	0.5 VL, 0.5 L	1 D
E3	1 H	0.6 H, 0.4 VH	0.3 VE, 0.7 E
E4	0.6 M, 0.4 H	0.3 VL, 0.7 L	0.8 D, 0.2 VD
E5	0.2 M, 0.8 H	0.75 H, 0.25 VH	0.2 E, 0.8VE
E6	0.8 M, 0.2 H	0.5 L, 0.5 H	0.6 D, 0.4 E
E7	0.8 L, 0.2 M	0.7 L, 0.2 H, 0.1 VH	0.1 D, 0.1 E, 0.8 VE
E8	0.4 M, 0.6 H	0.5 H, 0.5 VH	0.4 E, 0.6 VE
E9	0.8 L, 0.2 M	0.4 H, 0.6 VH	0.9 D, 0.1 E
E10	0.7 L, 0.3 M	0.6 L, 0.4 H	0.6 D, 0.4 E
E11	1, L	1, L	1, VD
E12	0.2 L, 0.5 M, 0.3 H	0.7 H, 0.3 VH	0.4 E, 0.6 VE
Aggregated linguistic variable	0.33 L, 0.38 M, 0.28 H	0.13 VL, 0.36 L, 0.33 H, 0.19VH	0.1VD, 0.4 D, 0.24 E, 0.26 VE

Having obtained the aggregated linguistic variables, the ER algorithm is performed to obtain the vulnerability estimates for each assessment unit. In the case of NS-OD, all the forty-eight rules are employed since all the linguistic variables are covered. By using Equations (3.6)–(3.8), the activation weights ω_k ($k = 1, \dots, 48$) are calculated for each rule in the rule base. Consequently, the selected fuzzy rule expression matrix

for the case of NS-OD is obtained and shown in Appendix J. By using Equations (3.10)–(3.22), the forty-eight rules are fused and the vulnerability estimates are obtained. As shown in Figure 4.5, the results, {16.14%, “Very vulnerable,” 55.85%, “Vulnerable,” 21.94%, “Strong,” 6.08%, “Very strong”}, can be interpreted in such a way that the vulnerability level of the case NS-OD are estimated as “Very vulnerable” with a belief degree of 0.1614, “Vulnerable” with a belief degree of 0.5585, “Strong” with a belief degree of 0.2194, and “Very strong” with a belief degree of 0.0608.

Next, Equation (3.24) is used to calculate the index value of the vulnerability estimates for a ranking purpose. From Figure 4.4, the utility centroid values assigning to each fuzzy vulnerability expression are generated as {0.078, 0.35, 0.65, 0.922}. Thus, the calculated index value of the vulnerability estimate for the case of NS-OD is 0.407.

$$IV_{NS-OD} = 0.1614 \times 0.078 + 0.5585 \times 0.35 + 0.2194 \times 0.65 + 0.0608 \times 0.922 = 0.407$$

Figure 4.5 Vulnerability estimates, Case of Navigation system—One day after explosion

Source: Author.

4.3 Application of the fuzzy TOPSIS

Having obtained the vulnerability estimates for each assessment unit, the results are aggregated for the generation of the vulnerability estimate for the port as a whole. As discussed in Section 3.4.1, bottleneck coefficients are adopted here as the weightings for each assessment unit during the combination process. In this section, the use of the fuzzy TOPSIS presented for the obtaining of the bottleneck

coefficients.

As a first step, the determinations of the linguistic variables and the triangular fuzzy numbers for the ratings of bottleneck indicators are carried out by the same group of ten analysts from the operation department of the Tianjin Port. A set of linguistic variables of “Very satisfied, Satisfied, Medium satisfied, Fair, Medium, Unsatisfied, Very unsatisfied” is determined for the descriptions of all the three bottleneck indicators. A validation process is carried out successively to guarantee the unbiased determination. To summarize the consensus reached by the analysts, detailed descriptions regarding the determined linguistic variables and the triangular fuzzy numbers are presented in Appendix K. Subsequently, the linguistic variables and the triangular fuzzy numbers for the ratings of importance weights of the bottleneck indicators are determined, as shown in Table 4.3.

Table 4.3 Linguistic variables for importance weights of bottleneck indicators

Linguistic variable	Triangular fuzzy number
Very low (VL)	(0, 0, 0.2)
Low (L)	(0.1, 0.2, 0.3)
Medium low (ML)	(0.2, 0.35, 0.5)
Medium (M)	(0.4, 0.5, 0.6)
Medium high (MH)	(0.5, 0.65, 0.8)
High (H)	(0.7, 0.8, 0.9)
Very high (VH)	(0.8, 1, 1)

Based on the determined linguistic variables, the group of ten analysts is asked to give ratings to the importance weights and the bottleneck indicators. For illustration, the ratings of Analyst No.1 are shown in Table 4.4. Ratings of other nine analysts are shown in Appendix L.

Table 4.4 Ratings for importance weights and bottleneck indicators (Analyst No.1)

Analyst	Importance weight and Assessment unit	Bottleneck indicator		
		B ₁	B ₂	B ₃
A1	Importance weight	L	VH	H
	Ship navigation system	F	MS	MS
	Loading and unloading system	VS	S	MS
	Storage system	MU	U	MU
	Collection and distribution system	VS	VS	VS

Next, the ratings of the ten analysts are aggregated to obtain the fuzzy decision matrix, which is shown in Table 4.5. Base on Table 4.5, the FPIS and FNIS are determined as:

$$FPIS = A^* = [(0.75, 0.75, 0.75), (1,1,1), (1,1,1)] ;$$

$$FNIS = A^- = [(0.06, 0.06, 0.06), (0.27,0.27,0.27), (0.2,0.2,0.2)].$$

Table 4.5 Weighted, normalized fuzzy decision matrix

Assessment unit	Bottleneck indicator		
	B ₁	B ₂	B ₃
Ship navigation system	(0.15, 0.31, 0.64)	(0.27, 0.62, 1)	(0.2, 0.42, 0.91)
Loading and unloading system	(0.06, 0.15, 0.36)	(0.4, 0.7, 1)	(0.21, 0.46, 0.78)
Storage system	(0.13, 0.25, 0.43)	(0.44, 0.67, 0.88)	(0.55, 0.77, 1)
Collection and distribution system	(0.22, 0.43, 0.75)	(0.36, 0.62, 0.98)	(0.33, 0.59, 1)

The distances between each assessment unit and the FPIS and the distances between each assessment unit and the FNIS are calculated, as shown in Table 4.6.

Table 4.6 Distances between assessment units and A* and distances between assessment units and A-

Distance	B ₁	B ₂	B ₃
d(A ₁ , A*)	0.43	0.47	0.57
d(A ₂ , A*)	0.57	0.38	0.56
d(A ₃ , A*)	0.50	0.38	0.29
d(A ₄ , A*)	0.36	0.43	0.45
d(A ₁ , A-)	0.37	0.47	0.43
d(A ₂ , A-)	0.18	0.50	0.37
d(A ₃ , A-)	0.24	0.43	0.60
d(A ₄ , A-)	0.46	0.46	0.52

The closeness coefficients of the four assessment units are calculated and shown in Table 4.7. The bottleneck coefficients are presented in the form of the normalized closeness coefficients. Until this step, the weightings for each assessment unit, namely the bottleneck coefficients are obtained. The port vulnerability assessment results, the analysis of the results, as well as the implications for practice are presented in the next section.

Table 4.7 Bottleneck coefficient

Assessment unit	di^*	di^-	CC_i	BC_i
Ship navigation system	1.48	1.26	0.46	0.24
Loading and unloading system	1.52	1.05	0.41	0.21
Storage system	1.18	1.27	0.52	0.27
Collection and distribution system	1.24	1.44	0.54	0.28

4.4 Results, discussion and implications

This section presents the vulnerability assessment results of the Tianjin port against the catastrophic explosion in 2015. The results include the vulnerability estimates for the four assessment units and the whole port during two assessment periods, namely one day and four months after the explosion. A sensitivity analysis of the input parameters is carried out to test the robustness of the proposed vulnerability assessment framework. Discussion of the results and implications obtained are presented at the end of this section.

Tables 4.8 and 4.9 show the vulnerability distributions, defuzzified values and rankings of each assessment unit. Number “one” indicates that the assessment unit in question is the most vulnerable, while “five” means the strongest. It can be seen from Table 4.8 that the storage system is the most vulnerable physical subsystem in the case of OD, followed by the ship navigation system, the loading and unloading system as well as the collection and distribution system. This is consistent with the fact that the explosion took place in the storage area. The ranking also implies the recovery priority, which should be set to the storage system at an early stage of recovery. After four months, as shown in Table 4.9, the vulnerability condition of the storage system has improved to some extent, however the ranking of which remains the first.

Table 4.8 Vulnerability estimates and ranking of the assessment units—
One day after explosion

Assessment unit	Vulnerability estimate	Defuzzified value	Ranking
Ship navigation system	16.14%, "VV", 55.85% "V", 21.94%, "S", 6.08%, "VS"	0.407	2
Loading and unloading system	14.81%, "VV", 54.21% "V", 23.38%, "S", 7.59%, "VS"	0.423	3
Storage system	24.82%, "VV", 62.32% "V", 12.39%, "S", 0.47%, "VS"	0.322	1
Collection and distribution system	13.82%, "VV", 52.66% "V", 26.23%, "S", 7.30%, "VS"	0.433	4
The whole port	17.55%, "VV", 56.36% "V", 20.87%, "S", 5.23%, "VS"	0.395	

Table 4.9 Vulnerability estimates and ranking of the assessment units—
Four months after explosion

Assessment unit	Vulnerability estimate	Defuzzified value	Rank
Ship navigation system	2.08%, "VV", 43.10% "V", 37.44%, "S", 17.38%, "VS"	0.556	2
Loading and unloading system	0.86%, "VV", 27.11% "V", 44.97%, "S", 27.06%, "VS"	0.637	4
Storage system	11.76%, "VV", 54.69% "V", 24.93%, "S", 8.61%, "VS"	0.442	1
Collection and distribution system	1.46%, "VV", 30.28% "V", 48.14%, "S", 20.13%, "VS"	0.606	3
The whole port	4.26%, "VV", 39.26% "V", 38.65%, "S", 17.83%, "VS"	0.556	

Further, in sections 4.4.1 and 4.4.2, two sets of results comparisons are carried out in order to reflect the recovery pace of the Tianjin Port at an early recovery stage. In detail, Section 4.4.1 performs the vulnerability assessment results comparison among different assessment units at the same assessment period. Section 4.4.2 compares the same assessment unit's vulnerability conditions between the two assessment periods. The sensitivity analysis of the input parameters is shown in Section 4.4.3.

4.4.1 Comparison of results in the same assessment period

Figure 4.6 shows the vulnerability distributions of each assessment unit in the OD cases. It can be seen that all assessment units distribute the highest at the level of “vulnerable”, and lowest under the level of “very strong”. “Very vulnerable” ranks higher than “strong” for the storage system, while “strong” ranks higher than “very vulnerable” for the rest of the assessment units.

As for the case of FM (shown in Figure 4.7), the loading and unloading system, as well as the collection and distribution system follow the same vulnerability distribution, in which “strong” distributes the most, while “very vulnerable” distributes. The distribution patterns of the ship navigation system and the storage system are similar in which “vulnerable” ranks the first and “strong” ranks the second. The difference happens in the rank of “very vulnerable” and “very strong”. “Very vulnerable” distributes higher than “very strong” in the case of the storage system while a reverse sequence is found in the case of the ship navigation system. As for the whole port system, “vulnerable” and “strong” rank nearly the same, followed by “very strong” and “very vulnerable”.

It is noted that, in the case of FM, the distribution level under “very vulnerable” of the storage system remains much higher than the other cases. This implies that port operators should continue to put efforts in recovering the storage areas in terms of capital and manpower. This is consistent with the news fact that, after four months, even if the debris has been removed from the accident site, a huge hole left by the explosion still existed (Beijing Youth Daily, 2015). Further investigation is needed when considering the termination of the investment.

Figure 4.6 Comparison of vulnerability assessment results among assessment units—
One day after explosion

Figure 4.7 Comparison of vulnerability assessment results among assessment units
—Four months after explosion

4.4.2 Comparison of results between two assessment periods

Vulnerability is a dynamic concept (Brooks, 2003). The comparison of assessment results between different assessment periods could reveal the system's adaptive capacity and the extent to which this adaptive capacity is realized as adaption. Based on the results, together with the information on recovery inputs, port managers are able to identify the effectiveness of the input and thus adjust the recovery scheme. Figure 4.8 shows the results of such comparisons for each assessment unit between the two assessment periods, namely one day and four months after the explosion. It can be concluded that all of the four assessment units' vulnerability conditions have improved during the four months. Telling from the shape of the distribution, the peaks of distribution of the loading and unloading system, as well as the collection and distribution system both switch from "vulnerable" to "strong". However, for the rest of the cases, the peaks remain at "vulnerable". Moreover, it can be seen that the vulnerability estimates of the ship navigation system are high, which indicates this subsystem is still in a vulnerable condition after four months of recovery. This unusual result is examined in a follow-up interview with the Tianjin Port operators. It is inferred that this vulnerability estimate may result from ship wrecks blocking the shipping lane in April 2017.

Figure 4.8 Comparison of vulnerability assessment results between two assessment periods

Table 4.10 shows the changing rates of the defuzzified values for each assessment unit and the whole port between the two assessment periods. It can be seen that, the vulnerability condition of the loading and unloading system has improved the most, followed by the collection and distribution system, the storage system and the ship navigation system. The increase in the defuzzified values for each assessment unit indicates the effectiveness of the recovery plan. An unusually high rate of change is found in the loading and unloading system. One possible reason is that intensive recovery schemes have been applied to every subsystem after the explosion regardless of the actual recovery need of each assessment unit. To be more specific, as shown in Figure 4.6, the loading and unloading system is relatively stronger than other subsystems in the case of OD. Therefore, its further improvement over four

months makes the subsystem very strong. This unusual high change rate of the loading and unloading system is also mentioned in the follow-up interview. The Tianjin Port operators revealed that this may result in the recent enhancement of the loading and unloading system in response to the large-scale trend of container ships. It can be seen that, the proposed framework works well in reflecting the reality, as well as revealing the excessive recovery investment.

Table 4.10 The rates of change of the defuzzified values between two assessment periods

Assessment unit	Defuzzified value of OD case	Defuzzified value of FM case	Rate of change
Navigation system	0.407	0.556	36.75%
Loading and unloading system	0.423	0.637	50.57%
Storage system	0.322	0.442	37.13%
Collection and distribution system	0.433	0.606	39.91%
The whole port	0.397	0.556	36.75%

4.4.3 Sensitivity analysis of input parameters

The sensitivity analysis of the input parameters is carried out to prove the robustness and sensitivity of the proposed method. This is achieved by measuring the changes in the vulnerability estimates when the fuzzy inputs are varied. The robustness is proved if the outputs keep their consistency when the model inputs have minor changes. The sensitivity is proved if outputs are able to reflect the major changes in the inputs. The experts (as shown in Appendix H) are numbered one to twelve and are grouped in different ways in each test group, as shown in Table 4.11. Ten out of twelve experts' opinions are selected and used as the inputs of the fuzzy ER method in each test group. Thus, twelve test groups are performed for each assessment case. The results are shown in Figure 4.9.

Table 4.11 The grouping for sensitivity analysis of input parameters

Test group	No. of experts	Experts' no.
1	10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
2	10	2, 3, 4, 5, 6, 7, 8, 9, 10, 11
3	10	3, 4, 5, 6, 7, 8, 9, 10, 11, 12
4	10	4, 5, 6, 7, 8, 9, 10, 11, 12, 1
5	10	5, 6, 7, 8, 9, 10, 11, 12, 1, 2
6	10	6, 7, 8, 9, 10, 11, 12, 1, 2, 3
7	10	7, 8, 9, 10, 11, 12, 1, 2, 3, 4
8	10	8, 9, 10, 11, 12, 1, 2, 3, 4, 5
9	10	9, 10, 11, 12, 1, 2, 3, 4, 5, 6
10	10	10, 11, 12, 1, 2, 3, 4, 5, 6, 7
11	10	11, 12, 1, 2, 3, 4, 5, 6, 7, 8
12	10	12, 1, 2, 3, 4, 5, 6, 7, 8, 9

As can be seen in Figure 4.9, in the cases of NS-OD, LUS-FM, SS-OD, SS-FM, CDS-OD, the vulnerability distributions are steady, which reveals that a good consensus was reached among the experts. The steady results also manifest the robustness of the proposed framework. In the cases of LUS-OD and CDS-FM, small variations are found in the results. However, the rankings of the four vulnerability levels of the twelve test groups remain the same. Such consistency and differences demonstrate that the method is robust yet sensitive to small divergences in opinions. In the case of NS-FM, larger differences are found. The level of “Strong” ranks the highest in test groups three and four, while the highest level is “Vulnerable” in the other test groups. This is because expert number two holds vast different opinions from the rest of the experts regarding the rating of the indicator of robustness (see details in Appendix I). Nevertheless, the method still shows its robustness when all the experts’ opinions are adopted as inputs. In such condition, “Vulnerable” ranks higher than “Strong”, which means the effect of large divergence is diluted. Furthermore, it is worth noting that a larger divergence happens in the case of FM, while in the case of OD, no large divergence is found. This may imply that experts tend to coincide in opinions during assessment periods just after the occurrence of the accident. However, it is more likely that they hold different opinions when a long time has passed. Thus, it highlights the necessity of the quantitative analysis of port vulnerability, especially during the assessment period long after the accident.

Figure 4.9 Results of sensitivity analysis of input parameters

It is implied to the port authority that the results are direct reflections of the port's vulnerability condition after the explosion. To be more specific, distributions of the vulnerability among multi-levels are obtained, instead of single-level estimations obtained by traditional vulnerability assessment methods. The fuzzy ER and fuzzy TOPSIS show their advantages in quantitatively assessing a port system's

vulnerability in a fast reaction at an early stage right after the accident, especially when a large amount of validated information is unavailable. The proposed framework can thus be easily extended to any port and port related industries when the system of interest has the feature of “black box” or “grey box”, such as naval ports, weapons factories, and military bases. Moreover, the assessment can further be refined to the scale of an assessment unit by adopting more complex assessment hierarchies. Lastly, by replacing the index system, other critical measurements, apart from vulnerability, such as the effectiveness of recovery plans, could also be evaluated.

Other port stakeholders can benefit from the flexible customization of the proposed framework in aspects of assessment units, assessment periods, indicators, as well as hazards. By applying the same customized framework to different ports within one region during same assessment periods, enlightenments can be derived from the comparison of the results during decision making. For example, for ocean carriers, the least vulnerable ports should be selected among several homogeneous ports within the same region during the process of route planning and bunkering ports selection. As for the hinterland manufacturers, proactive inventory plan adjustments could be performed based on the assessment results in both ex-ante and ex-post stages. Further, if potentially vulnerable ports are identified, it is better to increase the inventory of raw materials being imported from the identified vulnerable ports and plan to transfer the finished products being exported by the port to other ports in advance. Furthermore, by choosing losses as output, the results of the framework could act as catastrophe loss indices, which facilitate (re)insurance companies in the processes of pricing and quantifying the magnitude of insurance claims. It is expected that the proposed framework can shed light on the challenges of man-made catastrophe assessment.

4.5 Chapter summary

In this chapter, a vulnerability index is proposed to assess port vulnerability against non-repetitive catastrophes. Hence, question 3.a raised in Chapter 1 is tackled. In reality, port vulnerability data against catastrophes is of high level of uncertainty to

the public sector, even within the port especially when the assessment period is just after the occurrence of the event. In addition, vulnerability indicators concerning multi-dimension may be in diverse data formations. In order to deal with these challenges, a vulnerability index research framework integrating the fuzzy ER and the fuzzy TOPSIS is proposed. In the proposed framework, the fuzzy ER algorithm is firstly adopted to obtain the vulnerability estimates for each assessment unit. Subsequently, these estimates are combined for the generation of the vulnerability estimate for the whole port system. Fuzzy TOPSIS is used in this step for the calculation of the bottleneck coefficients, which are used as weightings for each assessment unit during the combining process. The proposed framework is performed in the case of the 2015 Tianjin Port Explosion as a real-world application. The economic, functional, and institutional dimensions of port vulnerability are examined by selecting efficiency, robustness, resilience as the vulnerability indicators. Regarding the assessment periods, port vulnerability assessments are carried out in two periods in order to examine the recovery capacity of the affected port. Results, discussions, and implications are given in this chapter. In the next chapter, port vulnerability assessment against repetitive catastrophes is conducted.

CHAPTER 5 PORT VULNERABILITY ASSESSMENT AGAINST REPETITIVE CATASTROPHES

This chapter aims to assess port vulnerability against repetitive catastrophes by developing a simulation-based port vulnerability assessment model. To be more specific, the physical and economic dimensions of port vulnerability are assessed by using the estimated port physical damage losses and port economic losses as measurements. Port functional vulnerability is also assessed in the process, performing as a bridge between the estimated amount of physical damages and the evaluated economic losses. Port functional vulnerability is manifested by the catastrophe-induced port disrupted periods. Primary data are used as the model inputs, including the actual port operation records and port catastrophic hazards information. The outputs of this model include the decreased port throughput, the estimated port physical losses, the estimated port economic losses, and finally, the total estimated port losses. The Port of Shenzhen, China and the hazard of typhoon is used as an example to demonstrate the applicability and significance of the proposed model. As an expanded use of the model, the total historical typhoon-induced loss and the predicted loss for the next five years are estimated for the largest container terminal of the Port of Shenzhen. Thus, the results of this model could be used as useful references for (re)insurance companies in catastrophe risk modelling and product pricing, which supplement the current literature on port vulnerability against catastrophes comprehensively. The development of the terminal operation simulation mode, the process of data acquisition and treatment, the results, discussion, as well as the policy implications are presented in the following sections.

The following publication from author is based on part of this chapter:

Cao, X., & Lam, J. S. L. (2018). Simulation-based Catastrophe-induced Port Loss Estimation. *Reliability Engineering & System Safety*, 175, 1-12.

Cao, X., & Lam, J. S. L. (2018). Simulation-based Severe Weather-induced Container Terminal Economic Loss Estimation. *Maritime Policy & Management*. DOI: 10.1080/03088839.2018.1516049.

Cao, X., and Lam, J.S.L., 2017, Simulation-Based Catastrophe-Induced Port Loss Estimation. The International Association of Maritime Economists Conference, Kyoto, Japan, 27-30, June 2017.

5.1 Terminal operation simulation model

5.1.1 Model development

As discussed in Section 3.4.2, a port system could be modelled as the combination of four subsystems, including ship navigation system, loading and unloading system, storage system, as well as collection and distribution system. Among these terminal operations, loading and unloading system is considered to be the most critical operation process in determining the throughput of a port (Kim and Park, 2004). Thus, in the development of the terminal operation simulation model, this paper mainly focuses on the process of container loading and unloading.

The first step in developing a simulation model is to identify the simulation procedures, the input information, the output information, and the modeling assumptions. As shown in Figure 5.1, the simulation starts with ship arrival and ends with ship departure. Once an entity of “ship” is generated, it goes through the procedures of berth allocation, berthing, quay crane allocation, loading and unloading, unberthing in sequence (Dragović et al, 2005). The following paragraphs describe each procedure in detail.

Figure 5.1 Terminal operation simulation flow chart

Source: Author.

Ship arrival is a queueing system and is implemented by the “Create” module in Arena. The interval time of ship arrival is calculated based on the terminal record. In the real container terminal operation, the ship arrival schedule of liner ships is relatively fixed. Assumed ship arrival distribution is usually adopted by existing literature (Dragović et al, 2017). In the present study, actual terminal operation record is collected and used for the benefit of enhancing the accuracy of simulation outputs.

After the ship entity is generated, it is transmitted to the procedure of berth allocation, which includes ship type classification, berth availability checking, and berthing (Dragović et al, 2006). In general, berths differ in size and are generally allocated to ships according to ship size. The first-come, first-served rule is adopted here, although in reality, the berth priority could follow the contract. Therefore, in this study, before the ship is allocated with a berth, ship size is classified based on lift per call (LPC, total moves of quay crane trolley per ship call). The probabilities of each LPC category are set in the “Decided” module, based on which the size of arrival ship is assigned. Then, the available berth will be allocated to the ship according to the ship size. If no berth is available at the moment, the ship will join the queue until there is an available berth. The berth access time is obtained as the difference between actual time of berthing and actual time of arrival.

Once a ship entity finished berthing, the process of quay crane allocation begins. In this paper, quay cranes are allocated based on LPC. The statistical distribution of crane numbers for each LPC category is calculated and is assigned in the “Assign” module. The module of “Decide” checks the availability of quay cranes. If all cranes are occupied, the ship waits in the berth until other ships release cranes. Idle time before, which refers to the time a ship waits for quay crane allocation, is calculated as the difference between loading and unloading commence time and actual time of berthing.

Table 5.1 Terminal operation model input and output under intact condition

Model input	
Port information	Number of berths Number of quay cranes
Ship arrival information	Actual time of ship arrival Actual time of berthing Loading and unloading commence time Loading and unloading complete time Actual time of ship departure Total moves of quay crane trolley per ship call (LPC)
Quay crane utilization information	Number of quay crane allocated per call
Model output	
Ship arrival number	
Container throughput	

After being allocated with quay cranes, the procedure of loading and unloading starts. The term “berth operation time” is used to refer to the time of loading and unloading, and is obtained as the difference between operation complete time and operation commence time. Likewise, idle time after, referring to the unberthing time for a ship, is calculated as the difference between actual time of departure and operation complete time. The statistical distributions of berth access time, idle time before, berth operation time, and idle time after are obtained through the function of “Input analyzer” and set in “Assign” module. Arena offers a function to record default and customized outputs by using the “Record” module. In this study, ship arrival number and container throughput are identified as the output of the model. The input information, output information and computing method for various necessary variables are summarized in Table 5.1.

5.1.2 Model verification and validation

Model verification and validation are critical steps in the development of a simulation model. The process of verification ensures the developed model behaves following model builders’ intentions, while validation means the process that ensures the model represents the real system appropriately (Kelton, 2002). Taking the advantage of the animation function Arena, the process of verification is performed. After setting the “Max Arrivals” field in the Create module to one and the model running speed to slow, the animation of

the ship entity is observed. It is shown that the ship entity goes through each module in sequence without any pauses, and finally disappears in the “Dispose” module. No error message returns during the whole process. Thus, it can be concluded that the built model behaves in the way in accordance with the builders’ intentions.

The validation is conducted by the correlated inspection approach (Law and Kelton, 1991). The confidence interval of the sample mean is firstly constructed. Subsequently, the confidence interval of the variance between the point estimate of difference and the observed difference is generated in order to determine whether the difference of the model output and the terminal throughput are statistically significant (Iyer Sivakumar and Chin, 2001).

The model output and the system throughput in 2016.8 are used for the model validation since the input data in this month is the most frequently used one among all months in all cases (see details in Section 5.2.1). With different random seed, the model inputs are used for multiple replications. It is inferred that a larger running replication number leads to a smaller half width of the confidence interval on the expected sample mean (Kelton, 2002). By setting an ideally small half width, the ideal running replication number of the model is estimated by Equation (5.1) (Kelton, 2002). In this research, a 2% margin of error (from the sample mean) is determined to be the ideal half width of a 95% confidence interval, considering the best accuracy and the calculation time. An initial replication number of 10 is set and is further adjusted to 93.

$$n \cong n_0 \frac{h_0^2}{h^2} \quad (5.1)$$

n_0 – the initial replication numbers;

h_0 – the half width of the results obtained from n_0 replications;

h – the ideal half width.

Out of 93 replications, a 95% confidence interval is built for the sample mean. Table 5.2 shows the generated confidence intervals and the gap between the terminal throughput and the sample mean. It is observed that the terminal operation model slightly over predicts the average throughput by 0.56%. The 95% confidence interval for the

throughput is (1.1168, 2.2459) for the intact case, in which the actual terminal throughput, namely 1.1354, is included.

Table 5.2. Model validation.

Date	Container throughput (million TEU)	Simulation output (million TEU)	Difference (%)	95% Confidence interval (million TEU)	95% confidence interval_Variance (million TEU)
2016 08	1.1354	1.1290	0.56	(1.1168, 2.2459)	(-0.1109, 0.1236)

To calculate the 95% confidence interval of the variance of the point estimate difference and the observed difference, Equations (5.2) to (5.5) (Iyer Sivakumar and Chin, 2001) are adopted. As shown in Table 5.2, the interval (-0.1109, 0.1236) contains 0, which means the difference between X_1 and $\hat{Y}_{(n)}$ is not statistically significant. Through the correlated inspection approach, it can be seen that, the simulated results agree well with the actual container throughput of the Port of Shenzhen.

$$\hat{W}_{(n)} = X_1 - \hat{Y}_{(n)} \quad (5.2)$$

$$W_i = X_1 - Y_i \quad (5.3)$$

$$V_{\hat{W}_{(n)}} = \frac{\sum_{i=1}^n [W_i - \hat{W}_{(n)}]^2}{n-1} \quad (5.4)$$

$$\hat{W}_{(n)} \pm t_{n-1, (1-(\alpha/2))} \sqrt{V_{\hat{W}_{(n)}}} \quad (5.5)$$

$\hat{Y}_n$ – sample mean of the n replications;

Y_i – model output of the i th replication;

n – replication number of running;

$\hat{W}_{(n)}$ – the point estimate of the difference between the terminal throughput and the sample mean of the model output;

X_1 – terminal throughput;

W_i – observed difference of the terminal throughput and the model output of the i th replication;

$V_{\hat{W}_{(n)}}$ – variance of point estimate of the difference and observed difference;

$\hat{W}_{(n)} \pm t_{n-1, (1-(\alpha/2))} \sqrt{V_{\hat{W}_{(n)}}}$ – the 100(1- α)% confidence interval of the variance.

5.1.3 Hazard-specific disruption inputs

Having developed the simulation model under intact operation condition, the hazard-specific disruption inputs are added to obtain the container throughput under disrupted conditions. This process begins with the identification of hazard-specific disrupted scenarios. The worldwide recognized gauges of physical severity of disasters are adopted for a scaling purpose, such as the seismic intensity for earthquake (Medvedev and Sponheuer, 1969), Saffir-Simpson scale (Schott et al, 2012) for hurricane/typhoon, spill tonnage (Swiss Re, 2016) for oil spill, and TNT equivalent (CEPAICE, 1967) for explosion. Subsequently, the probabilistic estimate of port physical damage degree as well as the disrupted and recovery period for each scenario is obtained by consultations with port engineers.

5.1.4 Estimation of total catastrophe-induced port loss

As discussed in Section 3.5, catastrophe-induced port loss is estimated as the measurement of port economic vulnerability in this study. Before the calculation, it is essential to talk about in depth the components in catastrophe-induced losses. Taking reference from HAZUS (FEMA, 2017), catastrophe-induced loss generally constitutes of four parts: direct physical loss, induced physical loss, direct economic loss, and indirect economic loss. Direct physical loss refers to any structural or equipment damages caused by the principle hazard in the hazard chain. While induced physical loss means the damages led by the induced hazards in the hazard chain. In practice, the physical damage

loss is commonly evaluated as the repair or replacement fee (Na and Shinozuka, 2009, Ronza et al, 2009). Production and income reduction due to the direct physical damage result in direct economic losses. The indirect economic loss is associated with the economic impact of other sectors except for ports, such as, the loss of manufactures in the industrial clusters that served by the affected port. In this study, only the direct physical damage and economic loss are considered. The total direct catastrophe-induced port loss is estimated as the sum of direct physical and direct economic loss, as shown in Equations (5.6)-(5.10).

$$TL = PL + EL. \quad (5.6)$$

$$PL = \sum_{i=1}^{NP} TLP_i P_i; \quad (5.7)$$

$$TLP_i = \sum_{j=1}^{MC_i} \sum_{k=1}^{H_{ij}} L_{ijk}, \forall i \in \{1, \dots, NP\}; \quad (5.8)$$

$$EL = \sum_{i=1}^{NP} C_i^{load \& unload} T_i^{de}; \quad (5.9)$$

$$T_i^{de} = T_i^{int} - T_i^{dis}, \forall i \in \{1, \dots, NP\}. \quad (5.10)$$

TL - total loss of the port caused by one catastrophe event;

PL - direct physical loss of the port caused by one catastrophe event;

EL - direct economic loss of the port caused by one catastrophe event;

NP - number of terminals in the study port;

TLP_i - total loss potential of the i th terminal;

P_i - probability of damage of the i th terminal;

MC_i - types of components of the i th terminal;

H_{ij} - number of components of the j th type in the i th terminal;

L_{ijk} - loss potential of k th component of the j th type in i th terminal;

$C_i^{load \& unload}$ - loading and unloading charge per TEU at the i th terminal;

T_i^{de} - decreased container throughput at the i th terminal;

T_i^{int} - container throughput at the i th terminal under intact condition;

T_i^{dis} - container throughput at the i th terminal under disrupted scenario.

In detail, terms T_i^{int} and T_i^{dis} in Equation (5.10) are obtained as outputs of the established terminal operation simulation model. By simultaneously considering $C_i^{load\&unload}$, EL is estimated. PL is jointly determined by TLP_i and P_i . Through collecting and investigating of port components behaviors during catastrophes, it was found that certain port components show higher vulnerability to certain catastrophe hazards. For example, as shown in Table 5.3, cranes, vehicles, and navigation aids are more vulnerable to hurricanes/typhoon events. Quay walls, yards, roads, cranes, warehouses and port auxiliary systems are more vulnerable to earthquakes. Therefore, in this study, key vulnerable components are considered in the estimation of TLP_i . Regarding the generation of P_i , one way is by referring to the component's fragility curves developed for wharf structures. When such fragility information is missing, another possible way is through consulting of experienced port operators and engineers. The method of obtaining P_i in this study is illustrated in Chapter 5.

Table 5.3 Hazard-specific key vulnerable port components identification

Catastrophic hazard	Major physical damage mode	Key vulnerable component	Reference
Hurricane/typhoon	Derailed cranes; collapsed cranes; overturned container trucks; damaged warehouse rooftops; drifted navigation aids	Quay crane; gantry crane; container truck; navigation aids	Nadkarni, 2001; Chambers, 2003a; Congressional Research Service [CRS], 2005; Smythe, 2013; Lam and Lassa, 2017
Earthquake	Fractured quay walls, jetties, yards, and roads; deformation of crane rails; buckling and bending of crane legs; collapsed crane structures; damaged warehouse; bending pipelines and joints; disrupted water, power, natural gas supply and telecommunication; silted channels	Quay wall; jetty; yard; road; quay crane; gantry crane; crane rail; warehouse; auxiliary system; channel	Prescott, 1996; Werner, 1997
Major oil spill	Major environmental pollution; polluted oil storage facilities	Oil storage facility	Kelly, 2011
Major fire and explosion	Damaged oil refineries, chemical storage facilities, port equipment, warehouses and buildings	Oil refinery; chemical storage facility; building	Lloyd's List, 2000; Leander and Lin, 2015; Osler, 2015

Furthermore, the proposed measurement is expanded for prediction of future catastrophe-induced losses. To achieve this, a port catastrophe database is established in order to analyze the frequencies of a certain type of catastrophe that affected the port under various disrupted scenarios. By considering the yearly adjustment coefficients, future catastrophe-induced losses are estimated by using Equations (5.11) and (5.12).

$$TL_{sum} = \sum_i^{PD} \sum_j^Y S_{ij} TL_{ij} \sigma_j; \quad (5.11)$$

$$\sigma_j = T_j / T_{base\ year}, \forall j \in \{1, \dots, Y\}. \quad (5.12)$$

TL_{sum} - total port loss over predictive period against one type of catastrophe;

Y - predictive period;

PD - number of disrupted scenarios;

S_{ij} - frequency of the i th disrupted scenario in the j th year;

TL_{ij} - expected total loss of the i th disrupted scenario in the j th year;

σ_j - adjustment coefficient of total loss for the j th year;

T_j - predictive throughput of the port in the j th year;

$T_{base\ year}$ - throughput of the studied port in the base year.

5.2 Data acquisition

Primary data are collected from representative ports that have large international influence and at the same time lie in disaster-prone areas. The largest terminal of the Port of Shenzhen is thus focused, which contains sixteen berths, eighty quay cranes, and two hundred gantry cranes. The Port of Shenzhen is selected because it is among the largest container ports worldwide, which ranks the third in the 2015 World Shipping Council (WSC) Container Ports Ranking (WSC, 2015). Moreover, as shown in Figure 5.2, the Port of Shenzhen lies in the South China Sea area, which is among the worldwide major typhoon basins in the northern hemisphere (World Meteorological Organization (WMO), 2015). News reports regarding port closures, operation disruptions are frequent during typhoon seasons (Chambers, 2003a; CRS, 2005; Smythe, 2013; Lam and Lassa, 2017). However, limited port vulnerability assessment methods

Table 5.4 Month data used as input for each disrupted scenario

Data used	Disrupted scenario
2016.8	1-5, 8-10, 14-15
2016.8-2016.9	7,19-20
2016.8-2016.10	6
2016.8-2016.11	13, 25
2016.8-2016.12	12, 18, 24
2016.8-2017.2	11, 17, 23
2016.8-2017.3	16
2016.8-2017.4	22
2016.8-2017.5	21

For the purpose of illustration, the statistical analysis of the model inputs in January 2017 is presented in Figures 5.3-5.6. The model inputs of the other study periods are analyzed in the same way. From Figure 5.3 to 5.6, the histograms of the ship arrival interval, the LPC grouping, the quay crane efficiency, as well as the idle time are shown. The probability distributions for each input are obtained by the “best fit” function in the “Input analyzer” of Arena which selects and adopts the distribution with the lowest square error (Kelton, 2002). The “fit all” summary and the distribution summary are shown in the Appendix N and Appendix O.

Figure 5.3 Distribution of ship arrival (2017.1)

Source: Author, based on information provided by the Port of Shenzhen

Figure 5.4 Distributions of number of containers handled (2017.1)

Source: Author, based on information provided by the Port of Shenzhen.

Figure 5.5 Distribution of quay crane efficiency (2017.1)

Source: Author, based on information provided by the Port of Shenzhen.

Figure 5.6 Distributions of ship idle time (2017.1)

Source: Author, based on information provided by the Port of Shenzhen.

As discussed in Section 5.1.4, cranes, vehicles, and navigation aids are considered as major exposures in the estimation of direct physical loss against the typhoon hazard. Table 5.5 presents the economic values of the major exposures at the Port of Shenzhen, collected via consultation with the port authorities.

Table 5.5 Major typhoon exposures of the case study port

Major exposure	Number	Price/unit	Total
Quay crane	81	\$1,700,000	\$137,700,000
Gantry crane	222	\$1,000,000	\$222,000,000
Container truck	200	\$450,000	\$90,000,000
Other equipment	null	null	\$2,000,000
Total Potential loss	null	null	\$451,700,000

5.2.2 Port typhoon data acquisition and treatment

5.2.2.1 Establishment of the port catastrophe database

In order to solve the scarcity reality of the available port catastrophic hazard data, this study establishes a port catastrophe database which records catastrophe events occurred in the area of ports worldwide in the recent century (1917-2017). The collection of these events is conducted by searching various sources of databases, including general databases such as ScienceDirect, ISI Web of Knowledge, SCOPUS, and Factiva;

maritime studies databases such as Lloyd's List, Tradewinds and IHS Fairplay. These databases are accessed with the digital library of the Nanyang Technological University (NTU). Google is used as a second channel. Based on the catastrophic hazards threatening seaport identified in Section 2.6, the hazards recorded in the established database include typhoon, storm surge, earthquake, tsunami, oil spill, as well as fire and explosion. Particulars of the events cover the date of occurrence, port affected, port closure durations, port recovery periods, port physical damages, as well as the economic loss. A sample of the established port catastrophe database is shown in Appendix P.

Regarding the hazard of typhoon, considering the availability of the typhoon track database, a supplementary searching method is used for the collection of the port-related typhoon events. As a first step, the worldwide typhoon center track coordinates and seaport coordinates are retrieved from the IBTrACS (Knapp et al, 2010) and the World Port Index (National Geospatial-Intelligence Agency, 2015), respectively. According to the data availability, the study period is from 1994 to 2015. Subsequently, by using Equation (5.13), the great circle distance between typhoon centers and ports are calculated. In this database, only the typhoon event occurred within the typhoon-affected distance of a seaport is considered and recorded. Finally, the past typhoon events, the wind speed values at the strike distances are recorded for each seaport. Thus, a worldwide seaport typhoon database containing the information of past typhoon events attacked the port, the frequencies, the strike distances, and the wind speeds at the strike distances is established.

$$d = r \arccos(\sin(y_1)\sin(y_2) + \cos(y_1)\cos(y_2)\cos(x_2 - x_1)) \quad (5.13)$$

d – the great circle distance between the geographical latitude and longitude of two points;

$(x_1, y_1), (x_2, y_2)$ – the latitude and longitude of the two points;

r – the radius of the earth.

Regarding the determination of the typhoon-affected distance of a port, currently, there is no sharp definition in the related literature. Thus, this paper proposes a concept of the largest possible typhoon-affected distance of a port in order to lay a foundation for the

following sections. Since a typhoon is a low-pressure weather system rotating around the typhoon centre with a radius of 200-500km (Daniels et al., 2006), it is considered that a port is affected by a typhoon event if the distance between the port and the typhoon centre is less than the typhoon radius. Hence, to involve all the possible threatening typhoon events, the largest possible typhoon-affected distance is set based on the largest possible typhoon radius, which is around 500km. That is to say, considering the studied port as a centre, any typhoon events appearing within the circle area with a radius of 500km is considered as potential threats to the normal operations of the port. Additionally, in such case, it is worth noting that the largest strike distance of a typhoon event is also 500km.

5.2.2.2 Determination of disrupted scenarios

To identify the factors that influence typhoon-induced port disruption and recovery periods, records of worldwide typhoon events that caused losses to ports were collected. It is found that the amount of information on typhoon events affecting port operations is scarce with fewer details released regarding disrupted periods and recovery periods in the public domain. By making every possible use of valuable information, the collected port disrupted and recovery periods are shown in Figure 5.7. It is found that typhoon strike distance and wind speed at the strike distance largely impact port disrupted periods and recovery periods. To be more specific, the shorter the strike distance and the larger the wind speed, the longer the disrupted period and recovery period.

Figure 5.7 Port recovery periods on given strike distance and wind scale (1998-2015)

Source: Drawn by author, based on Nadkarni (1998), Chambers (2003a), Sturgis et al. (2014), Liu (2016).

Having identified the strike distance and the wind speed as the major factors affecting typhoon-induced port disrupted and recovery periods, the next step is to define scopes and scales of these factors. Referring to the actual practices of terminal operation, the strike distance is firstly separated as the direct strike distance (0-200km) and the vicinity strike distance (more than 200km) (Zong and Chen, 1999). Regarding the upper bound of the strike distance, considering the conclusion obtained in Section 5.2.2.1, the upper bound of the strike distance is set to be 500 km in this study. Thus, a range of 0 km to 500 km for the strike distance, with a step size of 100 kilometers is determined. Regarding the scale of wind speed, the one to five rating system from the Saffir-Simpson Hurricane Wind Scale (Schott et al, 2012) is adopted for its worldwide recognition. Finally, as shown in Figure 5.7, twenty-five disrupted scenarios (indicated by the number in each block) are determined as the basis for the typhoon frequency analysis, the port physical damage probability analysis, and the estimation of port disrupted and recovery periods.

5.3 Analysis of typhoon frequency, determination of disrupted and recovery periods, physical damage probabilities

Based on the identified disrupted scenarios, the analysis of past typhoon frequencies in the area of the Port of Shenzhen is carried out. As seen in Appendix M, a total of thirty

typhoon events is found to hit the Port of Shenzhen within a strike distance of 500 km in the study period (1994-2015), which equals to an average of 1.43 per year. Among which, twenty-five cases fall in the scale of Category 1, while five cases belong to Category 2. The typhoon events occurred the most in August and September, reaching up to nine and ten cases, respectively. In this chapter, typhoon frequency is defined as the average number of typhoon events happening within the striking area of the studied port in one year. The typhoon frequencies during the study period are shown in Table 5.6, where the disrupted scenarios three and four appeared the most, accounting for eight and nine cases with frequencies of 0.38 and 0.43, respectively. The most destructive typhoon is Typhoon Vicente in 2012 (a Category 2 typhoon event with a strike distance of 99 km). By using Equations (5.11) and (5.12), the typhoon frequencies of each scenario are used as inputs in the past typhoon-induced port loss estimation as well as the future loss prediction, which is presented in Section 5.4.2 in detail.

The disrupted and recovery periods under each scenario is determined in a two-step manner. Firstly, the port logs recording past port severe weather events during the study period are collected. The typhoon events that have affected the port operation is filtered out and compiled by information of disrupted period, typhoon category and striking distance. Regarding the port of Shenzhen, two types of port natural disaster logs are found, namely the records of severe weather affecting port operation and the single typhoon event review. Although the study period is determined to be from 1994 to 2015 in this chapter, the records for the Port of Shenzhen are available from 2013 to 2017. Although the study period and the data available period do not overlap with each other entirely, it is believed that the data in 2016 and 2017 also show its reference value and are adopted here. The details of the events are shown in Appendix Q. It is noted that not all scenarios have happened and recorded in the area of the Port Shenzhen. Thus, for the rest of the scenarios which do not have references (such as scenarios 1,2,4,6,7,11-13,16-19,21-25), the consultation of port operators is used as a supplementary source. As a second step, the port operators are shown with Figure 5.7 which contains the typhoon-induced port disruption information collected from open sources. Based on the historical records and personal experience, the typhoon-induced port disruption periods are obtained for each scenario and shown in Table 5.6.

Having obtained the typhoon frequencies and port disrupted and recovery periods for each scenario, the next step is to generate the probabilistic estimates of typhoon-induced port physical damages. Loss exceedance curve is one feasible way for the derivation of earthquake-induced port physical damages probability (Wittkop et al., 2012). However, to the best of author's knowledge, in terms of typhoon related studies, no such curve has been developed for the whole port. Thus, similar to the way for the obtaining of port disrupted and recovery periods, port logs are used as the first channel. However, among all the eighteen typhoon events recorded at Shenzhen Port from 2013 to 2017, no damages were recorded. Therefore, such inputs are generated through the consultation of port engineers. The profile of the selected port engineers is shown in Appendix R with the results presented in Table 5.6.

The disrupted and recovery period is added to the "Failure data" module under "Resource data" module in order to obtain the container throughput under each disrupted condition, as the term T_i^{dis} in Equation (5.10). By subtracting the disrupted container throughputs (T_i^{dis}) from the intact container throughputs (T_i^{int}), the decreased container throughputs (T_i^{de}) are obtained. Subsequently, by using Equations (5.6)-(5.9), physical and economics losses are obtained. The results are shown in the next section.

Table 5.6 Estimated disrupted and recovery periods of typhoon-induced disruption for the Port of Shenzhen

Typhoon scale	Disrupted input	Strike distance (km)				
		0-100	101-200	201-300	301-400	401-500
Category 1	Scenario	1	2	3	4	5
	Typhoon frequency	0.05	0.14	0.38	0.43	0.19
	Disrupted and recovery period (day)	0-30	0-10	0-7	0-4	0-1
	Physical damage probability (%)	9.6-12.0	7.2-9.6	4.8-7.2	2.4-4.8	0-2.4
Category 2	Scenario	6	7	8	9	10
	Typhoon frequency	0	0	0.1	0.14	0
	Disrupted and recovery period (day)	10-90	10-50	0-20	0-10	0-3
	Physical damage probability (%)	16.8-21	12.6-16.8	8.4-12.6	4.2-8.4	0-4.2
Category 3	Scenario	11	12	13	14	15
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	20-200	10-150	0-100	0-30	0-10
	Physical damage probability (%)	51.2-64	38.4-51.2	25.6-38.4	12.8-25.6	0-12.8
Category 4	Scenario	16	17	18	19	20
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	60-240	50-190	40-140	10-50	0-40
	Physical damage probability (%)	79.2-99	59.4-79.2	39.6-59.4	19.8-39.6	0-19.8
Category 5	Scenario	21	22	23	24	25
	Typhoon frequency	0	0	0	0	0
	Disrupted and recovery period (day)	90-300	80-250	70-200	30-15	0-10
	Physical damage probability (%)	79.2-99	59.4-79.2	39.6-59.4	19.8-39.6	0-19.8

5.4 Results, discussion, and implications

This section presents the results of port ex-port vulnerability assessment against repetitive catastrophes, performing on the case study of the Port of Shenzhen and the hazard of typhoon. The main results include the decreased container throughput, the estimated typhoon-induced port direct physical losses, and economic losses under various typhoon disrupted scenarios. The annual estimated typhoon-induced loss of the studied terminal

from 1994 to 2015, as well as the predicted loss for the next five years, is also obtained. Finally, several applications and implications of the results for various end users of the model are presented.

5.4.1 Decreased port throughput

The simulated container throughput reductions for each disrupted scenario are shown in Table 5.7. It can be seen that, for each typhoon scale, the decreased container throughput declines as the strike distance increases, while for each strike distance, the decreased container throughput goes up with the increase of typhoon scale. The lowest container throughput reduction appears when a Category 1 typhoon hits the port at the distance interval of 401-500km. The highest reduction is approximately a thousand times higher than the lowest value. Such worst case appears when a Category 5 typhoon hit the port at the distance interval of 0-100km. Regarding the proportion of decreased throughput in intact throughput, the range is from 0.03% to 34.51%, which means, in the worst case, more than one-third of the port throughput is affected. Figure 5.8 shows the typhoon-induced throughput vulnerability surface for the terminal under study. This vulnerability surface shows its application in identifying the most frequent typhoon disrupted scenario and its throughput decrease in an intuitive way. A more precise throughput decrease could be generated through interpolation.

Table 5.6, Table 5.7, and Figure 5.8 together show their applicability in estimating the annual typhoon-induced loss for the largest terminal of the Port of Shenzhen and for the terminals of similar scales. In detail, regarding the Port of Shenzhen, it is found that disrupted scenarios three and four appeared the most in the past two decades, whose frequencies are 0.38 and 0.43 with a decrease in container throughput of 89,774 TEUs and 47,258 TEUs, respectively. Considering the estimated total loss of 38 USD millions and 22 USD millions (calculated by Equations (5.6)-(5.10)), the annual loss induced by these two scenarios is calculated to be approximately 24 USD millions.

Table 5.7 Simulated typhoon-induced decreased container throughput

Typhoon scale	Output	Strike distance (km)				
		0-100	101-200	201-300	301-400	401-500
Category 1	Decreased	432161	140394	89774	47258	4158
	Decreased/Intact	3.47%	1.13%	0.72%	0.38%	0.03%
Category 2	Decreased	1246488	788118	281448	140394	19640
	Decreased/Intact	10.02%	6.34%	2.26%	1.13%	0.16%
Category 3	Decreased	2223579	1917256	1199758	432161	140394
	Decreased/Intact	17.88%	15.42%	9.65%	3.47%	1.13%
Category 4	Decreased	3181954	2626275	2241383	788118	488386
	Decreased/Intact	25.59%	21.12%	18.02%	6.34%	3.93%
Category 5	Decreased	4247361	3661466	2993226	2206839	1199758
	Decreased/Intact	34.15%	29.44%	24.07%	17.74%	9.65%

Figure 5.8 Container throughput vulnerability surface

It should be noted that, in practical terminal operations, when the port is affected without major physical damages, the disrupted period and the recovery period are less significant. A one or two days' disruption is common for a terminal under study, while the recovery period largely depends on the degree of physical damages. The small amount of container decrease is able to be recovered by speeding up the operation productivity after the port reopens. For example, in the case of a loading port (which means the port's export boxes outnumber the import boxes), container ships that intend to call at the disrupted port may cancel the call, and unload the containers at other available ports along the itineraries. The containers to be loaded in the disrupted

terminal would wait in the yard for the next dispatched container ships until the port operation restarts. Similarly, the arriving ships could slow steaming in advance or wait in a sheltered anchorage until the typhoon leaves an unloading port (which means the port's import boxes outnumber the export boxes). However, situations can be quite different when serious physical damages occur. One to two weeks of disruption period and several months' recovery period are found in real cases (Nadkarni, 1998; CRS, 2005). The long-term disrupted and recovery period would drive liner shipping companies away temporarily or even permanently to alternative ports in the vicinity. In 2003, after the strike of Typhoon Maemi (disrupted scenario 11: a Category 3 typhoon impacted the Port of Busan at a very near strike distance of 76km), the Port of Busan lost half of its customers. Kwangyang Port and Masan Port are chosen as alternative ports for carriers and key manufacturers, such as LG Electronics (Lee, 2003). In 2005, Hurricane Katrina (disrupted scenario 11: a Category 3 hurricane with an even shorter strike distance at 65km) attacked the Port of New Orleans and other Lower Mississippi ports. Shipping lines serving the affected ports diverted their operations to Houston, Freeport, Pensacola and Port Everglades (Alexander and Irwin, 2005). Thus, it is seen that the need for assessing the worst-case port disruption scenarios induced by catastrophes is urgent, not only for port operators, but also for other port stakeholders, especially for the ocean carriers and shippers in the hinterland. Only by understanding in depth the potential consequences in advance, can the stakeholders prepare for the potential port disruptions in a fast react manner. To estimate the port disrupted and recovery periods, to estimate the potential physical damages, and to further evaluate the port economic losses as well as the stakeholders' losses are the major and challenging tasks within the whole research framework. Having obtained the estimated port disrupted and recovery periods in Section 5.3, the estimation of the potential port physical damage losses and economic losses are presented in the following paragraph.

5.4.2 Port physical damage loss and economic loss

Based on Equations (5.6) to (5.10), the estimated port physical loss, economic loss and the total loss are presented in Figure 5.9. It is observed that in every distance interval, the total loss increases with the rise of the typhoon scale, while the total loss increases

with the decrease of the strike distance on each typhoon scale. According to our estimation, the largest typhoon-induced total loss in a single attack reaches 0.91 USD billion for a terminal containing sixteen berths or terminals of similar sizes. As the strike distance increases, the average proportion of physical loss becomes smaller, from an average proportion of 54.07% in the case of 0-110 km to 39.48% in the case of 401-500 km. Such a change is consistent with the reality that the closer the strike distance, the higher the probability of structures and equipment damages.

Figure 5.9 Estimated loss for the case study for each strike distance interval

Furthermore, we expand the developed model in calculating the past typhoon-induced port loss as well as in predicting the future loss by using Equations (5.11) and (5.12). As shown in Figure 5.10, from 1994 to 2015, the total estimated typhoon-induced loss for the terminal reaches around 0.56 USD billion (in 2016 USD), which equals approximately 27

USD millions per year. On a rough estimation, the yearly typhoon-induced loss accounts for 8.3% of the terminal net profit in 2015. It is predicted that for the next five years (from 2016 to 2020), this loss will reach approximately 32 USD billions, which equals to 64 USD millions on a yearly basis, accounting for 19.7% of the terminal net profit. It is seen that, given the same typhoon frequency, the predicted annual average typhoon-induced loss has more than doubled in terms of both absolute and relative value. It can be inferred from Equations (5.11) and (5.12) that the increased typhoon-induced port loss results from a growth of exposure of the terminal against the hazard of typhoon.

Figure 5.10 Typhoon-induced port loss (1994-2020)

5.4.3 Implications of the results

Since it is not possible to reduce the frequency of natural disasters, the vulnerability of exposures becomes a vital factor in port typhoon risk management. In a related work, Lam and Su (2015) proposed several mitigation strategies for port operators in dealing with natural disasters, including the use of warning system in port operation, the establishment of port strategic alliances, updating contingency plans and drills, as well as improving the port infrastructures. It is found that, contingency plans and drills specifically for typhoon are widely adopted by ports facing regular typhoon risks (see contingency plans such as Zhuhai Port Authority, 2011 and Dalian Port 2015). Protective measures in contingency plans involve the strength enhancement of anchorage chains, the deployment of anti-wind cables to large machinery, the movement of valuable cargo and dry cargo, as well as the check of relief materials. Such

plans and drills show their effects to prevent short-term disruption impacts (such as disrupted scenario 2, 3, 4, 5, 9, 10, and 15, in which the longest ports disruption periods are within 10 days). Regarding extreme cases (such as disrupted scenario 11, 16, 21, 22, and 23, in which the longest port disruption periods have potentials to reach 200 days), port operators are suggested to put more efforts in adopting early warning systems, establishing regional port alliances and strengthening the wind proofing property of port infrastructures and equipment. However, these strategies require time-consuming and high investments, port operators should weigh the pros and cons based on the probability of extreme events occurring in the port area, and the estimated catastrophe-induced port loss. When the probability and the loss exceed some certain thresholds, it is advisable to designate catastrophe emergency coordinators or establish a catastrophe prevention department for ports with high strategic positions. This department should collaborate with the local government, the meteorological department, vicinity port operators, and port users to guarantee the visibility of information among all the related parties. It is also suggested for those regional governments which are located in disaster-prone areas to draft contingency plans specifically for worst cases, where the whole port may lose its functions for a long time.

5.4.4 Method validation

In order to test the accuracy of the proposed model, we propose a validation approach by comparing the decreased container throughput obtained from the proposed method with the decreased container throughput estimated by the reported growth-rate. In 2003, the Busan Port was attacked by the Typhoon Maemi. Catastrophic physical damages, as well as tremendous economic losses, were caused to the port by the disaster. In this study, this case is used to valid the proposed port loss estimation model. As a first step, the annual container throughput in 2003 under the intact condition is predicted by using the historical container throughput and the reported throughput annual growth rate. Secondly, the difference between this predicted value and the actual throughput in 2003 can thus be calculated and used as a benchmark. Thirdly, the decreased container throughput is simulated by using the developed model. Finally, the simulated value is compared with the benchmark value in order to test the accuracy of the proposed model.

It is reported that the container throughput of the Busan Port was expected to have an average annual growth rate of 22.9% under intact conditions (United Nations, Economic and Social Commission for Asia and the Pacific (UNESCAP), 2005). Thus, the annual container throughput in 2003 under the intact condition for the Port of Busan is predicted and is shown in Table 5.8. Also shown in Table 5.8 are the benchmark value and the simulated value of the decreased container throughput (see Appendix S for the model inputs). It can be seen that, the comparable results show the accuracy and reliability of the proposed model.

Table 5.8 Method validation

Method	Container throughput_ Intact (TEUs)	Container throughput_ Disrupted (TEUs)	Container throughput_ Decreased (TEUs)
Predicted	11,618,174	10,407,809	1,210,365
Simulated	11,747,732	10,674,611	1,073,121

It is noteworthy to discuss the factors which affect the accuracy of the proposed method. First of all, as a core of the simulation model, the accuracy of the estimates of physical damage degree under various disrupted scenarios affect the model accuracy. The degree of physical damages is one of the reasons that affect the length of disrupted and recovery periods. It is determined by various factors, such as the frequency and magnitude of the hazard events, as well as the strength of the port infrastructure and equipment. Thus, to enhance the accuracy of the model, it is suggested that different ports in different locations and types estimate the degree of physical damage by simultaneously considering the mentioned factors. Secondly, it is difficult to predict the recovery speed, which is another critical factor that affects the length of recovery periods. The recovery speed is driven by the recovery capability and the degree to which the capability is realized. Thus, it is suggested for the end users to follow the government policies on post-disaster relief and recovery closely to better estimate the port recovery speed. Thirdly, it is the uncertainty of whether the port is able to restore to its original operation level. One assumption in this study is that the container throughput reaches its original level once the recovery period ends. However, not all ports were able to restore to its original level, as shown historically. In the case of 1995 Kobe earthquake, after more than ten years, the Port of Kobe's container throughput was still

less than the level in 1994 (one year before the disaster) (Na and Shinozuka, 2009). Possible reasons may lie in (1) the decline of Japan's trade volume, and (2) the shipping companies once re-routed calls from the Port of Kobe did not call back again. However, in the case of 2003 Typhoon Maemi, the South Korean government invested 290 USD billions (in 2003 USD) in the construction of Busan new port. By the year of 2011, thirty new berths were constructed (UNESCAP, 2015). Although the development did not restore Busan to its original worldwide container port ranking (3rd among the 2002 rankings), it is able to hold the position of 5th or 6th amid fierce competitions from other ports in the region, such as Shanghai, Qingdao, and Ningbo. It is seen that governments' investments in port reconstruction plans differ from country to country, which depends heavily on how the government positions the port in the post-disaster era. On all accounts, it is a costly and long journey for ports to recover to their original levels after catastrophes.

5.5 Chapter summary

This chapter assesses port vulnerability against repetitive catastrophes by developing a simulation-based model. The physical and economic typhoon-induced port losses are estimated by using the probabilistic estimates of physical damages and the decreased container throughput under each identified disrupted scenario. Thus, port economic vulnerability is evaluated by measuring the decreased container throughput. A case study on the Shenzhen container terminal and the hazard of Typhoon is carried out to illustrate the real-world application of this model. The inputs of the model include the actual port operation records and the port catastrophe hazard data. The actual port operation records are acquired from the container terminal. However, currently, there is no database specifically recording catastrophes happened in port areas. Thus, to close this gap, this study establishes a port catastrophe database, which includes data of hazard magnitude, frequency, and the induced port disrupted and recovery time. The proposed framework is also used to estimate the total historical typhoon-induced loss and the predicted loss for the next five years. Results show their industrial applicability as useful references for port operators in terms of port catastrophe risk analysis and formulation of port catastrophe risks contingency plans. Outputs can also be useful for

other port stakeholders, such as local regulators, carriers, regarding port site selection, route planning and bunkering port selection.

The simulation-based model presented in this chapter, together with the vulnerability index method presented in Chapter 4, demonstrates how port vulnerability is assessed from a multi-dimensional perspective. The case studies used in these two chapters cover non-repetitive and repetitive catastrophes, as well as man-made and natural catastrophes, which supplements the current literature on port vulnerability against catastrophes comprehensively.

CHAPTER 6 ASSESSMENT OF PROPAGATION OF PORT VULNERABILITY TO INDUSTRIAL CLUSTERS AGAINST CATASTROPHE-INDUCED PORT DISRUPTIONS

In this chapter, propagation of port vulnerability along the maritime transportation network is assessed based on a proposed three-layer port-cargo-industrial cluster (PCI) model. By using cargoes as intermediaries between ports and industrial clusters, the propagation of vulnerability to the industrial clusters resulting from catastrophe-induced port disruptions is assessed. By doing so, the most vulnerable industrial clusters in the port hinterland are identified in the export and import modes, respectively. In order to demonstrate the feasibility of the proposed model, a case study is performed on the seaports in Guangdong province, China against the seasonal coastal catastrophic hazard, typhoon. The PCI model, the process of data acquisition, results, discussion, as well as the implications for practice are presented in this chapter.

The following publications from author are based on part of this chapter:

- Cao, X., and Lam, J.S.L., 2018, Catastrophe Risk Assessment Framework of Ports and Industrial Clusters: A Case Study of the Guangdong Province. *International Journal of Shipping Transport and Logistics*. Accepted.
- Cao, X., and Lam, J.S.L., 2017, Catastrophe Risk Analysis of Ports and Industrial Clusters: A Framework and Case Study. *The International Association of Maritime Economists Conference*, Kyoto, Japan, 27-30, June 2017.
- Cao, X., and Lam, J.S.L., 2015, A framework for port and industrial cluster catastrophe risk analysis. *The International Association of Maritime Economists Conference*, Kuala Lumpur, Malaysia, 24-26, August 2015.

6.1 Introduction of the port-cargo-industrial cluster model

As seen in Figure 6.1, the three-layer PCI model consists of the port layer, the cargo layer, the industrial cluster layer, as well as the input and output relationships between the layers. In detail, the combination of the lower two layers in the PCI model, including the port layer and the cargo layer, is essentially an input-output model. This input-output model depicts the interdependencies between ports and cargoes, linking the catastrophe-induced seaport vulnerability with the resulted cargo transportation vulnerability. The combination of the upper two layers of the PCI model, including the cargo layer and the industrial cluster layer, can be seen as another input-output model. This input-output model quantifies the interdependencies between the cargo transported through the seaports and the cargo consumers and providers, namely the industrial clusters. Thus, by combining the two input-output models through the equivalent rules, the proposed PCI model enables the quantification of the cascading vulnerability to the hinterland industrial clusters resulting from catastrophe-induced seaport inoperability. The results are able to identify the vulnerable seaports against catastrophes and the susceptible industrial clusters against seaport disruptions. The following paragraphs show a detailed description of the PCI model.

Figure 6.1 Topology of PCI model, import mode

Source: Author.

As shown in Figure 6.2, the import and the export are treated as two parallel modes and are studied in two different models. In the import mode, as shown in Figure 6.2(a), α_i represents the catastrophe risk inputs for the i th port (P_i). The details of the

generation of α_i is shown in Section 6.2. β_i^j denotes the cargo value proportion of the j th type of cargo (C_j) among all the types of cargoes imported through P_i . λ_j^k denotes the cargo value proportion of C_j among all types of cargo consumed by the k th industrial cluster (IC_k). By using Equation (6.1), the port catastrophe risk inputs (α_i) are converted into the outputs of propagation of vulnerability to the industrial clusters (ω_k). Figure 6.2(b) shows the export mode PCI model. β_j^i refers to the cargo value proportion of C_j among all types of cargoes exported through P_i . λ_k^j denotes the cargo value proportion of C_j among all types of cargoes produced by IC_k . Likewise, by using Equation (6.2), the outputs reflecting port catastrophe-induced industrial cluster vulnerability are obtained.

$\omega^k \leftarrow IC_k$	λ_1^k	λ_2^k	$\dots$	λ_j^k	$\omega_k \leftarrow IC_k$	λ_k^1	λ_k^2	$\dots$	λ_k^j
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$\omega^2 \leftarrow IC_2$	λ_1^2	λ_2^2	$\dots$	λ_j^2	$\omega_2 \leftarrow IC_2$	λ_2^1	λ_2^2	$\dots$	λ_2^j
$\omega^1 \leftarrow IC_1$	λ_1^1	λ_2^1	$\dots$	λ_j^1	$\omega_1 \leftarrow IC_1$	λ_1^1	λ_1^2	$\dots$	λ_1^j
	C_1	C_2	$\dots$	C_j		C_1	C_2	$\dots$	C_j
$\alpha_1 \rightarrow P_1$	β_1^1	β_1^2	$\dots$	β_1^j	$\alpha_1 \rightarrow P_1$	β_1^1	β_1^2	$\dots$	β_1^j
$\alpha_2 \rightarrow P_2$	β_2^1	β_2^2	$\dots$	β_2^j	$\alpha_2 \rightarrow P_2$	β_1^2	β_2^2	$\dots$	β_j^2
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$\alpha_4 \rightarrow P_i$	β_i^1	β_i^2	$\dots$	β_i^j	$\alpha_4 \rightarrow P_i$	β_1^i	β_2^i	$\dots$	β_j^i

(a) Import mode

(b) Export mode

Figure 6.2 PCI model

Source: Author.

$$\omega^k = \sum_{j=1}^{MQ} \left(\sum_{i=1}^{MP} \alpha_i \beta_i^j \right) \lambda_j^k, \forall k \in \{1, \dots, MR\}; \quad (6.1)$$

$$\omega_k = \sum_{j=1}^{MQ} \left(\sum_{i=1}^{MP} \alpha_i \beta_j^i \right) \lambda_k^j, \forall k \in \{1, \dots, MR\}. \quad (6.2)$$

MP - number of studied ports;

MQ - number of the types of studied cargoes;

MR - number of studied industrial clusters;

ω^k - propagation vulnerability output of the k th industrial cluster for the import model;

α_i - catastrophe risk input of the i th port;

β_i^j - cargo value proportion of the j th type of cargo among all types of cargoes
imported through the i th port;

λ_j^k - cargo value proportion of the j th type of cargo among all types of cargoes
consumed by the k th industrial cluster;

ω_k - propagation vulnerability output of the k th industrial cluster for the export model;

β_j^i - cargo value proportion of the j th type of cargo among all types of cargoes
exported through the i th port;

λ_k^j - cargo value proportion of the j th type of cargo among all types of cargoes
produced by the k th industrial cluster.

For a better illustration, Figures 6.3 and 6.4 visualize the transportation network depicting the process of import and export, respectively. It is noted that the number indicating α_i , β_i^j , λ_j^k , β_j^i , and λ_k^j in these two figures are for the purpose of illustration and does not denote real values. As seen in Figure 6.3, Port 1 imports two types of cargoes, Cargo 1 and Cargo 2. The cargo value proportion of Cargo 1 is 0.6 ($\beta_{i=1}^{j=1}$), while for Cargo 2, this value is 0.4 ($\beta_{i=1}^{j=2}$). The cargo value proportion of Cargo 2 being consumed by Industrial Cluster 1 is 0.7 ($\lambda_{j=2}^{k=1}$) while the rest of 0.3 ($\lambda_{j=2}^{k=2}$) is consumed by Industrial Cluster 2. Thus, the industrial cluster and the port are linked by the cargoes being transported through this transportation network. Likewise, Figure 6.4 demonstrates the graph lexicon for the export mode. In the following section, a case study is performed by using the Guangdong province, China and the hazard of typhoon as an example. The data acquisition is presented in Section 6.2. The results, discussion, and the implications of the results to the different stakeholders are shown in Section 6.3.

Figure 6.3 PCI model, import mode

Source: Author.

Figure 6.4 PCI model, export mode

Source: Author.

6.2 Data acquisition

This section shows a real-world application of the proposed PCI model, by using the Guangdong province, China as a case study. Comprehensively taking factors of the cargo throughput, the scale of industrial clusters and the frequency of natural catastrophes into account, the Guangdong province, China is selected as the case study. As shown in Figure 6.5, Guangdong is home to the largest number of major seaports (seaports with an annual throughput of one hundred million tons or more) along the Chinese coastline, accounting for 16% of total annual throughput nationwide in 2015 (National Bureau of Statistics of the People's Republic of China, 2015). The scale of industrial clusters in Guangdong Province ranks top five among all the Chinese provinces in terms of the number of industrial clusters, the number of enterprises in clusters and the enterprise profits (see details in Appendix T). Regarding natural

catastrophes, as shown in Figure 6.6, Guangdong encounters the most frequent typhoon and earthquake threats among all the coastal provinces in China. These two hazards are viewed as the most damaging natural catastrophes to seaports from past events (Nadkarni, 1998; Chang, 2000; Nadkarni, 2001; Chambers, 2003a; Chambers, 2003b; Lee, 2003; Abe and Hoontrakul, 2012; Sturgis et al, 2014; Liu, 2016). In this chapter, the hazard of typhoon is focused because of its characteristic of high frequency and the reoccurring nature.

Figure 6.5 Seaport cargo throughput proportions of major provinces in China (by tons, 2015)
Source: Computed and drawn by author. Data retrieved from National Bureau of Statistics of the People's Republic of China (2015).

Figure 6.6 Typhoon and earthquake frequencies of major coastal provinces in China (1951-2014)

Source: Computed and drawn by author. Data retrieved from China Meteorological Administration Tropical Cyclone Information Center (2015) database and National Bureau of Statistics of the People's Republic of China (2015).

Table 6.1 shows the data sources used in this chapter for each model input parameter. It is seen that primary and secondary data are used. The primary data are collected by the consultancy with the Guangdong Province port operators for the estimations of β_i^j and β_j^i . The secondary data are used for obtaining the values for λ_j^k and λ_k^j . As shown in Table 6.2, all the ten seaports in Guangdong are considered. Regarding the industrial clusters, six types of key industrial clusters in Guangdong Province are identified. Twenty-three cargo types ($j = 23$ in the import mode) are determined for the import model and thirty-one types of final products ($j = 31$ in the export mode) are identified in the export process.

Table 6.1 Parameters and data sources for the PCI model

Parameter	Data source	Data source
i	Historical data	Guangdong province port yearbook (Port and Harbor Association of Guangdong Province, 2012)
j	Historical data	National economic industry classification code table (National Bureau of Statistics of the People's Republic of China, 2017)
k	Historical data	Report on industrial clusters development in China (2008)
α_i	Historical data	IBTrACS (Knapp et al., 2010)
β_i^j	Interview	Port operators of Guangdong ports
λ_j^k	Historical data	Input and output table of Guangdong province (Statistics Bureau of Guangdong Province, 2012b)
β_j^i	Historical data and interview	Gross output value of industry, above designated size, by city (Statistics Bureau of Guangdong Province, 2012a)
λ_k^j	Historical data	Total value of imports and exports, by category of commodities (Statistics Bureau of Guangdong Province, 2012c)

Table 6.2 Descriptions of model input

Model input	Value	Description
i	10	Guangzhou Port; Shenzhen Port; Zhanjiang Port; Maoming Port; Zhuhai Port; Zhongshan Port; Huizhou Port; Shanwei Port; Shantou Port; Chaozhou Port
k	6	Digital information; Electrical equipment; Petrochemical; Textile and apparel; Food and drink; Building material
j_import	23	Farm, forest, livestock and fishery product; Coal; Oil and natural gas; Metal and metal ore; Non-metal ore; Food and tobacco; Textile; Textile garment, footwear, headgear, down feather and related product; Wooden product and furniture; Paper, printed matter, stationery and sporting product; Petroleum, coking product, nuclear fuel; Chemical product; Non-metal ore product; Metal smelting and rolling product; Metal ware; Flexible unit; Dedicated device; Transportation facility; Electric machinery and equipment; Communication device, computer and other electronic equipment; Instrument and meter; Other manufactured product; Scrap
j_export	31	Electric calculator; Data processing equipment; Electric motor and generator; Landline telephone set; Hand-held or vehicle-mounted cordless telephone; Loudspeaker; Radio recorder and audio system; Color TV set; Integrated circuit and part of electronic component; Camera; Electronic watch; Static converter; Primary cell and battery; Electric accumulator; Finished petroleum product; Raw silk; Textile; Garment and clothing accessory; Cereal; Vegetable; Fresh and dried fruit; Edible oil seed; Edible vegetable oil; Canned pork; Canned mushroom; Glass product; Porcelain and pottery ware for household use; Wood article for household or decoration use; Steel product; Aluminum product; Copper product

The choice of the port catastrophe risk input α_i determines the interpretation of the output ω_k and ω^k . For example, if a local government chooses the frequency of a specific type of hazard occurred in the port area as the input, the output thus depicts the transitional frequency of this type of hazard affecting the industrial cluster. For manufacturers who concern more on the continuity of business, the estimated port shutdown and recovery periods tend to be preferable as inputs. In such a circumstance, the outputs are measures of the expected downtimes of the industrial clusters as a result of the port disruption. For the purpose of illustration, the typhoon strike frequency of the Guangdong ports is used as α_i in this chapter. The value of α_i is obtained from the established port catastrophe database discussed in Section 5.2.2.1.

In the developed port catastrophe database, the distance between typhoon centres and the affected ports are calculated and recorded on a basis of six hours (Knapp et al.,

2010). Any distance less than the largest possible typhoon-affected distance (500km) is filtered out and recorded as a “strike” in the database. The total typhoon strike numbers and the strike frequency of each studied port are summarised in Table 6.3. It is noted that, the “strike number” shown in Table 6.3 refers to the number of strikes recorded based on a six-hour time interval, rather than the number of typhoon events. The typhoon strike frequency is calculated by the strike number divided by the number of years. It is observed that, from 1951 to 2014, the total number of typhoon strikes reached over twenty thousand within the Guangdong province seaports’ area during the past six decades. It is seen that most of the seaports in Guangdong Province suffer from high typhoon risks, especially Huizhou Port and Zhuhai Port, while Zhongshan Port is the least vulnerable to the typhoon hazard.

Table 6.3 Summary of port typhoon database, Guangdong Province (1951-2014)
Source: Author, based on based on Knapp et al. (2010) and National
Geospatial-Intelligence Agency (2015).

Port	Strike number	Strike frequency	Normalized frequency	Risk level
Huizhou Port	2993	46.77	0.47	High
Zhuhai Port	2971	46.42	0.46	High
Shanwei Port	2877	44.95	0.45	High
Shenzhen Port	2863	44.73	0.45	High
Maoming Port	2830	44.22	0.44	High
Chaozhou Port	2790	43.59	0.44	High
Shantou Port	2748	42.94	0.43	High
Zhanjiang Port	2742	42.84	0.43	High
Guangzhou Port	2492	38.94	0.39	Medium
Zhongshang Port	1409	22.02	0.22	Low
Sum strike no. and average strike frequency	26715	44.56	0.45	High

In order to assess the propagation of vulnerability to hinterland industrial clusters resulting from typhoon-induced port disruptions, the calculation is carried out in a three-step manner. In the first stage, the actual typhoon strike frequency of each seaport is applied as α_i . The outputs obtained in such circumstances denote the propagation of port vulnerability resulting from two sources, including (1) the interdependency between industries and (2) the heterogenous typhoon-induced port inoperability. In the

second stage, the value of α_i is set to be the lowest port typhoon strike frequency ($\alpha_i = 0.22$) for all the studied ports. With the same lowest typhoon input, the outputs indicate the propagation of vulnerability caused by (1) the interdependency between industries, as well as (2) the lowest homogeneous typhoon-induced port inoperability. As a third step, the outputs obtained from the previous two scenarios are compared. The difference is used as the measurement of the pure propagation of vulnerability to the industrial cluster by excluding the interdependency effects. Thus, in this section, a total of four cases considering two modes and two scenarios are carried out, including the case of import mode with the same typhoon input (Case_IWST); the case of import mode with actual typhoon inputs (Case_IWT); the case of export mode with the same typhoon input (Case_EWST); and the case of export mode with actual typhoon inputs (Case_EWT).

6.3 Results, discussion and implications

This section presents the assessment results of the propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions, performed on the case study of the Guangdong province, China against the hazard of typhoon. The outputs are normalized for the purpose of comparison. Higher outputs indicate higher propagation of vulnerability. The results of the Case_IWT and the Case_EWT are shown in Section 6.3.1, while Section 6.3.2 shows the outputs of the Case_IWST and the Case_EWST. Outputs comparisons showing the pure propagation of port vulnerability to the industrial clusters are presented in Section 6.3.3.

6.3.1 Cases of IWT and EWT

This section shows the results of the Case_IWT and the Case_EWT, which measure the propagation of vulnerability to the hinterland industrial clusters due to the combined resources of the industry interdependency, as well as the heterogeneous typhoon-induced port inoperability. As shown in Table 6.4, the average outputs of the import mode are higher than the export mode, which indicates the key industrial clusters' import process as a whole is more vulnerable comparing to the export process against typhoon-induced seaport disruptions in Guangdong Province.

Table 6.4 Model outputs, Case_IWT and Case_EWT

Industrial cluster	IWT		EWT	
	Output	Ranking	Output	Ranking
Digital information	0.4148	4	0.4120	5
Electrical equipment	0.5553	2	0.4221	2
Petrochemical	0.6880	1	0.3976	6
Textile and apparel	0.3953	5	0.4240	1
Food and drink	0.3670	6	0.4146	3
Building materials	0.4328	3	0.4135	4
Average	0.4755	N.A.	0.4140	N.A.

In the Case_IWT, the petrochemical industrial cluster has the highest output, followed by the industrial clusters of electrical equipment, building materials, digital information, textile and apparel, as well as food and drink. The high output of the petrochemical industrial cluster may result from the large cargo tonnages imported from ports with higher typhoon risks, such as the Zhanjiang Port, the Maoming Port, the Zhuhai Port, and the Huizhou Port. As for the Case_EWT, the results show that the most vulnerable industrial cluster is the textile and apparel industrial cluster against port disruptions during the export process in Guangdong Province. The second vulnerable one is the electrical equipment industrial cluster, followed by the food and drink industrial cluster, the building materials industrial cluster, the digital information industrial cluster, and the petrochemical industrial cluster. The contrast of the high vulnerability in the import case and the low vulnerability in the export case of the petrochemical industrial may be due to the small export amounts of petrochemical-related products. This is consistent with the fact that there is a trade deficit in the petrochemical industry of China. The other type of industrial cluster showing a large contrast of vulnerability under import and export modes is the textile and apparel industrial cluster. It ranks the 5th among the six types of industrial clusters under the import mode, while it ranks the 1st during the export process. The major reason is that the raw material can be easily accessed locally by inland transportation for the textile and apparel industry in China, however, this industry relies heavily on seaports for export.

6.3.2 Cases of IWST and EWST

This section shows the results of the Case_IWST and the Case_EWST. By excluding

the typhoon influences, these results are able to measure the propagation of port vulnerability to hinterland industrial clusters resulting from the interdependency among industries, as well as the homogeneous typhoon-induced port inoperability. As seen in Table 6.5, the outputs of the Case_IWST show a wider dispersion than the outputs of the Case_EWST, which is because the supply network of a manufacturer tends to be more complex than the distribution network. It is seen that, in the import mode (Case_IWST), the petrochemical industrial cluster is more vulnerable than other types of industrial clusters, while the least vulnerable industrial cluster is the textile and apparel industrial cluster. In the export mode (Case_EWST), all of the outputs are distributed around an expected value of 0.1102 with a rather small variance of 0.0001.

Table 6.5 Model outputs, Case_IWST and Case_EWST

Industrial cluster	IWST		EWST	
	Output	Ranking	Output	Ranking
Digital information	0.1843	4	0.1103	1
Electrical equipment	0.2070	3	0.1102	3
Petrochemical	0.2550	1	0.1101	5
Textile and apparel	0.1150	6	0.1101	5
Food and drink	0.1451	5	0.1103	1
Building materials	0.2298	2	0.1102	3
Average	0.1894	N.A.	0.1102	N.A.

6.3.3 Result comparison and implications of results

In order to examine the pure propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions, the results obtained in Sections 6.3.1 and 6.3.2 are compared, as shown in Table 6.6. The comparisons are carried out in two groups. The first comparison is performed between the Case_IWST and the Case_IWT. The second comparison is between the Case_EWST and the Case_EWT. Thus, both the import and export modes are considered. For a clearer illustration, the results of these comparisons are visualized in Figure 6.7. The propagation of port vulnerability under the import mode is shown by the blue colour lump and the result of the export mode is shown by the orange colour lump. It can be seen that, the increase in the propagation of port vulnerability under the import mode shows more complexities than that under the export mode.

Table 6.6 Results comparison
(between Case_IWST and Case_IWT ; Case_EWST and Case_EWT)

Industrial cluster	Output		Rate of change	Output		Rate of change
	IWST	IWT		EWST	EWT	
Digital information	0.1843	0.4148	125%	0.1103	0.4120	274%
Electrical equipment	0.2070	0.5553	168%	0.1102	0.4221	283%
Petrochemical	0.2550	0.6880	170%	0.1101	0.3976	261%
Textile and apparel	0.1150	0.3953	244%	0.1101	0.4240	285%
Food and drink	0.1451	0.3670	153%	0.1103	0.4146	276%
Building materials	0.2298	0.4328	88%	0.1102	0.4135	275%
Average	0.1894	0.4755	158%	0.1102	0.4140	276%

Figure 6.7 Visualized results comparison
(Case_IWT and Case_IWST; Case_EWT and Case_EWST)

As far as the import mode (Case_IWST and Case_IWT) is concerned, the industrial cluster of textile and apparel's output increases the most, followed by the industrial cluster of petrochemical, electrical equipment, food and drink, digital information, and building materials.

It can be inferred that the maritime cargoes supplying to the industrial cluster of textile and apparel rely on high typhoon risk ports during the import process. Combining the conclusions obtained from Section 6.3.1, it is concluded that the majority of the supplies for this industrial cluster rely on inland transportation, however, the minor supplies by maritime transportation depend on typhoon-risky seaports. Thus, control strategies, such as increasing inventories before typhoon seasons (namely, the second half year in the

case of Guangdong Province), are suggested to the manufacturers in the industrial cluster with such characteristics. Flexible strategies are also appropriate for such industries, which include using alternative unaffected ports, and sourcing from different locations.

The petrochemical industrial cluster has a high propagation of port vulnerability level in both cases of IWS and IWT, which means it largely relies on typhoon risky seaports during the import process. Since there are specialized requirements for the loading and unloading facilities of the terminal, the possibility of transferring to adjacent ports is quite low. Hence, flexible strategies are not preferable for such an industrial cluster. On the contrary, control strategies are preferable, such as increasing the inventory of raw materials transported by ships before typhoon seasons. Moreover, as a key industry, the petrochemical industry safeguards the national welfare and the people's livelihood. Industry stakeholders should formulate mitigation strategies in preparation for long-term port disruptions. Apart from the two strategies suggested, industry operators are recommended to enact mitigation strategies on a strategic level, such as building multiple plants, using multiple suppliers, and placing multi-location inventories.

The condition of the electrical equipment industry is similar to the condition of the petrochemical industry, in a way that they both use high typhoon-risk ports for its raw material supplies. What differs from the petrochemical industry is that it does not require specialized terminals for cargo loading and unloading. Thus, flexible strategies, such as transferring the cargoes to alternative ports, are feasible. Due to the characteristic of high cargo value in this industry, air transportation is considered when there is an imperative short of supply. Control strategies are also suitable for this industrial cluster. Possible suggestions include increasing inventories and preparing redundancy capabilities.

With regard to the clusters of food and drink as well as apparel, we find that the supply pattern of the two is similar. In detail, the supplies for both industries are relatively easy to be accessed. However, the requirement of retaining freshness determines the inoperability of increasing the inventory to against port typhoon risks for the food and drink industry. In turn, flexible strategies are advised to manufacturers in the two

clusters, such as transferring shipment to safer ports after receiving the typhoon landing warnings. In addition, alternative domestic supplies are also practicable for the easily accessed raw materials.

The digital information industrial cluster ranks the fourth in the IWT case with a medium rate of increase in the IWSST case, which means it does not over-depend on the typhoon risky ports in Guangdong Province.

Regarding the building material industrial cluster, it ranks the second in the IWT case with the lowest growth rate in the IWSST case. It can be inferred that, many of the supplies to this industry use maritime transportation. Moreover, the ports used by this industry are less vulnerable comparing to other Guangdong ports against the typhoon hazard. It is suggested that, for better proactively prepare for the potential port closure, the industry players for both clusters should bring the mentioned control and flexible strategies into their agendas.

Regarding the export mode, it can be seen from Figure 6.7 that the results of all the types of industrial clusters have similar growth rates. That is to say, as a manufacturing powerhouse, China, especially the Guangdong province, relies on typhoon risky seaports to a large extent in the export process. As such, manufacturers located in the typhoon risky seaports hinterland are suggested to take extra care in the management of the potential port operation disruptions. Manufacturers and their third-party logistics providers should keep close eyes on the port news and meteorology news during typhoon seasons, and thus enact effective countermeasures before and/or after the possible port disruptions. Flexible strategies are suggested to the manufacturers in all the mentioned industrial clusters. Firstly, the manufacturers are suggested to enhance flexibilities in the contracts signing with customers. To include the future market in addition to the spot market in the contracts during typhoon seasons is one feasible way for cargoes like cotton, soybeans and petrol oil. Secondly, it is recommended to add flexibility in the selection of transportation modes during typhoon seasons. For example, export cargoes can be transferred by land to the normally operated seaports before being transported by ships.

6.4 Chapter summary

This chapter aims to evaluate the possible propagational impacts bringing to the hinterland industrial clusters resulting from catastrophe-induced seaport disruptions, based on a three-layer PCI model connecting ports, cargoes and industrial clusters. In this way, the interdependency between ports and hinterland industrial clusters is examined. By using Guangdong Province, China and the typhoon hazard as a case study, the most vulnerable industrial clusters in this province were identified under both import and export modes. Finally, feasible mitigation strategies are suggested to each of the industrial cluster players, based on the level of the obtained propagation of vulnerability, as well as the supply and demand characteristics of the industry.

The assessment of the propagation of port vulnerability in the maritime transportation network in this chapter, together with the port vulnerability assessment against non-repetitive and repetitive catastrophes in Chapters 4 and 5, presents a comprehensive study for the research domain of vulnerability assessment against catastrophes. Until this chapter, the research objectives set in Chapter 1 are all achieved by answering the research questions raised. In the next chapter, the main research findings and contributions of this study are summarised and presented.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

As the last chapter of the thesis, Chapter 7 presents the main research findings and contributions achieved. It also provides the research limitations and directions for future studies in this research domain.

In Chapter 2, through an in-depth literature review on catastrophe risk analysis, port and maritime risk analysis, port vulnerability assessment, and industry risk analysis, it is found that quantitative port vulnerability assessments against catastrophes are relatively scarce. It is also found that few research efforts have been made to the study of the propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions. The combination of these two gaps is an issue of vulnerability assessment of port and hinterland industrial cluster against catastrophes. This is also the major research question addressed in this thesis. In order to solve this research question, in Chapter 3, a systematic research flow is designed. Firstly, two port vulnerability assessments are carried out against non-repetitive and repetitive catastrophes in Chapters 4 and 5, respectively. During the process of assessing port vulnerability against non-repetitive catastrophes, a vulnerability index is proposed, adopting the fuzzy ER and the fuzzy TOPSIS as the data fusion algorithms. A simulation-based model is developed for the assessment of port vulnerability against repetitive catastrophes. The analysis of the vulnerability results from these two chapters could offer managerial insights and policy implications to the port and insurance stakeholders. Moreover, this research takes a further step in assessing the propagation of port vulnerability to hinterland industrial clusters against catastrophe-induced port inoperability in Chapter 6. Outputs of this chapter can be useful references for port hinterland industrial cluster manufacturers in anti-catastrophe mitigation strategy formation. In summary, the study as a whole has devoted efforts in the evaluation of port and hinterland industrial clusters vulnerability against catastrophes. It does not only advance the existing knowledge but contributes to the port and manufacturing industries in practical policy-making.

The summary of the main research findings is presented in Section 7.1. The

contributions achieved are shown in Section 7.2. In Section 7.3, limitations of this study and recommendations for future research are discussed.

7.1 Summary of main findings

Five research objectives are laid down in order to tackle the research questions raised in Chapter 1. These research objectives are fulfilled by systematically executing the research design proposed in Chapter 3. The summary of the major findings is presented in this section.

- (1) To give definitions of port vulnerability from a multi-dimensional perspective.

Chapter 2 takes innovative steps in the discussion of what is port vulnerability from a multi-dimension perspective. Descriptions/definitions/concepts/measurements covering different perspectives of vulnerability are collected and analysed. A comprehensive definition of port vulnerability is given considering six dimensions. Six dimensions include the physical dimension, the functional dimension, the economic dimension, the environmental dimension, the institutional dimension, and the interdependent dimension. This concept development is carried out based on the hope that researchers working in the same scientific field use a common language. As such, a solid foundation has been laid for the research domain of port vulnerability and risk analysis.

- (2) To identify the types of major catastrophic hazards that affect port operations.

The second research objective is achieved in the second half of Chapter 2. The identification of the major port catastrophic hazards is carried out. Through literature review, eight natural hazard main types, ten natural hazard sub-types, and eleven man-made hazard types have been identified as port hazards. Subsequently, in order to identify hazards that lead to catastrophic consequences to ports, the scope is further narrowed down by filtering the identified hazard types based on a determined insured loss threshold. Typhoon, earthquake, major fire and explosion, oil spill, and war are identified as major port catastrophic hazard types, covering natural and man-made catastrophes. War, as a hostile act, is removed from the list during the validation. In a conclusion, two natural hazard types, namely typhoon and earthquake, as well as two man-made hazard types, including major fire and explosion, and oil spill, are identified as the major port catastrophic hazards.

- (3) To assess port vulnerability against non-repetitive catastrophes.

This research objective is realized by Chapter 4. Chapter 4 assesses vulnerability of the four assessment units of the Tianjin Port under the background of 2015 explosion in two assessment periods. Several key findings are revealed. Firstly, the collection and distribution system as well as the storage system are identified as the bottlenecks of the Tianjin Port. Secondly, the storage system is the most vulnerable among the four subsystems in both assessment periods. Thirdly, during the four months of recovery, the vulnerability condition of the loading and unloading system improves the most, which may imply an insufficient recovery investment to the storage system. The sensitivity analysis of input parameters shows the proposed framework is robust against small differences of experts' opinions yet sensitive to large differences.

- (4) To assess port vulnerability against repetitive catastrophes.

Chapter 5 attains the fourth objective. A research framework containing a simulation-based model is proposed. A port catastrophe database is established for the collection of port hazard data. By using the Port of Shenzhen and the typhoon hazard as an example, the physical and economic port losses are estimated. Five major conclusions are found. Firstly, the reduction in container throughput increases with more severe typhoon intensities and shorter strike distances. Secondly, the proportion of economic losses are greater than physical losses regarding typhoon strikes from longer distances. Regarding short-distance strikes, a reversed relationship is found. Thirdly, the worst-case scenario of a typhoon hit could cause a total loss of 0.91 USD billion for a terminal with sixteen berths, eighty quay cranes, and two hundred gantry cranes. Fourthly, the total typhoon-induced loss for the largest terminal in the Port of Shenzhen reaches 0.56 USD billion since 1994 (when the terminal was firstly put into production), which equals to 27 USD millions per year approximately, accounting for 8.3% of the terminal net profit in 2015. Lastly, the total predicted typhoon-induced loss for the same terminal for the next 5 years (from 2016 to 2020) reaches 0.32 USD billion, which equals to 64 USD millions on a yearly basis, accounting for 19.7% of the terminal net profit in 2015. This chapter proposes a quantifiable port vulnerability assessment method against repetitive catastrophes for the port operators and stakeholders when

sufficient data is available.

- (5) To assess propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced port disruptions.

This objective is met in Chapter 6. In Chapter 6, the propagation of port vulnerability to hinterland industrial clusters resulting from catastrophe-induced seaport disruptions is quantified by developing a three-layer port-cargo-industrial cluster model. By using Guangdong Province and the typhoon hazard as a case study, the most vulnerable industrial clusters in the port hinterland of Guangdong are identified for both import and export modes. Three major conclusions are obtained. Firstly, all the six key types of industrial clusters in Guangdong Province show dispersed vulnerabilities in the import mode, while the vulnerability conditions of the industrial clusters are similar to each other in the export mode. Secondly, the petrochemical industrial cluster is the most vulnerable one among the six types of key industrial clusters under the import mode, while this type of industrial cluster is the least vulnerable under the export mode. Thirdly, the textile and apparel industrial cluster ranks the first on the vulnerability propagation list under the export mode, while this type of industrial cluster is not as sensitive as other industrial types against typhoon-induced port disruptions during the import process.

To summarise, Chapters 4, 5, and 6 comprehensively achieve research objectives 3 to 5, by answering research questions 3.a, 3.b, and 4. These three chapters present a diversity of port vulnerability assessment methods against catastrophes from multi-dimension, covering natural and man-made, repetitive and non-repetitive catastrophes.

7.2 Main research contributions

As discussed above, the research objectives set for this research have been achieved. This study contributes to the current research domain of port and industrial cluster vulnerability assessment against catastrophe theoretically and practically. The multi-faceted contributions of this research are summarised below.

- (1) The contributions in Chapter 2 are threefold. Firstly, a systematic literature review

with regard to port and industrial cluster vulnerability assessment against catastrophes is conducted. The literature review strikes a balance among catastrophe risk, port risk, vulnerability assessment, and industry risk. New research gaps in this field are identified with research directions suggested. Secondly, as the first attempt in the literature to discuss port vulnerability from various perspectives, this chapter advances knowledge in the context of the multi-dimensional definition of port vulnerability. Thirdly, as an original output in this study, port catastrophic hazards are identified by a scrutinous review of the related literature, news records, and port documents. The port catastrophic hazard list, together with the multi-dimensional definition of port vulnerability, lays foundations and provides references for the following research works in the related research domain.

- (2) Chapter 4 makes three major contributions to research and practice. Firstly, this chapter develops a realistic yet effective way of assessing port vulnerability against catastrophes when critical masses and port vulnerability data are of high-level of uncertainty. Secondly, this study fills the research gap by focusing on non-repetitive and man-made catastrophes, instead of the frequently studied natural and repetitive catastrophes. Thirdly, implications are drawn from the findings which shed light on the practical uses of port authorities, port managers, service providers, port users, and (re)insurance companies.
- (3) There are four contributions in Chapter 5. Firstly, this chapter enhances the understanding of the catastrophe-induced port loss and port-related risk modelling. Secondly, a special focus on the worst-case scenario regarding typhoon-induced port losses is addressed, which cannot be found in the existing literature. Subsequently, a port catastrophic hazard database is established for the first time, which could be useful data sources for future related studies. Lastly, the results and managerial implications provided could guide various port stakeholders such as port operators and governments in risk analysis and mitigation, routing planning, port site selection.
- (4) The major contributions of Chapter 6 are as follows. Firstly, the research starts on a good note by mapping the interdependencies between the catastrophe-induced port

inoperability and the potential cascading effects on industrial clusters in the port hinterland. Secondly, this chapter addresses the current research gap by proposing a novel three-layer port-cargo-industrial cluster model, which is able to link the physical damages and operational disruptions of seaports to the operational risks of industrial clusters. Thirdly, results of this study could be used as practice evidence by end-users like suppliers, manufacturers, and third-party logistics companies in the formulation of risk mitigation strategies against long-term catastrophe-induced port disruptions.

As a whole, this thesis advances port and industrial cluster vulnerability assessment against catastrophes to a new and important area from a theoretical perspective, i.e. the definition of port vulnerability from a multi-dimensional perspective and the identification of port major catastrophic hazards. By adopting and applying various advanced algorithms, models and techniques, it also contributes to practical suggestions to various port stakeholders, when making decisions on port catastrophe risk management and port disruption-induced industrial cluster risk management. In conclusion, this research presents a useful reference in theory and in practice on handling the issues regarding port and industrial cluster vulnerability assessment against catastrophes.

7.3 Limitations and recommendations for future research

7.3.1 Research limitations

This research makes its efforts in assessing port vulnerability against catastrophes from a multi-dimensional perspective. However, for such an emerging topic, there is still ample room for future research. First of all, the use of expert opinions would be one major source of uncertainty in Chapter 4. Since the port system tends to show a state of “black box” to the public world when the assessment period is set to be just after the occurrence of disasters, the use of expert opinions is inevitable. Secondly, this study only considers principle hazards, without covering the secondary and even third-order hazards on the hazard chain. This is because of data limitation due to the low occurrence frequency nature of the secondary and third-order hazards. With the development of the

port catastrophe database, this objective could be met by including secondary and third-order hazards data. Thirdly, only container terminal is used as the illustration of the real-world application of the proposed port vulnerability assessment methods in Chapter 4 and 5. Bulk cargo terminal and specific cargo terminal are not covered in the thesis. This results from the nature of the studied ports based on the consideration of data availability. However, it should be noted that, through some method adjustments, the proposed methods in both chapters can also be applicable to other types of terminals. Finally, regarding the assessment of propagation of port vulnerability, only the industrial clusters in the adjacent port hinterland are taken into consideration. Since maritime transportation serves global trade, it is necessary to embrace international ports and/or industrial clusters into the research picture in the future.

7.3.2 Recommendations

Based on Chapters 4, 5 and 6, and the research limitations discussed above, this section presents recommendations and suggestions for future research in fields of port vulnerability assessment and catastrophe risk analysis.

- (1) In chapter 4, more historical data could be used as model inputs to reduce the uncertainty resulting from subjective opinion. Secondly, the input data could be processed by another MCDM method. By comparing the results obtained from the two MCDM methods, validation of the method could be achieved. Subsequently, the vulnerability indicators selected in Chapter 4 reflect the functional, economic, and institutional dimensions of port vulnerability. In future studies, vulnerability indicators depicting other dimensions could also be included. Finally, the proposed framework could be applied to other seaports against multi-hazard. Hence, comprehensive comparisons among different seaports' vulnerability against multi-catastrophic hazard can thus be obtained.
- (2) Chapter 5 could be extended for future studies in the following four ways. Firstly, losses from secondary hazards and third-order hazards on the hazard chain could be simultaneously considered with principle hazards in the

framework. Secondly, various port recovery speeds could be considered in the terminal operation simulation model. To achieve this, details of the port recovery plan and mitigation strategies used should be also included in the established port catastrophe database. Thirdly, similar to the extension study of Chapter 4, by using the proposed simulation model against various hazards, a generic comparison of ports vulnerability could be carried out. Lastly, by modifying the throughput unit, the ship arrival pattern and the physical damage probabilities, a bulk cargo terminal simulation model could be established based on the container terminal simulation model. Vulnerability assessment of bulk cargo terminals is thus achieved.

- (3) The extension proposal for chapter 6 is threefold. Firstly, adding international cargo flow data into the model, assessment of propagation of port vulnerability to industrial cluster resulting from domestic port disruptions could be achieved. Secondly, the process of the data acquisition could be enhanced. For example, a specific port cargo flow and cargo value datasets could be established for the better obtaining estimations of β_i^j and β_j^i . Additionally, the method for the obtaining of natural catastrophe risk inputs of ports could also be customized and expanded. For example, by simultaneously taking disaster frequency and magnitude into consideration, a more comprehensive view of the influences of events can be achieved. Lastly, the proposed framework could be applied to other types of hazards, transportation networks, as well as transportation modes. A vulnerability analysis against multi-catastrophic hazard among different regions can thus be achieved in the future studies.

In summary, research on port and hinterland industrial cluster vulnerability assessment against catastrophes has obtained increasing attention from academia and the industry. This thesis has contributed to this emerging research topic. Topics on port and industrial cluster vulnerability are still relatively novel. It shows ample room for future research efforts.

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APPENDICES

Appendix A Experts' profile for port-related catastrophic hazards validation

No.	Organization	Location	Title
1	International Transport Forum (ITF) at Organization for Economic Co-operation and Development (OECD)	France	Administrator Ports and Shipping
2	Marine Traffic	United Kingdom	Board member
3	World Maritime University	Sweden	Professor
4	University of Manitoba	Canada	Professor
5	Risk Management Solutions, Inc. RMS	United States of America	Model development operations, Vice President
6	Dalian Port	China	Director, the department of safety production
7	Tianjin Port	China	Director, the department of safety production
8	Xiamen Port	China	Director, the department of security
9	Yantian International Container Terminal	China	Terminal manager
10	Guangzhou Port	China	Director, the department of security

Appendix B Profile of analysts setting the fuzzy rule-base

No.	Organization	Highest education	Major	Working seniority (years)
1	Department of operation	B.Eng	Logistic management	8
2	Department of operation	M.Eng	Transportation planning and management	5
3	Department of operation	B.Eng	Machanical manufacturing and automation	6
4	Department of operation	M.Eng	Logistic management	6
5	Department of operation	M.Eng	Logistic management	5
6	Department of operation	B.Eng	Port management	7
7	Department of operation	B.Eng	Foreign trade transportation	7
8	Department of operation	B.Eng	Port management	8
9	Department of operation	B.Eng	Information management and information system	9
10	Department of operation	M.Eng	Transportation planning and management	6

Appendix C The established fuzzy rule-base with belief degree

Rule no.	Vulnerability indicator			Vulnerability estimate			
	Efficiency	Robustness	Resilience	Very vulnerable	Vulnerable	Strong	Very strong
1	High	Very high	Very easy	0	0	0	1
2	High	Very high	Easy	0	0	0.5	0.5
3	High	Very high	Difficult	0	0.5	0.5	0
4	High	Very high	Very difficult	0.1	0.7	0.2	0
5	High	High	Very easy	0	0	0.3	0.7
6	High	High	Easy	0	0	0.8	0.2
7	High	High	Difficult	0	0.8	0.2	0
8	High	High	Very difficult	0.2	0.8	0	0
9	High	Low	Very easy	0	0	0.6	0.4
10	High	Low	Easy	0	0.5	0.5	0
11	High	Low	Difficult	0.1	0.8	0.1	0
12	High	Low	Very difficult	0.3	0.7	0	0
13	High	Very low	Very easy	0	0.6	0.4	0
14	High	Very low	Easy	0	1	0	0
15	High	Very low	Difficult	0.2	0.8	0	0
16	High	Very low	Very difficult	0.4	0.6	0	0
17	Medium	Very high	Very easy	0	0	0.2	0.8
18	Medium	Very high	Easy	0	0	0.7	0.3
19	Medium	Very high	Difficult	0	0.5	0.5	0
20	Medium	Very high	Very difficult	0	1	0	0
21	Medium	High	Very easy	0	0	0.5	0.5
22	Medium	High	Easy	0	0	0.9	0.1
23	Medium	High	Difficult	0	0.7	0.3	0
24	Medium	High	Very difficult	0.2	0.8	0	0
25	Medium	Low	Very easy	0	0.1	0.9	0
26	Medium	Low	Easy	0	0.4	0.6	0
27	Medium	Low	Difficult	0.2	0.4	0.4	0
28	Medium	Low	Very difficult	0.2	0.8	0	0
29	Medium	Very low	Very easy	0	0.3	0.7	0
30	Medium	Very low	Easy	0	0.6	0.4	0
31	Medium	Very low	Difficult	0.3	0.7	0	0
32	Medium	Very low	Very difficult	0.6	0.4	0	0
33	Low	Very high	Very easy	0	0.2	0.8	0
34	Low	Very high	Easy	0	0.5	0.5	0
35	Low	Very high	Difficult	0	0.9	0.1	0
36	Low	Very high	Very difficult	0.3	0.7	0	0
37	Low	High	Very easy	0	0.6	0.4	0
38	Low	High	Easy	0	0.9	0.1	0

Cont'd Appendix C

Rule no.	Vulnerability indicator			Vulnerability estimate			
	Efficiency	Robustness	Resilience	Very vulnerable	Vulnerable	Strong	Very strong
39	Low	High	Difficult	0.2	0.8	0	0
40	Low	High	Very difficult	0.5	0.5	0	0
41	Low	Low	Very easy	0	0.9	0.1	0
42	Low	Low	Easy	0.2	0.8	0	0
43	Low	Low	Difficult	0.4	0.6	0	0
44	Low	Low	Very difficult	0.7	0.3	0	0
45	Low	Very low	Very easy	0.1	0.9	0	0
46	Low	Very low	Easy	0.4	0.6	0	0
47	Low	Very low	Difficult	0.7	0.3	0	0
48	Low	Very low	Very difficult	1	0	0	0

Appendix D EF interpretation

Fuzzy number	EF	Interpretation
[0, 0, 0.3, 0.4]	Low	The post-catastrophe output accounts for 0-40% of the full capacity of the port
[0.3, 0.4, 0.6, 0.7]	Medium	The post-catastrophe output accounts for 30-70% of the full capacity of the port
[0.6, 0.7, 1, 1]	High	The post-catastrophe output accounts for 60-100% of the full capacity of the port

Appendix E RO interpretation

Fuzzy number	RO	Interpretation
(0, 0, 0.3)	Very low	0-30% of the port can be normally operated after the catastrophe
(0.1, 0.35, 0.6)	Low	10-60% of the port can be normally operated after the catastrophe
(0.4, 0.65, 0.9)	High	40-90% of the port can be normally operated after the catastrophe
(0.7, 1, 1)	Very High	70-100% of the port can be normally operated after the catastrophe

Appendix F RE interpretation

Fuzzy number	RE	Interpretation
(0, 0.15, 0.3)	Very easy	The period the port needs to return to full capacity is very short
(0.2, 0.4, 0.6)	Easy	The port needs longer time to recovery, but still can be acceptable
(0.4, 0.6, 0.8)	Difficult	The recovery period for the port is long
(0.7, 0.85, 1)	Very difficult	The recovery period for the port is very long, and considered to be unacceptable (i.e. there may be new port construction plan)

Appendix G Profile of analysts for fuzzy rule-base validation

No.	Organization	Highest education	Major	Working seniority (years)
1	Department of operation	B.Mgt	Internation trade	12
2	Department of operation	B.Mgt	Shipping management	10
3	Department of operation	B.Mgt	Shipping management	9
4	Department of operation	B.Eng	Logistic engineering	16
5	Department of operation	B.Eng	Foreign trade transportation	11

Appendix H Expert profile for rating fuzzy ER

No.	Organization	Title and department	Working seniority (years)	Port document accessed
1	Tianjin Port Container Terminal Co., LTD	Director, Department of Safety Inspection	17	Three-day rolling plan, day and night plan, sea-side and land-side balance plan, four-hour machinery plan
2	China Tianjin Shipping Agency	Director, Department of Security	10	Ship schedule
3	Tianjin Sinotrans Container Development Co., LTD	Director, Department of Operation	15	Ship schedule, yard plan
4	China Communications Construction Company Tianjin Dredging Co., LTD	Director, Department of Safety Quality Environment Protection Inspection	10	Port overall layout plans, tide table, scheduling communication guidelines
5	Tianjin Port (Group) Co., LTD	Vice director, Department of Safety Supervision	21	Records of severe weather events, single severe event review, anti-disaster guidelines
6	Tianjin Port power company	Manager, Technical department	16	Port overall layout plans, power supply emergency plan, list of relief supplies, list of emergency personnel
7	Tianjin Port tug and barge company	Captain, Department of pilot	21	List of relief supplies, emergency personnel contact list
8	Tianjin Port Pacific International Container Terminal Co., Ltd	Director, Business department	27	Government document
9	Tianjin Port (Group) Co., LTD	Director, Department of Planning and Finance	23	Financial report, insurance document
10	Tianjin Port Coke Terminal Co., Ltd	Vice director, Department of Operation	18	Vessel Performance Report
11	Tianjin Port First Port Co., Ltd.	Director, Department of Safety	22	List of relief supplies, Records of severe weather events, single severe event review, anti-disaster guidelines
12	Tianjin Port (Group) Co., LTD	Director, Legal department	24	Contract, meeting minute, written judgement, insurance document

Appendix I Ratings for fuzzy ER

Case of NS-FM

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	1 H	0.1 L, 0.9, H	0.6 E, 0.4 VE
	E2	[0.7, 0.8]	0.8 VL, 0.2 L	0.5 D, 0.5 E
	E3	1 H	0.2 H, 0.8 VH	0.8 E, 0.2 VE
	E4	1 H	0.1 L, 0.9 H	0.5 E, 0.5 VE
	E5	[0.8, 0.9]	[0.8, 0.9]	[0.8, 0.9]
	E6	0.3 M, 0.7 H	0.4 L, 0.6 H	0.2 D, 0.8 E
	E7	0.1 M, 0.9 H	0.1 L, 0.9 H	0.1 E, 0.9 VE
	E8	[0.8, 1]	[0.8, 1]	E 0.3, VE 0.7
	E9	1 H	0.2 H, 0.8 VH	0.2 D, 0.8 E
	E10	0.6 M, 0.4 H	0.7 H, 0.3 VH	0.5 E, 0.5 VE
	E11	0.3 M, 0.7 H	0.8 H, 0.2 L	0.8 E, 0.2 VE
	E12	0.3 M, 0.7 H	0.6 H, 0.4 VH	0.3 E, 0.7 VE
Transformed rating	E1	1 H	0.1 L, 0.9, H	0.6 E, 0.4 VE
	E2	1 H	0.8 VL, 0.2 L	0.5 D, 0.5 E
	E3	1 H	0.2 H, 0.8 VH	0.8 E, 0.2 VE
	E4	1 H	0.1 L, 0.9 H	0.5 E, 0.5 VE
	E5	1 H	0.29 H, 0.71 VH	1 VE
	E6	0.3 M, 0.7 H	0.4 L, 0.6 H	0.2 D, 0.8 E
	E7	0.1 M, 0.9 H	0.1 L, 0.9 H	0.1 E, 0.9 VE
	E8	1 H	0.13 H, 0.87 VH	E 0.3, VE 0.7
	E9	1 H	0.2 H, 0.8 VH	0.2 D, 0.8 E
	E10	0.6 M, 0.4 H	0.7 H, 0.3 VH	0.5 E, 0.5 VE
	E11	0.3 M, 0.7 H	0.8 H, 0.2 L	0.8 E, 0.2 VE
	E12	0.3 M, 0.7 H	0.6 H, 0.4 VH	0.3 E, 0.7 VE

Case of LUS-OD

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	0.9 M, 0.1 H	[0.4, 0.5]	0.5 E, 0.5 VE
	E2	[0.3, 0.4]	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	0.2 M, 0.8 H	[0.6, 0.8]	0.5 E, 0.5 VE
	E4	0.4 M, 0.6 H	0.4 VL, 0.6 L	0.4 E, 0.6 VE
	E5	[0.7, 0.8]	[0.7, 0.8]	[0.6, 0.8]
	E6	0.7 M, 0.3 H	[0.4, 0.6]	[0.4, 0.7]
	E7	0.9 L, 0.1 M	0.8 H, 0.2 VH	0.2 E, 0.8 VE
	E8	0.5 M, 0.5 H	0.3 H, 0.7 VH	0.1 D, 0.8 E, 0.1 VE
	E9	[0.3, 0.4]	(0, 0.2, 0.4)	1 D
	E10	0.6 L, 0.4 M	0.5 L, 0.5 H	0.3 D, 0.7 E
	E11	[0.2, 0.3]	[0.2, 0.3]	[0.2, 0.3]
	E12	0.6 L, 0.4 M	(0.4, 0.6, 0.8)	(0.1, 0.3, 0.5)
Transformed rating	E1	0.9 M, 0.1 H	0.78 L, 0.22 H	0.5 E, 0.5 VE
	E2	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	0.2 M, 0.8 H	0.88 H, 0.12 VH	0.5 E, 0.5 VE
	E4	0.4 M, 0.6 H	0.4 VL, 0.6 L	0.4 E, 0.6 VE
	E5	1 H	0.75 H, 0.25 VH	0.75 E, 0.25 VE
	E6	0.7 M, 0.3 H	0.5 L, 0.5 H	0.36 D, 0.64 E
	E7	0.9 L, 0.1 M	0.8 H, 0.2 VH	0.2 E, 0.8 VE
	E8	0.5 M, 0.5 H	0.3 H, 0.7 VH	0.1 D, 0.8 E, 0.1 VE
	E9	0.5 L, 0.5 M	0.5 VL, 0.5 L	1 D
	E10	0.6 L, 0.4 M	0.5 L, 0.5 H	0.3 D, 0.7 E
	E11	1 L	0.25 VL, 0.75 L	0.5 VD, 0.5 D
	E12	0.6 L, 0.4 M	0.12 L, 0.76 H, 0.12 VH	0.29 VD, 0.65 D, 0.06 E

Case of LUS-FM

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	1 H	[0.8, 0.9]	0.6 E, 0.4 VE
	E2	[0.7, 0.8]	1 L	1 E
	E3	1 H	1 VH	0.4 E, 0.6 VE
	E4	1 H	1 VH	0.3 E, 0.7 VE
	E5	[0.7, 0.9]	[0.8, 0.9]	[0.7, 0.8]
	E6	[0.8, 0.9]	[0.5, 0.8]	[0.5, 0.8]
	E7	1 H	1 VH	1 VE
	E8	0.3 M, 0.7 H	0.1 H, 0.9 VH	0.8 E, 0.2 VE
	E9	0.4 M, 0.6 H	0.7 H, 0.3 L	0.8 D, 0.2 E
	E10	0.4 M, 0.6 H	0.2 H, 0.8 VH	0.2 E, 0.8 VE
	E11	[0.7, 0.8]	[0.8, 0.9]	[0.8, 0.9]
	E12	0.2 M, 0.8 H	(0.6, 0.8, 1)	(0.6, 0.8, 1)
Transformed rating	E1	1 H	0.29 H, 0.71 VH	0.6 E, 0.4 VE
	E2	1 H	1 L	1 E
	E3	1 H	1 VH	0.4 E, 0.6 VE
	E4	1 H	1 VH	0.3 E, 0.7 VE
	E5	1 H	0.29 H, 0.71 VH	0.43 E 0.57 VE
	E6	1 H	0.08 L, 0.84 H, 0.08 VH	0.1 D, 0.75 E, 0.15 VE
	E7	1 H	1 VH	1 VE
	E8	0.3 M, 0.7 H	0.1 H, 0.9 VH	0.8 E, 0.2 VE
	E9	0.4 M, 0.6 H	0.7 H, 0.3 L	0.8 D, 0.2 E
	E10	0.4 M, 0.6 H	0.2 H, 0.8 VH	0.2 E, 0.8 VE
	E11	1 H	0.29 H, 0.71 VH	1 VE
	E12	0.2 M, 0.8 H	0.5 H, 0.5 VH	0.28E 0.72 VE

Case of SS-OD

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	0.7 M, 0.3, H	[0.6, 0.7]	0.7 D, 0.3 E
	E2	[0.3, 0.4]	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	[0.2, 0.4]	0.1 VL, 0.9 L	1 VD
	E4	[0.2, 0.4]	0.3 VL, 0.7 L	1 VD
	E5	[0.1, 0.2]	[0.2, 0.4]	[0, 0.2]
	E6	[0.4, 0.6]	0.7 L, 0.3 H	0.3 D, 0.7 E
	E7	0.7 L, 0.3 M	(0, 0.2, 0.4)	[0.6, 0.7]
	E8	1 L	0.8 VL, 0.2 L	0.6 D, 0.4 E
	E9	[0.6, 0.7]	[0.3, 0.4]	0.3 VD, 0.7 D
	E10	0.8 L, 0.2 M	0.7 L, 0.3 H	0.7 D, 0.3 E
	E11	0.4 L, 0.6 M	0.4 L, 0.6 H	0.6 D, 0.4 E
	E12	1 L	0.9 VL, 0.1 L	(0.2, 0.4, 0.6)
Transformed rating	E1	0.7 M, 0.3, H	1 H	0.7 D, 0.3 E
	E2	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	0.6 L, 0.4 M	0.1 VL, 0.9 L	1 VD
	E4	0.6 L, 0.4 M	0.3 VL, 0.7 L	1 VD
	E5	1 L	0.13 VL, 0.87 L	1 VD
	E6	1 M	0.7 L, 0.3 H	0.3 D, 0.7 E
	E7	0.7 L, 0.3 M	0.5 VL, 0.5 L	1 E
	E8	1 L	0.8 VL, 0.2 L	0.6 D, 0.4 E
	E9	0.5 M, 0.5 H	1 L	0.3 VD, 0.7 D
	E10	0.8 L, 0.2 M	0.7 L, 0.3 H	0.7 D, 0.3 E
	E11	0.4 L, 0.6 M	0.4 L, 0.6 H	0.6 D, 0.4 E
	E12	1 L	0.9 VL, 0.1 L	0.36 VD, 0.51 D, 0.13 E

Case of SS-FM

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	0.9 M, 0.1 H	[0.8, 0.9]	0.7 E, 0.3 VE
	E2	[0.6, 0.7]	1 L	1 E
	E3	[0.6, 0.7]	0.5 L, 0.5 H	(0.4, 0.5, 0.6)
	E4	[0.5, 0.8]	0.2 VL, 0.8 L	0.4 E, 0.6 VE
	E5	[0.1, 0.3]	[0.2, 0.3]	[0.1, 0.3]
	E6	0.5 M, 0.5 H	0.6 L, 0.4 H	0.1 D, 0.9 E
	E7	1 H	(0.6, 0.8, 1)	[0.2, 0.4]
	E8	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.4 D, 0.6 E
	E9	0.3 M, 0.7 H	0.4 L, 0.6 H	0.3 D, 0.7 E
	E10	0.7 M, 0.3 H	0.8 H, 0.2 VH	0.7 E, 0.3 VE
	E11	0.1 M, 0.9 H	0.9 H, 0.1 VH	0.4E, 0.6 VE
	E12	0.1 L, 0.5 M, 0.4 H	0.3 VL, 0.7 L	(0.4, 0.6, 0.8)
Transformed rating	E1	0.9 M, 0.1 H	0.29 H, 0.71 VH	0.7 E, 0.3 VE
	E2	0.5 M, 0.5 H	1 L	1 E
	E3	0.5 M, 0.5 H	0.5 L, 0.5 H	0.5 D, 0.5 E
	E4	0.5 M, 0.5 H	0.2 VL, 0.8 L	0.4 E, 0.6 VE
	E5	1 L	0.13 VL, 0.87 L	0.82VD 0.18 D
	E6	0.5 M, 0.5 H	0.6 L, 0.4 H	0.1 D, 0.9 E
	E7	1 H	0.5 H, 0.5 VH	0.25 VD, 0.75 D
	E8	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.4 D, 0.6 E
	E9	0.3 M, 0.7 H	0.4 L, 0.6 H	0.3 D, 0.7 E
	E10	0.7 M, 0.3 H	0.8 H, 0.2 VH	0.7 E, 0.3 VE
	E11	0.1 M, 0.9 H	0.9 H, 0.1 VH	0.4E, 0.6 VE
	E12	0.1 L, 0.5 M, 0.4 H	0.3 VL, 0.7 L	0.12 D, 0.48E, 0.4 VE

Case of CDS-OD

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	0.6 M, 0.4 H	(0.2, 0.3, 0.4)	0.7 D, 0.3 E
	E2	[0.3, 0.4]	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	0.2 L, 0.8 M	0.1 VL, 0.9 L	1 VD
	E4	0.3 L, 0.7 M	0.3 VL, 0.7 L	0.5 E, 0.5 VE
	E5	[0.6, 0.8]	[0.8, 0.9]	[0.6, 0.8]
	E6	[0.2, 0.4]	[0.4, 0.6]	0.3 VD, 0.7 D
	E7	[0.3, 0.4]	(0, 0.2, 0.4)	0.2 D, 0.8 E
	E8	0.7 L, 0.3 M	0.8 H, 0.2 VH	0.7 E, 0.3 VE
	E9	[0.2, 0.4]	[0.5, 0.7]	(0.2, 0.4, 0.6)
	E10	0.6 L, 0.4 M	0.5 L, 0.5 H	0.7 D, 0.3 E
	E11	1 L	1 L	1 VD
	E12	0.3 L, 0.7 M	(0.4, 0.5, 0.6)	0.1 E, 0.9 VE
Transformed rating	E1	0.6 M, 0.4 H	0.1 VL, 0.9 L	0.7 D, 0.3 E
	E2	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.5 D, 0.5 E
	E3	0.2 L, 0.8 M	0.1 VL, 0.9 L	1 VD
	E4	0.3 L, 0.7 M	0.3 VL, 0.7 L	0.5 E, 0.5 VE
	E5	0.4 M, 0.6 H	0.29 H, 0.71 VH	0.75 E, 0.25 VE
	E6	0.6 L, 0.4 M	0.5 L, 0.5 H	0.3 VD, 0.7 D
	E7	0.5 L, 0.5 M	0.5 VL, 0.5 L	0.2 D, 0.8 E
	E8	0.7 L, 0.3 M	0.8 H, 0.2 VH	0.7 E, 0.3 VE
	E9	0.6 L, 0.4 M	0.12 L, 0.88 H	0.36 VD, 0.51 D, 0.13 E
	E10	0.6 L, 0.4 M	0.5 L, 0.5 H	0.7 D, 0.3 E
	E11	1 L	1 L	1 VD
	E12	0.3 L, 0.7 M	0.5 L, 0.5 H	0.1 E, 0.9 VE

Case of CDS-FM

Rating	Expert	Efficiency	Robustness	Resilience
Original rating	E1	0.9 M, 0.1 H	(0.7, 0.8, 0.9)	0.5 E, 0.5 VE
	E2	[0.6, 0.7]	1 L	1 E
	E3	0.5 M, 0.5 H	(0.6, 0.8, 0.9)	0.3 E, 0.7 VE
	E4	0.6 M, 0.4 H	0.7 H, 0.3 VH	(0.4, 0.5, 0.6)
	E5	[0.7, 0.8]	[0.8, 0.9]	[0.7, 0.8]
	E6	(0.6, 0.7, 0.8)	[0.6, 0.8]	0.2 D, 0.8 E
	E7	[0.6, 0.8]	(0.6, 0.8, 1)	1 E
	E8	0.3 M, 0.7 H	0.7 H, 0.3 VH	0.5 E, 0.5 VE
	E9	(0.6, 0.7, 0.8)	[0.6, 0.7]	(0.5, 0.8, 0.9)
	E10	0.7 M, 0.3 H	0.8 H, 0.2 VH	0.8 E, 0.2 VE
	E11	0.3 M, 0.7 H	0.8 H, 0.2 VH	0.8 E, 0.2 VE
	E12	0.2 M, 0.8 H	(0.6, 0.7, 0.8)	1 VE
Transformed rating	E1	0.9 M, 0.1 H	0.5 H, 0.5 VH	0.5 E, 0.5 VE
	E2	0.5 M, 0.5 H	1 L	1 E
	E3	0.5 M, 0.5 H	0.67 H, 0.33 VH	0.3 E, 0.7 VE
	E4	0.6 M, 0.4 H	0.7 H, 0.3 VH	0.5 D, 0.5 E
	E5	1 H	0.29 H, 0.71 VH	0.43 E 0.57 VE
	E6	0.2 M, 0.8 H	0.88 H, 0.12 VH	0.2 D, 0.8 E
	E7	0.4 M, 0.6 H	0.5 H, 0.5 VH	1 E
	E8	0.3 M, 0.7 H	0.7 H, 0.3 VH	0.5 E, 0.5 VE
	E9	0.2 M, 0.8 H	1 H	0.06 D, 0.5 E, 0.44 VE
	E10	0.7 M, 0.3 H	0.8 H, 0.2 VH	0.8 E, 0.2 VE
	E11	0.3 M, 0.7 H	0.8 H, 0.2 VH	0.8 E, 0.2 VE
	E12	0.2 M, 0.8 H	0.88 H, 0.12 VH	1 VE

Appendix J The selected fuzzy rule expression matrix, Case of NS-OD

Rule no.	Vulnerability indicator			μ_k	Vulnerability estimate			
	Efficiency	Robustness	Resilience		Very vulnerable	Vulnerable	Strong	Very strong
1	High	Very high	Very easy	0.009071	0	0	0	1
2	High	Very high	Easy	0.009325	0	0	0.5	0.5
3	High	Very high	Difficult	0.026039	0	0.5	0.5	0
4	High	Very high	Very difficult	0.013923	0.1	0.7	0.2	0
5	High	High	Very easy	0.013541	0	0	0.3	0.7
6	High	High	Easy	0.013862	0	0	0.8	0.2
7	High	High	Difficult	0.022961	0	0.8	0.2	0
8	High	High	Very difficult	0.019478	0.2	0.8	0	0
9	High	Low	Very easy	0.017658	0	0	0.6	0.4
10	High	Low	Easy	0.018041	0	0.5	0.5	0
11	High	Low	Difficult	0.022850	0.1	0.8	0.1	0
12	High	Low	Very difficult	0.024642	0.3	0.7	0	0
13	High	Very low	Very easy	0.010856	0	0.6	0.4	0
14	High	Very low	Easy	0.011160	0	1	0	0
15	High	Very low	Difficult	0.029529	0.2	0.8	0	0
16	High	Very low	Very difficult	0.016664	0.4	0.6	0	0
17	Medium	Very high	Very easy	0.023016	0	0	0.2	0.8
18	Medium	Very high	Easy	0.023489	0	0	0.7	0.3
19	Medium	Very high	Difficult	0.025317	0	0.5	0.5	0
20	Medium	Very high	Very difficult	0.031561	0	1	0	0
21	Medium	High	Very easy	0.020161	0	0	0.5	0.5
22	Medium	High	Easy	0.020576	0	0	0.9	0.1
23	Medium	High	Difficult	0.022324	0	0.7	0.3	0
24	Medium	High	Very difficult	0.027646	0.2	0.8	0	0
25	Medium	Low	Very easy	0.020059	0	0.1	0.9	0
26	Medium	Low	Easy	0.020471	0	0.4	0.6	0
27	Medium	Low	Difficult	0.022216	0.2	0.4	0.4	0
28	Medium	Low	Very difficult	0.027506	0.2	0.8	0	0
29	Medium	Very low	Very easy	0.026274	0	0.3	0.7	0
30	Medium	Very low	Easy	0.026814	0	0.6	0.4	0
31	Medium	Very low	Difficult	0.028710	0.3	0.7	0	0
32	Medium	Very low	Very difficult	0.036029	0.6	0.4	0	0
33	Low	Very high	Very easy	0.015327	0	0.2	0.8	0
34	Low	Very high	Easy	0.015691	0	0.5	0.5	0
35	Low	Very high	Difficult	0.025432	0	0.9	0.1	0
36	Low	Very high	Very difficult	0.022048	0.3	0.7	0	0
37	Low	High	Very easy	0.013160	0	0.6	0.4	0
38	Low	High	Easy	0.013472	0	0.9	0.1	0

Cont'd Appendix J

Rule no.	Vulnerability indicator			μ_k	Vulnerability estimate			
	Efficiency	Robustness	Resilience		Very vulnerable	Vulnerable	Strong	Very strong
39	Low	High	Difficult	0.022426	0.2	0.8	0	0
40	Low	High	Very difficult	0.018930	0.5	0.5	0	0
41	Low	Low	Very easy	0.017202	0	0.9	0.1	0
42	Low	Low	Easy	0.017575	0.2	0.8	0	0
43	Low	Low	Difficult	0.022318	0.4	0.6	0	0
44	Low	Low	Very difficult	0.024005	0.7	0.3	0	0
45	Low	Very low	Very easy	0.017852	0.1	0.9	0	0
46	Low	Very low	Easy	0.018275	0.4	0.6	0	0
47	Low	Very low	Difficult	0.028841	0.7	0.3	0	0
48	Low	Very low	Very difficult	0.025679	1	0	0	0

Appendix K Linguistic variable interpretation for fuzzy TOPSIS

Bottleneck coefficient	Linguistic variable	Triangular fuzzy number	Assessment unit			
			Ship navigation system	Loading and unloading system	Storage system	Collection and distribution system
Queue length (B ₁)	Very satisfied (VS)	(0, 0, 0.2)	0 to 0.2	1	1	1
	Satisfied (S)	(0.1, 0.2, 0.3)	0.2 to 0.4	2	2	2
	Medium satisfied (MS)	(0.2, 0.35, 0.5)	0.4 to 0.6	3	3	3
	Fair (F)	(0.4, 0.5, 0.6)	0.6 to 0.8	4	4	4
	Medium unsatisfied (MU)	(0.5, 0.65, 0.8)	0.8 to 1.2	5	5	5
	Unsatisfied (U)	(0.7, 0.8, 0.9)	1.2 to 1.6	6	6	6
	Very unsatisfied (VU)	(0.8, 1, 1)	more than 2	more than 6	more than 6	more than 6
Average waiting time, in minute (B ₂)	Very satisfied (VS)	(0, 0, 0.2)	0 to 30	0 to 2	0 to 2	0
	Satisfied (S)	(0.1, 0.2, 0.3)	30 to 60	2 to 4	2 to 4	0 to 1
	Medium satisfied (MS)	(0.2, 0.35, 0.5)	60 to 120	4 to 6	4 to 6	1 to 2
	Fair (F)	(0.4, 0.5, 0.6)	120 to 180	6 to 8	6 to 8	2 to 3
	Medium unsatisfied (MU)	(0.5, 0.65, 0.8)	180 to 240	8 to 10	8 to 10	3 to 4
	Unsatisfied (U)	(0.7, 0.8, 0.9)	240 to 360	10 to 12	10 to 12	4 to 5
	Very unsatisfied (VU)	(0.8, 1, 1)	more than 360	more than 12	more than 12	more than 5
Average service time, in minute (B ₃)	Very satisfied (VS)	(0, 0, 0.2)	0 to 720	1.5-1.8	1.8-2.2	0.1 to 0.2
	Satisfied (S)	(0.1, 0.2, 0.3)	750 to 900	1.8-2.2	2.2 to 2.5	0.2 to 0.5
	Medium satisfied (MS)	(0.2, 0.35, 0.5)	900 to 1080	2.2 to 2.5	2.5 to 3	0.5 to 1
	Fair (F)	(0.4, 0.5, 0.6)	1080 to 1440	2.5 to 3	3 to 4	1 to 2
	Medium unsatisfied (MU)	(0.5, 0.65, 0.8)	1440 to 1800	3 to 4	4 to 5	2 to 3
	Unsatisfied (U)	(0.7, 0.8, 0.9)	1800 to 2160	4 to 5	5 to 6	3 to 4
	Very unsatisfied (VU)	(0.8, 1, 1)	more than 2160	more than 5	more than 6	more than 4

Note: Queue length of the ship navigation system refers to the number of waiting vessels per berth; Queue length of the loading and unloading system, the storage system, as well as the collection and distribution system refers to the number of trucks waiting in the queue.

Appendix L Ratings for bottleneck indicators and importance weights (Analyst No.2-10)

Analyst	Importance weight and Assessment unit	Criterion		
		C1	C2	C3
A2	Importance weight	L	VH	H
	Ship navigation system	MS	MS	VS
	Loading and unloading system	S	F	S
	Storage system	MU	MU	MU
	Collection and distribution system	F	S	S
A3	Importance weight	ML	M	H
	Ship navigation system	VS	S	VS
	Loading and unloading system	MS	MS	MS
	Storage system	MU	F	F
	Collection and distribution system	F	F	F
A4	Importance weight	VL	M	H
	Ship navigation system	VS	S	S
	Loading and unloading system	MS	F	S
	Storage system	MS	MU	U
	Collection and distribution system	MU	F	MS
A5	Importance weight	M	H	VH
	Ship navigation system	F	S	VS
	Loading and unloading system	MS	F	MS
	Storage system	F	MU	U
	Collection and distribution system	F	S	F
A6	Importance weight	ML	VH	H
	Ship navigation system	MS	MS	VS
	Loading and unloading system	VS	S	MS
	Storage system	F	F	U
	Collection and distribution system	F	F	S

Cont'd Appendix L

Analyst	Importance weight and Assessment unit	Criterion		
		C1	C2	C3
A7	Importance weight	M	H	H
	Ship navigation system	VS	S	S
	Loading and unloading system	S	MS	S
	Storage system	MU	MU	MU
	Collection and distribution system	F	S	VS
A8	Importance weight	L	MH	H
	Ship navigation system	F	S	S
	Loading and unloading system	MS	F	VS
	Storage system	MS	U	F
	Collection and distribution system	S	VS	S
A9	Importance weight	MH	MH	H
	Ship navigation system	MS	S	MS
	Loading and unloading system	S	MS	S
	Storage system	F	MU	U
	Collection and distribution system	MU	S	MS
A10	Importance weight	M	VH	H
	Ship navigation system	F	MS	MS
	Loading and unloading system	VS	F	S
	Storage system	MU	F	MU
	Collection and distribution system	F	F	S

Appendix M Typhoon record in the area of Shenzhen Port (1994-2015)

Strike distance	Hurricane scale	Disrupted scenario	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Sum
0-100 km	Category 1	1	0	0	0	1	0	0	0	0	1
	Category 2	6	0	0	0	0	0	0	0	0	0
	Category 3	11	0	0	0	0	0	0	0	0	0
	Category 4	16	0	0	0	0	0	0	0	0	0
	Category 5	21	0	0	0	0	0	0	0	0	0
100-200km	Category 1	2	0	0	0	0	1	2	0	0	3
	Category 2	7	0	0	0	0	0	0	0	0	0
	Category 3	12	0	0	0	0	0	0	0	0	0
	Category 4	17	0	0	0	0	0	0	0	0	0
	Category 5	22	0	0	0	0	0	0	0	0	0
200-300km	Category 1	3	0	0	0	2	3	1	1	1	8
	Category 2	8	0	0	0	0	0	2	0	0	2
	Category 3	13	0	0	0	0	0	0	0	0	0
	Category 4	18	0	0	0	0	0	0	0	0	0
	Category 5	23	0	0	0	0	0	0	0	0	0
300-400km	Category 1	4	2	0	0	0	4	3	0	0	9
	Category 2	9	0	0	0	1	1	1	0	0	3
	Category 3	14	0	0	0	0	0	0	0	0	0
	Category 4	19	0	0	0	0	0	0	0	0	0
	Category 5	24	0	0	0	0	0	0	0	0	0
400-500km	Category 1	5	0	0	0	1	0	1	1	1	4
	Category 2	10	0	0	0	0	0	0	0	0	0
	Category 3	15	0	0	0	0	0	0	0	0	0
	Category 4	20	0	0	0	0	0	0	0	0	0
	Category 5	25	0	0	0	0	0	0	0	0	0
Sum			2	0	0	5	9	10	2	2	30

Appendix N Fit all summary of model inputs

Statistics	Function	Square Error	Statistics	Function	Square Error
Ship arrival interval	Weibull	0.00127	LPC_1	Beta	0.00869
	Gamma	0.00138		Uniform	0.00986
	Beta	0.00237		Weibull	0.0114
LPC_2	Beta	0.011	LPC_3	Beta	0.0224
	Uniform	0.0116		Weibull	0.0231
	Weibull	0.019		Uniform	0.0232
LPC_4	Beta	0.0174	LPC_5	Beta	0.211
	Erlang	0.0232		Gamma	0.284
	Exponential	0.0232		Exponential	0.298
LPC_6	Beta	0.211	LPC_7	Beta	0.211
	Gamma	0.285		Gamma	0.283
	Exponential	0.298		Exponential	0.298
Quay crane efficiency	Normal	0.00822	Idle time before	Beta	0.00225
	Weibull	0.00901		Lognormal	0.0104
	Beta	0.0106		Weibull	0.0254
Idle time after	Beta	0.00648			
	Lognormal	0.00979			
	Exponential	0.0406			

Note: The types of functions are displayed in ascending order based on the values of square errors.

Appendix O Distribution summary

Statistics	Distribution			Chi Square Test		Data Summary	
	Type	Expression	Square Error	Test Statistic	Corresponding p-value	Sample Mean	Sample Std Dev
Ship arrival interval	Weibull	-0.001+WEIB(0,0)	0.001268	4.67	0.701	1.99	1.85
LPC_1	Beta	18 + 977 * BETA(0, 0)	0.008691	17.4	0.0443	463	287
LPC_2	Beta	1e+003 + 988 * BETA(0, 0)	0.010973	8.74	0.202	1480	278
LPC_3	Beta	2e+003 + 985 * BETA(0, 0)	0.022402	12.7	0.0143	2440	291
LPC_4	Beta	3.02e+003 + 806 * BETA(0, 0)	0.017425	1.54	0.226	3360	265
LPC_5	Beta	4.02e+003 + 435 * BETA(0, 0)	0.210537	13.1	< 0.01	4240	308
LPC_6	Beta	5.24e+003 + 553 * BETA(0, 0)	0.210537	13.1	< 0.01	5520	391
LPC_7	Beta	6.16e+003 + 418 * BETA(0, 0)	0.210537	13.1	< 0.01	6370	296
Quay crane efficiency	Normal	NORM(0, 0)	0.008215	22.9	< 0.005	2.2	0.337
Idle time before	Beta	1 + 53 * BETA(0, 0)	0.002247	5.17	0.277	4.87	7.39
Idle time after	Beta	25 * BETA(0, 0)	0.006481	49.1	< 0.005	1.04	1.75

Appendix P Sample of the port catastrophic event database

Source: Author, based on sources of ScienceDirect, ISI Web of Knowledge, SCOPUS, Factiva, Lloyd's List, Tradewinds, IHS Fairplay and Google

No.	Date	Event	Port affected, country	Closure duration	Recovery period	Physical damage	Economic loss
Typhoon							
1	09/2003	Typhoon Maemi	Port of Busan, Korea	N.A.	8 months	<ul style="list-style-type: none"> •Huge crane losses •Flooded container yard 	<ul style="list-style-type: none"> •Loss of port users, e.g. shipping companies •New port construction plans with 290 billion USD investment •Estimation direct loss reached 58 million USD in only one terminal
Strom surge							
2	08/1985	Storm surge	Port of Tianjin, China	N.A.	N.A.	<ul style="list-style-type: none"> •Huge machinery losses •Flooded berths and warehouses •Damaged containers and cargos 	<ul style="list-style-type: none"> •Part of the enterprises in the port area stopped production •An estimation of 44.3 million USD of direct loss
Earthquake							
3	01/1995	The Great Hanshin Earthquake	Port of Kobe, Japan	Several weeks	2 years and 3 months	<ul style="list-style-type: none"> •232 out of 239 berths were damaged 	<ul style="list-style-type: none"> •Loss the position of the hub port in the area •Caused over 5 billion USD rebuild fee •Possibly overbuild after the shock

Cont'd Appendix P

No.	Date	Event	Port affected, country	Closure duration	Recovery period	Physical damage	Economic loss
Earthquake and tsunami							
4	03/2011	Tohoku Earthquake and Tsunami	Port of Kashima, Hitachinaka, Hitachi, Onahama, Soma, Sendai, Shiogama, Ishinomaki, Kesennuma, Ofunato, Kamashi, Miyako and Hachinohe, Japan	More than two weeks of port closure for most of the major ports	8 months	<ul style="list-style-type: none"> •Full damage to some ports •Partially damage to other ports •Damaged marshalling spaces 	<ul style="list-style-type: none"> •\$3.4 billion seaborne trade loss on the event day alone •Moved emergency cargo instead of commercial cargo in short term •Radiation risk to container terminals in the Tokyo area •Affected bulk cargo transportation, such as coal, wood chops and oil •Delay of shipyard deliveries and global just-in-time supply chains
Oil spill							
5	07/2010	Oil spill - due to pipeline fire and explosion	Port of Dalian, China	5 days	N.A.	<ul style="list-style-type: none"> •The major oil pipelines, a vicinity oil tank and a pump room were burned down 	<ul style="list-style-type: none"> •Estimation of direct economic loss reached 65 million USD •Caused seriously pollution to the air, the surrounding waters and the aquiculture areas

Cont'd Appendix P

No.	Date	Event	Port affected, country	Closure duration	Recovery period	Physical damage	Economic loss
Explosion							
6	08/2015	Chemical explosion - due to container chemical fire	Port of Tianjin, China	6 hours	N.A.	<ul style="list-style-type: none"> • Damaged terminal equipment, warehouses and port buildings • Major cargo damage • More than 110 people died, more than 300 people injured 	<ul style="list-style-type: none"> • Rejection of tankers and dangerous cargo ships in Tianjin Port and other Chinese coastal ports, except Shanghai Port and Ningbo Ports • Supply chain disruptions • Huge loss to insurance industry

Note: 1. Economic losses are converted to the USD according to the exchange rate at the time of the event 2. In cases of multi-ports closure, the one closure duration/recovery period denotes the longest closure duration/recovery period 3. The physical damages and business impacts shown in the table denotes the contents collected by authors from the news/literature, and do not cover all aspects of impacts.

Appendix Q Major typhoon exposures of the case study port

Date	Category	Port disruption (day)	Striking distance (km)	Scenario
2013/7/1	Cat 2	0.81	380	9
2013/8/1-2	Cat 2	1.00	422	10
2013/8/12	Cat 4	2.60	490	20
2013/9/21	Cat 2	2.08	498	10
2013/11/2	Cat 1	0.39	274	3
2014/7/17	Cat 3	1.50	434	15
2014/9/15	Cat 3	2.00	356	14
2015/6/23	Cat 1	0.08	487	5
2015/7/9	Cat 3	1.08	480	15
2015/10/5	Cat 2	2.04	258	8
2016/7/30	Cat 5	7.67	N.A.	N.A.
2016/8/17	Cat 2	1.05	N.A.	N.A.
2016/10/16	Cat 2	1.19	N.A.	N.A.
2016/10/19	Cat 4	2.08	N.A.	N.A.
2017/6/13	Cat 3	3.08	N.A.	N.A.
2017/7/22	Cat 3	5.17	N.A.	N.A.
2017/8/21	Cat 5	4.63	N.A.	N.A.
2017/8/25	Cat 4	6.83	N.A.	N.A.

Note: The data, typhoon category and port disruption period are extracted from the port logs; The striking distance is obtained from searching the established port catastrophe database.

Appendix R Port engineers profile

No.	Organization	Highest education	Major	Minor	Chartered	Working seniority (years)
1	Engineering supervision	M.Eng.	Civil engineering	N.A.	Senior	38
2	Shenzhen Port (Yantian International Container Terminal)	B.Eng.	Automatic control	N.A.	Vice-senior	31
3	Engineering supervision	B.Eng.	Industrial and civil architecture	Port engineering	Vice-senior	32
4	Shenzhen Port (Shekou International Container Terminal)	B.Eng.	Port and channel engineering	N.A.	Vice-senior	22
5	Shenzhen Port (Power supply department)	N.A.	Electrical Technology	Port power supply	Vice-senior	29
6	Shenzhen Port (Administrative department)	B.Eng.	Hydraulic transmission	N.A.	Vice-senior	25
7	Machinery plant	M.Eng.	Port machinery	N.A.	Senior	34

Appendix S Model input for Busan case

Input	Expression
Ship arrival	-0.001+WEIB(2.01, 1.05)
LPC1	14 + 985 * BETA(1.03, 1.34)
LPC2	1e+003 + 997 * BETA(1.08, 1.21)
LPC3	2e+003 + 991 * BETA(0.749, 0.885)
LPC4	3.01e+003 + 957 * BETA(0.915, 1.32)
LPC5	4.02e+003 + EXPO(302)
LPC6	5.13e+003 + 827 * BETA(0.964, 1.13)
LPC7	TRIA(6.01e+003, 6.17e+003, 6.58e+003)
QC efficiency	-1+5.39*BETA(41.9,37.4)
IdelTimeBefore	1 + LOGN(2.34, 3.54)
IdelTimeAfter	LOGN(0.961, 0.518)

Appendix T Scales of industrial clusters in major Chinese provinces and cities (2006)
Source: Compiled by author, based on the Report on Industrial Clusters Development in China (2008).

Province or city	Number of industrial clusters	Number of enterprises	Number of employees (10,000 people)	Revenue (in RMB hundred million)	Profit (in RMB hundred million)
Jiangsu	155	76171	386	13435	771
Shandong	220	68000	455	10664	706
Xinjiang	6	540	37	1895	549
Hebei	238	179000	343	6575	518
Guangdong	64	101500	355	6123	450
Hubei	206	10700	136	4354	284
Fujian	49	7652	164	5513	248
Shanxi	19	7284	91	1778	176
Chongqing	23	2400	64	2693	134
Anhui	140	19000	N.A.	1348	99
Yunnan	11	26268	27	1165	82
Sichuan	39	3236	40	671	55
Tianjin	17	5921	29	945	54
Guangxi	10	1508	15	617	29
Jiangxi	14	1881	15	349	24
Hainan	3	424	3	156	23
Jilin	10	2800	11	158	14
Heilongjiang	8	2000	11	77	6
Gansu	4	N.A.	19	1145	N.A.
Liaoning	19	10511	33	792	N.A.
Henan	142	62700	251	2749	N.A.
Zhejiang	601	308400	800	15826	N.A.
Shanghai	N.A.	N.A.	N.A.	N.A.	N.A.
Beijing	N.A.	N.A.	N.A.	N.A.	N.A.