Risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes

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ABSTRACT
There is an increase in risks and catastrophic losses in maritime transport including ports and cargo. Significant losses have been associated with large scale natural hazards, such as earthquakes, tsunami, cyclones, and other extreme weather events. This paper identifies the main gaps in understanding maritime risks in transportation research. The gaps are attributed to insufficient empirical work available from the maritime transport and logistics research community to guide multi-risk and natural hazards impact assessment on seaport and cargo. In addition, disaster studies communities have barely made adequate efforts to understand and assess port and cargo risks arising from multi-hazards and disaster events. This paper examines existing conceptual frameworks concerning exposure and risk assessments of natural catastrophe’s impacts. Furthermore, the paper identifies trends and gaps in risk assessment frameworks in the field of disaster studies that can be beneficial for maritime risk research. The authors propose a new risk assessment framework that can guide future research and multi-hazard risk assessment processes at different scales of maritime risks.

KEYWORDS
Maritime transport; cargo; port; natural hazard; climate extreme; risk assessment

1. Introduction

Ports and shipping are exposed to higher risks due to rapid changing environments (Notteboom and Lam 2014; WEF 2013). United Nations Conference on Trade and Development (UNCTAD)’s World Maritime Report 2011 boldly highlights the extreme events such as floods and cyclones in Australia and earthquakes in Japan become serious challenges to the world economy (UNCTAD 2011). Natural hazards and extreme climate events can be considered as ‘non-traditional risk’ despite long history of their effects on damages and losses in maritime transport. Over the past decades, there has been an increase in the number of natural hazards and catastrophic events (UNISDR 2009, 2011; IPCC 2011; EMDAT 2015; WEF 2013). While the number of death due to natural hazards decreases, there is an increase in economic losses and the number of people affected by natural hazards notably during the last four decades (EMDAT 2015).

Over 90% of global trade volumes are carried by sea. Maritime transport as a value driven system (Robinson 2002) and a capital-intensive industry is the backbone of global economic development (Berle, Asbjørnslett, and Rice 2011). The world food system depends on global supply chains served by maritime transport (Godfray et al. 2011). Therefore, seaports can be considered as critical infrastructure and lifelines for most countries. Climate extremes are likely to affect maritime sectors because there is strong evidence of more-intense precipitation...
extremes over the last decades (Seung-Ki et al. 2011) and changing patterns in accumulated
cyclone energy notably in North Atlantic, Northwest Pacific and North Indian (Klotzbach
2006; IPCC 2011). There is an increase in economic losses from weather- and climate-related
disasters and the estimates of annual losses have been around US$ 200 billion during 1980–
2010 (IPCC 2011).

An increase in risks from natural hazards means that maritime sectors are more exposed to
both geological hazards (e.g. tsunami-genic earthquakes) and climate extremes (e.g. super
cyclones, hurricanes and coastal floods) (Lam and Su 2015). The good news is that since 1990s,
awareness of the risks in the maritime sectors is also increasing. The maritime industry has been
adapting to the escalating risks by adopting a ‘risk-based “goal setting” regime’ (Wang 2006, 3).
Existing literature suggests that risk management has been partly considered by maritime trans-
port stakeholders. Wang (2006) argues that some international safety-related marine regulations
have been driven by the serious accidents where some of the accidents were associated with
extreme weather. Steep increase in the international safety regulations for maritime transport
during 1980–2000 has been associated with the responses to natural catastrophe events (Alderton
and Leggate 2005).

Nevertheless, a recent global survey by Becker, Inoue, and Fischer (2012) from 93 world
seaports reveals the mismatch in seaports’ capital planning cycle which is often limited to only
5–10 years. This is much shorter than the design lifespan of ports of about 30–50 years. In
addition, recent climate models suggest that adaptation for ports’ planning should be between
50–100 years. Proper practice in ports’ protection in Japan even suggests that port planning
should consider at least a 200-year return period of disasters such as tsunami and earthquakes
(Normile 2012).

Recently, there is a serious call from academia for transport stakeholders to take proactive
rational planning for natural hazards in supply chains (Knemeyer, Zinn, and Ergüloğlu 2009).
Despite the claim from Wang (2006) that maritime stakeholders have just been adopting the
risk-based policy, our literature review reveals that research on maritime transport and marine
cargo exposure to natural hazards has not been adequately developed. This field requires more
scientific investigation and exploration. Maritime transport researchers can ask whether pre-
sent world seaports, shipyards as well as other marine structures are able to stand against
future natural hazards and disaster risks in a longer time span. Boin, Kelle, and Whybark
(2010) argue for the ‘missing element’ in the supply chain studies and call for the birth of a
new field of study towards a more resilient supply chains system (see also Lam and Dai 2015;
Mansouri, Roshanak, and Ali 2010). There is also a call for research on maritime risk in the
key zones of maritime global critical infrastructure such as Malacca Straits and major East
Asian ports in order to anticipate disruptions in the global supply chain as large scale maritime
disasters can have cascading effects on global trade and economic network (Kyoto University
and IRGC 2011).

Hence, the objective of this paper is twofold. The first is to examine existing frameworks for
risk assessment in general and in particular exposure analysis of marine portfolios, primarily
exposure of marine cargo and port facilities to natural catastrophes. Furthermore, the study
identifies trends and gaps in risk assessment concepts and framework in the field of disaster
studies that can be beneficial for maritime risk research. The second, the authors propose a new
risk assessment framework that can guide future research and multi-hazard risk assessment
process at different scales of maritime risks.

The rest of the paper is structured as follows: Section 2 highlights existing studies on exposures,
vulnerabilities and risks of maritime transport to natural catastrophes. It also highlights research
gaps in both maritime transport and disasters studies concerning maritime risks. Section 3
examines existing risk, exposure and vulnerability assessment frameworks. A new framework
for seaports is proposed in Section 4. Final remarks concerning implications and future research
agendas are given in Section 5.
2. An overview of maritime transport exposure to natural hazards and climate extremes

Catastrophe risks of maritime transport have been investigated and discussed by different fields and research communities where each field uses its own methods, concepts, frameworks and models of risk. We identified several key research clusters that recently demonstrate interests in investigating maritime catastrophe risks, namely operations management and supply chain or production economics, climate change, hazards and disaster studies, and transport studies in general and in particular maritime transport. This section provides an up-to-date overview of these studies and identifies the research gaps.

2.1. Observed risk hierarchy in maritime transport

There has been a solid focus on regular operational risks made by maritime transport stakeholders. However, the stakeholders have a lack of awareness of exposure to natural hazards (Berle, Asbjørnslett, and Rice 2011). In addition, Berle, Asbjørnslett, and Rice’s (2011) observation confirms the fact that there is a lack of methods for addressing and planning for ‘low-frequency high-impact disruption scenarios’. Vilko and Hallikas (2012) and WEF (2013) have also provided similar findings concerning ‘low-frequency high-impact disruption scenarios’ in the context of maritime risks. With some modification, in Figure 1(a) we visualize Vilko and Hallikas’ (2012) and WEF (2013) observations concerning the fact that the maritime industry has paid attention to the daily port, shipping, and cargo risks namely operational risks (e.g. ship collision in the approach lane, lack of cargo-handling equipment, negligence) (Li, Yin, and Fan 2014a, 2014b) and supply risks (hazardous materials, lack of intermodal/multimodal equipment, bottlenecks in transportation routes, capacity problems in rail and road traffic, labor strikes at ports, etc.). In the middle of Figure 1(a), there are security risks (e.g. organized crime, drunken driver, terrorism) (Pristrom et al. 2013), policy risks (e.g. problems with customs clearance), macro risks (e.g. financial crisis). WEF (2013) views ‘environmental risk’ as natural hazards, while Vilko and Hallikas (2012) consider nuclear disasters nearby plants, oil catastrophe in shipping lanes and ports, ice conditions in winter, fire, epidemic and climate change as major examples of environmental risk. However, climate change is loosely mentioned and barely explored. We propose that the term climate extremes would be more suitable as a hazard since climate change is a very long

![Figure 1](image.png)

Figure 1. (a) Risk Hierarchy in Maritime Transport. (b) Spectrums of risk sources.
Source: (a) Authors. (b) Authors, adapted from Smith and Petley (2009), WEF (2013) and Bogardi et al. (2009).
term process which may or may not pose real risks. In Figure 1(a), we add climate extremes and earthquakes/tsunamis to the list of Vilko and Hallikas (2012) to formulate the risk hierarchy.

Berle, Rice, and Asbjørnslett (2011) and Vilko and Hallikas (2012) confirm the ‘risk hierarchy’ phenomenon in many local communities where there are tensions between ‘high-probability low consequence events’ versus ‘low-probability high consequence events’ in the context of maritime risk management. From disaster studies, Bogardi et al. (2009) find the tension between the everyday risks (such as poverty and urgent daily needs) versus prioritized long return period events such as tsunamis and super cyclones.

Referring to Figure 1(b), the spectrum of risk sources can be used to explain the natural and human systems (Smith and Petley 2009). Some hazards are considered as voluntary because they are more likely to be manmade. The involuntary hazards are the natural ones, while some hazards are considered as ‘in-between’ events such as climate extremes related hazards which are caused by complex interactions of human intervention and natural response. So far the stakeholders in maritime transport have paid more attention to the voluntary and manmade hazards while there is more to be done in the management of involuntary and natural hazards (Vilko and Hallikas 2012). Hazards can also be classified as intensive or extensive. Intensive hazards refer to the fact that natural hazards such as earthquakes and tsunami often concentrate on a specific spatial reality. Extensive hazards are defined as diffused events (Smith and Petley 2009) or events that occur more frequently elsewhere at smaller scales (UNSIDR 2009, 2011).

### 2.2. Impact of natural hazards on ports and cargo shipping

Evidence on disruptions of seaports because of natural hazards has been observed globally throughout human history. There is strong evidence that natural hazards and disasters disrupted maritime transport infrastructure and facilities. However, systematic records of the events remain lacking. Famous events include, for example, the Vesuvius eruption that buried Pompeii port and destroyed Naples ports (De Carolis and Patricelli 2003). The 1755 Great Lisbon Earthquake – the first modern disaster as once argued by Dynes (1997) – is one of the examples of how natural hazards could fundamentally halt the progress of an international port and its competitiveness during the eighteenth century. The history suggests that long term investment in ports that are exposed to certain natural hazards need to be evaluated systematically.

Some recent disasters in modern times had created serious damages and losses in ports. For instance, the MW 6.9 earthquake hit the port city of Kobe, Japan on 17 January 1995. In addition to the city’s damage, the earthquake triggered disasters that created systemic risks as it disrupted international supply chains such as shocks in computer production in Europe (Waters 2011). The Kobe seaport stopped operating for 2 months (Waters 2011) as it was heavily damaged (Chang 2000, 2010; Werner, Dickenson, and Taylor 1997; Werner 1998). Total economic loss is over US$ 100 billion in damage (Chang 2010). Chang (2010) provides quantitative evidence that Kobe’s economic performance such as income per capita and regional gross income during 1991–2004 experienced negative trend. Kobe earthquake had accelerated the decreasing rate of Kobe seaport’s competitiveness. The seaport was ranked at sixth globally in 1994 but later it was ranked 14th in 1997 and today it is ranked 28th in 2011. Cargo traffic, especially the container transshipments in 1995 at the port of Kobe fell down 60% from the 1994’s level. There was a small increase from the 1995’s level during 1996–2000 but since then, container transshipment call at Kobe was plunged more than 95% from the 1994’s level (Chang 2010). Kobe’s share of cargo traffic has been permanently lost to other Japanese seaports.

The Indian Ocean Tsunami in 2004 caused transoceanic impact which created heavy damages and losses at ports from Aceh ports (Indonesia) to other 15 countries’ coasts. Some traditional and small ports in faraway coasts such as Xaafuun Peninsula in Somalia (or 5000 km from the tsunami source in Indonesia) also experienced damages (Synolakis and Kong 2006).
The most recent incident is the Great Tohoku Tsunami (MW 9) occurred on 11 March 2011 which triggered tsunamis that hit many coastal cities in Japan. Tsunami run-up and heights in some of the spots reached up to 39 m (Mimura et al. 2011). Damage and loss assessment reports reveal that the total economic loss resulting from the tsunami-genic earthquake could be between 16 and 25 trillion yen (i.e. US$ 200–303 billion) (Dunbar et al. 2011). Munich Re reports that the overall earthquakes and weather-related catastrophes in 2011 are the costliest year ever, recorded a total natural catastrophe losses at about US$ 380 billion and total insured losses of US$ 105 billion (www.munichre.com). The Tohoku earthquake in March 2011 damaged not only Japanese seaports but also long distance seaports in California. A recent finding suggests that the total economic loss for California State was US$ 48 million (www.coastal.ca.gov).

2.3. Impact of climate extremes on global seaports

Coastal and port cities are also likely to be more exposed to climate extremes. The details concerning the impact of climate extremes are reported by IPCC (2011), showing that there will be increasing losses from hurricanes in the United States and the Caribbean and other sea basins. Using global data of 2005, Hanson et al. (2011) note that 13 out of 20 most populated world cities were port cities. Recent climate extremes at port cities that led to catastrophic damage can be exemplified by Katrina disasters where New Orleans in the United States experienced serious disruption and world record economic losses for 2005. In Asia, the extremes were exemplified by Pakistan floods in 2010 and Bangkok floods in 2011 where the events made national records in terms of historical damage and losses.

Hanson et al.’s (2011) scenarios of exposed assets and wealth at the port cities suggest that by 2070, 8 of the top 20 port cities are located in OECD countries such as United States (four cities: Miami, New York, New Orleans and Virginia Beach), Japan (two cities: Tokyo and Nagoya), and Netherlands (Amsterdam and Rotterdam). Asia contributes 12 cities to the top 20. China dominates the list with six cities (Guangzhou, Shanghai, Tianjin, Hong Kong, Ningbo, and Qingdao). Importantly, the speed of change in the increase of exposed assets is tremendous (Hanson et al. 2011). By percentage, Ningbo will likely to rise 12,000%, Dhaka and Kolkata will rise more than 6000%, while Bangkok, and Jakarta are likely to rise above 2500% in terms of exposed assets at ports. Based on the economic loss estimation due to extreme wind events done by Zhang and Lam (2015), it is also expected that Chinese ports such as Shanghai, Ningbo, and Shenzhen face increasing exposure as cargo and shipping volumes increase.

The problem is that, in general, there is insufficient port planning to natural hazards and adaptation. Based on the global survey from 93 ports, Becker, Inoue, and Fischer (2012) find that most ports have less than 10 years of planning horizon. As market evolves, port policy makers expand their facilities such as by building terminals, berths and land acquisition. Only a small percentage of seaports have forthcoming projects adapting to natural hazards. In fact, most ports only consider natural forces such as coastal flooding and they have already built infrastructure to protect port operations through building new breakwaters or storm barriers that would mitigate flooding and wave damage. However, their hazards scenarios are short term. Becker, Inoue, and Fischer (2012) highlight the fact that only 3 (without mentioning exactly where) out of 93 ports representing 3.2% planned to build protective structures while 22% made no plans to develop within the next 10 years.

2.4. Research gaps

Based on the literature survey, there is a pressing demand for building resilience of maritime transport (Lam and Bai 2016). The call has barely been addressed by researchers by conducting multi-risk assessment in the transportation context. Gurning and Cahoon (2011) is one of the few who analyze multi-mitigation scenarios anticipating maritime disruptions arising from different
hazards. They provide a framework which treats hazards as stimulators (e.g. severe weather states, tsunamis, and earthquakes) which can lead to disruptions, and then in turn create loss of earnings and loss of economic benefits. Cox, Prager, and Rose (2011) employ some concepts such as resilience and vulnerability from disaster and hazards studies to demonstrate the need for transportation system resilience measures. They suggest tools for prospective resilience measures for decision-makers. However, their study is exclusively focused on terrorism (London bombings).

It has been long observed that transport risk is associated with climate and weather (Andrey 2010). Even though it was obvious for civil engineers and ports designers to consider climate variables (such as wind velocity, floods’ return periods, and tidal waves history) to be calculated in the ports’ infrastructure reliability, our literature review suggests that more scientific research concerning multi-hazard risk assessment should be made systematically.

3. Examining risk, exposure, and vulnerability assessment frameworks

Supply chain literature defines risk as undesired consequences and a function of probability of loss and the significant of its consequences (Vilko and Hallikas 2012). The risk is presumably operationalized at the sea-land interface of the maritime transportation system which includes port environment and navigable waterways (vessel, terminal operations, intermodal connection point, road, rail, pipelines, bridges) and public infrastructure (highway, rail, pipeline system) (Berle, Asbjørnslett, and Rice 2011). This section provides insights from disaster studies research.

Disaster studies communities use different approaches to define risks. Natural hazards such as volcano eruption also take place in the other planets within our Solar System (and also outside our galaxy – see Glaze, Baloga, and Wimert 2011). Regardless of the scale of the events, they are simply natural happenings. There will be neither disasters nor catastrophes if the events cause no loss to human system on earth. Therefore, talking disasters is always anthropocentric. This level of understanding has been long maintained in the field of disasters studies. Existing literature challenges the term natural disaster – it is often mentioned in quotation ‘natural disaster’ to stress the important findings in early 1970s to reject the term ‘natural disaster’ through taking the naturalness out of natural disasters (O’Keefe, Westgate, and Wisner 1976; Wisner et al. 2004).

Alexander (1993, 4) defines ‘natural disaster’ as ‘some rapid instantaneous or profound impact of the natural environment upon socioeconomic system’. Four definitions of a natural hazard are considered by Alexander: a naturally occurring man-made geologic condition or phenomenon that presents a risk or is a potential danger to life or property; an interaction of people and nature governed by the coexistence state of adjustment of the human use system and the state of nature in the natural events system; ‘those elements in the physical environment [which are] harmful to man and caused by forces extraneous to him’; and the probability of occurrences within a specified period of time and within a given area of a potentially damaging phenomenon (Alexander 1993, 4). The highlight is the interaction between human life and natural phenomena. Such an interaction has increased since humans as a society have become dependent on these systems, thus a natural hazard could become disastrous to humans.

Also pointing out the interaction with humans, Burton, Kates, and White (1993) argue that disaster risk is a result of interaction between human–infrastructure systems and natural systems. The human–infrastructure system is associated with the term vulnerability which is either undefined or treated loosely as weakness of the transport network (Nagurney and Qiang 2009).

In 1982, the United Nations Office for Disaster Relief (UNDRO) defined risk as $R = EVH$, where $E$ denotes the element at risks measured by level of exposure of exposed population, properties, and valuable economic assets, $V$ denotes vulnerability function such as economic, social, and environmental vulnerability, $H$ denotes a natural hazard function which can be manifested in floods, tropical cyclones, tsunamis, and earthquakes (Alexander 1993). The 1982 UNDRO’s approach to risk and vulnerability assessment remains influential today.
There are different theoretical models for disaster risk assessment at global scale as categorized in Table 1 and Figure 2. Similar to the UNDRO model, Global Earthquake Model (GEM) defines risk and impact as a function of three components: hazard, exposure, and vulnerability (or namely triple helix – see Figure 2(c)). GEM defines a hazard as the probability levels of hazard occurrence. For instance, in the context of seismic hazard it can be the probability level of ground shaking resulting from earthquakes, within a given time span. Vulnerability is defined as the probability of loss given a level of ground shaking for physical vulnerability, or through indicators that envelop the socioeconomic factors known to be the driving forces of vulnerability. Exposure is the elements at risk (people, value, and assets) being exposed to natural hazards (GEM 2015).

World Risk Index, developed by United Nations University provides a slightly different function: Risk equals $E \times V$, where $E$ is the exposure to natural hazards, and $V$ is the vulnerability comprising average values of susceptibility (or likelihood of suffering harm), lack of coping capacity to reduce negative consequences during a disaster, and lack of adaptive capacity (for long-term strategies for societal change). Each component of vulnerability received a weighting factor 0.33 (UNU-EHS 2014).

In a rather established research tradition, especially in natural hazard and disaster risk research communities, ‘exposure’ is defined as the number of element or unit (e.g. of people, valuable goods/infrastructure, and activities) that is likely to experience and potentially be adversely affected by natural hazards (Peduzzi et al. 2009).

UNDP (2004) defines ‘vulnerability’ as a condition or process resulting from physical, social, economic and environmental factors that determine the likelihood and scale of damage from the impact of a given hazard. Disaster Risk Index (DRI) developed by UNDP (2004) is known as the first human vulnerability assessment exercise on a global scale, namely, a country-by-country comparison of human vulnerability and exposure to earthquakes, tropical cyclones, and flood hazards. The DRI consists of two indicators: the first is the Relative Vulnerability Index (RVI), which compares national data for exposed populations with recorded mortality. The second is the socioeconomic indicators of vulnerability at the national level, which refer to GDP per capita and

Table 1. Recent applications of global scale disaster risk assessment.

<table>
<thead>
<tr>
<th>Type of assessment</th>
<th>Risk function and/or indicators</th>
<th>Model as shown in Figure 2</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global port climate extreme exposure</td>
<td>Present and future exposure, global sea level rise, and exposed assets in GDP by elevation and extreme water levels</td>
<td>(a)</td>
<td>Hanson et al. (2011), Nicholls et al. (2008)</td>
</tr>
<tr>
<td>Global disaster risk mapping</td>
<td>Hazard (earthquakes: peak ground acceleration, liquefaction, wind forces), vulnerability and exposure (GDP, human development index, asset specifics such critical infrastructures)</td>
<td>(c)</td>
<td>GEM and Syner-G (<a href="http://www.vce.at/SYNER-G">www.vce.at/SYNER-G</a>) 2015</td>
</tr>
<tr>
<td>World Risk Index</td>
<td>Exposure to natural hazards; vulnerabilities measured by susceptibility (public infrastructure, poverty), coping capacities (government and authority) and adaptive capacities (education, adaptation, investment)</td>
<td>(b)</td>
<td>UNU-EHS (2014)</td>
</tr>
<tr>
<td>Disaster risk index</td>
<td>Relative Vulnerability Index and social-economic indicators (GDP, Human development index)</td>
<td>(b)</td>
<td>UNDP (2004)</td>
</tr>
<tr>
<td>Global disaster risk hotspots</td>
<td>Hazards hotspots (geographic distribution of hazards) and element at risks (exposed people and assets).</td>
<td>(a)</td>
<td>Arnold et al. (2005)</td>
</tr>
<tr>
<td>Global exposure and vulnerability towards natural hazards</td>
<td>Frequency of a given hazard that may occur at a unit (e.g. population) in a given exposed area and socio-political-economic context of this population.</td>
<td>(a)</td>
<td>Peduzzi et al. (2009)</td>
</tr>
</tbody>
</table>

Source: Compiled by authors.
density of population. Hanson et al. (2011) adopts a similar concept to demonstrate global climate change exposure assessment of ports and cities.

Global Disaster Risk Hotspots (GDRH) is another model developed for the sub-national scale for individual hazard analysis. The GDRH model includes assessment of disaster mortality data, economic losses, and the risk of economic loss as a proportion of GDP. In addition to these indicators, GDRH includes social–economic vulnerability indicators such as gross domestic product per inhabitant at purchasing power parity, Human Poverty Index (HPI), total debt serviced (percentage of the exports of goods and services), inflation, annual food prices, and unemployment (percentage of total labor force) (see Arnold et al. 2005).

Smith and Petley (2009) coined to term risk as double helix (Figure 2(a,b)) to illustrate the view concerning DNA code of risks as a joined and intertwined strands of DNA that underpin disasters. One strand represents social system (vulnerability) and the other represents natural systems (hazards). The two elements hazards and vulnerability are interwoven and interlinked like a DNA double helix – disasters arise from the complexity between them (Smith and Petley 2009). Paleo (2009) suggests exposure as part of vulnerability concepts and components (Figure 2(a)).

Figure 2(a,b) visualize the risk models displayed in Table 1. There are four risk scenarios. R1 denotes risk that is a function of perfect match between hazards, exposure and vulnerability (or disaster risks arise from a perfect match between hazards event, exposed assets/people and vulnerability of assets/people). R1 is the core of risks to be measured. R2 represents the fact like exposed buildings in Tokyo could stand against earthquakes in March 2011 since resilience of the buildings is higher than the seismic force translated to the buildings. R3 and R4 are ambiguous.
concepts because modelers often prefer double helix as an easy approach to separate vulnerability and exposure (assets at risks). However, they can be useful in illustrating the richness of risk as triple helix concept. R3 can be exemplified by vulnerability of port platforms that may fail from regular dynamic loads (especially those not from the seismic activity) or fatigue of structures due to regular dynamic loads on the platforms (such as mobile loads from trucks on the ports’ platforms). Other examples can also be attributed to the real risk that is rooted not from tsunami forces but due to failure to anticipate regular high tides in the design of ports. R4 shows that exposure as an embedded concept to vulnerability, which exemplifies the vulnerability of a port system or structure which may experience failure or collapse. The port may fail to cope with regular forces for instance in fatigue due to long term gravity forces (life and dead loads) over that may be rooted in either poor design or poor construction.

Figure 2(c) is called triple helix. Recent practice of risk as Triple Helix can be seen in IPCC (2011), GEM and Kakderi, Raptakis, and Pitilakis (2009). Despite World Risk Index 2014 uses R1 model (Figure 2(b)) where exposure is viewed as part of hazards, GEM seems to favor the illustrations described in Figure 2(a,c). Peduzzi et al. (2009) use R1 (regardless of Figure 2(a) or 2(b)) to consider exposure and natural hazards: in case of risk of asset losses, the element at risk is the exposed assets. The element at risk is the exposure function. Hazard refers to the frequency of returning period at a given magnitude. Borrowing from Wisner et al. (2004), Peduzzi et al. (2009) provide quantitative vulnerability measures as the degree of loss to each element should a hazard of a given intensity, frequency, and duration occur.

4. A framework for risk assessment at seaports

After examining the various frameworks earlier, the study has established the distinction and relationship between natural hazards, exposure, and vulnerability. Our analysis reveals that there are different developed risk assessment models to be used for maritime transport exposure to natural hazards. The reason behind this is due to the fact that various models were developed to answer different needs, hazards and purposes. Different academic disciplines use different terminologies and definitions. In addition, the purpose of risk assessment determines the required data and models. For instance, for the insurance industry, the main objective for risk assessment is to calculate quantitative risks that can be used for risk transfer policy and insurance premium calculation. For governments, a risk assessment may serve different societal and economic goals including social and environmental protection, risk reduction measures, allocation of resources for protection and investment as well as devising a more realistic public-private partnership in risk management.

Regardless of the difference in models, a systematic classification of the exposed elements and hazards is important for maritime risk assessment. The exposed elements can be classified as (1) building (warehouse, office buildings, maintenance buildings, passenger terminals, traffic control buildings); (2) utility systems (electric power system, water system, waste-water system, natural gas system, liquid fuel system, communication system, fire-fighting system); (3) transportation infrastructure (road system, railway system, bridges) (Kakderi, Raptakis, and Pitilakis 2009). Then the types of hazards can be identified with details on hazard indicators and scales of intensity, as shown in Table 2. With this understanding, the following illustration deepens the discussion by specifying risk quantification with a focus on ports.

It should be noted that exposure is not a standalone concept. Exposure is always embedded to either hazards or vulnerability as discussed in Section 3. Figure 2(a,b) show that risk is a function of hazards (can be in terms of the likelihood of a tsunami inundation and/or run-up) that may hit a specific location at ports consisting of cargo terminals, warehouses, and others. For this, the risk \( R \) of an exposed maritime transport asset to a single hazard \( H \) such as tsunami is multiplied by the ability of the asset to withstand tsunami forces. This can be hypothesized as such:
Recent tsunami-genic earthquakes in Tsukuba Japan (2011), Indian Ocean Tsunami 2004 and Kobe earthquake (1995) suggest that maritime transport elements or assets can be hit rather simultaneously by both earthquakes (e.g. foreshocks, main earthquakes, and high aftershocks) followed by a tsunami. For this, the quantitative expression can be made as

\[ R = H(\text{tsunami}) * \text{Exposed asset} * \text{Vul asset}. \]  

(1)

The actual manifestation of risk can be the number of cargo loss per event, which can be measured by metric tons or TEUs or real monetary values depending on data availability. Exposure assessment requires time dimension, e.g. how long an event of a particular natural hazard occurs in a certain element of a seaport (see Table 2). For aggregation of risk, this can be the number of maximum cargo and valuable assets at certain periods. For instance, assuming that seaports in the Philippines, Japan, and Taiwan also experience multi hazards such as tsunami, earthquakes, cyclones, and coastal floods, the risk function is largely modified by the number of hazards and the nature of exposure of the assets (flood zone versus tsunami inundation scenarios) and the vulnerability of the structures of seaport elements.

\[ R = H(\text{tsunami + earthquakes}) * \text{Exposed asset} * \text{Vul asset}. \]  

(2)

Exposures to multi-hazards can be expressed in Equation (3), where \( E \) is exposure, that is, a seaport element that is exposed, which is assumed to face different types of natural hazards \( (H) \), where \( i \) denotes the hazard indicator (from Table 2). \( V \) is vulnerability measured by a single element such as physical reliability of seaport structures. We define vulnerability as the reverse of resilience. Vulnerability can be reduced only to physical vulnerability of the existing seaport elements. However, existing concepts such as UNU-EHS (2014) can be used to demonstrate vulnerability indicators such as susceptibility, cf. Table 1 and Section 3, lack of coping capacity to reduce negative consequences during a disaster and lack of adaptive capacity for long-term strategies of ports (see Becker, Inoue, and Fischer 2012).

Hence, based on a comprehensive examination of the existing literature and information on past catastrophes, the framework and data required for a comprehensive seaport risk assessment is proposed as five key steps of exposure analysis as seen in Table 3. We suggest that exposure is an overarching variable. Exposure indicators include data on assets and values of ports, volume and values

\[ R = \sum_{i}^{n} (HE)V. \]  

(3)
of cargo, global ports database, potential inundation and run-up of tsunami, seasonal ships, and fleets at targeted ports. Natural hazard includes data such as global active faults seismic sources database, global seismic maps and history, global cyclone history and tracks, local flood history and local liquefaction map at targeted ports. Vulnerability indicators mainly focus on physical vulnerability such as liquefaction reliability of port structures. It is also essential to assess risk management measures including emergency/crisis management measures, fire mitigation measures, number of safety incidents, port management quality, insurance cover, and existence of disaster recovery planning.

Researchers have made clear messages that analyzing the future risks such as climate extremes cannot be simply based on past events database because of the limitation of recorded events and data (Hanson et al. 2011). Modern port development such as container systems and intermodal development have just started in 1960s. Amid a lack of recorded data from past events before 1960s, we suggest to use scenario based exposure analysis (e.g. Hallegatte et al. 2011).

One of the key challenges is data availability at smaller units and higher resolution data. On a positive note, amid the lack of historical data, computer-generated data for certain

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### Table 3. Proposed risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes.

<table>
<thead>
<tr>
<th>Key steps</th>
<th>Variables</th>
<th>Indicators</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1. Hazards identification</strong></td>
<td>Climatic hazards</td>
<td>Cyclone history and scenario; storm surge history and scenario</td>
<td>Historical climate data (e.g. recorded cyclone tracks); historical damage and loss</td>
</tr>
<tr>
<td></td>
<td>Geological hazards</td>
<td>Earthquake impact history and scenario; Tsunami inundation history and scenario</td>
<td>Seismic maps; historical earthquake and tsunami record</td>
</tr>
<tr>
<td><strong>Step 2. Identify physical vulnerability of ports including present and future effectiveness</strong></td>
<td>Earthquake mitigation measures</td>
<td>Physical/structural behavior under seismic influence</td>
<td>Earthquake scenario (e.g. peak ground acceleration)</td>
</tr>
<tr>
<td></td>
<td>Wind mitigation measures</td>
<td>Structural and infrastructural behavior under extreme wind</td>
<td>Wind scenario inundation scenario</td>
</tr>
<tr>
<td></td>
<td>Tsunami counter measures</td>
<td>Structural and infrastructural behavior during tsunamis</td>
<td>Tsunami inundation scenario; Potential sea current behavior</td>
</tr>
<tr>
<td></td>
<td>Liquefaction reliability of port structures</td>
<td>Potential liquefaction analysis</td>
<td>Liquefaction history; Soil behavior data</td>
</tr>
<tr>
<td><strong>Step 3. Identify risk management measures at seaports and beyond</strong></td>
<td>Emergency preparedness, crisis management and contingency planning</td>
<td>Contingency plans; risk management plans</td>
<td>Contingency planning documents; Crisis management documents</td>
</tr>
<tr>
<td></td>
<td>Fire mitigation measures</td>
<td>Fire mitigation measures (e.g. for post-earthquakes)</td>
<td>Fire incident history; Fire incident document</td>
</tr>
<tr>
<td></td>
<td>Port management quality</td>
<td>Port management quality</td>
<td>Recovery planning documents</td>
</tr>
<tr>
<td></td>
<td>Disaster recovery planning</td>
<td>Disaster recovery plans</td>
<td>Recovery planning documents</td>
</tr>
<tr>
<td></td>
<td>Risk transfers</td>
<td>Insurance cover</td>
<td>Insurance empirical data</td>
</tr>
<tr>
<td></td>
<td>Incident command systems</td>
<td>Safety incident history</td>
<td>Past incident lists</td>
</tr>
<tr>
<td><strong>Step 4. Identify assets and asset valuation</strong></td>
<td>Cargo volume and value</td>
<td>Existing and projected cargo volume and value</td>
<td>Cargo statistics; Shipment and transshipment statistics</td>
</tr>
<tr>
<td></td>
<td>Total values of ports</td>
<td>Economic valuation of port assets</td>
<td>Detailed valuation of each component of port facilities and infrastructure</td>
</tr>
<tr>
<td></td>
<td>Total wealth of port cities</td>
<td>Economic valuation of ports and port cities</td>
<td>Wealth statistics; welfare statistics; economic growth</td>
</tr>
<tr>
<td></td>
<td>Port dependent work force</td>
<td>Human resources</td>
<td>Disaggregated statistics on labor force; highly skilled workers, etc.</td>
</tr>
<tr>
<td><strong>Step 5. Exposure analysis [total risk]</strong></td>
<td>Exposure analysis</td>
<td>Exposure of port elements to different hazards and vulnerability scenarios</td>
<td>Analyze potential exposed assets; aggregation of risk</td>
</tr>
</tbody>
</table>

Source: Authors.
hazards can be obtained by specialists. Modelled/simulated data can be used to calculate relative exposure level of seaports to certain threats from natural hazards. Table 3 presents the projected needs for risk assessment of seaports to multi-hazards at various scales which will be useful for risk analysts and port decision makers. Previous gross analysis such as Løvholt et al. (2011) conduct a global scale tsunami exposure assessment by considering coastal areas with different elevation facing different scenarios of tsunami inundation. Hanson et al. (2011) investigate the exposed assets and people living in coastal cities that are likely to experience coastal flooding and climate extremes, breakdown by elevation. However, Løvholt et al. (2011) and Hanson et al. (2011) basically ignored vulnerability as their research questions address a gross assessment of the areas and assets/people that are potentially affected by natural hazards. Despite some contributions from previous studies concerning the real need to take natural hazards into port risk management, global studies may provide limited benefits for seaport level decision making. Being different from the literature, the proposed framework includes vulnerability and also outlines various groups of variables in a systematic manner.

5. Conclusions and recommendations for future research

Exposure is an intermediary concept that seeks to explain harmful outcomes of the processes between natural hazards (natural system) and the infrastructure/built environment context (human system). By ‘nature’, any seaport infrastructure system and marine cargo shipping has been exposed to one or more (natural) forces capable of creating damages and losses. Some are considered normal and seasonal events such as heavy rainfall combined by fog which create poor visibility for shipping. These are normal parameters of climate variability. Some can be considered extreme events that occur incidentally based on certain return periods (from annual, decadal, century and millenniums). The extreme events often lead to catastrophic outcomes and may cause heavy disruption. This paper adds value to maritime policy and research by critically assessing the concepts and existing conceptual frameworks. We argue for a risk assessment meaningful for seaports and shipping managers and wider stakeholders. Assessment models should provide clearer and sharper guidance pertaining to real world risk management and risk reduction decision making along maritime transport and supply chains. Different scales of analysis and different scenarios should be provided. For instance, despite some level of uncertainty, cyclones do not occur randomly because level of exposures must also relate to its spatiality in certain latitude as shown in the historical cyclone tracks occur at a particular time. Therefore, the scenarios should include a seasonal timeframe when certain cargo quantity of TEUs or tonnages is situated in a particular time (e.g. monthly peak season instead of annual aggregation) in a particular seaport.

We conclude that new and comprehensive risk assessment frameworks for marine exposure to different natural hazards are needed to answer different needs of risk management decision making at different levels. The proposed framework in Section 4 presents an original contribution that can be used as one of the alternative frameworks for future agendas concerning catastrophic risk assessment of seaports at different scales. Each risk assessment model can suggest different policy implications in maritime transport policy. Present exercises in risk assessment have been largely limited to a single natural hazard approach. Therefore, for future research agenda, one can assess multi-hazard scenarios and the impacts on maritime transport. In addition, research can be extended to investigate the interplay between existing human-made hazards and multi-hazards and their impact on both maritime transport and supply chains. Social-economic and political implications of multi-stressors and complex interplay between the hazards can be considerable and are important topics which deserve more research.
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