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Catastrophe risk assessment framework of ports and industrial clusters: a case study of the Guangdong province

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Abstract: Seaports, as critical infrastructures, are vulnerable to natural catastrophes such as hurricane/typhoon, earthquake, and tsunami. The inoperability of a port caused by these hazards tends to activate domino effects to the adjacent industrial clusters in the hinterland. Limited works addressed high-impact and low-probability (HILP) catastrophe risks and fewer studied industrial cluster risks resulting from catastrophe-induced port disruptions. This paper aims to assess ports and industrial clusters catastrophe risks, based on a three-layer port-cargo-industrial cluster (PCI) model. By using the Guangdong province in China and the typhoon hazard as a case study, we find that the petrochemical industrial cluster is the most vulnerable in the Guangdong province against typhoon-induced port disruptions in the import mode, while the textile and apparel industrial cluster is the least vulnerable. These two industrial clusters exchange rankings under the export mode. Proactive preparations can thus be made to avoid any possible prolonged production downtimes.

Keywords: port; industrial cluster; catastrophe; natural hazard; port disruption; risk assessment; risk analysis; typhoon; port-cargo-industrial cluster model.

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1 Introduction

As key nodes, seaports play crucial roles in global supply chains. Since about 90% of the world trade cargoes in volume are moved by sea transport, any disruption 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 as a whole (Lam and Yip, 2012). Nowadays, many seaports have gradually converted their role from a traditional regional gateway to a complex centre combining logistics-related and value adding activities (Garcia-Alonso et al., 2016). The functional diversification of ports has increased system efficiency but at the same time makes the seaport more vulnerable to a diverse set of risks (Lee et al., 2012).

Due to the special coastal location of seaports, they are vulnerable to catastrophes such as earthquake, tsunami, typhoon and storm surge. Once being affected by any catastrophes, seaports tend to be inoperative and are put into a tight spot of delays, deviations, disruptions, and even loss of service platforms (Gurning and Cahoon, 2011). As the lifeline infrastructure, the proper functioning of the seaport is the safeguard of normal productions of industrial clusters. Any port inoperability will propagate to the industrial clusters served by the port due to the interdependency between the two. Examples of the propagation risks to industrial clusters due to catastrophe-induced port disruptions are oft-cited. The 1995 great Hanshin earthquake damaged much of the port infrastructures in Kobe, costing Osaka region an estimated $115 billion (in 1995 dollars) of loss and second-order losses to shippers and exporters abroad which cannot be estimated (Chang, 2000). Another example is the closure of ports of Yokohama and Tokyo in fear of radiation contamination following the 2011 Tohoku earthquake and tsunami. The port closures caused up to nearly 3 months’ suspension of automobile production schedules (Abe and Hoontrakul, 2012). This cost Toyota alone an estimated $73 million per day with domino effects to automobile manufacturers all over the world (Bradsher, 2011).

In 2006, the Economist Intelligence Unit (EIU) conducted a worldwide survey to 225 executives from big, medium and small companies to seek their attitudes to, and experiences of, building preparations for catastrophes into their risk management processes. 50% of the respondents showed that they saw preparations for catastrophe events as crucial, but had insufficient time or resources to offer full attention to the preparation (Economist Intelligence Unit, 2006). Even if there is evidence that catastrophe risk management is on the corporate agenda, there remains a sense from respondents that they do not put as much time and efforts for preparing for potential catastrophes as they should. Scholars have argued that port disruptions related to various catastrophic risk factors have become more frequent (Sheffi, 2005). Due to the domino effects, it is crucial for the manufacturing industry to better understand port catastrophe risks. Thus it can be seen that, there is a strong need to establish a procedure for both researchers and practitioners from ports and industrial clusters to identify possible sources of catastrophe risk a port may face, quantify the direct damages to the port and the indirect propagation risk to the industrial cluster, and then select the appropriate countermeasures that are able to mitigate the inoperability.

Hence, this paper aims to fill the research gap by developing a ports and industrial clusters catastrophe risk assessment framework. Catastrophes that have large possibilities to occur in the port areas are first examined, followed by the assessment of propagation risks to the industrial clusters. This paper is organised into six sections. Section 2 contains a literature review which focuses on port risk analysis, catastrophe risk management, and interdependency studies between ports and industrial clusters. Section 3 introduces the proposed ports and industrial clusters catastrophe risk assessment framework. Section 4 presents the case study performed in the Guangdong province and typhoon hazards. Results and discussions are shown in Section 5. Finally, Section 6 concludes the paper with main contributions.

2 Literature review

2.1 Port risk analysis

Ports are critical infrastructures and complex systems which underpin industrial developments. Ports are vulnerable to many types of risks due to their complexity and geographical position. John et al. (2014) divide the risks ports will encounter in operation into five categories: operational risks, security risks, technical risks, organisational risks, and natural risks.

Operational risk factors include port equipment/machinery failures, ship accident/groundings, cargo spillages, and human related errors (John et al., 2014). Among those, accidents happen within the port area usually take more time and human labour to recover for they are usually related to leakages of hazardous materials (Ronza et al., 2009). Studies on port accidents mainly focus on two aspects:

1. The study of previous accidents to explore accidents' causes, damages and consequences (Darbra and Casal, 2004; Ronza et al., 2009; Yip, 2008).
2. Use the probability of various accidents' scenarios to predict the frequency of accidents in the future operations (Ronza et al., 2003).

Port security risk factors contain terrorist attacks, sabotage, arson, and surveillance system failures (McGill et al., 2007). After the attack of 9.11, security experts have shown more concerns on the efficiency and robustness of port security (John et al., 2014). Pinto and Talley (2006) find that regarding the four phases of the security incident cycle of ports, namely prevention, detection, response and recovery, more emphases have been placed on the phases of prevention and detection, but little on the phases of response and recovery. Bichou and Evans (2007) summarise the drawbacks of the conventional maritime and port risk analysis models as:

1 The inconsistencies in the maritime news dissemination.

2 The negligence of the risk analysis of the supply chain dimension.

As ports are integrated portals with two types of gates: land and sea, a port system need different entity managements for different modes. Technical solutions play crucial roles during all the three periods of a critical maritime system: marine constructions, port maintenance, and port operations (John et al., 2014). Mokhtari et al. (2011) identify information technology systems, aids to navigation, short of equipment, and dredging maintenance as the significant factors in causing severe port disruption events.

The main organisational risk factors consist of human error risks and legal risks (John et al., 2014; Mokhtari et al., 2011). Events such as regulatory changes, delays in contracts, labour strikes, poor scheduling management leading to berth, and gate and storage area congestions are major causes of short period port disruption events.

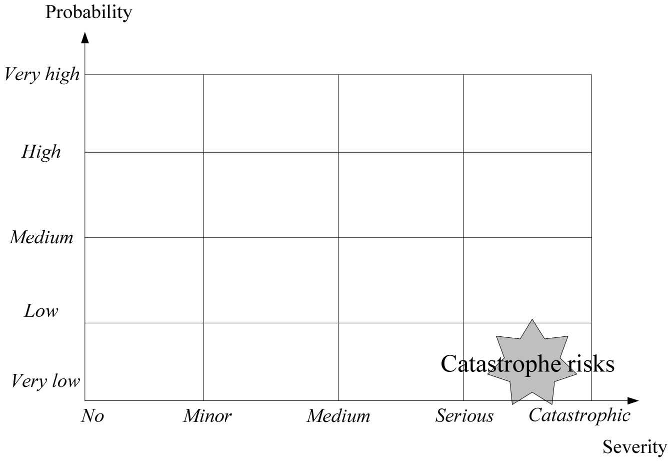
Natural disasters fall under the realm of catastrophe risks to a large extent. The international disaster database EM-DAT categorises natural disasters into geophysical, meteorological, hydrological, climatological, biological and extra-terrestrial. Earthquakes, volcanic activities, and storms are major natural disasters that have the potential to affect port areas. Lam and Su (2015) find that Asian ports encounter a rising trend of disruptive events due to natural disasters. The consequence of these hazards has increased the cost of maintenance, reconstruction and preparedness (John et al., 2014). Embracing cargo into the study, Lam and Lassa (2017) propose a novel multi-hazard risk assessment framework for ports and cargoes exposing to natural catastrophes.

Recent studies have shown a trend that embeds port risks into a bigger risk picture such as industry risks, supply chain risks, and critical infrastructure system risks (Hsieh et al., 2014; Lam and Yip, 2012; Lam et al., 2017; Pant et al., 2011; Tan et al., 2015; Trepte and Rice, 2014). Pant et al. (2011) use a method of inoperability input-output model to quantify the economic interdependency between inland port disruption and the industries served by the port. Lam and Yip (2012) depict port disruptions on supply chains by using the Petri net approach. The paper shows the stepwise process and efficiency of the method in analysing port disruption-related supply chain risks. Hsieh et al. (2014) study the interdependency within a port system and between the port system and other critical infrastructures. 14 port vulnerability factors have been categorised into four indicator groups, namely accessibility, capability, operational efficiency, and industrial cluster/energy supply. By using the method of fuzzy cognitive maps, sensitivity model, and GIS, results show that capacity and efficiency affect port vulnerability in the most significant way. As for Trepte and Rice's (2014) study, port disruptions and their impact on commodity flows are analysed. Their results show the importance of port resilience due to ports' influence on commodity trade and the economy.

2.2 Catastrophe risk management

Risk, by its dichotomous quantitative definition, equals to the product of the hazard probability/frequency and the severity/loss of the damages (Brindley, 2004). Figure 1 shows a risk matrix visualising the risks that a port incurs based on this dichotomous risk definition. Risks falling in the upper left hand side of the risk matrix could be described as daily operational risks. These are regularly occurring events such as the breakdown of one quay crane, a short-term labour strike, and the congestion at the gate of a port. A catastrophe event is, reversely, defined as a high negative impact event with a low probability (HNILP) which is a subset of high impact, low probability (HILP) event (Bank, 2005). Catastrophe risks are located in the bottom right corner of Figure 1.

Figure 1 Probability/severity risk matrix of catastrophe risks



Source: Authors

The similarity between extreme events and HILP events has long existed in the literature (Bier et al., 1999; Lee et al., 2012; Ord et al., 2010). Bier et al. (1999) define extreme events as rare, severe, and outside the normal range of experience, while HILP events are the abbreviation of 'high-impact, low-probability' events.

The distinction between catastrophes, extreme events and HILP events is trivial and vague while from the definitions we can conclude that the common feature of the three kinds of events is low probability. In terms of impacts, extreme events are not necessarily catastrophic (Bier et al., 1999), unlike catastrophes which stress negative impacts. In terms of affected objects, the object of extreme events can vary from small to large systems such as a computer, a dam, a nuclear reactor, while the range of influences is usually broad for catastrophes (Bostrom and Cirkovic, 2011). Thus, it can be seen from the description that catastrophe events are a subset of extreme events which have a feature of high-impact and low-probability (HILP).

Taxonomy of threats for complex risk management has been developed by Coburn et al. (2014). A list of macro-catastrophes that have the potential to cause social and economic systems damages and disruptions has been presented. Threats are categorised into six groups: finance and trade, geopolitics and society, natural catastrophe and climate, technology and space, health and humanity, and others. Among these, earthquake, windstorm, tsunami, volcanic eruption falling under the section of natural catastrophes; nuclear meltdown falling under technological catastrophes are the main threats to ports. A lot of literature have studied the economic impact and the influence of terrorism and disasters to transportation systems (e.g., Chang and Nojima, 2001; Coffman and Noy, 2012; Toya and Skidmore, 2007; Yang et al., 2009). However, few have studied port related catastrophe risks (Chang, 2000; Chang and Nojima, 2001; Hanson et al., 2011; Na and Shinozuka, 2009). Due to the common feature of catastrophe risks and extreme event risks, the method for assessing and managing extreme events could be used as a useful reference here.

Table 1 summarises the methods which have been used in the assessment of catastrophe risks with references from Bier et al. (1999). The approaches could be categorised into explicitly probabilistic manner, semi-probabilistic/quasi-probabilistic manner, non-probabilistic but quantitative approach, qualitative approach, and simulation-based approach. Apart from the features of extreme events mentioned above, non-linearity is another important identification of extremes which means that a minor change in some causal factors can lead to a large increase in the severity. In the circumstances of sparse data and tail distribution of catastrophe events, Bayesian method becomes more popular than classical statistical methods. Some updates have been made to the Bayesian to better cope with the absence of data and tail distribution, such as the updated method of hierarchical Bayesian method, empirical Bayesian methods, standardised or ‘reference priors’, ‘ignorance’ or ‘non-informative’ priors, and maximum entropy priors (Bier et al., 1999). 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. Fuzzy set theory and the theory of interval-valued probabilities related approaches are classified under such kind of method (Kaufmann and Gupta, 1991; Walley, 1991).

Bigün (1995) uses an explicitly probabilistic manner to predict future catastrophes based on Bayesian. Ord et al. (2010) talk about the serious consequences of probability estimation of catastrophe risks by using a report’s estimate. The other method of analysing catastrophe risks and their economic loss is simulation. 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 repair costs, and changing building codes could be significantly varied in the long time interval between occurrences. Kozlowski and Mathewson (1995) also discuss the problem of using historic data. They summarise 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.
3. The insurance coverage module which translates the damaged exposure to insured damaged exposure.

Table 1 Approaches for studying catastrophe risk assessment

Method type	*Method*	*Reference*
Explicitly probabilistic manner	Bayesian method	Bigün (1995), Li et al. (2010)
Semi-probabilistic/ quasi-probabilistic	Fuzzy set logic	Zadeh (1965), Kaufmann and Gupta (1991)
	Dempster-Shafer theory	Shafer (1976), Mu et al. (2008)
	The theory of interval valued probabilistic	Walley (1991)
Non-probabilistic but quantitative approach	Chaos theory	Gleick (1989), Sellnow et al. (2002)
	Catastrophe theory	Poston and Stewart (2014), Su et al. (2011)
Qualitative approach	Surprise theory	Fiering and Kindler (1984)
Simulation-based approach	Simulation	Clark (1986), Kozlowski and Mathewson (1995)

Source: Authors

Based on the review as discussed above, among the various studies of port risks, many focus on the HPLI daily operational risk. Limited studies focus on the impacts of HILP catastrophes, such as typhoon, earthquake and tsunami. As for the study of catastrophe risks, most of which lay emphases on catastrophe insurance, catastrophe risk modelling and disaster economics, but few on the catastrophe risk specifically for ports.

2.3 Interdependency studies between ports and industrial clusters

To link the physical damages and operational disruptions of seaports to the economic and functional disruptions of industrial clusters is no easy work. The methods that have been used in researching the interdependency between two infrastructure systems are surveys (National Petroleum Council, 2001; Pederson et al., 2006; The White House, 2003), simulation (Brown et al., 2004; Bush et al., 2005; North, 2001), input-output model (Haimes and Jiang, 2001; Pant et al., 2011), network-based approach (Nozick et al., 2005; Qiao et al., 2007) and system-of-systems approach (Friesz et al., 2001; Nagurney and Dong, 2002). The existing methods that address infrastructure systems interdependency have some shortcomings. Economics models like input-output models 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 economy and functional aspects. The approach of multilayer infrastructure network computable general equilibrium that combines the two features together (Zhang and Peeta, 2011) is considered more comprehensive.

There are quite limited references studying industrial loss due to port disruptions (Pant et al., 2011; Zhang and Lam, 2016). In the work of Pant et al. (2011), authors estimate a loss of $37.9 million for eight industries across ten primary states due to a two-week inland terminal closure in May for the port of Catoosa, Oklahoma by using an integrated method of simulation and multi-regional inoperability input-output model. This loss could reach $190 million in busier months of commerce. Zhang and Lam (2016) propose a three-stage framework for the assessment of economic losses of industrial clusters due to port disruptions. To the best of authors' knowledge, there is no literature that studies industrial cluster loss caused by port catastrophe risks. This work aims to bridge this gap by proposing a three-layer model connecting ports, cargoes, and industrial clusters. Thus, catastrophe risks to ports and the propagation risks to industrial clusters due to port disruptions can be obtained.

3 PCI models for catastrophe risk assessment framework

The proposed PCI model is the hybrid of the input-output model (Leontief, 1986) 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. Catastrophe risk inputs of ports could be converted into risk outputs of industrial clusters by using the cargoes as the intermediaries. To be more specific, 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 risks with the resulted cargo risks. 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 risks to the industrial clusters resulting from catastrophe-induced seaport inoperability. The results can thus identify the vulnerable seaports against catastrophes and the susceptible industrial clusters against seaport disruptions. The following paragraph shows a detailed description of the PCI model.

As shown in Figure 2, import and export are treated as two parallel modes and are studied in two different models. In the import mode, as shown in Figure 2(a), α_i represents the catastrophe risk inputs for the i^{th} port (P_i). 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 (1), the port catastrophe risk inputs (α_i) are converted into the propagational risk outputs of the industrial clusters (ω_k). Figure 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 (2), the port catastrophe-induced industrial cluster risk outputs are obtained.

Figure 2 PCI model, (a) import mode (b) export mode

$$\begin{array}{cc|cccc}
\omega^k & \mathrm{IC}_k & \lambda_1^k & \lambda_2^k & \cdots & \lambda_j^k \\
\vdots & \vdots & \vdots & \vdots & \iddots & \vdots \\
\omega^2 & \mathrm{IC}_2 & \lambda_1^2 & \lambda_2^2 & \cdots & \lambda_j^2 \\
\omega^1 & \mathrm{IC}_1 & \lambda_1^1 & \lambda_2^1 & \cdots & \lambda_j^1 \\
\hline
 & & \mathrm{C}_1 & \mathrm{C}_2 & \cdots & \mathrm{C}_j \\
\hline
\alpha_1 & \mathrm{P}_1 & \beta_1^1 & \beta_1^2 & \cdots & \beta_1^j \\
\alpha_2 & \mathrm{P}_2 & \beta_2^1 & \beta_2^2 & \cdots & \beta_2^j \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\alpha_4 & \mathrm{P}_i & \beta_i^1 & \beta_i^2 & \cdots & \beta_i^j
\end{array}
\qquad
\begin{array}{cc|cccc}
\omega_k & \mathrm{IC}_k & \lambda_k^1 & \lambda_k^2 & \cdots & \lambda_k^j \\
\vdots & \vdots & \vdots & \vdots & \iddots & \vdots \\
\omega_2 & \mathrm{IC}_2 & \lambda_2^1 & \lambda_2^2 & \cdots & \lambda_2^j \\
\omega_1 & \mathrm{IC}_1 & \lambda_1^1 & \lambda_1^2 & \cdots & \lambda_1^j \\
\hline
 & & \mathrm{C}_1 & \mathrm{C}_2 & \cdots & \mathrm{C}_j \\
\hline
\alpha_1 & \mathrm{P}_1 & \beta_1^1 & \beta_2^1 & \cdots & \beta_j^1 \\
\alpha_2 & \mathrm{P}_2 & \beta_1^2 & \beta_2^2 & \cdots & \beta_j^2 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\alpha_4 & \mathrm{P}_i & \beta_1^i & \beta_2^i & \cdots & \beta_j^i
\end{array}$$

(a) (b)

Source: Authors

$$\omega^k = \sum_{j=1}^{4}\left(\sum_{i=1}^{3}\alpha_i\beta_i^j\right)\lambda_j^k \tag{1}$$

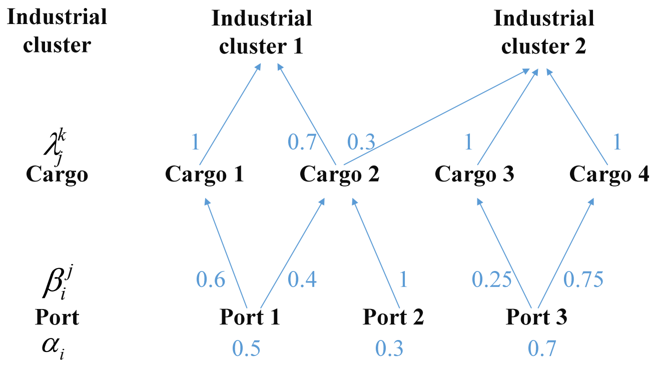
$$\omega^k = \sum_{j=1}^{4}\left(\sum_{i=1}^{3}\alpha_i\beta_j^i\right)\lambda_k^j \tag{2}$$

where

ω^k	the risk output of the k^{th} industrial cluster for the import model
α_I	the catastrophe risk input of the i^{th} port
β_i^j	the cargo value proportion of the j^{th} type of cargo among all types of cargoes imported through the i^{th} port
λ_j^k	the cargo value proportion of the j^{th} type of cargo among all types of cargoes consumed by the k^{th} industrial cluster
ω_k	the risk output of the k^{th} indutrial cluster for the export model
β_j^i	the cargo value proportion of the j^{th} type of cargo among all types of cargoes exported through the i^{th} port
λ_k^j	the cargo value proportion of the j^{th} type of cargo among all types of cargoes produced by the k^{th} industrial cluster.

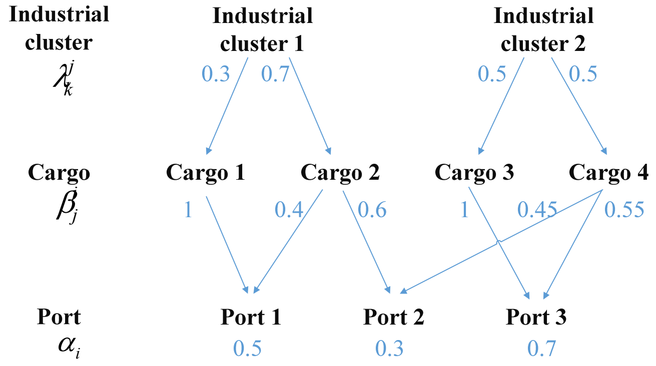
For a better illustration, Figures 3 and 4 visualise the transportation network depicting the process of import and export, respectively. As seen in Figure 3, port 1 imports two types of cargoes, cargo 1 and cargo 2. The cargo value proportion of cargo 1 is 0.6 ($\beta_{i=1}^{j=1}$), while for cargo 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 4 demonstrates the graph lexicon for the export mode. In Section 4, a case study is performed by using the Guangdong province, China and the hazard of typhoon as an example. The results, discussion and the implications of the results to different stakeholders are shown in the fifth section.

Figure 3 PCI model, import mode (see online version for colours)



Source: Authors

Figure 4 PCI model, export mode (see online version for colours)



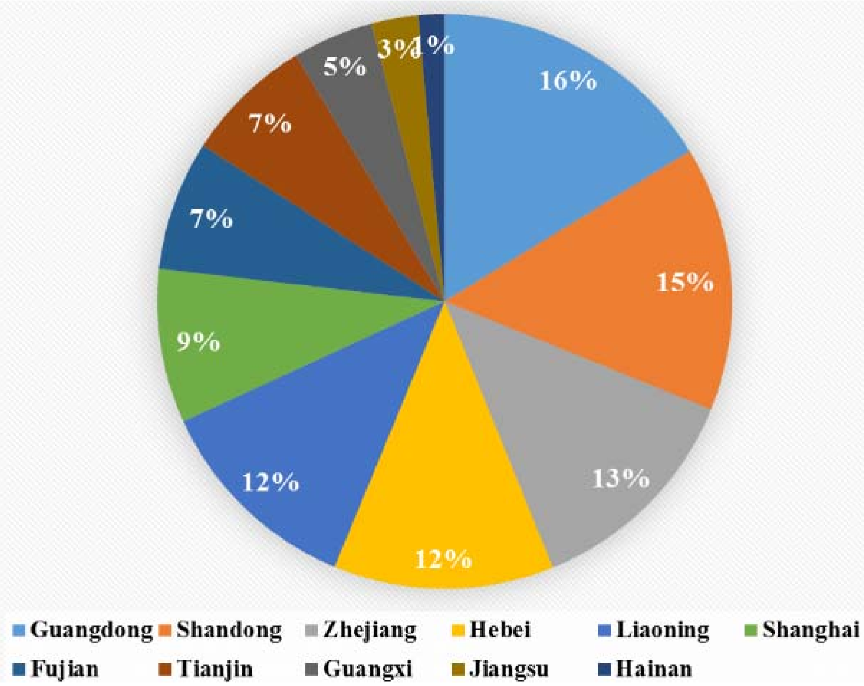
Source: Authors

4 Case study

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 port cargo throughput, the scale of industrial clusters and the frequency of natural catastrophes into account, the Guangdong province, China is selected. As shown in Figure 5, Guangdong is home to the largest number of major seaports (seaports with an annual throughput of 100 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 scales of industrial clusters of the Guangdong province rank 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 A). Regarding natural catastrophes, as shown in Figure 6, Guangdong encounters the most frequent typhoons and earthquakes 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, 2003b; Lee, 2003; Abe and Hoontrakul, 2012; Sturgis et al., 2014; Liu, 2016). In this study, the hazard of typhoon is focused because of its characteristic of higher frequency and the reoccurring nature.

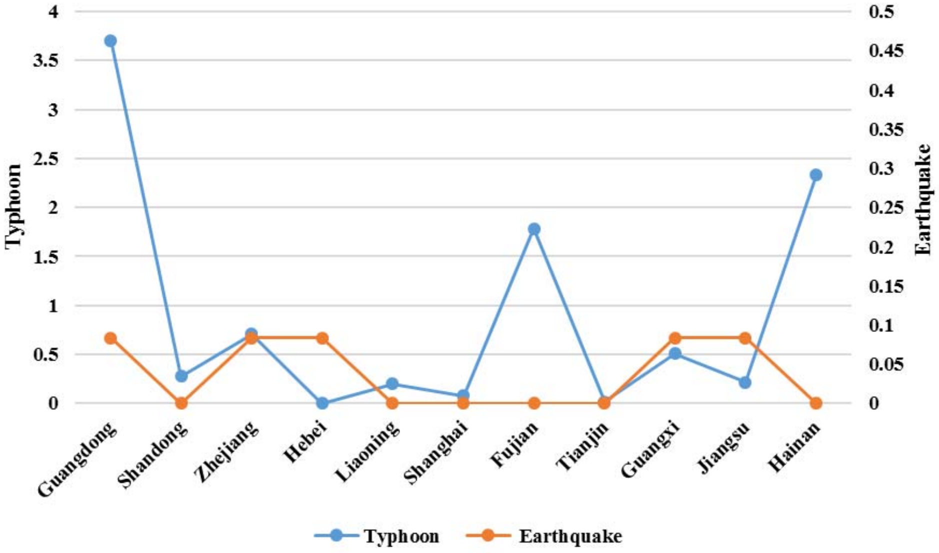
Figure 5 Seaport cargo throughput proportions of major provinces in china (by tons, 2015) (see online version for colours)



Source: Data retrieved from cargo throughputs of major seaports (National Bureau of Statistics of the People's Republic of China, 2015). Computed and drawn by authors

Table 2 shows the data sources used in this research for each model input parameter. Primary and secondary data are used. The primary data are collected by the consultancies 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 of λ_j^k and λ_k^j. As shown in Table 3, all the ten seaports in Guangdong are considered. Regarding the industrial cluster, six types of key industrial clusters in Guangdong are identified. 23 cargo types (j = 23 in the import mode) are determined for the import model and 31 types of final products (j = 31 in the export mode) are identified in the export process.

Figure 6 Typhoon and earthquake frequencies of major coastal provinces in china (per year, 1951–2014) (see online version for colours)



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

Table 2 Parameters and data sources of the PCI models for catastrophe risk assessment framework

Parameter	*Data source*	*Database or interviewee*
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)

Regarding the typhoon-affected distance of a port, there is no sharp definition in the related literature (Zhang and Lam, 2015). Thus, this paper proposes a concept of the typhoon-affected distance of a port to ensure the accuracy of the proposed model. Since a typhoon is a low-pressure weather system rotating around the typhoon centre with a radius of 200 km–500 km (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 typhoon-affected distance of a port is set based on the largest possible typhoon radius, which is 500 km, in this study. That is to say, considering the studied port as a centre, any typhoon events appearing within the circle area with a radius of 500 km is considered as potential threats to the normal operations of the port and are considered in the determination of α_i.

Table 3 Descriptions of model input parameters

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; colour 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; aluminium product; copper product

This paper develops a seaport typhoon database, in which the distances between the typhoon centres and the affected ports are recorded on a basis of six hours due to the availability of typhoon track data (Knapp et al., 2010). Any distance less than 500 km is filtered out and recorded as an ‘attack’. The total typhoon attack numbers and attack frequencies of each studied port are summarised in Table 4, from 1951 to 2014. It is observed that the total number of typhoon attacks reached 26,715 within the Guangdong province seaports’ area during the past six decades. It is seen that most of the seaports in Guangdong suffer from high typhoon risks, especially Huizhou port and Zhuhai port, while Zhongshan port is the least vulnerable against the typhoon hazard.

The case study is carried out in a three-step manner. In the first stage, the actual typhoon frequencies of each seaport are applied as α_i. The outputs obtained in such circumstances denote the combined propagational risks to the studied industrial clusters resulting from the interdependencies between industries and the typhoon-induced port inoperability. In the second stage, the value of α_i is set to be the lowest port typhoon attacks frequency ($\alpha_i = 0.22$) for all the studied ports. With the same lowest typhoon input, the outputs indicate the combination risks to the industrial clusters caused by the interdependencies between industries as well as the homogeneous lowest typhoon effects. As a third step, the output differences between the previous two scenarios are obtained as the measurements of the pure propagational typhoon effects to the industrial clusters by excluding the industrial interdependency risks. Thus, a total of four cases considering the two modes and the two scenarios of typhoon inputs are carried out, which include 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).

Table 4 Summary of port typhoon database, Guangdong Province (1951–2014)

Port	*Number of attack*	*Frequency*	*Normalised frequency*	*Risk level*
Huizhou port	2,993	46.77	0.47	High
Zhuhai port	2,971	46.42	0.46	High
Shanwei port	2,877	44.95	0.45	High
Shenzhen port	2,863	44.73	0.45	High
Maoming port	2,830	44.22	0.44	High
Chaozhou port	2,790	43.59	0.44	High
Shantou port	2,748	42.94	0.43	High
Zhanjiang port	2,742	42.84	0.43	High
Guangzhou port	2,492	38.94	0.39	Medium
Zhongshang port	1,409	22.02	0.22	Low
Sum attack no. and average frequency	26,715	44.56	0.45	High

Source: Authors

5 Results, discussions and implications

This section presents the results of catastrophe risk assessments of ports and industrial clusters, performed on the case study of the Guangdong province against the hazard of typhoon. The outputs are normalised for the purpose of comparison and higher outputs indicate higher risks. The risk outputs of Case_IWT and Case_EWT are shown in Section 5.1, while Section 5.2 shows the risk outputs of Case_IWST and Case_EWST. Outputs comparisons showing the propagational risks of the industrial clusters resulting from typhoon-induced port disruptions are carried out in Section 5.3.

5.1 Cases of IWT and EWT

This section shows the results of the Case_IWT and Case_EWT, which measure the propagational risks to the industrial clusters due to the combined resources of industry interdependencies and typhoon-induced port inoperability. As shown in Table 5, the average risk 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 export process against typhoon-induced seaport disruptions.

In the Case_IWT, the petrochemical industrial cluster has the highest risk output, followed by the industrial clusters of electrical equipment, building materials, digital information, textile and apparel, as well as food and drink. The high risk output of the petrochemical industrial cluster may result from the large cargo tonnages imported from ports with higher typhoon risks, such as Zhanjiang port, Maoming port, Zhuhai port and Huizhou port. As for the Case_EWT, the results show the highest risk output of textile and apparel industrial cluster, followed by the industrial clusters of electrical equipment, food and drink, building materials, digital information and petrochemical. The contrast of the high risk output in the Case_IWT and the low risk output in the Case_EWT for the petrochemical industrial may be due to the small export amount of petrochemical related products, which is consistent with the fact of the trade deficit in the petrochemical industry in China. The other type of industrial cluster showing a large contrast of risk outputs under import and export modes is the textile and apparel industrial cluster. It ranks the fifth among the six types of industrial clusters under the import mode while ranks the first during the process of export. The major reason is that the raw material can be easily accessed locally by inland transportation for the textile and apparel industry, however, this industry relies heavily on seaports for export.

Table 5 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		0.4140	

5.2 Cases of IWST and EWST

This section shows the results of the Case_IWST and the Case_EWST. By excluding the differences of the typhoon influences, the outputs of the PCI model measure the interdependencies between different industrial sectors with the same typhoon influence. As seen in Table 6, the outputs of the Case_IWST shows a wider dispersion than 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 faces higher interdependency risks than other types of industrial clusters, while the lowest interdependency risk level happens in the textile and apparel industry. In the export mode (Case_EWST), all the risk outputs are distributed around an expected value of 0.1102 with a variance of 0.0001.

Table 6 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		0.1102	

5.3 Results comparisons

This section shows two groups of result comparisons:

1 The Case_IWST and the Case_IWT.

2 The Case_EWST and the Case_EWT.

Table 7 Model output comparisons (Case_IWST and Case_IWT; Case_EWST and Case_EWT)

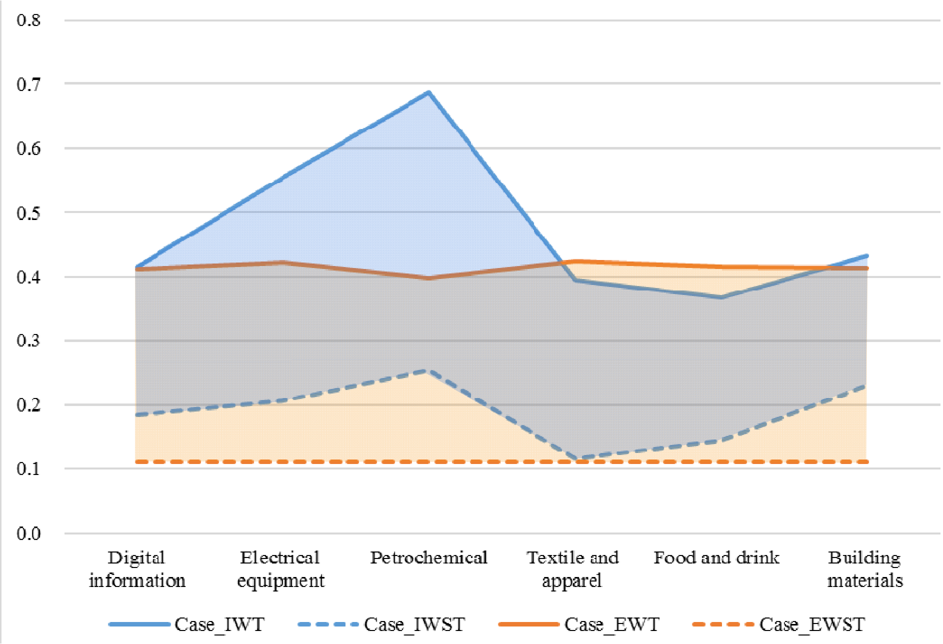
Industrial cluster	*Output*		*Rate of change*	*Output*		*Rate of change*
	IWST	*IWT*		*EWST*	*EWT*	
Digital information	0.1843	0.4148	125%	0.1103	0.4120	274%
Electrical equipment	0.2070	0.5553	168%	0.1102	0.4221	283%
Petrochemical	0.2550	0.6880	170%	0.1101	0.3976	261%
Textile and apparel	0.1150	0.3953	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%

In Table 7, the pure propagational typhoon-induced risks to the industrial clusters are shown by the rates of change and are visualised in Figure 7. The blue colour lump shows the typhoon-induced propagational risks of the import mode and the results of the export mode are shown by the orange colour lump. It is seen that, the increases in risks due to the typhoon hazard in the import mode show more complexities than the export mode. Thus, in the following discussion, the analyses of the import mode cases are given priority and are sorted by the industries' vulnerability degrees. Since all types of industrial clusters show similar propagational risks in the export mode, the export mode is discussed regardless of the industry type subsequently. Furthermore, mitigation strategies are suggested to the stakeholders based on the discussion.

As far as the import mode (Case_IWST and Case_IWT) is concerned, the industrial cluster of textile and apparel's risk 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 processes. Combining the conclusions obtained from Section 5.1, 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, are suggested to the industrial clusters with such characteristics. Flexible strategies are also appropriate for such industries, which include using alternative unaffected ports and souring from different locations.

Figure 7 Results comparisons (Case_IWT and Case_IWST; Case_EWT and Case_EWST) (see online version for colours)



The petrochemical industrial cluster has high risk outputs in both cases, which means it largely relies on typhoon risky seaports during import. Since there are specialised requirements for the loading and unloading facilities of terminals, the possibility of transferring to adjacent ports is 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 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 specialised 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.

The supply condition of the food and drink industry and the textile and apparel industry are similar. 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, 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 IWST case, which means it does not over-dependent on the typhoon risky ports. Regarding the building material industrial cluster, it ranks the second in the IWT case with the lowest growth rate in the IWST 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 potential port closure, the industry players for both industrial clusters should bring the mentioned control and flexible strategies into their agendas.

Regarding the export mode, all types of industrial clusters have a similar growth rate of risk outputs. That is to say, as a manufacturing powerhouse, China, especially the Guangdong province, reclines on typhoon risky seaports to a large extent in the export processes. As such, manufacturers located in the typhoon risky seaports hinterland are suggested to take extra care on 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. First, 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. Second, 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 Conclusions

This study quantified the propagational risk of industrial clusters resulting from catastrophe-induced seaport disruptions by adopting a three-layer PCI model connecting ports, cargoes and industrial clusters. By using the Guangdong province and typhoon hazard as a case study, the most vulnerable industrial clusters were identified. Feasible mitigation strategies were suggested to each of the industrial clusters based on the degree of vulnerability and the characteristics of industries. Three major conclusions are obtained. Firstly, the six key types of industrial clusters in Guangdong show dispersed vulnerabilities in the import mode, while the vulnerabilities of the industrial clusters are similar to each other in the export mode. Secondly, the petrochemical industrial cluster is the most vulnerable industrial cluster among the six 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 under the export mode while this type of industrial cluster is not as sensitive as other industrial types to typhoon-induced port disruptions during the import process.

This paper makes three major contributions to the academia and practical field on catastrophe risk management. Firstly, this study advances knowledge of port catastrophe risks, as well as the interdependencies between the catastrophe-induced port inoperability and the potential cascading effects to industrial clusters in the port hinterland. Secondly, this research addresses the current research gap by linking the physical damages and operational disruptions of seaports to the operational risks of industrial clusters. Thirdly, results of this study could be useful references for the formulation of mitigation strategies for various industry stakeholders, such as suppliers, manufacturers and third-party logistics companies. However, the quality of the input data can be enhanced through two ways:

1. The establishment of port cargo flow and cargo value datasets for the estimation of β_i^j and β_j^i.
2. The development of more frequent time interval typhoon database for the generation of port typhoon attack frequencies.

The proposed framework could be applied to other types of hazards, transportation networks, as well as transportation modes. A multi-hazard catastrophe risk analysis among different regions can thus be achieved in future studies. In addition, the method to obtain the natural catastrophe risk inputs of ports can be expanded.

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Appendix

Table A1 A scales of industrial clusters in major Chinese provinces and cities, sorted by profit (2006)

Province or city	*Number of industrial clusters*	*Number of enterprises*	*Number of employees (10,000 people)*	*Revenue(hundred million RMB)*	*Profit (hundred million RMB)*
Jiangsu	155	76,171	386	13,435	771
Shandong	220	68,000	455	10,664	706
Xinjiang	6	540	37	1,895	549
Hebei	238	179,000	343	6,575	518
Guangdong	64	101,500	355	6,123	450
Hubei	206	10,700	136	4,354	284
Fujian	49	7,652	164	5,513	248
Shanxi	19	7,284	91	1,778	176
Chongqing	23	2,400	64	2,693	134
Anhui	140	19,000	n.a.	1,348	99
Yunnan	11	26,268	27	1,165	82
Sichuan	39	3,236	40	671	55
Tianjin	17	5,921	29	945	54
Guangxi	10	1,508	15	617	29
Jiangxi	14	1,881	15	349	24
Hainan	3	424	3	156	23
Jilin	10	2,800	11	158	14
Heilongjiang	8	2,000	11	77	6
Gansu	4	n.a.	19	1,145	n.a.
Liaoning	19	10,511	33	792	n.a.
Henan	142	62,700	251	2,749	n.a.
Zhejiang	601	308,400	800	15,826	n.a.
Shanghai	n.a.	n.a.	n.a.	n.a.	n.a.
Beijing	n.a.	n.a.	n.a.	n.a.	n.a.

Source: Report on industrial clusters development in China