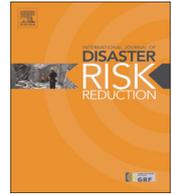




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# Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making

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## ABSTRACT

This paper investigates the impact of floods on the global economy through supply chains, and proposes measures for the related supply chain risk. We examine Thailand's 2011 flood since it is a notable example of the impact of floods both on industries and the whole economy. The protracted floods affected the primary industrial sectors in Thailand, i.e., the automotive and electronics industries, with a devastating impact on the whole economy. The impact of natural hazards on the global supply chain is increasing. However, the impact on each firm that is exposed is different depending on how well they are prepared and how they respond to the risks. Designing supply chains in a more resilient way will ultimately reduce risks to the economy. Comparing different supply chains and industries' structure in Thailand, this study identifies the factors in private investment decision-making, such as *locations of facilities, alternate locations of production, the diversified sources of procurement, emergent assistance from other partner companies in the same supply chain, and degree of the recovery of customers* and proposes a hypothesis and related questions for future research.

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## 1. Introduction

Floods on one side of the earth affect the economy on the other side of the earth through global supply chain networks. Today's global supply chain has achieved cost reduction by reducing inventory, shortening transportation timelines, and streamlining production systems. However, with lean and complex supply chains, there is much more susceptibility to systemic risk, a financial term used to describe a risk originating from one node of a financial network which then harms the entire financial market. This notion of risk is applicable to supply chains. While a more efficient production and transportation system is more capital intensive and cost efficient, in the event of a

natural disaster, the entire system may suffer disruption and break down. The Economist [1] reported that while death rates from natural disasters have been falling, their economic cost continues to increase drastically. This cost includes place based impacts and supply chain impacts. However, the latter have not been systematically reported or broken out.

According to Bolgar, [2] Accenture, a global management consulting firm, revealed that 93% of the companies studied consider supply chains as their top priority. Further, 30% of the companies attributed 5% of their lost revenue to the disruption of their supply chains. Supply chains are important, not only for a company but also for a nation. For instance, in January 2012, the Obama administration released the National Strategy for Global Supply Chain Security, which focuses on energy, container shipment, and cyber networks. For both companies and governments, weather-related hazards are one of the

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biggest sources of risk to the supply chain. A studied carried out by Zurich Financial Services Group and Business Continuity Institute [3] revealed that 51% of supply chains were affected by adverse weather over the past year. 49% of businesses lost productivity from such disruption, while their cost increased by 38% and their revenue decreased by 32%.

In this paper we (i) investigate the impacts of floods on supply chains using the case of Thailand's 2011 flooding focusing on automobile and electronics industries; and (ii) propose components that should be considered in measuring supply chain risk by proposing future research questions.

## 2. Reviews of important concepts and indices

In this section, we review some concepts to provide a context for an analysis of the Thailand floods of 2011 and other cases related to the impact of floods on supply chain networks.

### 2.1. Direct and indirect damages

There are a number of definitions of damage caused by disasters (See for example, Rose [4]). Yet, Table 1 is the common understanding among existing studies [5]. In this study, direct damage refers to the physical damage by natural hazards to facilities or equipment while indirect damage refers to the damage which is not physically damaged by natural hazards to facilities or equipment but is caused by ripple effects.

**Table 1**  
Different aspects of flood damages.  
Source: Jonkman, et al. [5].

	Tangible and priced	Intangible and unpriced
<b>Direct damage</b>	<ul style="list-style-type: none"> <li>● Residences</li> <li>● Capital assets and inventory</li> <li>● Business interruption (inside the flooded area)</li> <li>● Vehicles</li> <li>● Agricultural land and cattle</li> <li>● Roads, utility and communication infrastructure</li> <li>● Evacuation and rescue operations</li> <li>● Reconstruction of flood defenses</li> <li>● Clean up costs</li> </ul>	<ul style="list-style-type: none"> <li>● Fatalities</li> <li>● Injuries</li> <li>● Inconvenience and moral damages</li> <li>● Utilities and communication</li> <li>● Historical and cultural losses</li> <li>● Environmental losses</li> </ul>
<b>Indirect damage</b>	<ul style="list-style-type: none"> <li>● Damage for companies outside the flooded area</li> <li>● Adjustments in production and consumption patterns</li> <li>● Temporary housing of evacuees</li> </ul>	<ul style="list-style-type: none"> <li>● Societal disruption</li> <li>● Psychological Traumas</li> <li>● Undermined trust in public authorities</li> </ul>

### 2.2. Time to recovery and financial impact

Second, the performance indices that measure the impact of a disaster on supply chains are reviewed. Simchi-Levi [6] proposes the Risk Exposure Index, which assesses a cost induced by a potential disruption based on the Time to Recovery (TTR) for each level or node, and the resulting Financial Impact (FI). Those individual risk components are then summed up to obtain a comprehensive FI for the entire supply chain. There are several aspects of TTR. For example, time to resume operations, even partly, if a facility has been stopped, is a major indicator of resiliency that has frequently gained attention in the real business world. Time to return to the "pre-disaster" level of production can also be an important indicator in terms of the real impact of disruption. In the real world, Cisco Systems, Inc. has already adopted this notion of TTR, which is "...based on the longest recovery time for any critical capability within a node, and is a measure of the time required to restore 100% output at that node following a disruption [7]." Thus, to measure resiliency of supply chains or impacts of floods to supply networks, this paper will focus on TTR, the time needed for both part and full restoration.

Regarding the financial impact of the floods, the operational profits from the financial statements of a company as affected by the amount of extraordinary losses caused by disasters are of particular interest. This approach, that examines financial performance to see resiliency and robustness of supply chains, is similar to the trends in businesses. For example, Gartner, which is the leading information technology research company, have annually published Supply Chain Top 25 ranking since 2005. In 2012, Gartner attempted to measure resiliency of supply chain. The company assumed that companies with good and steady financial performance are more likely to manage supply chain than companies with unstable performance, though they did not examine TTR [8].<sup>1</sup>

### 2.3. Perspectives for analyzing supply chain resiliency and robustness

Third, the concepts that are needed to analyze product and process features are introduced. We use the four perspectives proposed by Fujimoto [9]: *dependence*, *visibility*, *substitutability*, and *portability*. The first perspective is dependence on suppliers. Extreme dependence on one supplier's product can make the supply network vulnerable. The second is *visibility of supply chains*. If the downstream companies in supply chains are unaware of a serious bottleneck in a supply network, there is a greater chance that the network cannot respond to the disruption quickly. The third is *design information substitutability*. If a product uses a specific design for a particular product, especially when the supplier uniquely controls design resources and processing of the product, then in a crisis, such products will be extremely difficult to replace by

<sup>1</sup> Hofman and Aronow [8] uses three-year average of return on asset (ROA) and revenue growth and standard deviations of these two financial indicators to calculate resiliency of supply chains.

switching suppliers or processors. Finally, the study uses the perspective of *design information portability*, which determines whether the design information used at a certain manufacturing plant can be transferred to another plant should a crisis arise. This, if each node in a supply chain possesses design information portability, it will contribute to the resiliency of the supply chain.

These concepts are corroborated by much of the empirical research. For example, through the case study and phone interview with the executives, Blackhurst, Craighead [10] found that the executives considered visibility as a key issue related to dealing with disruptions, particularly in trying to discover disruption. After collecting questionnaires from 760 executives from firms operating in Germany, Wagner and Bode [11] estimated ordinary least square regression models. They revealed that supply chain characteristics such as a dependence on certain customers and suppliers, the degree of single sourcing or dependence on global sourcing are positively correlated to a firm's perceived exposure to supply chain risk. They also found the unexpected result that dependencies on suppliers would decrease the exposure to natural hazard risks. They attributed this result to the fact that Germany is less vulnerable to natural hazards and suggested that future study must investigate the relationship between a firm's reliance on a supplier and exposure to catastrophe risks. From this perspective, Thailand's 2011 floods also provide a valuable insight.

## Part I: Case study of Thailand's floods of 2011

### 3. Overview of the Thailand's flood in fall 2011

#### 3.1. Contributing factors to floods

The Thailand flood impacts resulted from both natural and human-made factors. The first factor was a "La Niña" event that increased rainfall by 143% in the northern regions of Thailand early in the monsoon season, which consequently doubled runoff [12,13]. Due to this heavy rainfall, reservoirs exceeded their threshold storage level to prevent floods by the time large tropical storms such as Nock-Ten and Muifa arrived in late July 2011 [13]. In particular, the north-central region of Thailand had 40% above normal precipitation in September, and this represented the seventh straight month of above-normal rainfall levels [14].

The second factor was the topology of the region. Due to the gentle slope of the downstream parts of the Nan and Yom Rivers, which consist of the upstream of the Chao Phraya River system, a large area was flooded, and a high volume of discharge flowed into the lower watershed from the narrow section of the river system [12]. In addition, the Chao Phraya River has only modest bank full capacity, particularly in the downstream section, which is flood prone. Thus, there was much more water upstream than the downstream channel was able to manage [15]. Then, the water that flowed into the lower watershed broke water gates and levees downstream from the Chao Phraya River [12].

The third factor was the land-use of the region. Bangkok is located on former floodplains, where natural waterways and wetlands were replaced with urban structures [16]. Although Bangkok and surrounding industrial parks

are located in flood-prone areas, developers had failed to prepare for the strong likelihood of persistent and recurrent flooding [13]. In addition, land subsidence in Bangkok might have worsened floods' damage, given that the elevation of Bangkok is 0.5 meter to 1.5 meter above mean sea level [17]. Land subsidence in Bangkok was 10cm per year in 1978, though the rate declined to 0.97 cm per year between 2002 and 2007 [18]. Cumulative subsidence is reported by several studies. Nutalaya, Yong [19] reported that it was 160 centimeter between 1933 and 1988 while Ramnarong [20] found that it was 54 centimeter between 1978 and 1982. Consequently many areas in the city are vulnerable to persistent flooding even if the water conveyed over the levees or through levee breach is modest.

The fourth factor was the water management in the region. There are two competing objectives that confound water management: (i) storing water for use during the dry season; and (ii) minimizing flooding during the wet season [21]. In addition, Thailand has had to adapt to rapid changes in water use as a result of the country's swift evolution from an agricultural to an industrial nation. Due to the urbanization and decentralization of Thailand, it has also become difficult to secure floodplains [22]. Poor governance and coordination of the national and local governments have also made it difficult to control floods as a whole [22]. The floods were not individually extreme in terms of the return period of the peak flow. However, the duration of flooding was extreme, and the recurrent input of water overwhelmed the storage capacity of the reservoirs and the bank capacity of the rivers, following the existing reservoir operation policy. If the reservoirs had been drained or lowered in anticipation of the floods, some of the damage could have been avoided. However, if the floods had not materialized subsequently, regional water supply would have been adversely impacted. As it turned out the reservoirs were filled by the first flood wave and given the subsequent rainfall maintaining rivers below the bank full capacity was not feasible. The situation could have been averted or the impact reduced if accurate climate forecasts were available. Consequently, a combination of management and physical constraints conspired to create the flood impacts.

#### 3.2. Physical damage

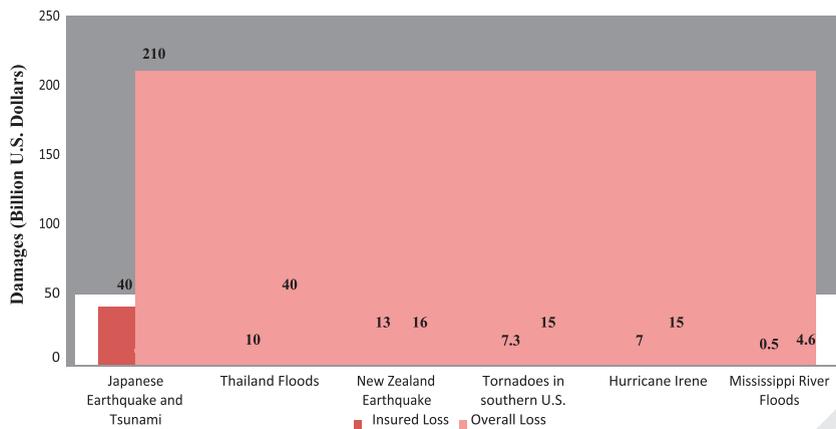
The flood in Thailand that occurred in fall 2011 is the most notable example showing the impact of floods both on industries and the whole economy. The floods began in the

**Table 2**  
Impact of 2011 floods in Thailand.

Impacted households <sup>a</sup>	1,886,000
Destroyed homes <sup>b</sup>	19,000 homes
Displaced people <sup>a</sup> (Affected people)	2.5 million people
Casualty	813 people
Impacted farm land <sup>a</sup>	17,578 square kilometers
Economic damage and losses <sup>b</sup>	Thai Baht 1.43 trillion (USD 46.5 billion)
In Manufacturing Sector	Thai Baht 1007 billion (USD 32 billion)

<sup>a</sup> The Government of Thailand [24].

<sup>b</sup> The World Bank [25].



**Fig. 1.** Damages of the major disasters in 2011.

Source: Munich Re. [23].

summer of 2010 and gradually subsided by the end of the year. According to Department of Disaster Prevention and Mitigation, Ministry of Interior of Thailand, there were 1.8 million households affected, 813 casualties [23], and 17,578 square kilometers of inundated farm lands (Table 2).

#### 4. Costs to the whole economy of Thailand

##### 4.1. Loss of GDP

The impact of the prolonged floods on the world and the Thailand economy was devastating. UNISDR [26] estimated that Thailand's 2011 flood reduced the world's industrial production by 2.5%. The World Bank [15] estimated that the real GDP growth rate declined from 4.1% expected to 2.9%. The impact of the flooding in Thailand was obviously reflected in the insured damage, which has been assessed \$10 billion (Fig. 1) [23]. The top three major non-life insurance companies in Japan paid out \$5.3 billion for the damage caused by the flooding in Thailand, an amount that was greater than the one resulting from the earthquake and the tsunami on March 11, 2011 [27].

##### 4.2. Impact on industrial parks

In addition to affected farmland, seven industrial parks were inundated (Table 3). The total number of companies in the seven inundated industrial parks was 804. Of those, 56.7% were owned or operated by Japanese companies. It took from 33 to 62 days to complete discharging from the inundated industrial complexes (Table 3).

Table 4 originally reported by Sukegawa [29]<sup>2</sup> shows what percentage of facilities in these inundated industrial parks restored operations. 75 % of factories in the seven inundated industrial parks have resumed operations, including resumption of operations in part, as of June 1, 2012. However, only

<sup>2</sup> Sukegawa [29] in Japan External Trade Organization (JETRO) inquired to Industrial Estate Authority of Thailand (IEAT). JETRO asked about the level of recovery of all of 839 factories in all of 7 inundated parks.

40% of those factories have recovered to pre-flood levels of production. Therefore, some 17.5 % of factories located in the seven inundated industrial parks could not resume operations. Saha Ratta Nanakorn Industrial Estate, which was the first one inundated, has the lowest percentage, 59%, of restoration, while the first three industrial parks inundated have the highest percentages of closing businesses (11% for Saha Ratta Nanakorn Industrial Estate and Hi-Tech Industrial Estate, and 14% for Rojana Industrial Park).

#### 5. Impacts on industries and firms

##### 5.1. Overview of affected industries

Due to the damage to these industrial parks, the manufacturing sector contributed to 8.6% of the decline of the real GDP between October and December 2011 [22]. The manufacturing industry comprised 39.0% of Thailand's GDP in 2011, and the damage to the manufacturing sector was 122 billion baht, which represented 71% of the total loss of real GDP (171 billion baht) [30]. For this reason, the disruption of supply chains in the manufacturing sector had such a large influence on the Thai economy as a whole.

Specifically, according to METI [22]<sup>3</sup>, the following products in the manufacturing industry declined productions in November 2011: transport machinery industry (such as pickup truck and passenger car) was minus 84.0%, compared to the same month of the last year; office equipment (mainly HDD) was minus 77.2%; information and communications equipment (semiconductor devices, IC communication equipment, television, radio, TV etc.) was minus 73.0%, electrical products such as air conditioning, refrigerator was minus 58.7%. Therefore, this paper will focus on these two sectors: automobile and electronics sectors.

<sup>3</sup> METI stands for Ministry of Economy, Trade, and Industry of Japanese government. 2012's White Paper on International Economy and Trade published by Ministry of Economy, Trade and Industry of Japanese government has featured Thailand floods of 2011 in one of their chapters.

**Table 3**  
List of flooded industrial parks.  
Source: JETRO [28].

Industrial Park or Estate	Province	Number of companies (number of Japanese companies)	In un dated date	Date completed draining water	Time to finish drainage (days)
Saha Ratta Nanakorn Industrial Estate	Ayutthaya	42 (35)	Oct. 4, 2011	Dec. 4, 2011	62
Rojana Industrial Park	Ayutthaya	218 (147)	Oct. 9, 2011	Nov. 28, 2011	51
Hi-Tech Industrial Estate	Ayutthaya	143 (about 100)	Oct. 13, 2011	Nov. 25, 2011	44
Bang Pa-in Industrial Estate	Ayutthaya	84 (30)	Oct. 14, 2011	Nov. 17, 2011	35
Nava Nakorn Industrial Estate	Pathum Thani	190 (104)	Oct. 17, 2011	Dec. 8, 2011	53
Bankadi Industrial Park	Pathum Thani	34 (28)	Oct. 20, 2011	Dec. 4, 2011	46
Factory Land (Wangnoi) Industrial Park	Ayutthaya	93 (7)	Oct. 15, 2011	Nov. 16, 2011	33
Total		804 (451)			

**Table 4**  
Status of recovery of in un dated industrial parks (As of June 1, 2012).  
Source : Sukegawa [29].

Industrial park or estate	Number of factories	Operation has restored		% yet	Operation has not restored	Businesses has closed	
		Fully Restored	Partly Restored				
Saha Ratta Nanakorn Industrial Estate	46	14	13	59	14	30%	5 11%
Rojana Industrial Park	213	69	85	72	30	14%	29 14%
Hi-Tech Industrial Estate	143	75	27	71	25	17%	16 11%
Bang Pa-in Industrial Estate	90	46	31	86	12	13%	1 1%
Nava Nakorn Industrial Estate	227	55	107	71	57	25%	8 4%
Bankadi Industrial Park	36	7	17	67	9	25%	3 8%
Factory Land (Wangnoi) Industrial Park	84	70	14	100	0	0%	0 0%

## 5.2. Automobile sector

The Federation of Thai Industries reported that the total number of cars produced in 2011 was 1.45 million, which was 20% below the expected production number (1.8 million cars) at the beginning of 2011 [31]. This number was down 11.4% when compared with the production of cars in 2010 (1.64 million cars), and experts attribute the decline to the supply chain disruption caused by the Japanese earthquake and the Thai floods. Particularly, the production from October 2011 to December 2011 declined drastically while the production in April and May 2011 decreased possibly due to the time-lagged effect of the Japanese earthquake and Tsunami in March 2011 (Fig. 2).

### 5.2.1. Direct and indirect damage to Japanese automakers

Thailand is one of the production hubs for global automobile manufacturers, particularly for Japanese automakers. Japanese firms and their family companies account for approximately 90% of sales and exports of automobile in Thailand. Thus, this paper focuses on Japanese automakers to measure the impacts of floods on the automobile sector in Thailand. First, Honda Motor Company, Ltd. had to stop its operations beginning on October 4, 2011, at the Ayutthaya factory and beginning on October 6, 2011, at its factory near Bangkok. Specifically, the factory

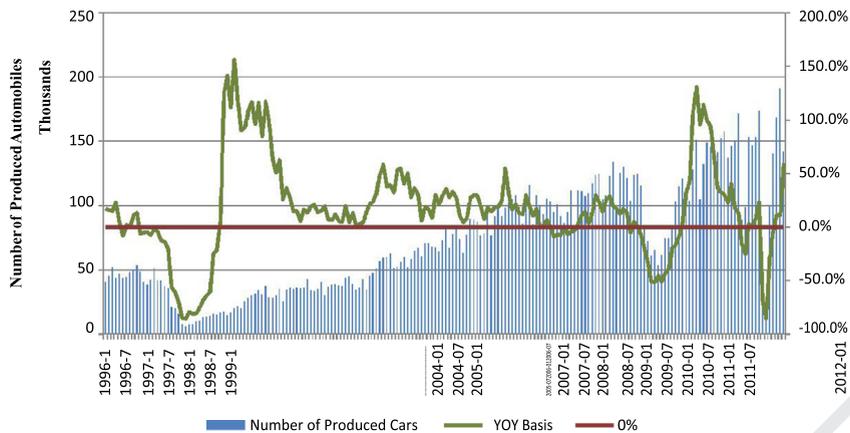
at Ayutthaya was inundated on October 8. As far as Toyota Motor Corporation Ltd. and Nissan Motor Company Ltd. are concerned, their factories were not inundated, but their operations were shuttered due to lack of parts from suppliers beginning on October 10, 2011, for Toyota, October 11 for Ford, and October 17, 2011, for Nissan.

### 5.2.2. Needed time to recover

The time required to recover from the Thai floods, namely TTR, differed with each automaker and was largely dependent upon the extent of the damage suffered at the factories in question. Toyota required 42 days to resume operations; Nissan, on the other hand, resumed operations in just 29 days. In contrast, Honda, whose factory at Ayutthaya was inundated, required 174 days to resume its production cycle due to the extensive nature of the damage to its facility (Table 5).

### 5.2.3. Consequences and impact

The impacts vary by company. Toyota lost more cars to the Thai floods than to the Japanese tsunami. Toyota, Honda, and Nissan lost 240,000, 150,000, and 33,000 cars, respectively, because of the Thai floods (Table 6). Toyota and Honda were more impacted by the flood than Nissan; and Nissan recovered more quickly than other auto companies because it had dissolved the Keiretsu



**Fig. 2.** Monthly production of automobiles in Thailand (passenger and commercial cars).  
Source: METI [22].

**Table 5**

Damages to factories of Japanese automakers and required TTR.  
Source : Press release of each companies.

	Factory	Place	Damage	Starting date for adjusted/stopped production	Date when production is resumed	TTR (days)	
	<b>Honda</b>	Honda Automobile	Rojana Industrial Park	Factory was Inundated on Oct 8th 2011, and stopped the production	Stopped production since 10/4/2011	3/26/2012 (Partly resumed)	174
	<b>Honda</b>	Thailand Manufacturing Company Ltd	Bangkok	No inundation of factory. Stopped production due to the lack of parts supply	Stopped production since 10/6/2011	11/14/2012 (Partly resumed)	40
	<b>Honda</b>	Suzuka Factory	Japan	Adjusted production due to the lack of parts supply	Adjusted production since 11/7/2011	12/5/2011 (Normal level of production)	28
	<b>Honda</b>	Saitama Factory	Japan	Adjusted production due to the lack of parts supply	Adjusted production since 11/17/2011	12/5/2011 (Normal level of production)	18
	<b>Honda</b>	6 Factories in the north America	North America	Adjusted production due to the lack of parts supply	Adjusted production since 11/2/2011	12/1/2011 (Normal level of production)	30
	<b>Honda</b>	Malaysia	Malaysia	Stopped production due to the lack of parts supply	Stopped production 10/25/2011	not available	Not available
	<b>Toyota</b>	Toyota Motor Thailand Ltd, Samrong Assembly	Samut prakan Province, Thailand	Factories were not Inundated Stopped production due to the lack of parts supply	Stopped Production since 10/10/2012	11/21/2011 (Partly resumed)	42
	<b>Toyota</b>	Toyota Motor Thailand Ltd, Gateway Assembly	Chachoengsao Province	Factories were not Inundated Stopped production due to the lack of parts supply	Stopped Production since 10/10/2013	11/21/2011 (Partly resumed)	42
	<b>Toyota</b>	Toyota Motor Thailand Ltd, Baan Poe Assembly Plant	Chachoengsao Province	Factories were not Inundated Stopped production due to the lack of parts supply	Stopped Production since 10/10/2014	11/21/2011 (Partly resumed)	42
	<b>Nissan</b>	Nissan Thailand, HQ Assembly Plant	Samut Prakan Province	Factories were not Inundated Stopped production due to the lack of parts supply	Stopped production since 10/17/2012	11/14/2011 (Partly Resumed)	29
	<b>Nissan</b>	Siam Motors and Nissan HQ Assembly Plant	Samut Prakan Province	Factories were not Inundated Stopped production due to the lack of parts supply	Stopped Production Since 10/17/2012	11/14/2011	not available

system<sup>4</sup>, diversified sources of supply, and globalized the procurement system [32]. Also, Nissan had a higher

inventory to prepare for increasing sales. In contrast to Nissan, whose plants were not inundated, Toyota lost the almost same amount of operating profit as Honda even though Toyota's three assembly plants were not inundated and Honda's plants were (Tables 5 and 6). This shows that supply chain characteristics, for example, the damage to

<sup>4</sup> A Keiretsu is a group of closely related family companies, often with interlocking ownership.

critical node such as an assembly plant, inventory management, and the degree of a firm's reliance on suppliers, translates into damages across supply networks. (Fig. 3)

In order to show the interdependencies of automobile sectors among countries, the study referred to the Intermediate goods trade of transportation machinery between Thailand and other countries. Table 7 shows that the exports from Thailand are more important for the Philippines (14.30%), Malaysia (26.00%), and Indonesia (25.80%) than for Japan (8.0%) and NAFTA (0.30%). Therefore, this study looked at Malaysia and Indonesia to examine the indirect effects of the flooding in Thailand to the supply chains.

The decrease in production impacted the sales for the trade partners to which manufactured cars in Thailand are exported. Fig. 4 and Table 8 show how Thailand's year-over-year (YOY) basis of automobile production is associated with those of Malaysia and Indonesia. Indonesia's

YOY basis is robust, while Malaysia experienced a decrease in automobile production between October 2011 and January 2012, when Thailand was experiencing supply chain disruptions. However, after February 2012, when Thailand resumed production, Malaysia seemed to need even more time to resume sales.

Fig. 5 demonstrates how the reduced production of automobiles in Thailand influenced the consumption of automobiles in Malaysia and Indonesia. Malaysia's sales of automobiles decreased, up to a minus 25%, until April 2012. Indonesia's consumption was relatively robust; however, consumption in November 2011 became negative even though Indonesia was experiencing a constant increase in sales in most of the previous months.

In addition, between January 2011 and November 2011, the import of transport equipment in the Philippines from Thailand declined by 21.5% compared to the same period in 2010 (automobiles' decline rate was 36.9% and

**Table 6**  
Impacts of the Thailand floods on Japanese major automakers.  
Source: Press release of each companies.

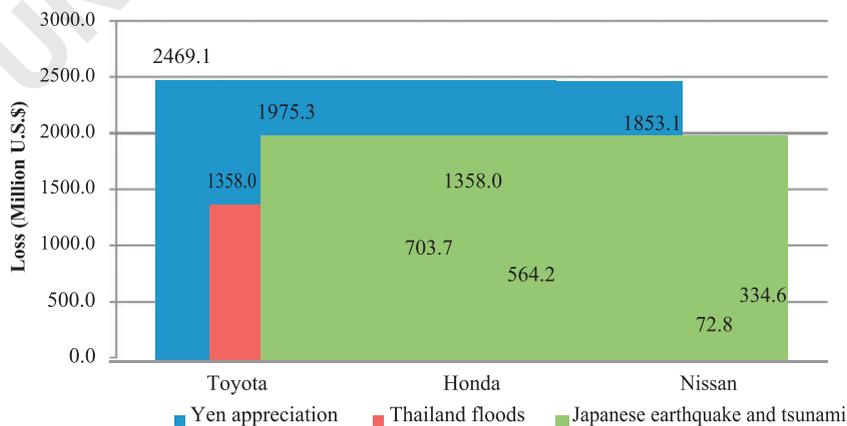
Statistics	Toyota	Honda	Nissan
Number of lost cars at global due to Thailand floods (thousand cars)	240	150	33
Operating profit (billion yen)	270 (\$3.4B) <sup>a</sup>	200 (\$2.5B)	510 (\$6.4B)
Lost operating profit due to Thailand floods (billion yen)	100 (\$1.25B)	110 (\$1.4B)	5.9 (\$0.07B)
Percentage of loss of operating profit caused by Thailand flood to operating profit	37.04%	55.00%	1.16%
Operating Profit (% compared to 2010)	-42.30%	-64.90%	-4.70%
Net profit (billion yen)	200 (\$2.5B)	215 (\$2.7B)	290 (\$3.6)
Net profit (% compared to 2010)	-57.50%	-59.70%	-9%

<sup>a</sup> The exchange rate was used for 80 Japanese yen for 1 U.S. dollars, which was the rate at that time.

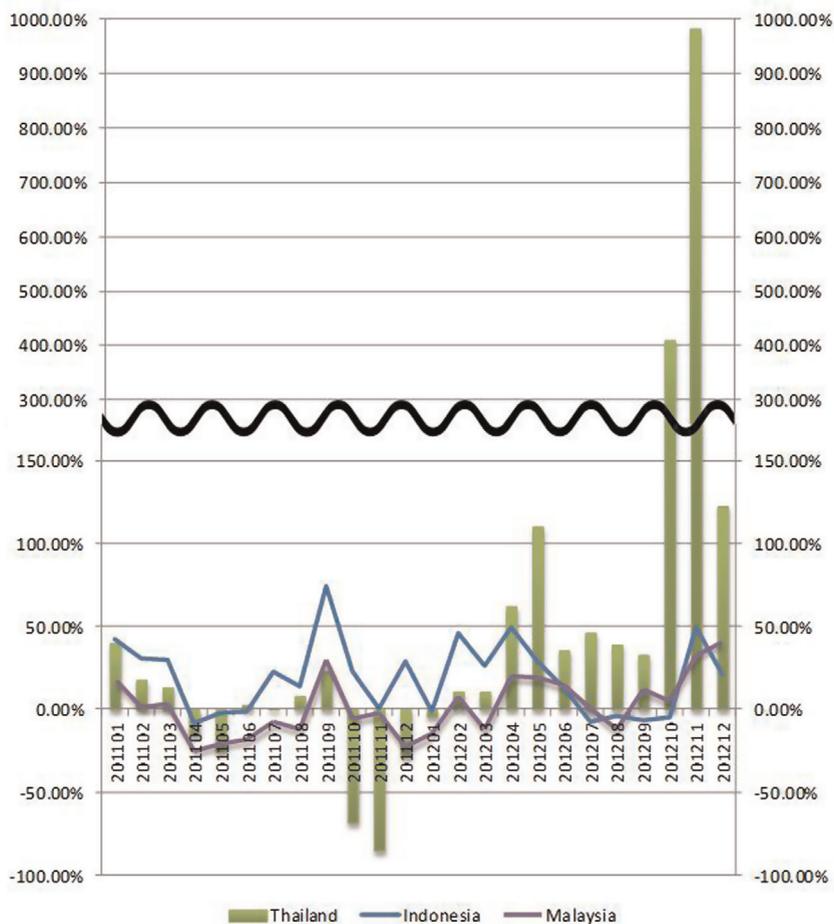
**Table 7**  
Trade of intermediate goods of transportation machinery of Thailand in 2010.  
Source: METI [22].

	Export from Thailand	Import to Thailand
<b>NAFTA</b>	306 0.30%	156 0.20%
<b>Taiwan</b>	71 2.70%	124 2.20%
<b>South Korea</b>	29 0.60%	190 1.60%
<b>Japan</b>	603 8.00%	3770 9.0%
<b>China</b>	57 0.30%	269 1.30%
<b>Philippines</b>	103 <b>14.30%</b>	361 <b>42.30%</b>
<b>Malaysia</b>	685 <b>26.00%</b>	101 6.80%
<b>Indonesia</b>	792 <b>25.80%</b>	282 <b>20.00%</b>

Upper cell is amount (\$1 million) and lower cell is share in the exports/imports of a partner country (%). Total amount of exports is \$4.1 billion and that of imports is \$ 6.0 billion.



**Fig. 3.** Decreased operating profits of Japanese major automakers (April–December 2011).  
Source: Press releases of each company.



**Fig. 4.** Production of automobiles in Thailand, Indonesia, and Malaysia on YOY basis.

Source: Markline. The wavy line in the figure shows that the range has been omitted to include the wide range of the statistics.

automobile parts' decline rate was 35.1%), while the total import in the Philippines from Thailand decreased by 8.3% [33]. As a result of the lack of import from Thailand, the sales of new automobiles in the Philippines decreased by 4.0%, up to 140,000 cars [33]. This example shows that the impact of supply chain disruption will resonate to overseas' markets through global supply chains.

#### 5.2.4. Cause of the damage

An analysis by METI (2012) concluded that the automobile sector suffered these enormous losses primarily because one company, that produces critical components for automobile makers, was inundated. The manufacturer in question produces components such as power integrated circuits (IC); system LSIs for audio and navigation; transistors; and condensers. Although METI (2012) did not specify the name of the company, it is very likely ROHM Co., Ltd., a major producer of ICs and other electronic components. It has been reported that one of its competitors, Renesas Electronics Corporation, alternatively produced for ROHM. METI (2012) claims that due to the dearth of electronics components as a direct result of the flooding, automobile sectors were indirectly impacted, and

in particular passenger vehicles that routinely include such electronics equipment in their design. The second reason the damage to the automobile industry was so great was the location of facilities and factories. METI (2012) and Ishii (2006) both argue that transportation costs were the primary factor in these automakers' decisions to invest in these Thai locations, which are close to ports, and that it is normal for the industry to select such a location since automobiles are both large and heavy, representing substantial shipping costs.

#### 5.3. Electronics sector

This section will examine mainly the impacts of floods on Hard Disk Drive (HDD) makers.

##### 5.3.1. Direct and indirect damage to HDD makers

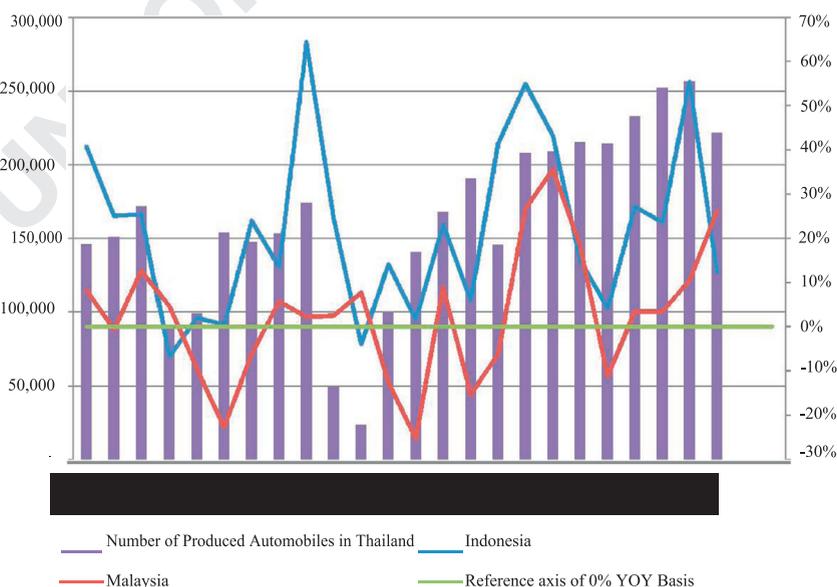
The electronics sector was also severely impacted. Before the 2011 floods, Thailand produced approximately 43% of the world's hard disk drives [22]. Western Digital Corporation, which produced one-third of the world's hard disks, lost 45% of its shipments because their factory in Bang Pa-in Industrial Estate, Ayutthaya was inundated

[34]. The Toshiba factory, one of the four major makers of HDD, was also inundated. Toshiba was able to execute alternate production in the Philippines. While factories of Samsung and Seagate Technology, other two makers of the four major manufactures, were not inundated, they were forced to reduce production due to the lack of parts from suppliers who were impacted.

**Table 8**  
Automobile production (Number of cars on YOY basis).  
Source: Markline

	Thailand (%)	Indonesia (%)	Malaysia (%)
Jan-11	40.81	41.96	17.42
Feb-11	17.91	31.05	1.55
Mar-11	13.72	29.56	3.00
Apr-11	-15.16	-8.30	-24.66
May-11	-25.24	-1.99	-20.34
Jun-11	3.20	-1.75	-18.04
Jul-11	1.01	22.38	-7.85
Aug-11	8.60	13.40	-11.93
Sep-11	23.13	74.42	29.46
Oct-11	-67.62	22.33	-5.49
Nov-11	-84.92	0.53	-2.51
Dec-11	-27.64	28.62	-22.85
Jan-12	-3.90	-1.40	-14.67
Feb-12	11.51	45.57	7.48
Mar-12	10.89	25.89	-12.27
Apr-12	62.80	49.53	19.80
May-12	110.52	28.48	18.95
Jun-12	35.87	12.74	14.67
Jul-12	46.25	-7.13	0.44
Aug-12	39.96	-4.04	-12.15
Sep-12	33.52	-6.78	11.88
Oct-12	410.05	-5.24	5.03
Nov-12	982.85	48.92	32.85
Dec-12	122.63	20.72	40.95

Bold numbers are months of negative YOY Basis.



**Fig. 5.** Number of produced automobiles in Thailand and YOY Basis of number of sold automobiles in Malaysia and Indonesia.

5.3.2. Needed time to recover

Table 9 shows the damages and needed TTR of major makers of HDD in the world. Western Digital partly restored the production after 46 days of stoppage. Toshiba, which has factory in Nava Nakorn Industrial Estate, needed 114 days to restore operations.

5.3.3. Consequences and impacts

HDD shipments from the industry's five major manufacturers declined severely in the fourth quarter of 2011 to 123.3 million units, which was down 30% from 175.2 million units the quarter before [35]. The effect of the lost electronic parts production rippled across the global economy. The lack of hard disk drives increased the price of desktop HDD by 80–190% and mobile HDD by 80–150%. This clearly shows that the world economy is closely interconnected through a global supply chain network and the indirect damage of disasters now easily affects the consumer market at the global scale in the electronics sector.

In terms of the impact on the market price, even six months after all the inundated industrial parks completed water drainage after the flooding, most of the prices of both hard disk drives (HDD) and solid state disks (SSD) remain higher than the prices before the floods [36] (Fig. 6).

5.3.4. Differences in electronics industry

Another example illustrating that the impact of floods was distinct among companies in the same industry is shown in the electronics sector. In the beginning of 2012, Western Digital's earnings decreased 35%, up to 145 million dollars, while Seagate increased its profit from 150 million dollars to 563 million dollars. This is primarily because Western Digital's factories were in the flood zones, while Seagate was mainly affected through their

**Table 9**

Damages to major HDD makers.  
Source: Press release.

Company	Place of factories	Damage	State of operation /production
<b>Western Digital</b>	1) Bang Pa-in Industrial Estate	Factories inundated (2 m)	- Stopped production since Oct 16, 2011
	2) Nava Nakorn Industrial Estate		- Partly restored on Nov 30, 2011 - Needed days to restore:46 days
<b>Toshiba</b>	Nava Nakorn Industrial Estate	Factory was inundated (1 m)	- Stopped production since Oct 11, 2011 - Alternate production in Philippines - Partly restored Thai factory on Feb 1, 2012 - Need dates to restore: 114 days
<b>Seagate Technology</b>	1) Seagate Teparuk, Amphur Muang, Samutprakarn Province	Factories were not inundated	- Some adjusted production due to the lack of supply from suppliers
	2) Seagate Korat, Amphur Sungnoen, Nakhon-Ratchasima		
<b>Samsung</b>	In South Korea	Factories were not inundated	- Some adjusted production due to the lack of supply from suppliers

supply chain [37]. As a consequence, Seagate recaptured the top position in hard disk drive shipments during the fourth quarter of 2011, since it only declined 8% compared to third -quarter figures of 50.8 million units. Western Digital's shipment, on the other hand, declined significantly by 51%, from 57.8 million units in the earlier quarter [35]. Thus, the causes for these differences must be investigated in the future study.

#### 5.4. Difference between automobile and electronics sectors

The production recovery of HDD makers was slower than that for automobiles. Fig. 7 shows that the transport equipment industry recovered more quickly than the HDD sectors. Many companies in the electronics industry had facilities in Ayutthaya, where industrial parks were inundated. In contrast, some automobile manufacturers had recently acquired facilities in regions southeast of Bangkok, such as Chonburi and Rayong Province, where only some companies were inundated. On the other hand, METI (2012) described the different responses among these two sectors in terms of alternate production. Major producers of HDD and electronic component parts fully operated their facilities in countries other than Thailand for alternate production. However, automobile companies could not transfer their production to other areas. In this sense, the design information portability of the automobile sector was lower than that of the electronic sector.

## 6. Recovery and new responses

### 6.1. Importance of the issues and ignorance among some companies

Interestingly, existing surveys demonstrate that many companies will not significantly change their investment

behavior. According to a survey conducted by Japan External Trade Organization (JETRO)<sup>5</sup>, 78% of 50 companies directly impacted by the floods continued to operate in the same location [38]. The survey also concluded that some of these companies could not transfer to different facilities due to a lack of financial capacity. In comparison, 16 % moved their operations to places other than the original inundated industrial complexes [38]. This is consistent with the results of a survey conducted by METI [39]<sup>6</sup>. Of 67 surveyed companies, some 68% responded that they would not change their plans for investment in plant and equipment in fiscal year (FY) 2011 as a result of the business impact of the floods in Thailand (Fig. 8). Additionally, of 62 Japanese companies surveyed, 66% answered that Thailand still represented an appealing investment (Fig. 9). This is because companies might have stronger incentives to invest to Thailand since Japan and Thailand have had a free trade agreement since 2007.

However, the METI [39] survey also revealed changes in attitudes regarding the need for alternative procurement sources. In Thailand, of 17 companies surveyed, a mere 24% indicated that they would replace all of their substitute suppliers with their original suppliers once the original suppliers recovered from the floods (Fig. 10). In Japan and other affected countries, only a few companies (below 10% of 52 firms surveyed) answered that they would replace all of their substitute suppliers with their original suppliers, and approximately 20% of 52 companies in Japan and other countries answered that they would resume less

<sup>5</sup> JETRO conducted the survey on January 11 of 2012 to 95 companies. 50 companies (40 manufactures and 8 non-manufactures) were directly impacted. 45 companies (33 manufactures and 12 non-manufactures) were indirectly impacted.

<sup>6</sup> METI conducted the survey from November 30, 2011 to December 7, 2011 to 67 large companies (including 59 manufacturers and 8 non-manufacturers).

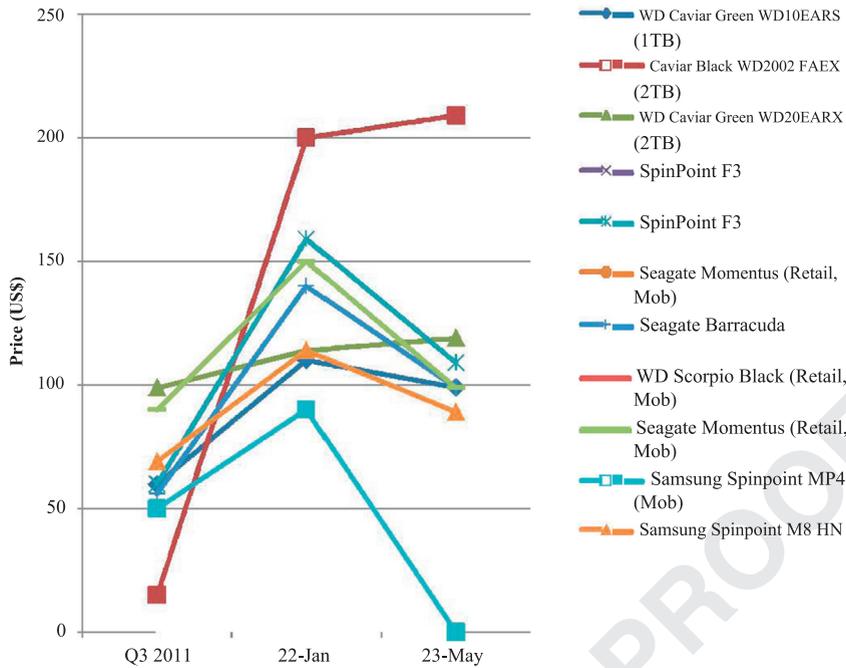


Fig. 6. Change of prices of HDD and SSD. Source: Hruska [36].

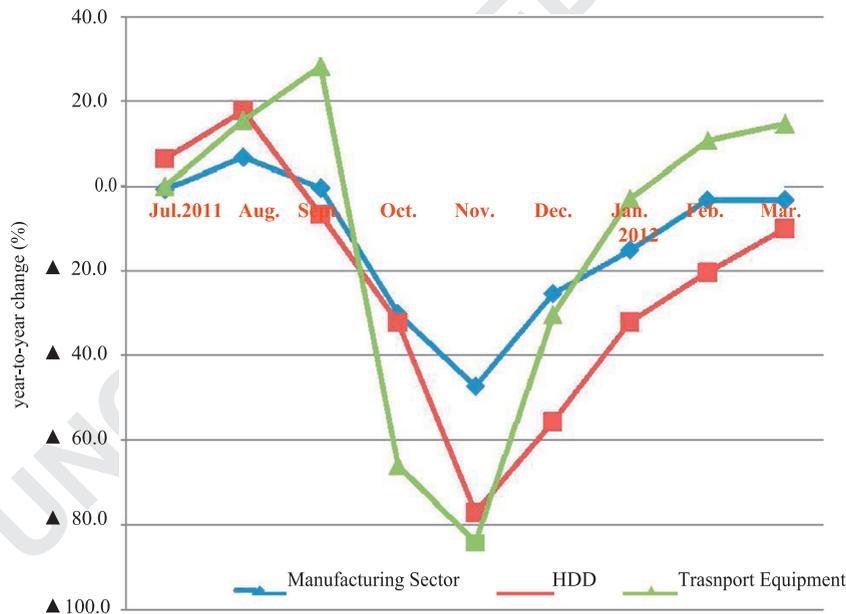


Fig. 7. Production index of manufacturing, HDD and transport machinery. Source: The Office of Industrial Economy through METI [22].

than half of their business with their original suppliers (Fig. 10). This demonstrates that there is a very real risk of suppliers losing customers, and that they must seriously consider flood risks in their investment decisions.

### 6.2. Responses in automobile and electronics industries

Some of the companies have already started redesigning the supply chain network. Toyota has reported that

they are going to move some of the production in Japan to different regions, such as to the US, in order to change their globally centralized production system to a regionally independent production system, such as General Motors has already done. Takahashi [40] also reported that Toyota requested that about 500 of their suppliers disclose details of their supply chains. After receiving responses from about half of them, they found that 300 production places could be vulnerable to risks. Then, Toyota requested that

1 these suppliers mitigate risks by measures such as diversifying procurement, securing alternate facilities, and increasing inventories. At the same time, Toyota expects that

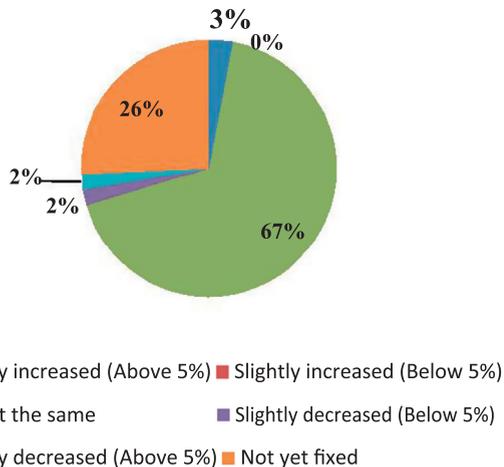


Fig. 8. Change in FY 2011 equipment investment plan under the impact of the flood in Thailand. The number of Japanese companies that responded is 65. Source: METI. [39]

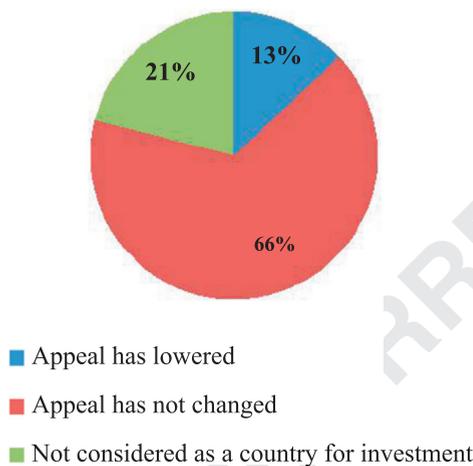


Fig. 9. Change in appeal of Thailand as the country for investment after the flood. The total number of Japanese companies that responded is 62. Source: METI. [39]

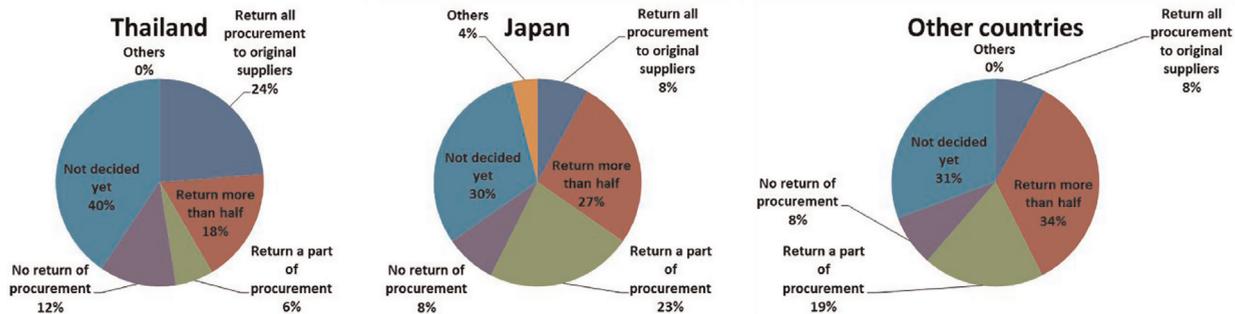


Fig. 10. Substitution procurement period and prospect for substituting suppliers in Thailand, Japan and other countries. The total numbers of manufacturing companies that responded are 17, 26, and 26 respectively. Source: METI [39].

suppliers will benefit, since they are trying to reduce the number of types of parts and increase the lot size of order from each supplier. In June 2013, Honda also started constructing its new automobile production plant in Prachinburi Province, which faces less flood risks since it is located at a higher elevation.

Also In the electronics industry, Kaga Electronics decided to close their factory in Rojana Industrial Park in Ayutthaya, which was inundated by the flood, and move to Amata Nakorn Industrial Estate, which is less vulnerable to flood risks. According to the METI that collected a survey from 67 companies from 13 industries operating in Thailand, 44% of the respondents were considering moving their production system [39]. Therefore, it is critical for local governments to properly manage floods since they will lose important economic advantages if many companies move their production hubs to safer areas.

### 6.3. Responses in insurance industry

The flood in Thailand has shown the insurance industry the importance of the supply chain for them, as well. For instance, Swiss Reinsurance Company Ltd expected the amount of its exposure from the flood would be approximately \$600 million for their company and \$10 billion to the entire industry, while Munich Reinsurance Company estimated its losses at approximately \$655 million [23,41]. It required some time before the total effect of insured damages was confirmed. This was partly because of the limited ability of survey companies to evaluate business interruption losses, such as lost revenue, especially in association with supply chains, because of the lag time to resume operating machinery, and retooling and rehiring of staff [41].

In Thailand, fire and profit insurance covered flood risks before 2011, while in other countries such as Japan, fire insurance does not cover flood risks. This increased the insured losses in Thailand drastically. Yet, after the floods in 2011, major insurers began executing sub-limits for flood coverage. Responding to this, the Thai government established the National Catastrophe Insurance Fund of Thailand (NCIF) in March 2012. Based on this fund, a Catastrophe Insurance Policy (CIP) was created in July 2012. Companies can apply for insurance that covers flood

risks provided by CIP through private insurance companies.

#### 6.4. Responses in the government and international society

In March 2012, the Thai government proposed strategies and action plans for flood prevention. These include local defense; industrial park protection; inner logistic roads; river dredging, dike and water gate; flood collection area and infrastructure strengthening; and forestation and dam management. The government also proposed action plans (Table 10).

Foreign governments, particularly the Japanese government, have provided assistance to Thailand. The Japan International Cooperation Agency (JICA) completed the Flood Management Plan of the Chao Phraya River in July 2013 and provided technical assistance for a Single Command Authority of water management. In addition, the JICA continues to assist the Thai government with upgrading infrastructure such as major transportation routes and constructing new water gates that contribute to maintaining supply chains.

## Part II: Research questions

### 7. Research questions and indices for supply chain resiliency

This section of the paper will discuss research questions and a hypothesis that were developed in the wake of Thailand's floods, and other cases of supply chain risks.

#### 7.1. Critical node and link

The first research question reflects the observation that the loss is greater if a factory that produces a unique component or plays a critical role in a supply chain is directly impacted by a disaster. This is obvious from the case of Honda or Western Digital in Thailand. When examining the time needed to recover, the electronics sector took longer to recover to "pre-flood" levels of production than the automobile industry for the simple reason that the electronics sector's facilities were more directly damaged by floods.

*Q1: How can critical nodes and/ or links such as assembly factories or transportation hubs whose flooding would lead to significant and persistent supply chain losses be reliably identified in the supply chain network?*

This is also hypothesized from the results of the questionnaire done by METI [39]. Of 55 companies surveyed in Thailand, some 55% pointed out that they had to cease production because their facilities were submerged (Fig. 11). This number is relatively high compared to the 22% of firms that indicated they had to decrease production due to stagnant procurement from customers adversely affected by the floods. This is consistent with the claim of Fujimoto (2011) that extreme dependence on one supplier can be a "weak link" in a supply chain. Other

**Table 10**

Proposed action plans by Mr. Chadchart Sittipunt, Deputy Minister of Transport, The Royal Thai Government.  
Source: Sittipunt [30].

Action plan	Immediate (6 months)	Medium (1–3 Years)	Long (3–5 Years)
1 Dike in industrial Parks	x		
2 King Dike	x		
3 Dredging River Delta	x		
4 Road Rehabilitation	x		
5 Water Detention Area	x	x	
6 Raising Level of Highway	x	x	
7 River/Canal Dredging	x	x	
8 Upgrading Logistic Routes	x	x	x
9 New Dam and Reservoir		x	x
10 New Flood Way			x
11 Single Command Center	x	x	
12 Forecasting and Warning Systems	x	x	

cases, such as the fire at Aisin Seiki [53]<sup>7</sup> and the damage to Micro Control Unit's (MCU) facilities following the Japanese Earthquake [54]<sup>8</sup>, also lend qualitative support to this question. Yet, there are a few studies that quantitatively examine this question from the network analysis perspective.

#### 7.2. Alternative bridge tie

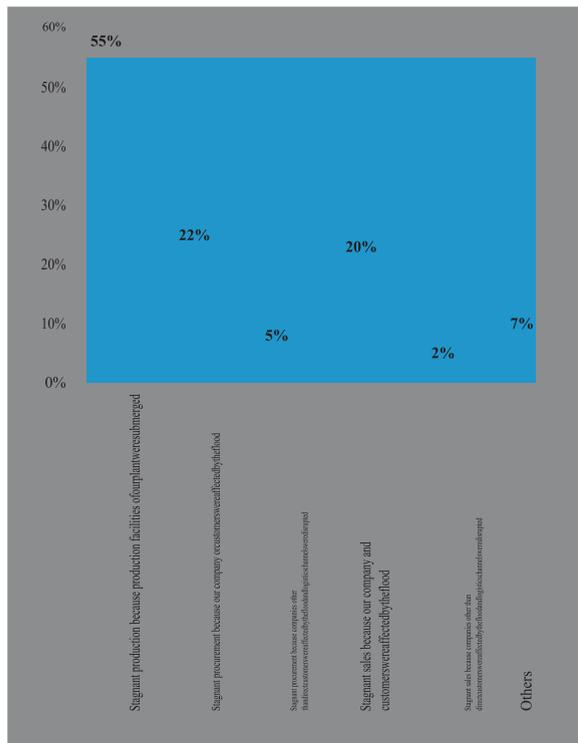
The second question to be addressed is as follows:

*Q2: How can the effectiveness of bridge ties to a different supply network be established as an aid to recovery from a flood induced supply chain problem? What are the associated global material supply chain constraints and resulting impacts?*

In the case of the 2011 Thailand floods, Nissan recovered more rapidly than Toyota and Honda because it had diversified its suppliers and owned alternative sources.

<sup>7</sup> Aisin Seiki Co., which produced 99% of Toyota's critical valves, had a fire on February 1st, 1997. Because of the Just-in-time system, Toyota kept only enough inventory of the valve for 4 h of production. Initially Toyota estimated 2 weeks to resume partial production and 3 months for full production. Toyota had to stop all of 20 assembly plants in Japan, and lost 14,000 cars a day. Toyota sent more than 400 engineers to help Aisin to resume operations. In the end, they could recover production in 5 days.

<sup>8</sup> Renesas Electronics Corporation had to stop Naka factory, which is their main factory in Ibaraki that produces MCU for major automakers such as Toyota and General Motors, after the Japanese Tohoku Earthquake and Tsunami in March 2011. Right after the earthquake, they estimated that they could resume partial production in July 2011. Yet, more than 2000 engineers from their business partners helped them to recover, and consequently Renesas could restore operations on April 23<sup>rd</sup> 2011.



**Fig. 11.** Factor or lower production level in Thailand. Total number of manufacturing companies that responded is 55. Multiple choices.  
Source: METI [39].

Yet, given that the alternate bridge will contribute to the resiliency of a supply network, what factors contribute to the establishment of an alternative bridge tie? In order to have an alternative bridge, companies should have design information substitutability [9]. By doing so, a company can bring its design to other facilities in a crisis, and manufacturers can shift production of their parts to another supplier, or, suppliers can shift their operations to facilities that have not been adversely affected. In the case of the automakers in Thailand, this did not happen, with the result that the auto makers could not transfer their operations, or manufacturers could not find other suppliers in the automobile sector. In contrast, the electronics sector was able to transfer production to other countries in response to the lack of production in Thailand [22]. For example, Toshiba Storage Device relied on an alternate production in Philippines before they restored the Thai factory on February 2nd 2012 after 144 days of shutdown.

The survey conducted by METI [39] may give some tentative basis to answer this question. For example, some 60% of companies in Thailand could not substitute procurement sourcing because fundamental product design were submerged. However, design substitutability might conflict with the competitiveness of companies that gain an advantage in the marketplace because of their irreplaceable designs [39]. Therefore, in order to make indices of substitutability, we must consider the balance between substitutability and competitiveness.

### 7.3. Strong ties

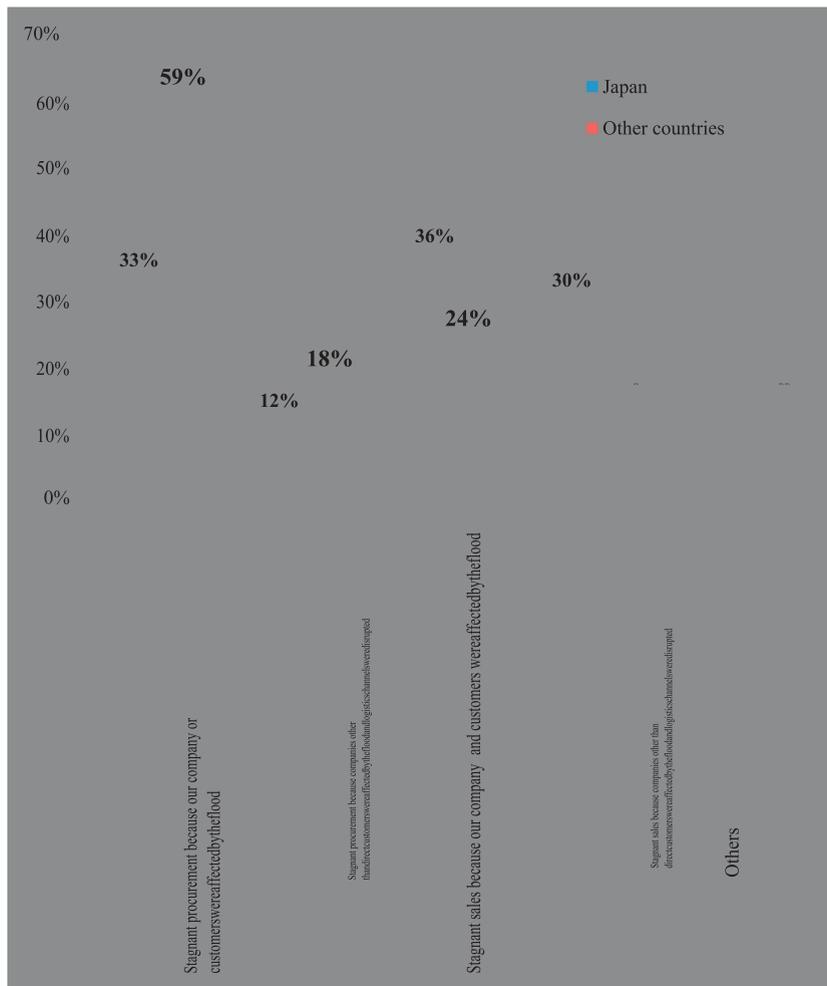
Another observed case favoring a well-managed supply chain occurred when Toyota's supplier Aisin had a fire on February 1, 1997, which caused Toyota to lose its supply of brake parts, since Aisin provided 99% of Toyota's valves at that time. Fujimoto [9] claimed that Aisin resumed operations within one week, although it was originally expected to be out of business for three months. The timeframe for resumption of operations was significantly reduced when Toyota dispatched its engineers to repair Aisin's facility. As a result, even though Toyota was initially expected to incur greater losses as a result of the disruption, since it would lose 14,000 a day, [53] its intervention minimized the damage. If a company depends only on one company for a specific part, it may incur greater damages, as suggested by Q1. Yet, as this case shows, if the ties between the two companies are strong as well as pliable, both companies may be able to avoid some damage. Therefore, the hypothesis is as follows:

*H1: If a supply chain is comprised of strong ties to one company exclusively, then immediate damages from a disaster will likely be greater. Yet, even if business partners in the same supply chain network are not directly impacted by disaster, the impacted node may receive help from them and may therefore be able to recover more quickly, with the result that damages may be mitigated.*

Here, the strong ties are defined as repeated, affective, relational exchanges [55]. Strong ties would promote trust, create social norms, and facilitate cooperation as a consequence [55]. Though H1 hypothesizes that strong ties would reduce risks to disasters, other studies such as Uzzi [56] and Afuah [57] claim that strong ties may induce idiosyncratic features and become less valuable for firm performance in the future. Thus, it is important to examine H1 in the context of resiliency, robustness, and competitiveness of supply networks.

### 7.4. Direction of arrows

The Thailand floods revealed that manufacturing is affected not only by the lack of procurement, but also by decreases in sales. According to the METI survey (2011), of 33 production bases located in Japan, some 66% declined production due to "stagnant sales" because the surveyed companies, their customers (tier 1), or companies under them (tier 2) were affected by the flood, or because logistics channels were disrupted (Fig. 12). This number is higher than the statistic representing stagnant procurement resulting from flood damage to a company and its customers, which is 33%. Since their customers are affected, producers must reduce production even when they have sufficient capacity. In contrast, in other countries, of 17 companies surveyed, 59% selected "stagnant procurement resulting from flood damage to our company and customers" for their first choice (Fig. 12). This shows that companies must manage supply chains by looking not only at their supply side, but also at the other side, i.e., the



**Fig. 12.** Factors of lower production in Japan and other countries. The total numbers of manufacturing companies that responded are 33 for Japan and 17 for other countries. Multiple choices. Source: METI. [39]

demand side. With this in mind, a modeled network needs to distinguish directions of the link/edge. Thus, the third question is as follows:

*Q3: The direction of links in a network affects the robustness and resiliency of a supply network. How does the complexity of a network, including the direction of links affect the robustness and resiliency of a supply chain network to floods?*

### 7.5. Supporting policies

These hypotheses are related to the factors that this study proposes as indices, such as *locations of facilities, alternate locations of production, the diversified sources of procurement, emergent assistance from other partner companies in the same supply chain, and degree of the recovery of customers.* The next question is which policies could generate the types of factors found to determine these resilient supply chains. The simulation conducted by Miles

and Chang (2003) indicated that the pre- disaster mitigation measures directed at lifeline systems and restoration of transportation system after disasters significantly benefited recovery period for businesses. During the Thai floods of 2011, lifeline and the transportation system had a damage of 57.4 billion Thai Baht [15]. The damage is relatively lower than the damage in manufacturing sector (1007 billion Thai Baht) [15]. Yet, there is a possibility that the loss of the lifeline and transport systems negative would affect the manufacturing sector. There are few studies or reports that examines the interdependencies between lifeline and transport systems and supply chains in the context of resilience to disasters. Thus, the last research question is as follows:

*Q4: How do transportation and lifeline systems affect the performance of entire supply chains during floods?*

## 8. Conclusion

The impact of floods in Thailand on the economy in terms of supply chains was examined. Components that should be investigated to assess key supply chain risks from such events were identified. The review suggests that automotive and electronic products supply chains had somewhat different mechanisms of risk transmission and response that translated into different times to recovery, loss and market performance at the individual company level. The need for flood prone countries to consider local risk proofing as part of industrial development was emphasized, both by the nature of the resulting losses to the country and to the global supply chain, and due to the realignment of potential future investment and supplier networks. Regional flood proofing could benefit from systemic risk analysis and its use in infrastructure design, land use zoning, water infrastructure operation, transportation systems functioning, and climate and flood forecasts. Resilience in the supply chains of those who had higher inventories and alternate suppliers was demonstrated consistent with the expectation of supply chain performance under disruption. This brings up the question of how best supply chains could be optimized considering market, production, inventory and disruption due to natural hazards.

Surveys show that most of the affected companies want to operate in the same locations and indeed, they answered that Thailand is still an attractive place for their investment. Given the fact that the Chao Phraya basin has had recurrent floods, unless proper measures are provided, similar disasters may happen again in the near future. The government has announced some measures to prevent future floods, but private sectors must also take proper preventive and responsive measures in their investment decision-making. Companies have to maintain competitiveness while increasing resiliency. Costs might increase when manufactures ask their suppliers to diversify risk and procurement sources. Thus, it is important to identify how they can build resiliency in a more efficient way without losing their economic competitiveness, which is a critical consideration in future research.

By examining the case study of Thailand and other cases related to extreme events and their concurrent risks, this study suggests four research questions and one hypothesis using the concept of Network Analysis.

Q1: How can critical nodes and/ or links such as assembly factories or transportation hubs whose flooding would lead to significant and persistent supply chain losses be reliably identified in the supply chain network?

Q2: How can the effectiveness of bridge ties to a different supply network be established as an aid to recovery from a flood induced supply chain problem? What are the associated global material supply chain constraints and resulting impacts?

### H1.

Q3: How does the complexity of a network, including the direction of links affect the robustness and resiliency of a supply chain network to floods?

Q4: How do transportation and lifeline systems affect the performance of entire supply chains during floods?

These research questions and hypothesis are related to indices that were proposed, such as *locations of facilities, alternate locations of production, the diversified sources of procurement, emergent assistance from other partner companies in the same supply chain, and degree of the recovery of customers.*

Future research should quantitatively examine the resiliency and robustness of supply chains to disruptions caused by extreme events, and to formulate a way to reduce vulnerability to risks while maintaining competitive edge. In so doing, the potential effectiveness of different strategies for risk management in such situations, ranging from redundancy in the supply chain, increased inventory to targeted insurance, and their combination could be assessed. The role and utility of climate and weather forecasts to take defensive action can be part of this examination.

### Uncited references

[42–52].

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