Transportation Research Part A 91 (2016) 17–33

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Estimating economic losses of industry clusters due to port disruptions

Yi Zhang, Jasmine Siu Lee Lam *

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

ARTICLE INFO

Article history:
Received 26 July 2015
Received in revised form 9 April 2016
Accepted 26 May 2016
Available online 21 June 2016

Keywords:
Port disruption
Economic loss
Economic impact
Industry cluster
Risk assessment
Risk mitigation

ABSTRACT

Seaport operations are highly important for industries which rely heavily on imports and exports. A reliable evaluation of port risks is essential to govern the normal running of seaborne transportation and thus the industrial economies. The occurrence of a breakdown in the trade facilitators, such as ports, will disrupt the smooth flow of supply chains for the industries. The estimation of the economic loss for an industry when a port gets disrupted is a challenging task as the relationship between the port and industry clusters is complex. This study aims to develop a systematic framework for performing economic loss estimation of industry clusters due to port disruptions. The whole risk assessment is split into three stages focusing on the establishment of a network flow model, economic estimations and evaluating risk mitigation strategies. The proposed idea is demonstrated by a case study on Shenzhen port and its related manufacturing industries. A dynamic inventory control strategy used by manufacturers is found to be beneficial for mitigating port disruption risks.

1. Introduction

In an increasingly globalized economy, the scope of supply chains expands beyond national and regional boundaries. Seaports play a crucial role of facilitating international trade in both inbound and outbound supply chains. Any risks faced by ports affect not only port operations but also trade flows and various supply chain parties. Any changes in the port operation status could have a direct impact on cargo delivery, affecting regional and even global activities. Correspondingly, ports are required to be resilient and reduce expected/unexpected losses in order to continue serving the supply chains (Mansouri et al., 2010). This is particularly important for industries which rely largely on seaborne transport. However, ports and shipping are regarded as the most uncertain and volatile component within the supply chains (Sanchez-Rodrigues et al., 2010). Many potential risks could cause a halt in the functioning of ports. For example, Chopra and Sodhi (2004) classified supply chain risks into nine categories, namely, disruption, delay, systems, forecast inaccuracies, intellectual property breaches, procurement failures, system breakdown, inventory problems, and capacity issues. Among these risks, port disruption is recognized as one of the major threats that may happen due to various causes especially from environmental factors (Lam and Su, 2015; Zhang and Lam, 2014, 2015a). A port disruption is defined as an event that could cause a sudden interruption on material flow in the transport system, which may lead to a stoppage in cargo movement (Wilson, 2007). Such a risk event can be caused by natural or man-made hazards such as typhoon and fire and may result in long delays of cargo flows at ports and massive adverse impacts on multiple elements of a supply chain simultaneously.

* Corresponding author.
E-mail addresses: ZHANG.YI@ntu.edu.sg (Y. Zhang), SLLam@ntu.edu.sg (J.S.L. Lam).

http://dx.doi.org/10.1016/j.tra.2016.05.017
0965-8564/

The need for risk based policies or management strategies has been articulated widely. Focusing on the safety and security of the port based transportation system, there have been several studies of port risk assessment. Svensson (2000) is one of the few pioneers who developed a conceptual framework for the analysis of port vulnerability within a supply chain. Merrick et al. (2002) established a risk model that was capable to assess the risks of accidents involving oil tankers in the coastal area. Yang et al. (2014) developed a risk quantification approach to assess port facility security. A fuzzy quantitative analysis was proposed by Pak et al. (2015) to evaluate the safety levels of ports. Similar techniques can also be seen in Beer et al. (2013). Although these former studies have greatly enhanced our understanding in port risk measures, they did not investigate the economic impact of port disruption. While port risk assessments are essentially required by policy makers including port authorities, terminal operators, and economics and trade authorities, the literature has not provided any generally accepted approaches to measure economic losses of industry clusters due to port disruption in a quantitative manner. Furthermore, port disruption risks are more than safety and security issues to cover other forms of interruptions like natural hazards. Hence, the demand for a systematic framework in performing economic loss estimation of industry clusters due to port disruption is very strong.

To address these research gaps, this paper aims to develop a framework of calculating the port disruption resulted economic losses for adjacent industry clusters. To analyze the propagation of port disruption within the industry cluster, a Petri Nets (Petri, 1962) model is utilized to model the relationship between the port and industries. The stepwise process and efficient environment characteristics of Petri Nets model are used for conducting simulations of cargo flows between ports and industry clusters. Moreover, based on the flows of cargo, an approach for the economic loss estimations of port adjacent industries is proposed. This covers both the inbound and outbound logistics. The study calculates the direct economic losses of industries resulted from a port disruption. Then in turn, an optimized risk mitigation scheme is aimed to be found from a scenario analysis.

After the introduction, the remaining of this paper is organized as follows. An overview of port disruption risk literature will be given. Then, the framework of the economic loss estimation for port adjacent industry clusters is elaborated. To demonstrate the proposed procedures, Shenzhen port is selected in a case study. Detailed steps in the economic loss estimations are then presented and explained. After which, a case study focusing on the printer industry is investigated. Next, based on the results, an investigation on how to utilize the loss estimation in a risk mitigation scheme is provided. The last section draws the conclusion.

2. Literature review

As globalization prevails, the world economy has become more intertwined and integrated. This imposes higher challenges on supply chain management as the members in supply chains become more interconnected (Lam and Dai, 2015). In a more interconnected global supply chain, a disruption at any stage of the chain could lead to a domino effect on the rest of the parties including shippers, consignees, shipping companies, intermodal transport providers and other ports. Although ports as vital trade facilitators and components of the supply chains are among the most significant causes for uncertainty (Sanchez-Rodrigues et al., 2010), there are limited researches on port related industrial risks and port disruptions' economic loss estimation.

Several studies related to port disruption can be found from the literature. Beside the direct impact on a particular supply chain node, disruption could also result in indirect impact on the rest of supply chain network. Chang (2000) studied the earthquake in Kobe, Japan which happened in 1995 and discovered that the disaster substantially affected Kobe port's performance in terms of losing a significant share of transhipment traffic. Other than natural disasters, man-made risks such as terrorist attack could affect port related industries greatly. Rosoff and von Winterfeldt (2007) and Park (2008) analyzed the impact of the shutdown of Los Angeles and Long Beach ports due to terrorist attacks. They found that such kind of major port disruption caused considerable economic losses and extensive interruptions to trade activities. Paul and Maloni (2010) conducted a more generic simulation study to include both natural and terrorism-related disasters at ports. Through the cases of the North American container port network, the study illustrated the effect of cost increases generated by port disasters. More recently, Kajitani et al. (2013) analyzed the economic impacts caused by a chemical explosion in the Straits of Malacca and Singapore. An explosion and fire will affect the associated ports resulting in a prolonged blockage of this critical navigation channel and the transhipment traffic. The literature also extended to focus on port disruption risk mitigation. Lewis et al. (2013) studied the macro effects of generic strategies of port disruption risk management including contingency plan, inventory management, and efficient capability. Lam and Su (2015) also examined the trend of port disruption and risk mitigation strategies for reducing the likelihood and severity of various types of port disruptive events.

To enhance the coverage and depth of the literature review, the more generic studies on port economic impact analysis are also referred to. Table 1 summarizes the three existing methods for port disruption economic impact analysis and overall port economic impact analysis. Firstly, the Input Output Model provides a detailed overview of the underlying relations between all parties involved in port activities, inside and outside the port area. However, the reliability of the data used need to be carefully examined and in many cases data about risk and economic losses may not be available (Coppens et al., 2007; Danielis and Gregori, 2013; Zhang and Cao, 2015). Secondly, the Gravity Model predicts trade flows and therefore economic developments between ports/countries. It can be used in disruptive events like mechanical breakdown of port machineries, natural disasters and terrorist attack. Despite the benefits, the estimation of the logarithm is infeasible due to the presence of heteroskedasticity in trade data and the existence of zero flows. Thus, different estimation techniques are required to be

Table 1
Existing methods for port (disruption) economic impact analysis.

Methods	Objective and advantages	Difficulties and disadvantages	Examples of related risk events	Reference
Input Output Model	*Objective*: Give a detailed overview of the underlying relations between all parties involved in port activities, inside and outside the port area *Advantages*: • Able to quantify the relations among different industry sectors • The model structure is relatively easy to follow	*Difficulties*: • Mass data collection is required and data may not be available even lots of resources are utilized • Some deviations were pointed out between the figures from different sources *Disadvantages*: The reliability of the data used need to be extensively examined	Risks interfering smooth material and traffic flow: *Internal risks*: Mechanical breakdown of port machineries *External risks*: Natural disasters; Terrorist attack	Coppens et al. (2007), Danielis and Gregori (2013), Park (2008) and Rosoff and von Winterfeldt (2007)
Gravity Model	*Objective*: Predict trade flows and therefore economic developments between ports/countries *Advantages*: • Useful in analyzing bilateral trade flows and trade-related impact	*Difficulties*: • Presence of heteroskedasticity in trade data or the existence of zero flows make the estimation of the logarithm infeasible *Disadvantages*: Different estimation techniques are required to be carried out by before applying the method	Risks in disrupting trade flows *Internal risks*: Mechanical breakdown of port machineries *External risks*: Port congestion; Natural disasters; Terrorist attack	Danielis and Gregori (2013) and Gómez-Herrera (2013)
Computable Equilibrium Model	*Objective*: Analyse system-wide impact of changes caused by risks, policy, or other external factors *Advantages*: • Consist of a level of disaggregation which allows structural change analysis	*Difficulties*: • Modelling of a nodal congestion function which considers the issue of spatial competition • Unrealistic to assume ports as perfect competitors *Disadvantages*: If all considerations were to be taken into account, modelling the system would be very difficult. Companies need to separate link costs from the nodal costs	*Internal risks*: Technology obsolescence in port infrastructures *External risks*: Port congestion	Danielis and Gregori (2013) and Haddad et al. (2010)

performed before applying the gravity model (Gómez-Herrera, 2013). Thirdly, the last major existing method for port (disruption) economic impact analysis is the Computable Equilibrium Model which analyses the system-wide impact of changes caused by risks, policy, or other external factors. Being equipped with a level of disaggregation, it enables structural change analysis and incorporates market mechanisms and price incentives. However, due to limitations such as spatial competition in maritime transport modelling the system would be very difficult. Model users also have to separate link costs from the nodal costs (Haddad et al., 2010). Some less common methods such as economic base (EB) study and the income-expenditure approach can be found in Shan et al. (2014).

To summarize the literature review, quite few of these studies provided a comprehensive way to assess the problem from the fundamentals (e.g. model construction) to the final analysis (e.g. economic impact estimations). With the aim of advancing the field of port risk assessment, there is a strong need for establishing a detailed framework to highlight every step that is needed in the risk assessment. We also find that little attention has been devoted to the research on industrial risk and economic impacts of port disruptions on industry clusters. Studies with greater depths are required to further understand and analyze this research topic.

3. Framework of economic loss estimation and mitigation

In order to estimate the economic loss of industries resulted from port disruption, it is important to know how disruption risks can be incorporated in the port network system. Usually, the loss estimations are based on a complete risk assessment process in the network flow with a full consideration of all the risk events. Based on the traditional risk assessment procedures (Omer et al., 2012), the framework of economic loss estimation of industry clusters arising from port disruptions is developed herein.

The whole process can be divided into three stages which include a total number of six steps in the assessment:

(1) Define the boundary of the problem within the network.
(2) Identify the elements (e.g. the transportation nodes) in the network flow.
(3) Connecting all the elements in the cargo flow network based on the flow directions of cargoes.
(4) Assess the flow of the network when disruption occurs.
(5) Analytically quantify the economic losses for the elements being affected.
(6) Evaluate the benefits of different port risk mitigation schemes using scenario analysis.

Fig. 1 illustrates the flow of the whole risk assessment process. The current work focuses on the investigation of the basic structures of port related industries; however, the framework can be applied to other industries which include both inbound and outbound supply chains.

3.1. Stage 1: Constructing the network flow model for the port adjacent industry clusters

The initial step in the economic loss estimation and mitigation is to simulate a complex system for the supply chain network of the industry cluster. In the first step of the proposed framework, the boundaries of the problem including the spatial boundaries, operational boundaries and economic boundaries are necessarily identified. The boundaries define the scope of the network being analyzed which is essential for the simulation of the network model. Following the defined boundaries, the nodes in the network are identified in the next step. The nodes represent ports, industries and the links among these elements. It also covers all the inland and maritime routes that exist among the network. All the fundamental elements and factors which constitute the supply chain are depicted in the first stage.

The last step in this stage is to determine the flow of the network. The network flow of the cargo between the ports or ports and related industries depends on the required conditions. Disruptive events in ports would lead to other alternative ways for the cargo flow. Therefore, the conditions or requirements are assessed for the connections between the transportation nodes. Meanwhile, the boundary should also define the time frame of the analysis. As our investigation mainly focuses on port disruption risks, the computed economic losses should cover a period which includes the number of days that takes the port to recover its full operational capacity. Normally, this is longer than the duration of the disruptive events.

3.2. Stage 2: Compute the economic losses of each transportation element when port disruption occurs

For the supply chain system, a disruptive event can potentially hamper the ability of some transportation nodes to continue functioning. However, we should recognize that the influences of the malfunction in the supply chain elements are quite different. Disruptive events might not only result in a halt in the cargo flow, but may also lead to some chain effects in industry productions (Ham et al., 2005). For example, the bullwhip effect is a typical example of such influence in the supply chain. In this paper, such influence is measured in terms of the impact on the total economic cost of the system.

Most port related industries have both inbound and outbound business, i.e. import and export. The considered supply chain includes major participants namely, the raw material supplier, cargo carrier, port, manufacturer, and consignee, as well as the insurance companies who pay for the loss according to the insured sum. It should be recognized that a disruption will

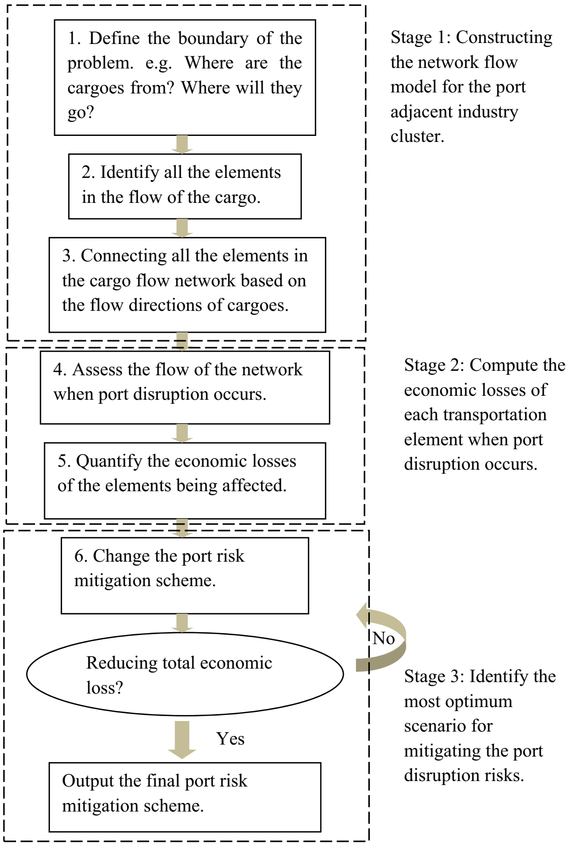


Fig. 1. Framework of the economic loss estimations for industry clusters due to port disruptions.

limit both the capability of a port in sending and receiving the goods (DiPietro et al., 2014). The key elements regarding the impacts of port disruption on the port related industry cluster are highlighted in Fig. 2. The estimation of the economic losses has to consider both effects on the inbound and outbound supply chains. As such, we propose to approach the economic loss estimation through four different scenarios. Assuming a manufacturing industry has to import the raw materials from a port and export its manufactured products through the same port, the loss can be computed from two outcomes resulted from the port disruption: the import of raw materials and the export of finished products (see Fig. 3). Based on the highlighted factors in Fig. 2, the economic losses are further classified into four different kinds, namely, *direct loss in the import of raw materials*, *loss of delay in the import of raw materials*, *direct loss in the export of products* and *loss of delay in the export of products*. The detailed calculation formulas of these losses are proposed and explained in the followings.

Direct loss in the import of raw materials:

$$C_{direct,import} = p_{raw}V_{import}\Delta t + c_{raw}V_{import}\Delta t$$

The direct loss counts the immediate monetary loss due to the damage of cargoes. p_{raw} is the value per unit of raw materials being imported to the manufacturing industry. V_{import} is the volume of the import. c_{raw} is the unit transportation, storage or any extra costs for removing the damaged cargoes from the port. When computing the loss of damage in imported raw materials and exported finished products, the calculation assumes the cargoes amounting to days of supplies are damaged. Δt is the total disruption time at the port. Note that c_{raw} may or may not be borne by the manufacturer. But since it is borne by a participant in the cargo network flow (i.e. the port/insurance company depending on case by case), we also calculate it in the total loss estimations.

Loss of delay in the import of raw materials:

$$C_{delay,import} = \begin{cases} 0, & \text{for } \Delta t \leqslant I_{raw} \\ p_{product}V_{production}(\Delta t - I_{raw}), & \text{for } I_{raw} \leqslant \Delta t \leqslant I_{raw} + I_{product} \\ p_{product}V_{production}(\Delta t - I_{raw}) + r_{cancel}p_{product}V_{production}(\Delta t - I_{raw} - I_{product}), & \text{for } I_{raw} + I_{product} \leqslant \Delta t \end{cases}$$

The economic loss of delay in the import refers to the loss caused by the unpunctual arrival of raw materials. There are several parameters related to the manufacturing in this computation: $p_{product}$ refers to the value of unit product, $V_{production}$ refers to the number of produced products in unit times, I_{raw} is the time that the raw material inventory can provide to

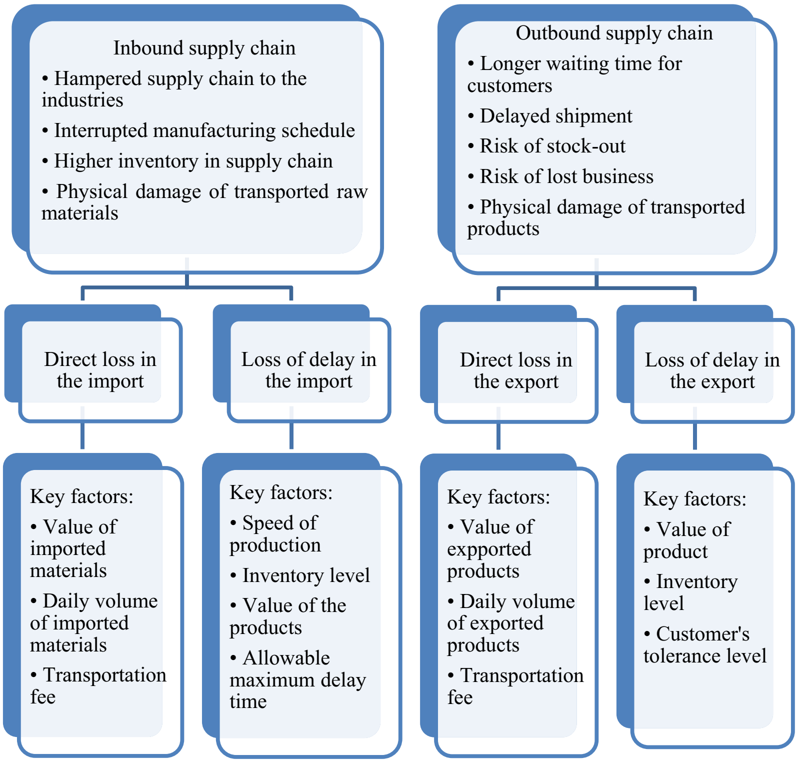


Fig. 2. Impacts of port disruption on the port adjacent industry clusters.

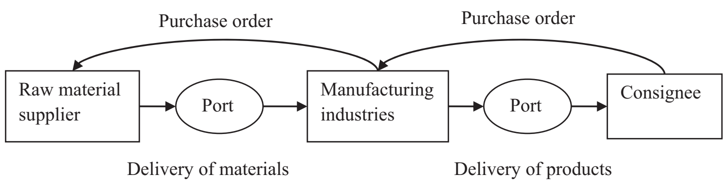


Fig. 3. Inbound and outbound supply chain of an industry cluster via a port.

continue the production, $I_{product}$ is the time that the finished product inventory can provide to continue the supply and r_{cancel} is the cancellation rate. There are three different cases with regard to the delay time caused by the port disruption. If the delay time is less than the buffer time provided by the inventory of raw materials (e.g. $\Delta t \leqslant I_{raw}$), there would be no delay in the manufacturing since the inventory level is sufficient. If the delay time is larger than the buffer time provided by the inventory of raw materials (e.g. $\Delta t \geqslant I_{raw}$), this will cause a temporal stoppage in the production. However, if the inventory of finished products is sufficient to provide the supply (e.g. $\Delta t - I_{raw} \leqslant I_{product}$), the loss would only be the halt in the production (e.g. $p_{product}V_{production}(\Delta t - I_{raw})$). But if the existing products are insufficient to support the normal flow of cargo to the port, a delay in the arrival of products for the customer is expected. This delay of order could lead to some cancellations of orders. Therefore, a loss in the total number of products is considered (e.g. r_{cancel}).

Direct loss in the export of products:

$$C_{direct,export} = p_{product}V_{export}\Delta t + c_{product}V_{export}\Delta t$$

The direct loss in export is quite similar to that of import, although the value of the export ($p_{product}$) is expected to be higher than import since the export is manufactured goods. The extra transportation, storage or other fees per unit for removing the damaged cargoes from the port ($c_{product}$) is also different. V_{export} refers to the volume of the export per unit time.

Loss of delay in the export of products:

$$C_{delay,export} = \begin{cases} 0, & for\ \Delta t \leqslant I'_{product} \\ r_{cancel}p_{product}V_{export}(\Delta t - I'_{product}), & for\ I'_{product} \leqslant \Delta t \end{cases}$$

The export of the products can be directly related to the arrival of the products to the customers. There are two cases at the customer's side. First, the inventory of the products at the customer's place ($I'_{product}$) can provide enough buffer time to continue the supply to customers on order ($I'_{product} \geqslant \Delta t$). Thus, the loss will be minimal. Second, the inventory is insufficient ($I'_{product} \leqslant \Delta t$), resulting in late delivery of goods. Therefore, an amount of cancellation in order may occur. It is realized that customers may claim some compensation when there is a delay in product delivery. However, this kind of penalization is very complex depending on the policies between the customer and the company. Thus, only the losses due to cancellation actions which usually involve more substantial amounts are considered in the present assessment. Meanwhile, we should note the computation of the loss of delay for finished products only counts the manufactured products based on the available raw materials in store. The raw materials do not include the transported ones that have not arrived at the port. The computation of losses of delay for the raw materials and finished products do not overlap.

The approximation of the economic loss is based on the identified nodes in the supply chain system which would be affected during the port disruption (Trbojevic and Carr, 2000). The estimation is formulated according to the commodity flow from the manufacturer to the customers. Therefore, the estimated economic losses include the total losses from major participants along the cargo network flow. For example, the economic loss of cargo damages should be borne by the insurance company up to an insured amount. If the cargo is not sufficiently insured, the cargo owner will bear the loss/part of the loss. However, in this study, these losses are all counted in the total economic loss calculation. The assessment caters for the loss incurred by the industry cluster instead of individual companies. Therefore, the key is the *amount* of economic loss, *not who* will ultimately pay for the loss.

3.3. Stage 3: Identify the most optimum scenario for mitigating the port disruption risks

Risk mitigation strategies often require financial analysis to facilitate their implementation (Tang, 2006). The loss estimation or risk assessment can provide the information about the severity of port disruption events. To mitigate the impact of disruption risks, manufacturing firms could deploy such analysis through a coordinated/collaborative mechanism. Therefore, the last stage in the proposed framework is to have a full understanding of the importance for each transportation element. First, the manufacturing firm could coordinate with upstream partners to ensure reliable supply of raw materials when port disruption occurs. For example, the suppliers also need to consider contingency plans. The manufacturer can work together with the supplier to help each other come up with creative responses to disruptive events. This could increase the trust and strengthen the business relationship between the manufacturing firm and the upstream suppliers. Moreover, in order to know how reliable the suppliers are, periodic assessments of suppliers' risks should be done by the manufacturing firm. Second, the manufacturing firm could collaborate with downstream partners to control and modify the product demand in a beneficial manner. The manufacturing firm can alert the downstream companies to stay aware. For example, once the manufacturing company knows what places and shipping routes are involved, it should stay up on the news. A proactive manufacturer is able to sniff out possible events that could affect the downstream companies and update the latest situations to the staff members who work directly with the downstream companies. It should also discuss with the downstream companies on how to reduce the loss that may occur during the disruption. For example, consignees could try to find the finished products from other sources. Third, the manufacturing firm could improve the risk mitigation scheme by communicating with the port to assess various types of private information. For example, if the business involves assembly parts shipped from foreign countries, the manufacturing firm needs to find out where the raw materials come from. How do they get to the manufacturer and by what route does the supplier ship the parts to the firm? Would there be any alternative transportation for delivering the raw materials? Successful implementation of these schemes should help both the port and industry clusters to make necessary preparations, such as the planning of inventory level and allocation of transportation vehicles for transferring the cargo.

Another important aspect that we have to point out is that port disruption events are often unpredictable. It is also necessary to evaluate the benefits of implementing the economic loss estimations under uncertainty. The finding of the most optimum scenario should take into account the various levels of port disruption risks (e.g. different number of disruptive days). The current framework proposes to apply a scenario analysis to determine the optimum risk mitigation scheme. Fig. 4 shows the process of determining the optimum risk mitigation scenario with considerations of uncertainty in port disruptions. The optimum scenario will be obtained by comparing the implementations of different risk mitigation schemes. If the applied scheme could lead to the minimum incurred financial losses, it means that it is worth implementing that scheme.

There are several advantages of using these developed procedures in assessing the risks with regard to port disruption. First of all, the proposed method can help to highlight the importance of each element among the supply chain system. It provides a direct reflection of the risks encountered by the members through the cargo flow network. Thus, practitioners can make optimum design of the network in order to reduce the risks to a minimum level. Second, this approach provides the most direct and detailed information about money loss among the supply chain. Risk managers can have a more comprehensive understanding of the situations of disruption risks. The risks can be represented in a quantified way which can help the managers to conduct optimum risk mitigating strategies. Moreover, the results can provide relevant implications to the government. If a port appears to be too risky, the government may try to enhance the facilities in order to help the whole industry cluster. This not only benefits some specific companies but the whole regional economy. The method could serve as a general tool for measuring the resilience of an industry cluster.

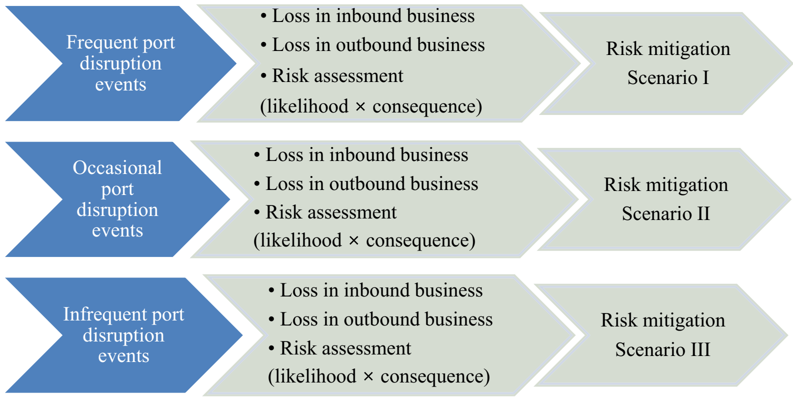


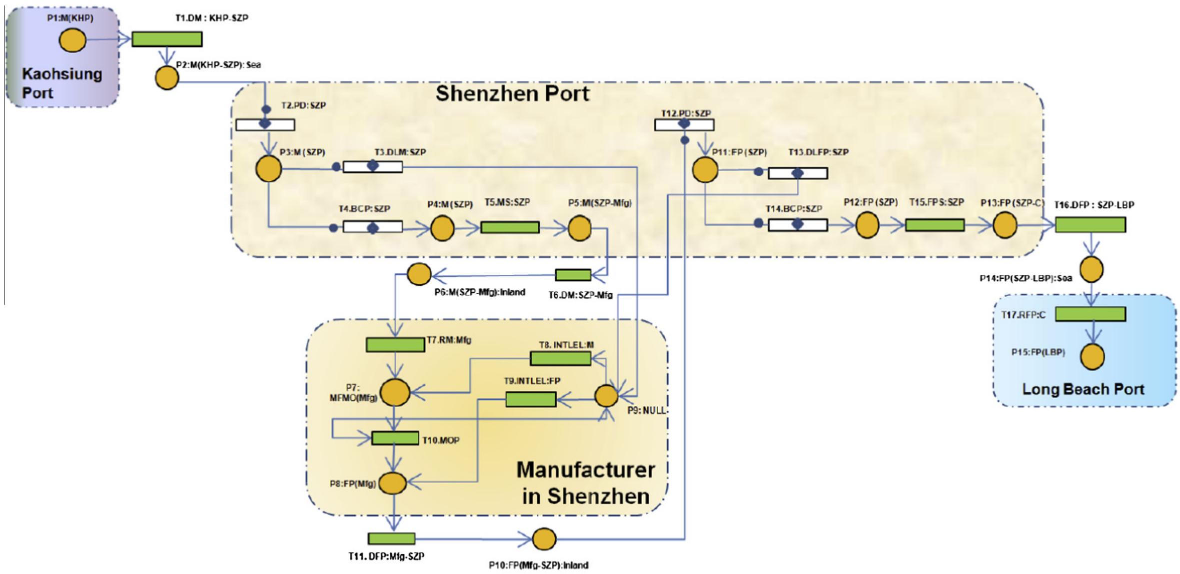
Fig. 4. Determine the optimum mitigation scenarios for different port disruption risks.

4. Case study: Manufacturing industry in Shenzhen

4.1. Formulation of network

To demonstrate the proposed framework in assessing port disruption risks for the manufacturing industry, the Shenzhen manufacturing industry is chosen for the following investigation. The port of Shenzhen is located in the Pearl River Delta in South China. Shenzhen has experienced rapid economic growth over the past decades. With the support from the fast growing seaports and river ports, the Pearl River Delta becomes a key manufacturing base which has various kinds of trade business. The port of Shenzhen is now the world's third busiest port in terms of container throughput handled in 2014. The significant role of Shenzhen and its relationship with the global and regional supply chains is considered an interesting case for studying the economic impact of port disruption on industry clusters.

As discussed in the previous section, the initial step is to establish a network flow model for the supply chain system between a port and the adjacent industry. Here, a Petri Nets model which was proposed by Lam and Yip (2012) in the analysis of port disruption impact to the industry cluster is utilized. Lam and Yip (2012) outlined a multi-modal and multi-port supply chain system into a Petri Nets model (see Fig. 5). The supply chain starts from importing raw materials from Kaohsiung to Shenzhen port, then manufacturing in mainland China, to exporting of products to Long Beach port in the US. The Petri Nets model considers two possible causes of port disruption in Shenzhen. One event is the transported materials being damaged or lost when it arrives/leaves Shenzhen port. In this case, the manufacturer has to use the existing inventory for the scheduled production to prevent any delay. Another event or consequence of port disruption is a halt in port operations and



Note: circle = place; rectangle = transition; ◆ = disruption

Fig. 5. Petri Nets model of the multimodal and multi-port supply chain system (Lam and Yip, 2012).

cargo flow. This would delay the supply of raw materials, but the manufacturer still has to fulfil customer demand if there is sufficient inventory.

The Petri Nets model plotted in Fig. 5 includes the logical functions and time factors of basic disruption events in the supply chain system. In this model, Shenzhen serves both the inbound and outbound logistics of cargo flows. Port disruption occurs in Shenzhen (transition 2 PD:SZP) after raw materials are transported by sea, represented by P2:M(KHP-SZP):Sea. When the cargoes arrive safely, there can be two possibilities. First, the transported materials may be damaged or lost if the disruption causes damages to the cargo directly. Thus, after P3:M(SZP), one directed arc leads to transition 3 (DLM: SZP) in Fig. 5. Therefore, the impact of such port disruption on the adjacent industry is: manufacturer has to use existing inventory to continue with the production. The second possibility after port disruption is that a halt in port operations and cargo flow could occur. Thus the other directed arc leads to transition 4(BCP:SZP) which is the time when the port tries to resume port operations. However, in quantifying the total economic losses, both parts are counted in the computation.

For the outbound logistics, cargoes are sent by inland transport operators to the port of Shenzhen which is indicated in transition 11 (DFP:Mfg-SZP) and place 10 (FP(Mfg-SZP):Inland). Transition 12 (PD:SZP) models port disruption that occurs in outbound logistics of the supply chain. Same as the inbound logistics, cargoes may be damaged/lost (transition 13 DLFP:SZP) and it could lead to a halt in the product flow (transition 15 FPS:SZP). More details about the flow of the Petri Nets model can be found in Appendix A.

4.2. Industry cluster: HP printer

To exhibit the proposed framework in calculating the economic loss, the printer industry in Shenzhen is selected in this investigation using the printer business of Hewlett-Packard (HP). It was reported that the annual production of printers in Shenzhen is around 100 million which is nearly half of the global production. More than 80% of these manufactured printers are exported from Shenzhen port to the rest of the world. Therefore, the analysis of the impact of port disruption on the printer industry in Shenzhen is of great significance from the economic point of view. Values of the parameters needed for the economic estimation according to Section 3 are recorded in Table 2. As the location of the printer manufacturer is relatively close to Shenzhen, the inland transport is not covered in this example.

Table 2 shows that the import has a lower cargo value compared to the export. The inventory of the finished products is set to be half day which is the same as raw materials. This is indeed common as most companies prefer to have minimum inventory level of mature products. To simplify the problem, the daily flow of the raw materials, production speed and volume of export are assumed to be the same. However, in reality, it should be noted that certain variations are associated with the volume. For the transportation fees of imports and exports, these are obtained from the standard transportation charge rate (both Kaohsiung to Shenzhen and Shenzhen to Long Beach) given by an anonymous logistics company. The cancellation rate is assumed to be 1% which is independent of the days of delay. Note the economic loss induced from delayed delivery may be borne by HP or the port or the insurance company depending on the contract policy. But since the economic loss calculation estimates the losses of the industry cluster along the supply chain, the developed calculation method is appropriate to estimate the total loss. According to the results reported in Zhang and Lam (2015b), the duration of climate-induced port disruption events in Shenzhen is usually within 4 days. Therefore, in this study, the economic loss estimation firstly considers four cases having port disruption duration of 1 day, 2 days, 3 days, and 5 days. These selected cases are close to the reality. Other than that, we also choose to investigate an extreme case having port disruption period of 10 days. This is aimed to estimate the economic losses when a port disruption event is catastrophic. Finally, following the calculation procedures proposed in Section 3, the results of the estimated economic losses for the HP printer business in Shenzhen are recorded in Table 3.

The results in Table 3 provide the information about the importance of each factor in the economic loss. Port disruption is found to have a significant effect on the printer industry for the loss in import. The direct loss in the import of raw materials is less influential when compared to the loss of delay in supplying of raw materials. This is more obvious when the port disruption causes a delay in the manufacturing which leads to a large financial loss. However, this is different in the export. The direct loss of export is much more critical than the loss of delay especially when the port disruption time is long. The main reason is because the values of printers are high. Any damages associated with the printers during the transport of the

Table 2
Estimated parameter values for HP printers in Shenzhen. *Source:* estimated by the authors from various sources (see http://new.hpstore.cn/hp-cuxiao.html).

Parameter	Value	Parameter	Value
p_{raw}	US$50/unit	V_{import}	750 units/day
$p_{product}$	US$500/unit	$V_{production}$	750 units/day
I_{raw}	0.5 day	V_{export}	750 units/day
$I_{product}$	0.5 day	c_{raw}	US$2/unit
$I'_{product}$	0.5 day	$c_{product}$	US$5/unit
r_{cancel}	1%/day		

Table 3
Estimated economic loss for HP printer business in Shenzhen.

Port disruption duration	Import		Export	
	Direct loss in the import of raw materials	Loss of delay in the import of raw materials	Direct loss in the export of products	Loss of delay in the export of products
1 day	US$39,000	US$187,500	US$378,750	US$1875
2 days	US$78,000	US$566,250	US$757,500	US$5625
3 days	US$117,000	US$945,000	US$1,136,250	US$9375
5 days	US$195,000	US$1,702,500	US$1,893,750	US$16,875
10 days	US$390,000	US$3,596,250	US$3,787,500	US$35,625

finished products will incur high value losses. However, the delay in the export does not affect the manufacturing. Thus, the loss is minimal.

Generally, the proposed economic analysis provides detailed information about the losses among inbound and outbound supply chains. The influence of the disruption time on the overall economic performance of port related industries is more comprehensively reflected using the proposed approach. Such analysis helps to identify the most critical factors in the supply chain for the industry when an unexpected port disruption occurs. This offers risk managers the opportunity to provide more robust solutions via a full consideration of various port disruption risks.

4.3. Effects of inventory level

A further stage in the risk assessment is to utilize the economic estimations for designing risk mitigation strategies. One particular use of the above analysis is to evaluate the importance of inventory levels in the supply chain. As discussed in Section 3, a port disruption can generally have two effects on the industry cluster: disruptions in delivering raw materials from a supplier and disruptions to the transportation of product from the manufacturer to customers. Thus, the inventory factors would also have their own functionalities within the supply chain when a port gets disrupted (Zipkin, 2000). Examples of papers addressing this point include Moinzadeh and Aggarwal (1997), Kleindorfer and Saad (2005) and Tomlin (2006). It is reported that most port related industries use inventory for mitigating port disruption risks (Lewis et al., 2013). Therefore, it is important to know how the inventory levels could affect the total economic losses.

To investigate the importance of inventory levels, the economic losses are compared for four scenarios having different inventory levels. Notice the printer industry in Shenzhen has three inventory factors (I_{raw}, $I_{product}$, $I'_{product}$), therefore, the chosen scenarios focus on these parameter values. In Scenario 1, the inventory level for the raw materials (I_{raw}) is increased to 1 day while the rest are kept the same. In Scenarios 2 and 3, the inventory of the product at the manufacturer and the customer's place are all increased to 1 day. Besides these scenarios, a base scenario, which has the same values of inventory levels as Table 2, is also adopted in this study for the purpose of comparison. The basic information of these case studies is provided in Table 4.

In order to show the effects of inventory levels under different risk conditions, the analysis considers four cases having port disruption time of 1 day, 2 days, 3 days and 4 days. Based on the procedures provided in Section 3, the calculations of economic losses are repeated for all these scenarios. Detailed results are summarized and plotted in Fig. 6.

As can be seen from Fig. 6, Scenario 1 has the minimum total loss for all the considered port disruption cases. The main reason is because the loss component C_{delay_import} is largely reduced in this scenario. This is especially obvious in the case of a one-day port disruption. The provided inventory is sufficient to mitigate the port disruption risks such that the industries could still continue its manufacturing even there is a stoppage of raw material supply. Therefore, an increase in the inventory C_{delay_import} is much helpful in reducing the total economic loss as it could help to prevent the happening of stoppage in the manufacturing company. Compared to Scenario 1, the changes of inventory levels in Scenario 2 and 3 have very little effects to the total economic loss. In Scenario 2, C_{delay_import} is reduced compared to the base scenario, whereas in Scenario 3, the loss component C_{delay_export} is reduced. However, either of these two only reduces a very small amount in the total loss. In fact, both Scenario 2 and Scenario 3 aim to help in the distribution of finished products to the customers. But they provide no preventions to the stoppages in manufacturing. This means the delay of import is a major event that will lead to large economic losses for the industry. These also imply that among the four loss components, C_{delay_import} is the one that could be largely changed by adjusting the inventory level. C_{delay_import} is found to be very sensitive to I_{raw}. Compared to the delay

Table 4
Investigated different inventory levels for HP printer business in Shenzhen.

	I_{raw} (day)	$I_{product}$ (day)	$I'_{product}$ (day)
Base scenario	0.5	0.5	0.5
Scenario 1	1	0.5	0.5
Scenario 2	0.5	1	0.5
Scenario 3	0.5	0.5	1

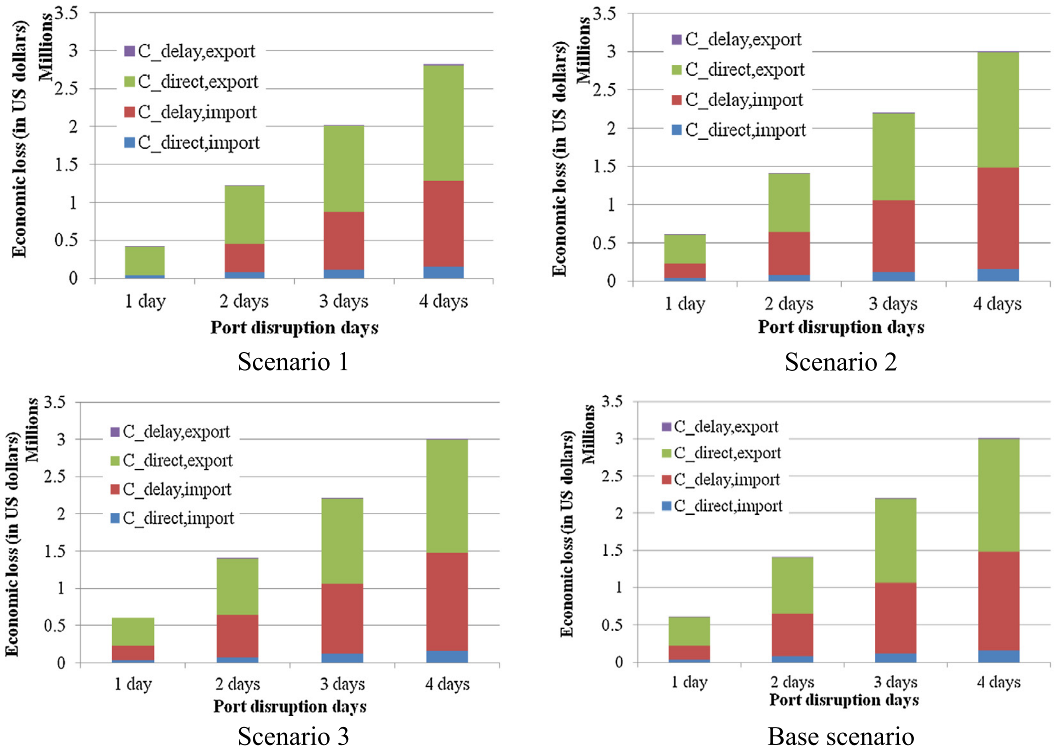


Fig. 6. Estimated economic loss for different inventory levels.

induced losses, the direct loss (C_{direct_import} and C_{direct_export}) could not be easily reduced. The change of inventory levels will not affect any components in the direct loss. From this observation, we could conclude that I_{raw}, being the most critical inventory factor in governing C_{delay_import}, should be paid more attention to in risk management.

The effects of inventory levels can be seen more clearly from a sensitivity analysis. Here, the equations for calculating the sensitivities for each of the inventory factors leading to economic losses are derived.

Sensitivity of I_{raw} to the total loss

$$\frac{dC_{total}}{dI_{raw}} = \begin{cases} 0, & \text{for } \Delta t \leqslant I_{raw} \\ -p_{product}V_{production}, & \text{for } I_{raw} \leqslant \Delta t \leqslant I_{raw} + I_{product} \\ -p_{product}V_{production} - r_{cancel}p_{product}V_{production}, & \text{for } I_{raw} + I_{product} \leqslant \Delta t \end{cases}$$

Sensitivity of $I_{product}$ to the total loss

$$\frac{dC_{total}}{dI_{product}} = \begin{cases} 0, & \text{for } \Delta t \leqslant I_{raw} \\ 0, & \text{for } I_{raw} \leqslant \Delta t \leqslant I_{raw} + I_{product} \\ -r_{cancel}p_{product}V_{production}, & \text{for } I_{raw} + I_{product} \leqslant \Delta t \end{cases}$$

Sensitivity of $I'_{product}$ to the total loss

$$\frac{dC_{total}}{dI_{product}} = \begin{cases} 0, & \text{for } \Delta t \leqslant I'_{product} \\ -r_{cancel}p_{product}V_{export}, & \text{for } I'_{product} \leqslant \Delta t \end{cases}$$

It can be seen that the sensitivities of the inventory levels to the total loss are time varying. Depending on the length of disruption period, the sensitivity values of the inventory levels to the total economic loss can be changed. For instance, if the inventory levels in the base scenario are utilized, the sensitivity values can be computed and plotted in Fig. 7.

It can be seen from the results that the sensitivity of I_{raw} is much higher than the other inventory levels for disruption period of larger than 0.5 day. The sensitivities of $I_{product}$ and $I'_{product}$ are the same when disruption time is longer than 1 day. But the sensitivity value of $I_{product}$ decreases to zero when disruption time is shorter than 1 day. These results agree well with the conclusions obtained in the above case study while the inventory level of finished product only takes effects after 1 day port disruption period. The sensitivity analysis can provide an estimate of the importance for each inventory level in the supply chain.

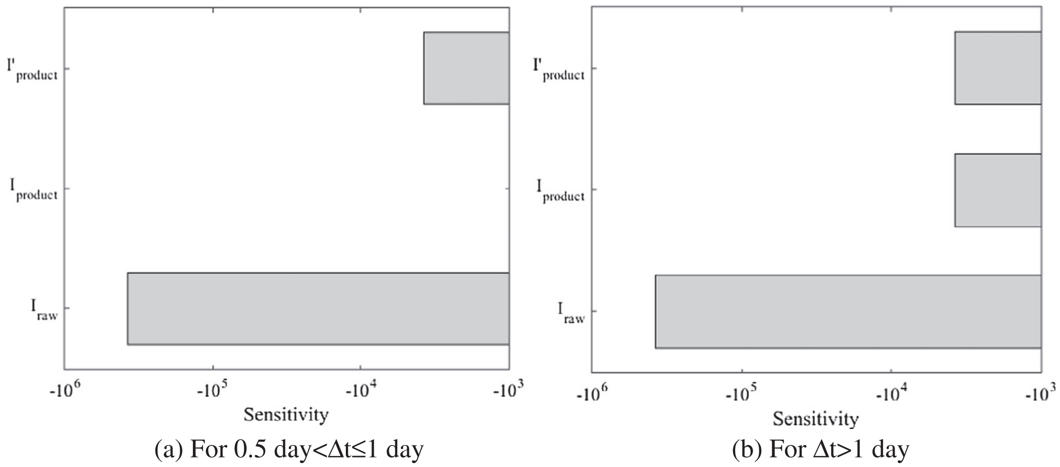


Fig. 7. Sensitivities of inventory levels to the total loss.

4.4. Optimal inventory control

The evaluation of economic losses provides a systematic approach to estimate the impact of port disruption on the adjacent industries. However, port managers are more interested in finding out the optimal strategy that could help minimize the total loss. As highlighted above, the control of the inventory would be one of such techniques. But the question is how to set the optimal values of the inventories in such a way that minimizes the potential risks. Adopting a dynamic inventory control would be a possible solution. For example, the inventory level could be set to a particular value that could provide enough supply to the industries when a port gets disrupted (Qi et al., 2009). The literature has shown that a dynamic inventory control could benefit the supply chain companies (Chen et al., 2011). It would be economical to control all the inventories according to the risk levels. Therefore, the study extends to analyze the total economic losses when different inventory control schemes are applied.

We adopt a dynamic inventory control strategy which includes an implementation of the port risk analysis. That is, the planned inventory levels in each month will be adjusted according to the monthly estimated port disruption days. This means the management of inventory is dynamic and relies on the risks considered for the port disruption. The information regarding the potential port disruption days resulted from extreme wind events in Shenzhen are collected from the official climate website (www.tianqi.com). Detailed results are plotted in Fig. 8. Generally, it was estimated that Shenzhen port has four months having the potential disruption risks. These are June (0.25 day/month), July (0.5 day/month), August (0.5 day/month) and September (1 day/month). Therefore, in this study, we make our analysis focusing on the inventory control for these four months.

To highlight this innovation, the economic losses of the four schemes using different inventory controls are computed. The results are recorded in Table 5. The first scenario is our proposed dynamic inventory control where the inventory levels are set differently for each month considering the variations of port disruption risks. The second scenario is a very conservative scheme. All the inventory levels are set at a value corresponding to the worst case (e.g. 1 day of port disruption per month). Scenarios 3 and 4 are designed to have a lower inventory level, where Scenario 3 has set all the inventory levels to 0.5 day and Scenario 4 has set all the inventory levels to 0.25 day. The inventory levels in second, third and fourth scenarios are all fixed. The control in these schemes does not cater for the time varying effects of port disruption risks.

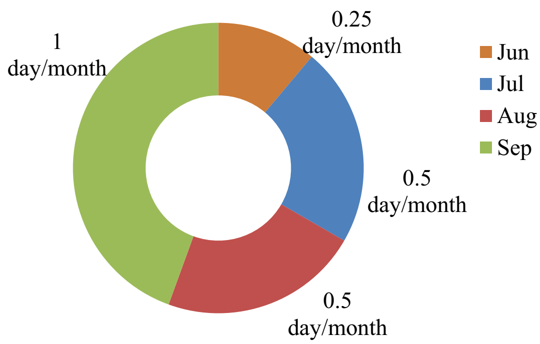


Fig. 8. Estimated port disruption days in Shenzhen.

Table 5
Investigated different inventory control scenarios.

Scenario 1				Scenario 2			
	I_{raw} (day)	$I_{product}$ (day)	$I'_{product}$ (day)		I_{raw} (day)	$I_{product}$ (day)	$I'_{product}$ (day)
June	0.25	0.25	0.25	June	1	1	1
July	0.5	0.5	0.5	July	1	1	1
August	0.5	0.5	0.5	August	1	1	1
September	1	1	1	September	1	1	1
Scenario 3				Scenario 4			
June	0.5	0.5	0.5	June	0.25	0.25	0.25
July	0.5	0.5	0.5	July	0.25	0.25	0.25
August	0.5	0.5	0.5	August	0.25	0.25	0.25
September	0.5	0.5	0.5	September	0.25	0.25	0.25

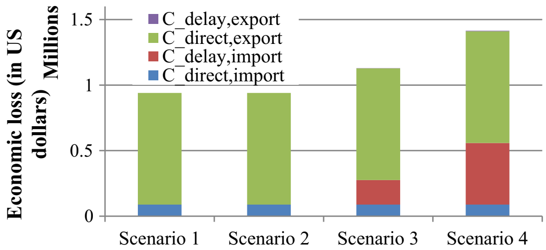


Fig. 9. Economic losses in different inventory control scenarios.

Based on the same procedures, the economic loss for the Shenzhen printer industry is calculated repeatedly for these four inventory control scenarios. The results including the losses in both inbound and outbound businesses are illustrated in Fig. 9.

It can be seen from the figure that Scenarios 1 and 2 have lower economic losses in the estimations compared to the other two. In fact, the results of Scenario 1 and Scenario 2 are quite similar which implies the dynamic inventory control (Scenario 1) has the same effectiveness as the conservative scheme of holding more inventory (Scenario 2). This means the dynamic inventory strategy is very useful in mitigating port disruption risks without incurring excessive inventory holding cost. However, it should be pointed out that the loss estimation can only be considered as a lower bound of the total cost because the cost of inventory is not counted in the computation. For example, the rental fee of warehouse for holding the stocked goods is not included in this estimation. Thus, it should be realized that the dynamic inventory control (Scenario 1) is more economical as it could help to avoid utilizing unnecessary facilities in holding the stocks. Compared to Scenarios 1 and 2, Scenarios 3 and 4 have much higher losses and this is mainly due to the loss of delay in the import. In other words, these two scenarios have underestimated the port disruption risks and thus leading to stoppages of manufacturing in the industry. With the time varying effects in the port disruption risks, Scenarios 3 and 4 can only help to reduce the total loss to a certain extent. The results show that these two scenarios are very sensitive to changes in risk conditions (number of disruption days). A feature of the result is a direct reflection of port disruption risks encountered by the industries represented in a quantified way, whilst the traditional qualitative analysis may only provide rough evaluations.

Furthermore, even if the uncertainties associated with the disruption time is considered, the optimum scenarios can also help to reduce the loss. For example, if the randomness of the disruption time is taken into account, the economic losses in each scenario would also become randomized. Following the same calculation procedures, the economic losses in different inventory control scenarios with random disruption time are computed and shown in Fig. 10. Scenarios 1 and 2 are still the optimum choices as the mean of the random loss is the lowest among all. Meanwhile, it should be noticed that the economic loss in Scenarios 1 and 2 also has the minimum standard deviation. This implies that the randomness of incurred economic loss is lower than the other two scenarios. Therefore, Scenarios 1 and 2 are also the best preferences for random port disruptions.

To sum up, the above analysis demonstrates the need to account for potential port disruption risks in the inventory control. The results directly illustrate the influence of port disruption period on the overall economic performance when different inventory schemes are applied. This could help practitioners to determine the most beneficial inventory control strategy for the manufacturing industry under an unexpected port disruption.

5. Policy and managerial implications

This study gives valuable policy and managerial implications for policy makers, port managers, and managers of manufacturing industries.

With regard to the implications for policy makers such as port and economic development authorities, this work provides insightful knowledge for them to investigate the influence of port disruption on the regional economy. Such risk analysis would be very helpful for examining trade activities and is key to the economic planning and development. From the

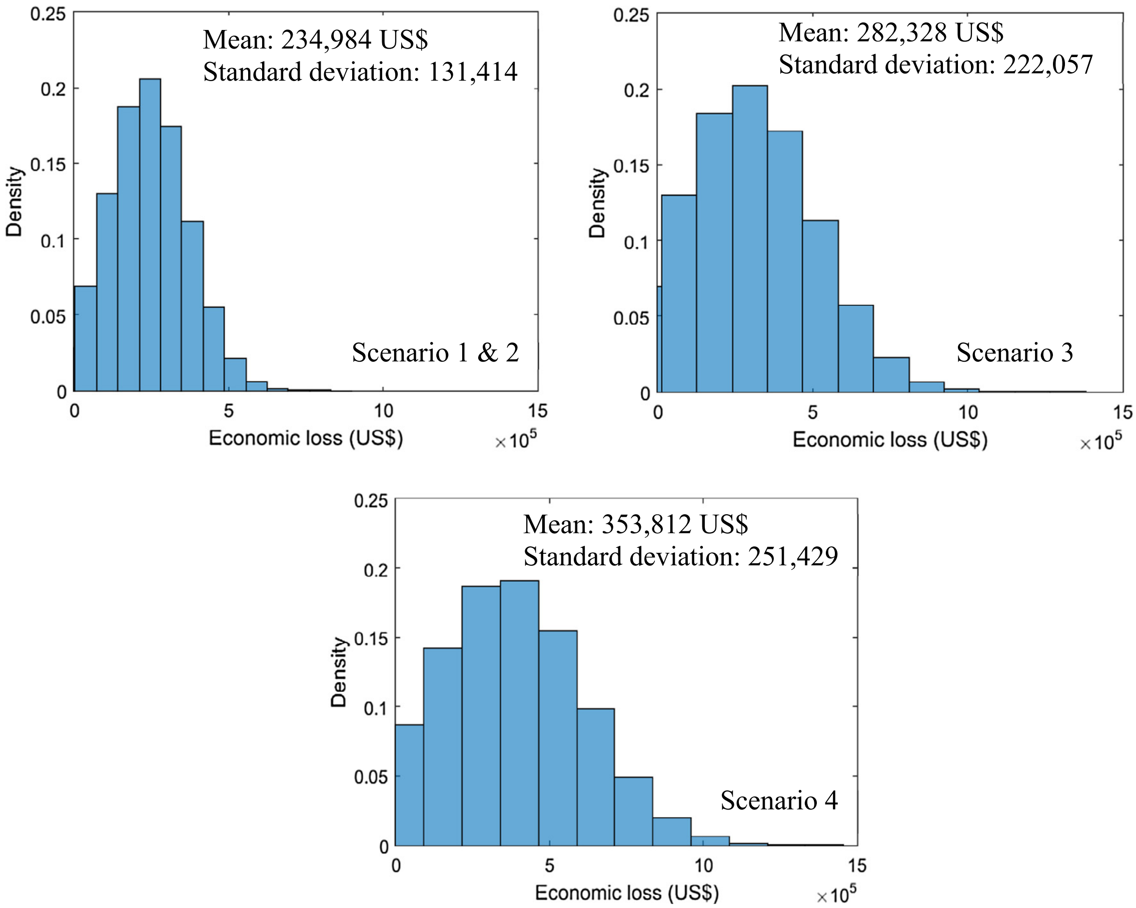


Fig. 10. Economic losses in different inventory control scenarios with random port disruption time.

national economic point of view, port risk mitigation strategies would also mean the enhancement of logistic abilities of the nation, which is seen as a key determinant for attracting foreign direct investment (Panayides et al., 2015). The developed framework in our paper is clearly in line with the growing literature that has stressed the importance of port risk considerations for the supply chain system and regional economy. Particularly, this study unveils the economic loss of port adjacent industries due to port disruption through different components which might be affected by various factors. In addition, the flow of cargo and parties involved are clearly outlined. This provides policy makers a better knowledge of the supply chain system around the port.

The results in this paper also provide relevant implications to the managers of both port and the adjacent industries. First, port managers can adopt the research approach to measure the economic impact of a disruption event occurred at the port. If the port appears risky at the eyes of industry managers, the port managers should improve the resilience of port facilities, because manufacturers are deterred by ports having uncertain operation status (Wilson, 2007). In this case, the port manager could share the analysis and results as performed in this study with the industries. The information could facilitate industry managers to make optimized supply chain plans for their own. In return, industry managers will be more willing to share their supply chain or risk mitigation schemes with the port. The proposed framework can be used to assess various risk mitigation strategies between the port and industries. As a result, the port could build a collaborative relationship with the industries and would have lower loss when disruption occurs. Second, an in-depth analysis of economic losses of industries due to port disruption would also allow industry managers to redesign their supply chain system. The supply chain management and inventory control must carefully consider port disruption risks like natural hazards, port security, information flow, and human-made disasters. Third, the analysis can be used as a benchmarking guide among competing ports. A port manager may compare the port's performance from the risk management point of view with its competitors. Likewise, an industry manager can assess the ports and make port selection decisions accordingly.

Moreover, industry managers who are interested to invest in new projects are suggested to carefully evaluate the potential economic loss based on the established analysis in this work which includes the concern of port disruption risks. The results suggest managers to focus on the performance of the supply chain when port disruption occurs and conduct risk-based design for inventory management. In addition to traditional analysis based on cost and profit, a more complete examination including risk factors ultimately determines the success of an investment venture.

6. Conclusion

This paper analyses the impact of port disruption on industry clusters by examining direct and indirect economic losses. An original contribution is made by proposing a systematic framework to calculate industrial economic losses when a port disruption occurs. A Petri Nets model is used in this paper to formulate the flow of the supply chain. A case study is conducted for the port of Shenzhen. Using the HP printer industry as an example, this paper demonstrates the use of the proposed approach in calculating the industrial economic losses resulted from port disruption in Shenzhen. A comprehensive discussion for the industrial loss is provided. The performed analysis helps policy makers and industry practitioners to have a clear understanding of the economic losses when port disruption occurs. Furthermore, this work also investigates various scenarios of inventory control to find out the most appropriate scheme to reduce the total economic loss. Quantification of the potential loss could help industry managers to evaluate the performance of the supply chain for the considered port disruption risks.

While this work endeavors to develop a framework in assessing the economic losses of industries resulted from port disruption, assumptions were made in the assessment which are also the study's limitations. First, the identification of the boundaries for an industry cluster is based on the cargo flow network. The considered supply chain in the current analysis is constituted by major participants namely, the raw material supplier, cargo carrier, port, manufacturer, and consignee, as well as the insurance companies who pay for the loss according to the insured sum. However, it should be realized that an industry cluster's supply chain includes more participants such as freight forwarder and customs office. The present study does not consider the economic losses incurred by these participants. Second, in the economic loss estimations, the value of daily production is used as a measure of the actual economic losses. However, the produced units may only be sold partially and, thus, the lost sales would not have a direct relationship with the production. Therefore, we have to assume all the products can be consumed when the port disruption event occurs. Only under such consumption, the loss of production opportunities implies lost sales. Third, the setting of the four scenarios could be very different based on the different cases. For example, the process of cargo delivery has been simplified by only focusing on the seaborne transportation. In the actual cargo flow, the cargo delivery should also involve land transport. The implemented scenarios are highly dependent on the logistic services adopted by the companies. Fourth, like in the real world the considered port disruption events are sudden and difficult to be predicted. The study assumes that industry managers would not have enough time to find another supply chain to replace the current used one (i.e., an alternative port, carrier, supplier, route). Thus, the opportunity cost of the cargo transport is not included. Lastly, the current approach does not consider the extra inventory cost for the overstay of cargo at the warehouse. It assumes the volume of delayed cargo is not very large and the manufacturer or logistic company has reserved enough buffer space for the delayed cargo. Therefore, the inventory cost of delayed cargos is minimal.

The conclusions drawn from this study should be seen in the light of these limitations. The influences of these limitations to the assessment results may need further investigations in the future. Furthermore, for future studies, different types of risk mitigation strategies can be investigated. This study focuses on the role of a gateway port serving the imports and exports of industry clusters. Future researchers can extend the study to transhipment hub disruption.

Acknowledgments

The study was supported by the Singapore MPLP project, Nanyang Technological University ref. M4061473 and Research Grant ref. M060030008.

Appendix A. Explanations of the Petri Nets components

The information of the nodes and connections in the Petri Nets model is given (see Tables A.1–A.4).

Table A.1
Interpretation of transitions connected to and from Shenzhen Port and operations in the port.

Coding number	Transition name	Description
1	T1:DM:KHP-SZP	Deliver material: from Supplier in Kaohsiung to Manufacturer in Shenzhen
2	T2:PD:SZP	Port disruption in Shenzhen Port
3	T3:DLM:SZP	Damage or loss of material in Shenzhen Port
4	T4:BCP:SZP	Back up the port disruption (attempt to resume port operations)
5	T5:MS:SZP	Material staying at Shenzhen Port during the backup time of Shenzhen port disruption
6	T6:DM:SZP-Mfg	Deliver material: from Shenzhen Port to Manufacturer
12	T12:PD:SZP	Port disruption in Shenzhen Port
13	T13:DLFP:SZP	Damage or loss of finished product in Shenzhen Port
14	T14:BCP:SZP	Back up the port disruption (attempt to resume port operations)
15	T15:FPS:SZP	Finished product staying at Shenzhen Port during the backup time of Shenzhen port disruption
16	T16:DFP:SZPLBP	Deliver finished product: from Shenzhen Port to customer in Long Beach
17	T17:RFP:C	Receiving finished product at customer in Long Beach

Table A.2
Interpretation of places connected to and from Shenzhen Port and operations in the port.

Coding number	Place name	Description
1	P1:M(KHP)	Material at Supplier's port (Kaohsiung)
2	P2:M(KHPSZP):Sea	Material on the way from Kaohsiung Port to Shenzhen Port (Sea transportation)
3	P3:M(SZP)	Material staying in Shenzhen Port
4	P4:M(SZP)	Material waiting for backup in Shenzhen Port
5	P5:M(SZP-Mfg)	Material ready to be delivered from Shenzhen Port to Manufacturer
6	P6:M(SZPMfg):Inland	Material on the way from Shenzhen Port to Manufacturer (Inland transportation)
11	P11:FP (SZP)	Finished product staying in Shenzhen Port
12	P12:FP (SZP)	Finished product waiting for backup in Shenzhen Port
13	P13:FP (SZPC)	Finished product ready to be delivered from Shenzhen Port to Customer
14	P14:FP(SZPLBP):Sea	Finished product on the way from Shenzhen Port to Long Beach Port (Sea transportation)
15	P15:FP(LBP)	Finished product at Customer's port (Long Beach)

Table A.3
Interpretation of transitions in Manufacturer.

Coding number	Transition name	Description
7	T7:RM:Mfg	Receiving material at Manufacturer
8	T8:INTLEL:M	Setting up inventory level of material
9	T9:INTLEL:FP	Setting up inventory level of finished product
10	T10:MOP	Manufacturing operation for product
11	T11:DFP:Mfg-SZP	Deliver finished product: from Manufacturer to Shenzhen Port

Table A.4
Interpretation of places in Manufacturer.

Coding number	Place name	Description
7	P7:MFMO(Mfg)	Material for manufacturing operation in Manufacturer
8	P8:FP(Mfg)	Finished product in Manufacturer
9	P9:NULL	NULL
10	P10:FP(MfgSZP):Inland	Finished product on the way from Manufacturer to Shenzhen Port (Inland transportation)

References

Beer, M., Zhang, Y., Quek, S.T., Phoon, K.K., 2013. Reliability analysis with scarce information: comparing alternative approaches in a geotechnical engineering context. Struct. Saf. 41, 1–10.

Chang, S., 2000. Disasters and transport systems: loss, recovery and competition at the Port of Kobe after 1995 earthquake. J. Transp. Geogr. 8 (1), 53–65.

Chen, L.X., Chen, Y.H., Pang, Z., 2011. Dynamic pricing and inventory control in a make-to-stock queue with information on the production status. IEEE Trans. Autom. Sci. Eng. 8 (2), 361–373.

Chopra, S., Sodhi, M.S., 2004. Managing risk to avoid supply-chain breakdown. MIT Sloan Manage. Rev. 46 (1), 53–61.

Coppens, F., Lagneaux, F., Meersman, H., Sellekaerts, N., Van de Voorde, E., Van Gastel, G., Verhetsel A., 2007. Economics Impact of Port Activity: A Disaggregate Analysis – The Case of Antwerp. National Bank of Belgium Working Paper, 110.

Danielis, R., Gregori, T., 2013. An input-output-based methodology to estimate the economic role of a port: the case of the port system of the Friuli Venezia Giulia Reagion, Italy. Marit. Econ. Logist. 15 (2), 222–255.

DiPietro, G.S., Matthews, H.S., Hendrickson, C.T., 2014. Estimating economic and resilience consequences of potential navigation infrastructure failures: a case study of the Monongahela River. Transport. Res. Part A-Policy Pract. 69, 142–164.

Gómez-Herrera, E., 2013. Comparing alternative methods to estimate gravity models of bilateral trade. Empirical Econ. 44 (3), 1087–1111.

Haddad, E.A., Hewings, G.J., Perobelli, F.S., Santos, R.C., 2010. Regional effects of port infrastructure: a spatial CGE application to Brazil. Int. Regional Sci. Rev. 33 (3), 239–263.

Ham, H., Kim, T.J., Boyce, D., 2005. Assessment of economic impacts from unexpected events with an interregional commodity flow and multimodal transportation network model. Transport. Res. Part A-Policy Pract. 39 (10), 849–860.

Kajitani, Y., Cruz, A.M., Tatano, H., Nakano, K., Choi, J., Yasuda, N., 2013. Economic impacts caused by failure of a maritime global critical infrastructure – a case study of chemical facility explosion in the Straits of Malacca and Singapore. J. Transport. Secur. 6 (4), 289–313.

Kleindorfer, P.R., Saad, G.H., 2005. Managing disruption risks in supply chains. Prod. Oper. Manage. 14 (1), 53–68.

Lam, J.S.L., Dai, J., 2015. Developing supply chain security design of logistics service providers: an analytical network process-quality function deployment approach. Int. J. Phys. Distrib. Logist. Manage. 45 (7), 674–690.

Lam, J.S.L., Su, S., 2015. Disruption risks and mitigation strategies: an analysis of Asian ports. Marit. Policy Manage. 42 (5), 415–435.

Lam, J.S.L., Yip, T.L., 2012. Impact of port disruption on supply chains: a Petri Net approach. Lect. Notes Comput. Sci. 7555, 72–85.

Lewis, B.M., Erera, A.L., Nowak, M.A., White, C.C., 2013. Managing inventory in global supply chains facing port-of-entry disruption risks. Transport. Sci. 47 (2), 162–180.

Mansouri, M., Nilchiani, R., Mostashari, A., 2010. A policy making framework for resilient port infrastructure systems. Mar. Policy 34 (6), 1125–1134.

Merrick, J.R.W., van Dorp, J.R., Mazzuchi, T., Harrald, J.R., Spahn, J.E., Grabowski, M., 2002. The Prince William Sound risk assessment. Interfaces 32 (6), 25–40.

Moinzadeh, K., Aggarwal, P., 1997. Analysis of a production/inventory system subject to random disruptions. Manage. Sci. 43 (11), 1577–1588.

Omer, M., Mostashari, A., Nilchiani, R., Mansouri, M., 2012. A framework for assessing resiliency of maritime transportation systems. Marit. Policy Manage. 39 (7), 685–703.

Pak, J.Y., Yeo, G.T., Oh, S.W., Yang, Z., 2015. Port safety evaluation from a captain's perspective: the Korean experience. Saf. Sci. 72, 172–181.

Panayides, P.M., Parola, F., Lam, J.S.L., 2015. The effect of institutional factors on public–private partnership success in ports. Transport. Res. Part A: Policy Pract. 71, 110–127.
Park, J., 2008. The economic impacts of dirty bomb attacks on the Los Angeles and Long Beach Ports: applying the supply-driven NIEMO. J. Homel. Secur. Emerg. Manage. 5 (1), 1–20.
Paul, J.A., Maloni, M.J., 2010. Modeling the effects of port disasters. Marit. Econ. Logist. 12 (2), 127–146.
Petri, C., 1962. Kommunikation mit Autimaten PhD dissertation. University of Bonn.
Qi, L., Shen, Z.J.M., Snyder, L.V., 2009. A continuous-review inventory model with disruptions at both supplier and retailer. Prod. Oper. Manage. 18 (5), 516–532.
Rosoff, H., von Winterfeldt, D., 2007. A risk and economic analysis of dirty bomb attacks on the ports of Los Angeles and Long Beach. Risk Anal. 27 (3), 533–546.
Sanchez-Rodrigues, V., Potter, A., Naim, M.M., 2010. Evaluating the causes of uncertainty in logistics operations. Int. J. Logist. Manage. 21 (1), 45–64.
Shan, J., Yu, M., Lee, C.Y., 2014. An empirical investigation of the seaport's economic impact: evidence from major ports in China. Transport. Res. Part E: Logist. Transport. Rev. 69, 41–53.
Svensson, G., 2000. A conceptual framework for the analysis of vulnerability in supply chains. Int. J. Phys. Distrib. Logist. Manage. 30 (9), 731–750.
Tang, C.S., 2006. Perspectives in supply chain risk management. Int. J. Prod. Econ. 103 (2), 451–488.
Tomlin, B., 2006. On the value of mitigation and contingency strategies for managing supply chain disruption risks. Manage. Sci. 52 (5), 639–657.
Trbojevic, V.M., Carr, B.J., 2000. Risk based methodology for safety improvements in ports. J. Hazard. Mater. 71 (1–3), 467–480.
Wilson, M.C., 2007. The impact of transportation disruptions on supply chain performance. Transport. Res. Part E: Logist. Transport. Rev. 43 (4), 295–320.
Yang, Z., Ng, A.K.Y., Wang, J., 2014. A new risk quantification approach in port facility security assessment. Transport. Res. Part A: Policy Pract. 59, 72–90.
Zhang, Y., Cao, Y.Y., 2015. A fuzzy quantification approach of uncertainties in an extreme wave height modeling. Acta Oceanol. Sinica 34 (3), 90–98.
Zhang, Y., Lam, J.S.L., 2014. Non-conventional modeling of extreme significant wave height through random sets. Acta Oceanol. Sinica 33 (7), 125–130.
Zhang, Y., Lam, J.S.L., 2015a. Estimating the economic losses of port disruption due to extreme wind events. Ocean Coast. Manage. 116, 300–310.
Zhang, Y., Lam, J.S.L., 2015b. Reliability analysis of offshore structures within a time varying environment. Stoch Environ. Res. Risk Assess. 29, 1615–1636.
Zipkin, P.H., 2000. Foundations of Inventory Management. Irwin/McGraw-Hill, New York.